Special Publication SJ93-SP4

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

Prepared for

St. Johns River Water Management District
Orange County Public Utilities Division
City of Cocoa

Prepared by

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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 eastern-most Orange County, however, the Floridan aquifer contains water with chloride concentrations that exceed the EPA recommended limit of 250 mg/l for public supplies. Freshwater for central Brevard County is obtained from the Cocoa well field in eastern Orange County. Increased demands on the Floridan aquifer in Orange and Osceola counties, along with anticipated increases in water demand in the rapidly growing urban areas of western Orange and northwestern Osceola counties, have demonstrated the need for regional water resource management efforts.

The study described in this report is a portion of an ongoing program to address the pressing need for a long-term, environmentally sound, water resources management policy, under joint funding by the St. Johns River Water Management District (SJRWMD), the City of Cocoa, and the Orange County Public Utilities Division (OCPUD). The primary purpose of this study is to provide the means for regional analysis of ground-water resources in eastern Orange County to guide planning and management efforts. The major emphasis is on the Floridan aquifer system.

It was decided that the best technical approach to address the given problem would be a series of three, mutually dependent, numerical modeling studies that incorporate the large amount of hydrogeological data available for the east-central Florida region. The first phase (Phase I) of the study 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 and Birdie, 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 District in assessing the impacts of utilizing sources of fresh ground water in Orange and Seminole Counties over a twenty-year planning period (Blandford and Birdie, 1992). 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 well field 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 and final phase of the study (Phase III) is the topic of this report. The primary purpose of the Phase III 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 eastern Orange County and immediately adjoining regions. The model also needed to retain sufficient flexibility such that future refinements could be made as additional data is acquired. Of particular importance is the potential for the degradation of fresh ground-water resources in the vicinity of the Cocoa well field and Orange County's proposed Eastern Regional well field (ERWF). The scope of work for the Phase III 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 eastern Orange 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 well fields as a demonstration of the model's capability to forecast impacts of future ground-water demand at existing and potential well field sites.

- Assess drawdown impacts and water quality degradation for the years 2010, 2060 and 2110 subject to withdrawal and well field location scenarios provided by the District as a demonstration of the model's capability to forecast impacts of alternative future ground-water development scenarios.

The overall technical approach for the Phase III modeling consisted of five major steps. First, the relevant hydrogeological literature and data pertaining to the study area was 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 well fields, and the results of the earlier (Phase II and Phase IV) 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 are dependent largely upon the Phase IV regional modeling results (Blandford and Birdie, 1992). 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 years 2010, 2060 and 2110 based upon projected ground-water withdrawals for the year 2010 and proposed well field locations.

The computer code DSTRAM was selected for use during this study. 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. 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.

In order to correctly calibrate the Phase III 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. However, in the vicinity of the Cocoa well field, chloride concentrations have been increasing gradually since the first wells were put on-line. It is important that the calibrated model have the ability to simulate the increase in chloride concentrations with time at the Cocoa well field, particularly in the Upper Floridan aquifer, from which the water supplies are obtained.

For much of eastern Orange County, it is a reasonable assumption that essentially natural hydrogeologic conditions prevailed prior to construction of the Cocoa well field. Therefore, 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 32 years or so (the first Cocoa well was completed in 1956). All postdevelopment (average 1988) simulations, therefore, were transient simulations run for a time period of 32 years; predevelopment simulation results were used as a starting condition. All predevelopment model simulations were run to steady state.

The Phase III model was successfully calibrated to predevelopment and average 1988 conditions and is suitable for the prediction of regional scale trends in chloride concentrations over the long term (decades). The model simulations conform well to the conceptual model of the ground-water flow system, and the simulation results match well with observed hydraulic heads (generally within 2 ft) and chloride concentrations. The only calibration targets that were not met particularly well in the simulations are the observed chloride concentrations in the middle semiconfining unit at the Cocoa C well, and the observed increase in chloride concentration from predevelopment to average 1988 conditions in the deep (Lower Floridan) Cocoa C sampling zone. Given the absence of data concerning aquifer characteristics in the vicinity of Cocoa C, however, it is doubtful that an improved calibration could be obtained in this region without making arbitrary and unjustifiable (in terms of observed data) changes to the model.

Although the Phase III 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

2) Observed potentiometric head in the Lower Floridan

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

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

Due to the above data constraints, the model can not be considered to be rigorously calibrated with respect to the Lower Floridan. This has potential implications for the simulation results within the Upper Floridan since the Lower Floridan is the major source of salt for this unit. At present, the simulated chloride concentrations in the Lower Floridan are in reasonable agreement with observed chloride concentrations at the Sand Lake Road test well, the Merritt Island injection test well, the ERWF deep test well, the Cocoa R test well, and the Orange County Landfill and Deseret Ranches geophysical test sites. However, taken as a whole with respect to the size of the modeled area, these calibration (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.

Using the calibrated Phase III model, a series of 5 predictive simulations were performed. The first, or base-case, simulation incorporated the actual estimated 2010 pumpage at the ERWF, the Cocoa well field, and at all other withdrawal points within the model domain. The four additional simulations are various permutations of the first based upon projected 2010 demand. The purpose of these simulations 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. Of particular interest is the potential for increased chloride concentrations in the vicinity of the Cocoa well field, since this well field is vulnerable to the upconing and lateral 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, 1992). Projected pumping increases were only derived for municipal and industrial supplies obtained from the Upper and Lower Floridan; 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.

The Phase IV modeling results indicated that substantial drawdowns from average 1988 conditions would occur in eastern Orange County in response to the projected 2010 pumping rates. Much of the simulated drawdown was attributable to Orange County's proposed ERWF, at which about 30 ft of drawdown for 2010 was simulated. Simulated drawdown at the Cocoa well field varied from about 15 ft at the West well field to about 10 ft at the East well field. Even when pumping due to ERWF was eliminated, wide-spread drawdowns of over 10 ft were simulated for much of eastern and central Orange County.

For the base-case 2010 predictive simulation, the 2010 pumping estimates used in the current model were the same as those used in the Phase IV predictive simulation. Orange County's ERWF had a projected 2010 withdrawal rate of 45.4 million gallons per day (MGD), and the Cocoa well field had a projected withdrawal rate of 28 MGD (the projected total withdrawal for the Cocoa well field is actually 31 MGD, but 3 MGD is supposed to be obtained from the intermediate aquifer that overlies the Upper Floridan, and thus was neglected in the model). The increased Cocoa well field pumping for 2010 conditions was distributed among the Cocoa wells that existed in 1988, and among a series of new wells in both the West and East Cocoa well fields, some of which were being constructed as of the writing of this report. The total projected 2010 average daily flow (ADF) required by the City of Cocoa is actually 48.2 MGD, but 17.2 MGD of this total is expected to be obtained from the Taylor Creek Reservoir, which is several miles south of the City of Cocoa's Dyal Water Treatment Plant. Furthermore, due to the vulnerable nature of the East Cocoa well field, the current well field consumptive use permit (CUP) limits total discharge from the East well field to 5.2 MGD, and it limits the completion depth of the new wells in the East well field (Cocoa wells 38-44) to about the upper one-third or so of the Upper Floridan. These conditions and restrictions were taken into account in developing the 2010 pumping estimates for the Cocoa wells.

Each of the four additional predictive simulations (referred to as simulations A, B, C and D), are founded upon the base-case scenario, but certain withdrawals were varied among well fields to observe the potential effects of distributing pumping in a different manner. Each scenario was specified by the District. The premise of each of the four predictive scenarios is outlined below:

Scenario A - All projected 2010 Cocoa average daily flow (ADF), 48.2 MGD, was withdrawn from the Upper Floridan at the Cocoa well field, except for 3 MGD which is assumed to come from the intermediate aquifer and was neglected in this study. The balance of the projected increase in ADF (17.2. MGD) was distributed between the new Cocoa wells and the existing West Cocoa well field wells (nos. 13-19). All other withdrawals were unchanged.

Scenario B - Same as scenario A, except the balance of the projected increase in ADF (17.2 MGD) was distributed among all the existing and planned Cocoa wells based upon well capacity.

Scenario C - The pumping at Orange County's ERWF was reduced from 45.4 MGD to 15.4 MGD. The balance of 30 MGD was withdrawn from the Lower Floridan at Orange County's Orangewood well field, which is located southwest of Orlando in the vicinity of the Sand Lake Road test well. The Orangewood well field was considered to be off-line in the base-case simulation. All other withdrawals were unchanged.

Scenario D - Same as Scenario C, except that ADF at the ERWF was 32.6 MGD (= 15.4 MGD + 17.2 MGD); the additional 17.2 MGD is Cocoa's projected increase in ADF.

Scenarios A and B are designed to examine potential impacts if Cocoa's additional demand past 1995 could not be supplied by the Taylor Creek Reservoir. Scenario C is designed to examine the potential benefits of moving some of the large ERWF projected demands to another, possibly better suited, location in the county. Scenario D is a hybrid management scenario of the other three simulations. Each Phase III predictive modeling scenario was conducted as a transient simulation, with results obtained for 2010, 2060 and 2110. Emphasis, however, should be placed upon the 2010 results only, since hydrologic conditions, available data, and the calibrated model itself may well change substantially prior to the later (2060 and 2110) simulation dates. For example, the predictive simulations described below are already partially outdated since Orange County does not presently expect to obtain withdrawals of 45 MGD from ERWF, but rather plans to use other well fields to supplement ERWF production (Review Comments of David MacIntyre submitted to Rob Teegarden, October 7, 1992). A summary of the predictive simulation scenarios is provided in Table E.1. For each of the predictive scenarios, the Phase IV regional model was run to obtain boundary conditions for the Phase III subregional model. This procedure was necessary since simulated drawdowns in response to estimated 2010 withdrawals extend well beyond the Phase III model domain.

The base-case predictive simulation indicates that poor quality water will continue to upcone at the East Cocoa well field, and lateral intrusion of poor quality water into the West Cocoa well field will continue to occur. However, as of the year 2010, all of the Cocoa production wells in the West well field continued to produce water with chloride concentration less than 250 mg/l in the simulation, and the same was indicated for the year 2110 with the exception that Cocoa well 7A produced water in excess of 250 mg/l. The regional 250 mg/l isochlor in eastern Orange County moved a relatively small distance to the west towards the Cocoa well field by 2010, but by the year 2060 this isochlor moved a significant distance west and combined with the 250 mg/l isochlor formed by upconing in the northern half of the East Cocoa well field.

The results of the base-case predictive simulation also indicate that there is the potential for substantial lateral intrusion of poor quality water in the Lower Floridan in the vicinity of the east side of Orlando and Winter Park. There is the potential that the Orlando Utility Commission's (OUC) Conway Plant will be adversely effected. Simulated drawdowns from 1988 conditions in the Lower Floridan in the vicinity of Orlando are about 20 ft. However, it must again be emphasized that the Lower Floridan aquifer was not rigorously calibrated in this study, and

Table E.1 Summary of predictive simulations.

Predictive Simulation	Comments	Predictive Simulation Withdrawal in million gallons per day		
		Cocoa Well Field	ERWF*	Orangewood Well Field
Base-Case		28.0	45.4	0.0
A	Increased withdrawal at Cocoa well field (relative to base case) distributed among new wells and existing wells 13-19, regardless of well capacity	45.2	45.4	0.0
B	Increased withdrawal at Cocoa well field (relative to base case) distributed among all existing and planned wells based upon well capacity	45.2	45.4	0.0
C	Withdrawal at Orangewood from the Lower Floridan aquifer	28.0	15.4	30.0
D	Withdrawal at Orangewood from the Lower Floridan aquifer	28.0	32.6	30.0

* Orange County planned Eastern Regional Well Field

additional hydrologic data and aquifer properties need to be obtained before highly certain predictions of drawdowns and chloride concentrations may be made for the Lower Floridan.

In predictive simulations A and B, 17.2 MGD of additional pumping was added to the estimated 2010 Cocoa well field withdrawal. The additional pumping represents the balance of the City of Cocoa's projected 2010 demand, which is planned to be obtained from the Taylor Creek Reservoir. In predictive simulation A, the increased withdrawal was distributed among the existing West Cocoa well field wells and the new Cocoa well field wells. In predictive simulation B, the additional pumping was distributed among all of the existing and proposed Cocoa wells based upon well capacity.

The results of predictive simulations A and B are very similar. The increased withdrawals caused additional drawdowns in the Upper Floridan of about 5 ft in the vicinity of the Cocoa well field, and of about 2 ft in the vicinity of ERWF. Simulated chloride concentrations in the Lower Floridan are nearly the same as for the base-case predictive simulation, but chloride concentrations in the Upper Floridan in the vicinity of the Cocoa well field increased significantly relative to the base-case simulation. By the year 2010, simulated chloride concentrations at Cocoa well 7A are in excess of 250 mg/l, and by the year 2060 simulated chloride concentrations reach 250 mg/l at Cocoa well 14. Also, from about Cocoa well 14 to a location slightly east of the East Cocoa well field, simulated chloride concentrations throughout the Upper Floridan equal or exceed 250 mg/l.

In predictive simulation C, pumping at ERWF was reduced from 45.4 MGD to 15.4 MGD. The balance of 30 MGD was withdrawn from the Lower Floridan at Orange County's Orangewood well field, which is about 5 miles due west of the western model boundary in the vicinity of the Sand Lake Road test well; the Orangewood well field was considered to be off-line in the base-case simulation. All other withdrawals were unchanged from the base-case simulation.

The results of this predictive simulation indicate that drawdown in the Upper Floridan would be reduced by about 15 ft in the vicinity of ERWF and by about 5 ft in the vicinity of the Cocoa well field. Despite the decreases in simulated drawdowns, however, the predicted chloride concentrations in the Upper Floridan are very similar to those of the base-case scenario. This result indicates that to a large degree, the degradation of water quality at the Cocoa well field is due primarily to pumping at the well field, rather than increased drawdown caused by simulated withdrawals at ERWF. Simulated chloride concentrations in the Lower Floridan are slightly less than those of the base-case scenario, since the potentiometric surface of the Lower Floridan increased by several feet in response to the decreased pumping at ERWF.

The modeling scenario for predictive simulation D is similar to that of predictive simulation C; the only difference is that a total of 32.6 MGD was withdrawn from the ERWF, rather than 15.4 MGD. The increased withdrawal of 17.2 MGD is equal to the City of Cocoa's projected increase in average daily flow for 2010. The results of this simulation are very similar to those of predictive simulation C and the base-case scenario, with the exception that the simulated potentiometric surface in the vicinity of ERWF is about 5 ft higher than in the base-case simulation. In terms of chloride concentrations, there is no substantial difference between predictive simulations C and D and the base-case predictive simulation, particularly in the vicinity of the Cocoa well field.

In addition to the predictive simulation modeling results, a number of conclusions can be based upon the modeling study. First of all, the model simulations indicate that the upconing and lateral migration of high chloride water in the immediate vicinity of the Cocoa well field is due primarily to pumping and local hydrogeologic conditions at the well field. This is despite the fact that predicted pumping at ERWF contributes to predicted drawdowns at the Cocoa well field by about five feet. The simulated westward migration of the regional 250 mg/l isochlor in eastern Orange County (dashed line in Figure 3.5) is not substantial as of 2010, but there is significant movement by 2060; the westward migration of this isochlor is due primarily to the combined effects of pumping at the Cocoa well field and ERWF. The Cocoa H monitoring well would be a good existing well to sample on a regular basis (perhaps annually) to document the westward movement of the 250 mg/l isochlor if it does in fact occur.

The modeling results also indicate that the movement of chlorides in the Lower Floridan is relatively independent of pumping in the Upper Floridan. In the predictive scenarios, there was a substantial lateral migration of 250 mg/l water in the Lower Floridan towards the cone of depression caused by Lower Floridan pumping in the vicinity of Orlando. In fact, the migration of the salty water was most likely inhibited by the proximity of the western and northern Phase III model boundaries. The extent of the lateral movement of saltwater in the Lower Floridan did not change appreciably between the various predictive scenarios, which differed primarily due to the prescribed pumping in the Upper Floridan. It must be noted, however, that historically significant increases in chloride concentrations at the Cocoa C well in the Lower Floridan have been observed; the concentrations presumably increased in response to pumping at the Cocoa well field. As noted earlier, the model simulations are not highly accurate with respect to the observed chloride concentrations at the shallow Cocoa C sampling zones (those in the middle semiconfining unit), or the increase in chloride concentrations with time at the deep Cocoa C sampling zone (top of the Lower Floridan).

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 scale. The model is not suitable for the prediction of chloride concentrations on a local scale at individual wells. As with all models used for predictive purposes, the model formulation and simulation results should be periodically evaluated and reassessed as additional data (at existing and new observation points) becomes available. New data and conceptualizations of the ground-water flow system should be incorporated into the modeling framework as required. 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 have additional data on hydraulic parameters of the Lower Floridan and the middle semiconfining unit; chloride observations in the Lower Floridan and the middle semiconfining unit; and water level elevations in the Lower Floridan. The major sources of error in the Phase III model stem directly from the lack of data available for the Lower Floridan aquifer.

To address the need for more information, a data collection program should be established to characterize the chloride and water level distributions within the Lower Floridan. This program should include a series of monitoring wells placed along at least one, and preferably two or three, lines that intersect the saltwater wedge at right angles (in eastern Orange County this would be a line of wells in approximately west-east orientation, rather than a north-south orientation). It would be advantageous if there were an Upper Floridan monitoring well in close proximity to each Lower Floridan monitoring well so that the direction of vertical ground-water flow between the Upper and Lower Floridan aquifers could be determined. The major purpose of the monitoring program would be to:

1) Characterize the lateral and vertical distribution of chloride concentrations in the Lower Floridan.

2) Characterize vertical ground-water flow between the Upper and Lower Floridan.

3) Monitor changes in Lower Floridan chloride concentrations, particularly in the freshwater-saltwater (chloride concentrations greater than 250 mg/l) transition zone resulting from natural and/or anthropogenic causes.

4) Develop baseline data against which future effects may be evaluated

The information gained from such a program could be used to evaluate the accurateness and adequacy of the current modeling approach and simulation results. If necessary, the new data could be used to update and recalibrate the model, and improve its reliability for predicting the impact of stresses (such as increased pumping) on the hydrologic system.

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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 eastern-most Orange County, however, the Floridan aquifer contains water with chloride concentrations that exceed the EPA recommended limit of 250 mg/l for public supplies. Freshwater for central Brevard County is obtained from the Cocoa well field in eastern Orange County. Increased demands on the Floridan aquifer in Orange and Osceola counties, along with anticipated increases in water demand in the rapidly growing urban areas of western Orange and northwestern Osceola counties, have demonstrated the need for regional water resource management efforts.

The study described in this report is a portion of an ongoing program to address the pressing need for a long-term, environmentally sound, water resources management policy, under joint funding by the St. Johns River Water Management District (SJRWMD), the City of Cocoa, and the Orange County Public Utilities Division (OCPUD). The primary purpose of this study is to provide the technical basis needed to determine the potential effects of alternative withdrawal scenarios on the ground-water resources in eastern Orange County. The major emphasis is on the Floridan aquifer system.

It was decided that the best technical approach to address the given problem would be a series of three, mutually dependent, numerical modeling studies that incorporate the large amount of hydrogeological data available for the east-central Florida region. The first phase (Phase I) of the study 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 District in assessing the impacts of utilizing sources of fresh ground water in Orange and Seminole Counties over a twenty-year planning period (Blandford and Birdie, 1992). 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 well field 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 Phase II modeling report is included with this report as an appendix.

The third and final phase of the study (Phase III) is the topic of this report. 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.

1.2 Purpose and Scope of Work

The primary purpose of the Phase III modeling effort is to develop a three-dimensional, density-dependent ground-water flow and solute transport simulation capability that is suitable for the prediction of ground-water levels and chloride concentrations in eastern Orange County and immediately adjoining regions. Of particular importance is the potential for the degradation of fresh ground-water resources in the vicinity of the Cocoa well field and Orange County's proposed Eastern Regional well field (ERWF). The scope of work for the Phase III 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 eastern Orange 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 well fields.

- Assess drawdown impacts and water quality degradation for the years 2010, 2060 and 2110 subject to withdrawal and well field location scenarios provided by the District.

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 various 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 was 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 well fields, and the results of the earlier (Phase II and Phase IV) 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, 1992). 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 well field locations.

2.2 Code Selection

The computer code DSTRAM was selected for use during this study. 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 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). DSTRAM has also been verified against problems with known solutions.

- 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, 1992). 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 III 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 Formation, which consists of marine interbedded sands and clays that are often phosphatic. The Hawthorn Formation 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 surficial aquifer on a regional scale is to either recharge the underlying Upper Floridan aquifer,

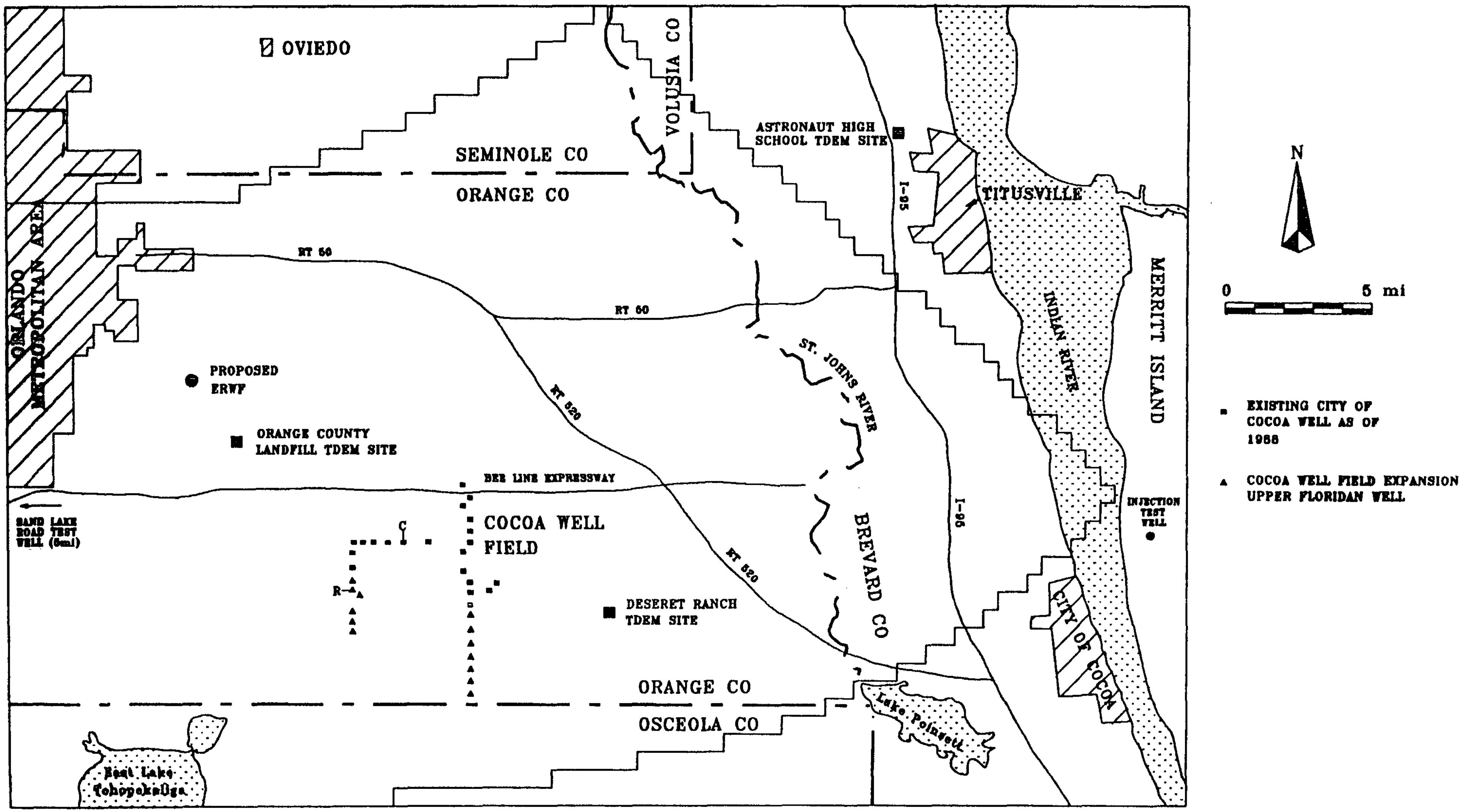


Figure 3.1 General base map for the Phase III study area and location of model domain.

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 Formation	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

Surficial 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), and McKenzie-Arenberg and Szell (1990).

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 productive 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 the vicinity of the Cocoa well field, 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 (CH_2M Hill, 1988 and Tibbals and Frazee, 1976). 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 ranges from about 2,300 - 2,500 ft in eastern and central Orange County. 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 thickness of the Upper Floridan is approximately 300 ft throughout much of the Phase III study area (Miller, 1986).

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 thickness of the middle semiconfining unit ranges from about 600 ft in western Orange County to about 800 ft in central and eastern Orange County (Miller, 1986). 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 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 was reasonable for the regional characterization of ground-water flow.

This Phase III 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 SJRWMD (Brian McGurk, personal communication).

The first step performed in order to define the three-dimensional geometry of the Floridan aquifer system within the study area was the comparison of the hydrogeological maps in Tibbals (1990) and Miller (1986) with other available sources of information. These maps were found to be quite accurate; no major discrepancies were observed between the map values and those obtained from well logs or other documented sources. For example, at Orange County's proposed Eastern Regional well field (ERWF), the hydrogeological analysis of a test well completed into the top of the Lower Floridan indicated thicknesses of 332 ft and 620 ft respectively for the Upper Floridan and the middle semiconfining unit. Miller's maps indicate that the Upper Floridan and middle semiconfining unit are about 300 ft and 600 ft thick, respectively, at the same location. Similarly, at Cocoa well 7A in the Cocoa well field the Upper Floridan is 320 ft thick as determined from geophysical well logs; Miller's maps indicate thickness of the Upper Floridan at the same location to be slightly greater than 300 ft. At Cocoa well 19, the Upper Floridan is about 275 ft thick as determined by geologic and geophysical logs (CH_2M Hill, 1982), which again is close to Miller's estimate of about 300 ft.

Since the hydrogeologic maps in Miller (1986) were found to be accurate, and since Miller provided maps of the top and bottom elevation of each major hydrogeologic unit, Miller's maps were used without modification to define the three-dimensional geometry of the Upper Floridan, the middle semiconfining unit, and the Lower Floridan within the study area. 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. Figure 3.3 was adapted from Miller (1986); it illustrates the altitude (relative to mean sea level, or msl) of the top of the Upper Floridan, the bottom of the Upper Floridan, the top of the Lower Floridan and the bottom of the Lower Floridan. 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.

3.4 Water Quality

This section provides an overview of the water quality in the Upper and Lower Floridan aquifers within the Phase III 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

Both Toth (1988) and Tibbals (1990) provide extensive discussions concerning water quality in the Upper Floridan, and to some degree the Lower Floridan, within the vicinity of the study area. In general, the dissolved solids (and chloride) content of the ground water decreases from east to west in both the Upper and Lower Floridan (Figure 3.4). Also, the isochlors are not oriented due north-south, but rather are tilted and exhibit a slightly northwest-southeast orientation. The poor quality water in eastern Orange and Brevard Counties 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.

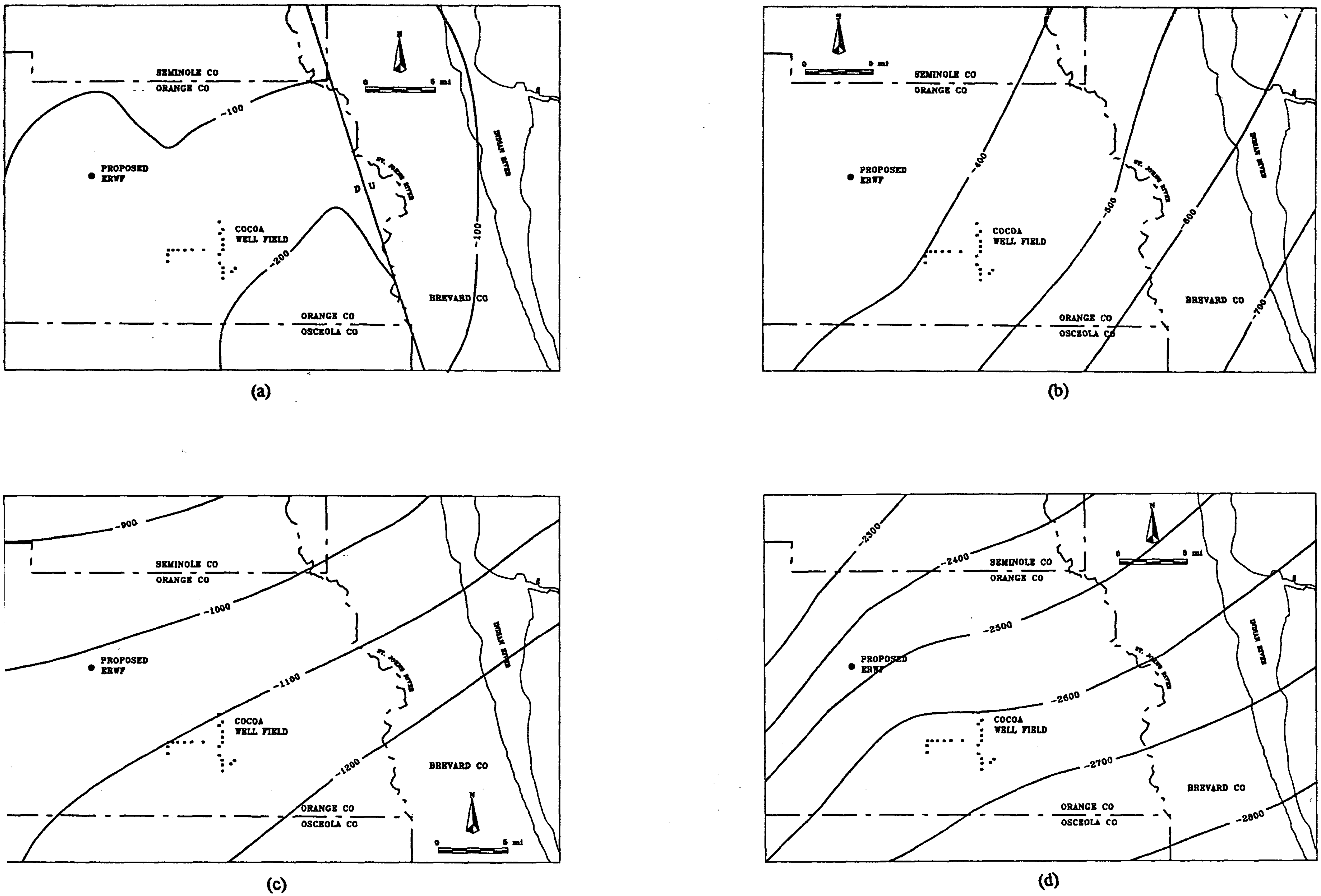


Figure 3.3 Altitude, in feet above mean sea level, of the top of the Upper Floridan (a); the bottom of the Upper Floridan (b); the top of the Lower Floridan (c); and the bottom of the Lower Floridan (d).

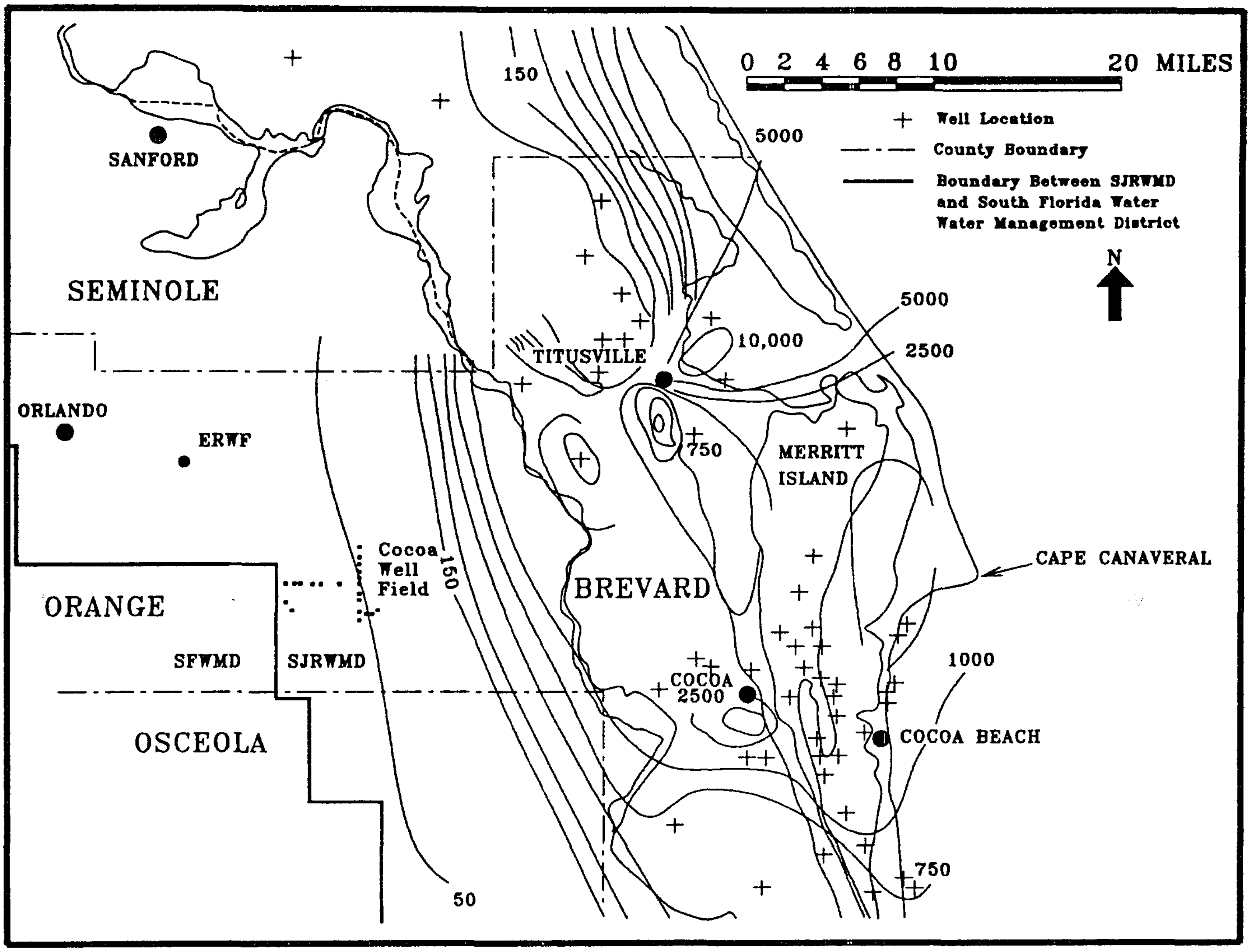


Figure 3.4 Contour map showing chloride concentrations in mg/l for the Upper Floridan (adapted from Toth, 1988).

Although Toth (1988) and Tibbals (1990) present general maps of chloride concentrations in eastern Orange County, it was decided that a more refined estimate of the 250 mg/l isochlor location would have to be made within the study area, since this isochlor is a key model calibration target. This task was accomplished by performing a detailed review of chloride sampling locations in eastern Orange County available in the District's digital data base. A summary of the wells used to determine the location of the 250 mg/l isochlor is presented in Table 3.1. One notable feature of the data presented in Table 3.1 is that for wells that have been sampled for chloride over a period of years, there is no appreciable change in chloride concentrations with time discernable (examine, for example, wells OR0011, OR0065, OR0003 and OR0029). This observation is consistent with that of Toth (1988).

Figure 3.5 illustrates the estimated location of the regional 250 mg/l isochlor in eastern Orange County developed for this study, and the observation well locations used to conduct the analysis. Since there is no evidence that there has been significant movement of the 250 mg/l isochlor through time in eastern Orange County (with the exception of the local area in the vicinity of the Cocoa well field, as discussed below), it was assumed that the isochlor location remained essentially unchanged from predevelopment to current (average 1988) conditions.

The general location of the 250 mg/l isochlor presented in Figure 3.5 is in good agreement with previously published studies, such as Toth (1988) and McKenzie-Arenberg and Toth (1990). The 250 mg/l isochlor lies just east of a 250-500 mg/l chloride concentration zone as delineated by Sprinkle (1982) and reproduced in Tibbals (1990). Planert and Aucott (1985) indicate the position of the 250 mg/l isochlor to be about 1 mile to the west of that illustrated in Figure 3.5, but they do not present the observation points used to determine that location.

Chloride concentrations generally increase steadily to the east of the 250 mg/l isochlor outlined in Figure 3.5. In the vicinity of the St. Johns River and points further east in Brevard County, chloride concentrations in the Upper Floridan are generally about 1,000 - 2,000 mg/l or greater.

Table 3.1 Summary of chloride observation data used to determine the position of the 250 mg/l isochlor in eastern Orange County.

SJRWMD Well ID	Casing Depth (ft)	Well Depth (ft)	Number of Samples	Period of Record	Average Conc. (mg/l)	High Conc. (mg/l)	Low Conc. (mg/l)	Comments
OR0079	--	--	8	1960-1971	365	390	340	
834059	--	--	1	1960	325	325	325	
832056	--	--	4	1962-1978	1,762	1,850	1,650	
832104	--	--	10	1968-1969	72	73	71	
832102	--	--	2	1968	82	83	81	
OR0011	--	200	19	1953-1977	640	690	615	
832058	--	--	1	1962	500	500	500	
OR0470	231	313	1	1963	39	39	39	Samples about upper 60 ft of Upper Floridan
OR0065	--	--	8	1965-1977	42	45	40	
OR0003	252	495	11	1961-1987	66	116	23	Samples lower 240 ft of Upper Floridan
828054	--	--	2	1964	4,090	7,059	1,119	
OR0029	244	390	8	1960-1972	346	351	340	Samples top 150 ft of Upper Floridan
823056	--	--	1	1961	339	339	339	
820055	--	--	1	1963	580	580	580	

-- Not Available

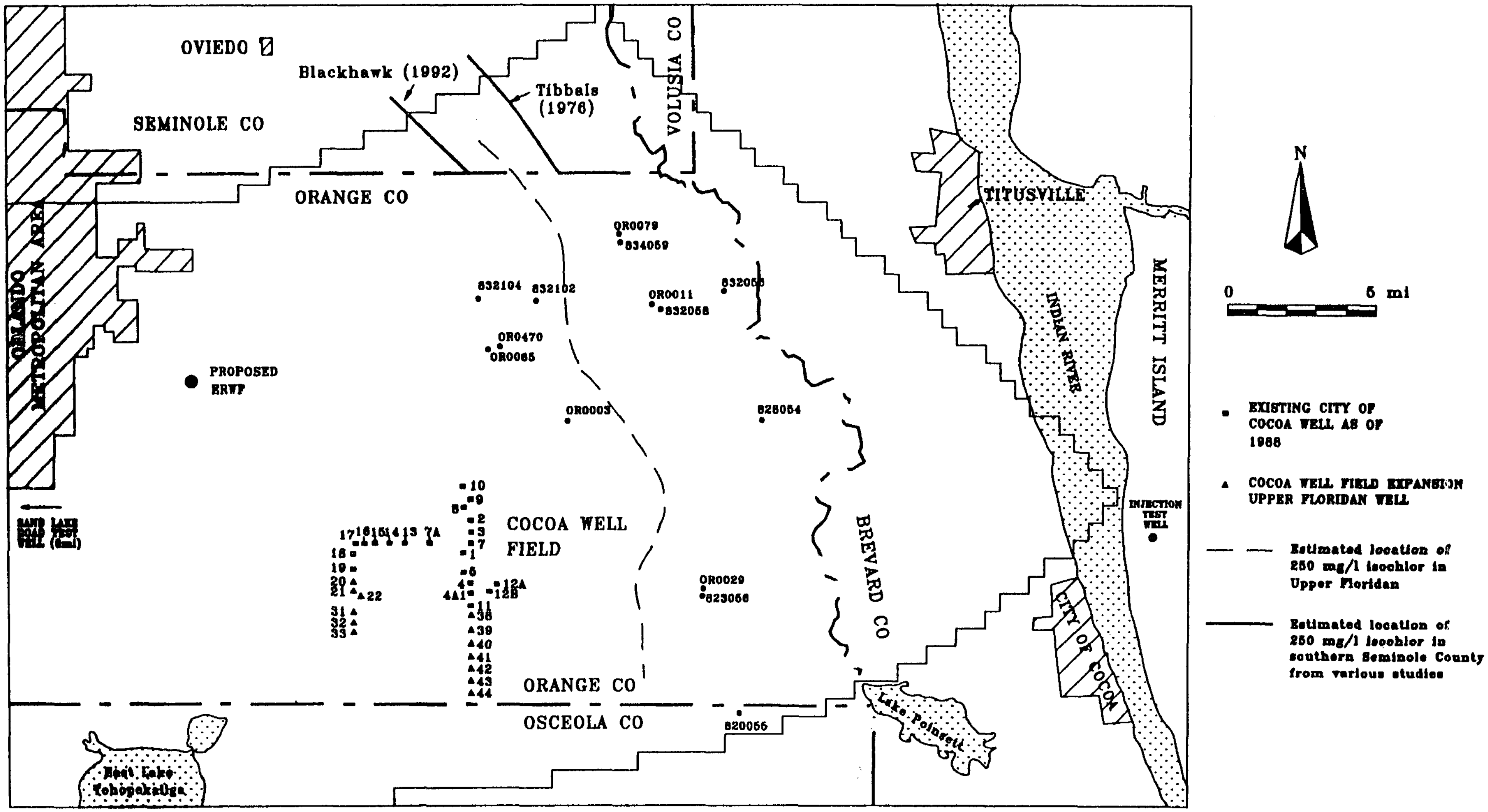


Figure 3.5 Sampling points for which a record of chloride concentration is available in eastern Orange County, and interpreted position of the regional 250 mg/l isochlor.

Figure 3.5 also displays the locations of the existing operational wells in the Cocoa well field. Most of the wells in the north-south trending East well field were constructed and placed into service in the late 1950's, while the wells in the east-west trending West well field were drilled and began operating in the early to mid 1960's. The wells in the East well field generally had low chloride concentrations when they were drilled (less than 50 mg/l), but as the wells were placed into service chloride concentrations of the extracted water approached or exceeded 250 mg/l within about 5-8 years (Fayard, 1989). Chloride concentrations in Cocoa wells 7A, 13 and 14 of the West well field (Figure 3.5) have been slowly but steadily increasing since the 1960's, although as yet the chloride concentrations for these wells has not exceeded 250 mg/l. Some wells in the East well field have been plugged back to various shallower depths, and a marked decrease in chloride concentrations was subsequently observed at these wells (i.e. Cocoa wells 5, 7, 9 and 10). Table 3.2 summarizes the important features of the Cocoa wells, and Figure 3.6 illustrates the behavior of chloride concentrations with time at Cocoa wells 3, 9 and 7A.

Tibbals and Frazee (1976) present a detailed study of the Cocoa well field area. They suggest that the vertical hydraulic connection between the Upper Floridan and deeper regions of the Floridan aquifer system that contain salty water is reasonably good in the vicinity of the East well field, but that the vertical connection is poor in the vicinity of the West well field. They hypothesize, therefore, that the increased chloride concentrations in the East well field are due to the upward movement of salty water from beneath the well field. Elevated chloride concentrations in wells 7A and 13, however, are attributed to the lateral movement of salty water from the East well field towards the West well field.

Based upon a detailed review of the available literature and data, as well as the modeling results presented in this report, the explanation of the mechanism for heightened chloride concentrations in the vicinity of the Cocoa well field presented by Tibbals and Frazee (1976) appears to be valid. The available data do not support the conceptualization that the increased chloride levels at the East well field are due primarily to the lateral, rather than the vertical, migration of salty water.

Table 3.2 Summary data for existing City of Cocoa wells completed in the Upper Floridan aquifer.

Well Name	Completion Date	Well Depth (ft)	Casing Depth (ft)	Pre-Pumping Chloride Conc. (mg/l)	Current Chloride Conc. (mg/l)[a]
East Well Field					
Cocoa 1	Dec. 1956	710[b]	374	NA	NA
Cocoa 2	Jan. 1957	616	271	NA	450
Cocoa 3	Feb. 1957	496	266	30	350
Cocoa 4	Feb. 1957	524	251	NA	225
Cocoa 4A1	April 1972	527	266	NA	190
Cocoa 5	March 1957	516[c]	251	NA	135[c]
Cocoa 7	May 1957	490[d]	285	49	80[d]
Cocoa 7A	April 1962	710	237	25	185
Cocoa 8	June 1957	640	255	NA	350
Cocoa 9	April 1957	525[e]	230	30	130[e]
Cocoa 10	April 1957	506[f]	229	NA	50[f]
Cocoa 11	June 1958	580	323	NA	190
Cocoa 12A	Dec. 1959	600	275	NA	350
Cocoa 12B	Aug. 1961	519	260	NA	220
West Well Field					
Cocoa 13	June 1962	509	244	36	140
Cocoa 14	Sept. 1962	761	252	38	105
Cocoa 15	Feb. 1964	702	262	54	60
Cocoa 16	Feb. 1964	600	255	55	55
Cocoa 17	Feb. 1964	600	252	55	55
Cocoa 18	April 1982	600	254	56	60
Cocoa 19	Nov. 1981	600	254	57	60

[a] Approximate average concentration for mid to late 1980's
[b] Original depth reported as 710 ft; measured depth in 11/87 was 545 ft; plugged back in 11/87 to 374 ft.
[c] Well plugged back from 516 ft to 409 ft in 1984
[d] Well plugged back from 490 ft to 399 ft in 1986
[e] Well plugged back from 525 ft to 385 ft in 1985
[f] Well plugged back from 506 ft to 350 ft in 1986
NA Not available

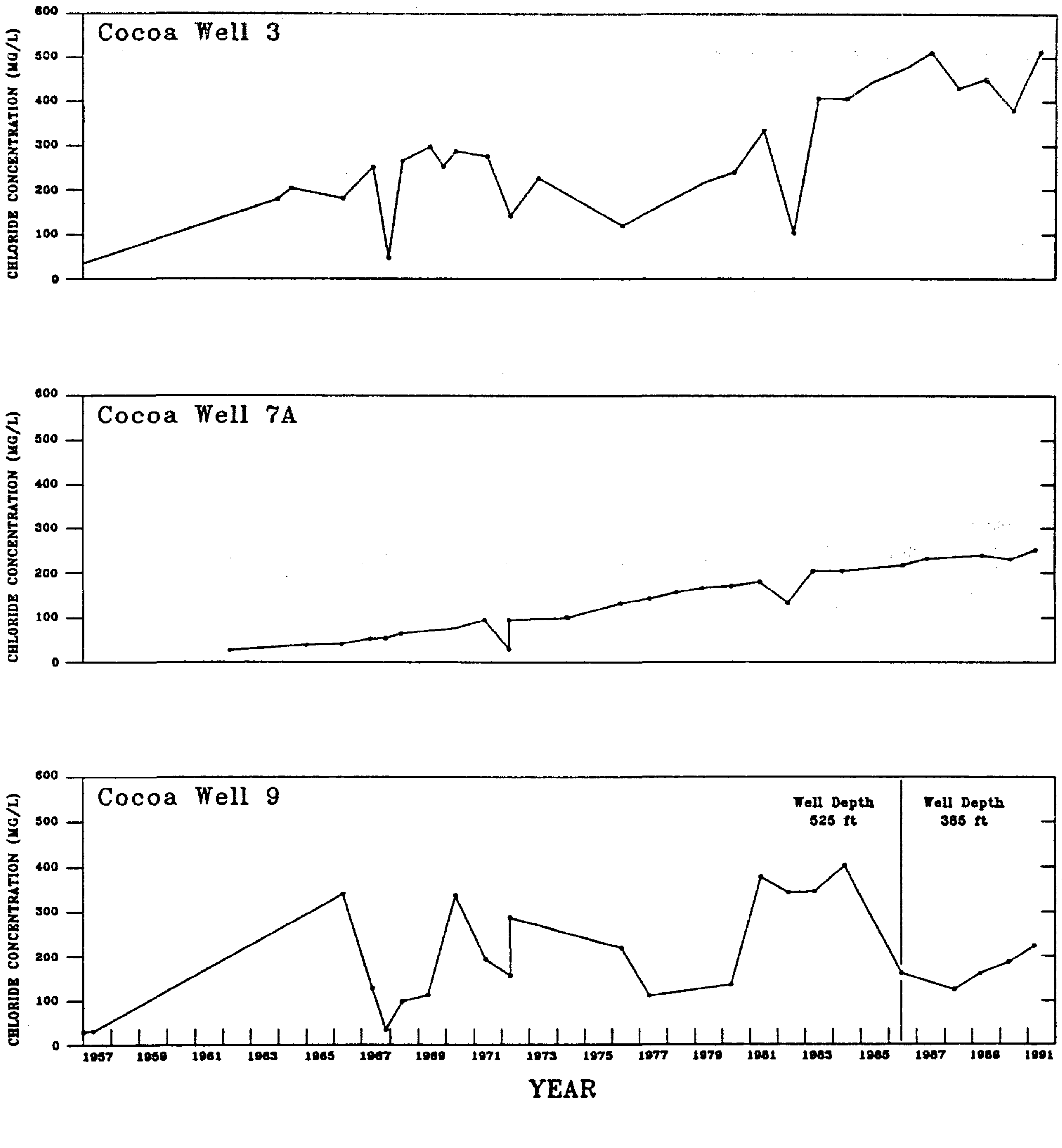


Figure 3.6. Chloride concentrations as a function of time at Cocoa wells 3, 9 and 7A after Fayard (1989). See Figure 3.5 for Cocoa well locations.

3.5.2 Lower Floridan

Observed data concerning the variation of chloride concentrations in the Lower Floridan are very limited. Within the Phase III study area, there are five deep test/monitor wells that penetrate all or portions of the Lower Floridan and provide useful water quality data. These wells are the Merritt Island injection test well located near the center of Merritt Island; the Sand Lake Road injection test well located just south of Orlando; the Cocoa C and Cocoa R salinity monitoring wells at the Cocoa well field; and the Lower Floridan exploratory well at Orange County's ERWF site. There are also two test sites within the study area, at the Orange County Landfill and Deseret Ranches, where chloride concentrations with depth were estimated using geophysical methods. The data obtained from each of these wells and the geophysical test sites is summarized below.

The Merritt Island injection test well is located on Merritt Island due east of the Cocoa well field (Figure 3.1). The construction and testing of this well was conducted in 1984 and is documented in Geraghty & 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 3.3 lists observed values of chloride concentration versus depth at the Merritt Island test well. This table shows that the average chloride concentration within the top of 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 below land surface (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).

The Sand Lake Road injection test well, completed in 1977, is located just south of Orlando (Figure 3.1). The construction and testing of this well is documented in Geraghty & Miller

Table 3.3 Chloride and total dissolved solids concentrations for various depth intervals at the Merritt Island deep injection test well (Geraghty & 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.

(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 & 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.

The Cocoa C salinity monitoring well is located in the West Cocoa well field adjacent to Cocoa well 14 (Figure 3.1). This well was constructed in 1965 and was originally completed with five sampling zones (numbered from the bottom up), but Zone 2 was subsequently plugged. The remaining sampling zones are open to the intervals indicated in Table 3.4. Zone 1 samples the Lower Floridan; Zone 4 samples the middle semiconfining unit; and Zone 5 samples the Upper Floridan and the middle semiconfining unit. Zone 3 lies very close to the contact between the top of the Lower Floridan and the bottom of the middle semiconfining unit, but is probably open to the middle semiconfining unit since chloride concentrations have not changed significantly through time at this sample location, while chloride concentrations in Zone 1 have increased from about 750 mg/l in 1967 to approximately 2,600 mg/l in 1989. Chloride concentrations have remained relatively stable in monitoring Zones 3 and 4 over the period 1967 - 1989 at about 81 mg/l and 40 mg/l, respectively (Table 3.4).

In the vicinity of the Cocoa C monitoring well, chloride concentrations are relatively low within the Upper Floridan and the middle semiconfining units, but the water quality quickly becomes non-potable (chloride concentrations greater than 250 mg/l) in the Lower Floridan. However, since the deepest sampling zone only penetrates about the upper one-sixth of the Lower Floridan, the nature of the vertical transition of chloride throughout the remainder of the Lower Floridan is unknown.

In 1991, the Cocoa R salinity monitoring well was constructed about 0.75 miles due south of Cocoa well 19, in the midst of the West Cocoa well field expansion. Water quality at this site was sampled over three zones during the construction process, but only one sampling zone open to the top 100 ft of the Lower Floridan was left open upon final well completion. The chloride sampling results for the Cocoa R well are presented in Table 3.4 (Kevin Bral, CH2M Hill, personal communication, 1992). The results in Table 3.4 indicate that at Cocoa R, chloride concentrations are low (less than 50 mg/l) throughout the Upper Floridan and much or all of the middle semiconfining unit. Within the bottom of the middle semiconfining unit or the top of the Lower Floridan, chloride concentrations exceed 250 mg/l. Within the Lower Floridan, chloride concentrations increase significantly with depth.

Table 3.4 Depth intervals and abbreviated chloride concentration history for Cocoa C and Cocoa R salinity monitoring well sampling zones (Fayard, 1989 and CH2M Hill, 1992).

Cocoa C Salinity Monitoring Well		
Zone No.	**Depth Interval (ft bls)**	**Chloride Concentration History**
1	1,351 - 1,357	Initially 750 mg/l in 1967. Increased to about 2,600 mg/l by 1989.
3	1,218 - 1,224	Relatively stable at about 81 mg/l from 1967 - 1989.
4	1,044 - 1,050	Relatively stable at about 40 mg/l from 1967-1989.
5	248 - 1,004	No data available.

Cocoa R Salinity Monitoring Well		
Zone No.	**Depth Interval (ft bls)**	**Chloride Sampling Results**
1 - Temporary	300 - 618	45 mg/l
2 - Temporary	300 - 966	46 mg/l
3 - Temporary	300 - 1,505	1,260 m/l
1 - Final	1,098 - 1,205	352 mg/l

As part of the aquifer testing and well field evaluation project conducted by Orange County for their proposed ERWF, a Lower Floridan exploratory well was constructed at that site in 1989 (Jammal and Associates, 1990). The ERWF site is located about seven miles east of Orlando, and about nine miles northwest of the Cocoa well field (Figure 3.1). This well was completed to a total depth of 1,385 ft, and penetrates about 235 ft (the upper one-sixth) of the Lower Floridan. The water quality at this site in both the Upper and Lower Floridan aquifers is excellent. The maximum chloride concentration measured in the Lower Floridan was 10 mg/l.

Estimates of chloride concentration in the Lower Floridan are available for two additional sites at which time domain electromagnetic measurements (TDEM) were made (Blackhawk Geosciences, 1991). At the Orange County Landfill site (Figure 3.1), which is situated approximately mid-way between the ERWF and the Cocoa well field, the chloride concentration as of 1991 was estimated to be 2,880 mg/l or greater at a depth of 2,304 ft below msl, which is roughly 200 ft above the base of the Lower Floridan at that location. At the Deseret Ranch site, located approximately 7 miles southeast of the Cocoa well field, the chloride concentration as of 1991 was estimated to be in excess of 3,270 mg/l at 1,292 ft below msl, which is roughly 400 ft above the base of the Lower Floridan. An average porosity of 25 percent was used to determine each of the chloride concentration estimates; estimated concentrations would be lower if larger average porosities were assumed, or they would be higher is smaller average porosities were assumed.

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 mg/l developed by C.L. Sprinkle and reproduced in Tibbals (1990). This map is reproduced for the Phase III study area in Figure 3.7. This map appears to be fairly accurate based upon an analysis of available chloride sampling locations and other studies that have evaluated chloride concentrations at depth, such as Blackhawk Geosciences (1992). Perhaps the most important feature that this map 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 (Figures 3.4 and 3.5, and Tibbals

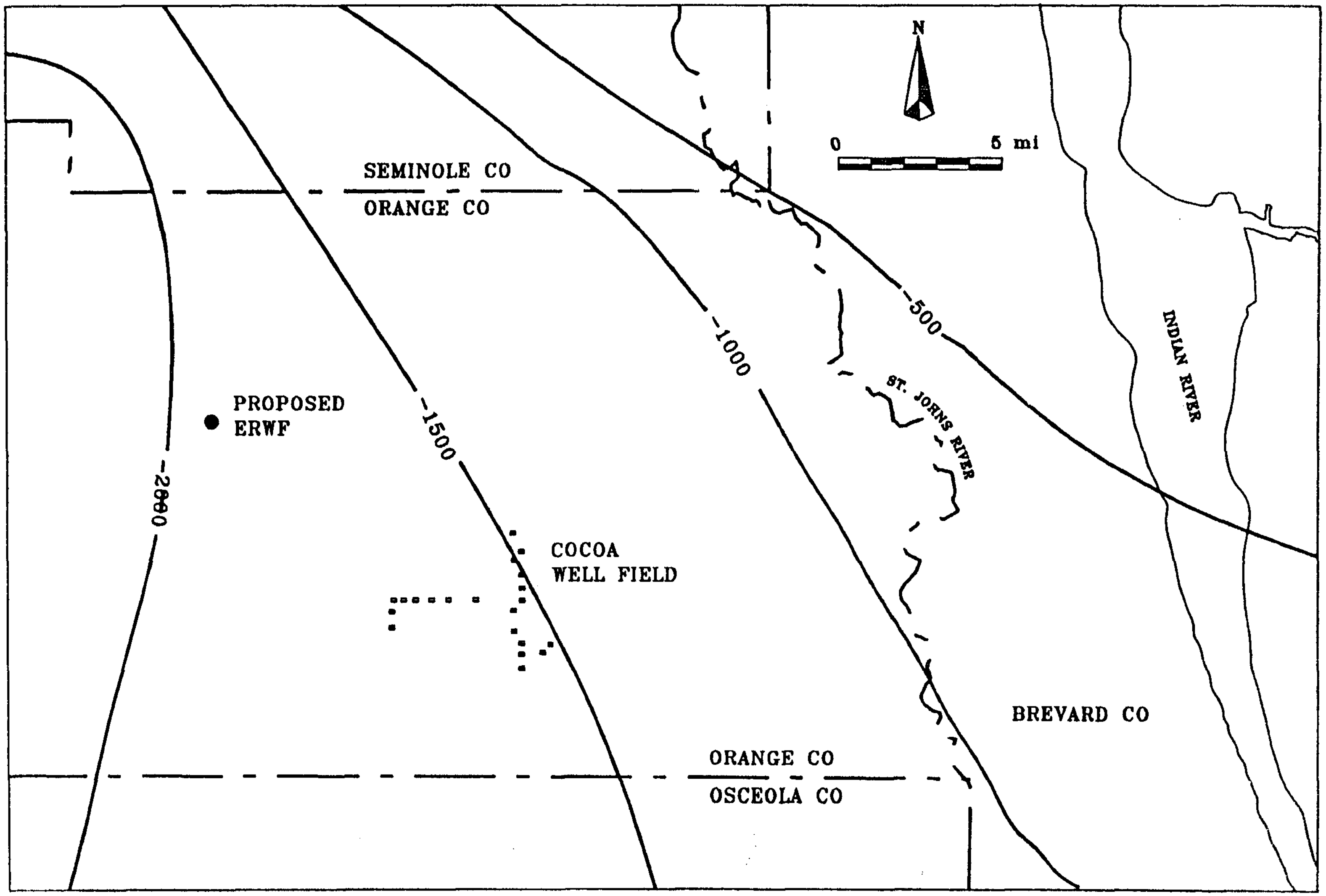


Figure 3.7 Estimated depth to water having chloride concentration greater than 10,000 mg/l. Datum is sea level. Adapted from Tibbals (1990).

1990). This map proved useful in determining the eastern model boundary conditions, as is described in Section 4.6.4.

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 is 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 **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, 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

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

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

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

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

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

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

where H is defined as

$$H = \frac{p}{\rho g} + z \qquad (4.4)$$

and

$$\eta = \frac{(\rho_s - \rho_o)}{\rho_o c_s} \qquad (4.5)$$

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

$$H = h + \eta c z \qquad (4.6)$$

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

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

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

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

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

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 ($\lambda = 0$). 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 salt transport in east-central Florida is illustrated in Figure 4.1. The basic model 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 (1992)). 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) must be discretized into multiple layers to reasonably account for density-dependent ground-water flow and 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.

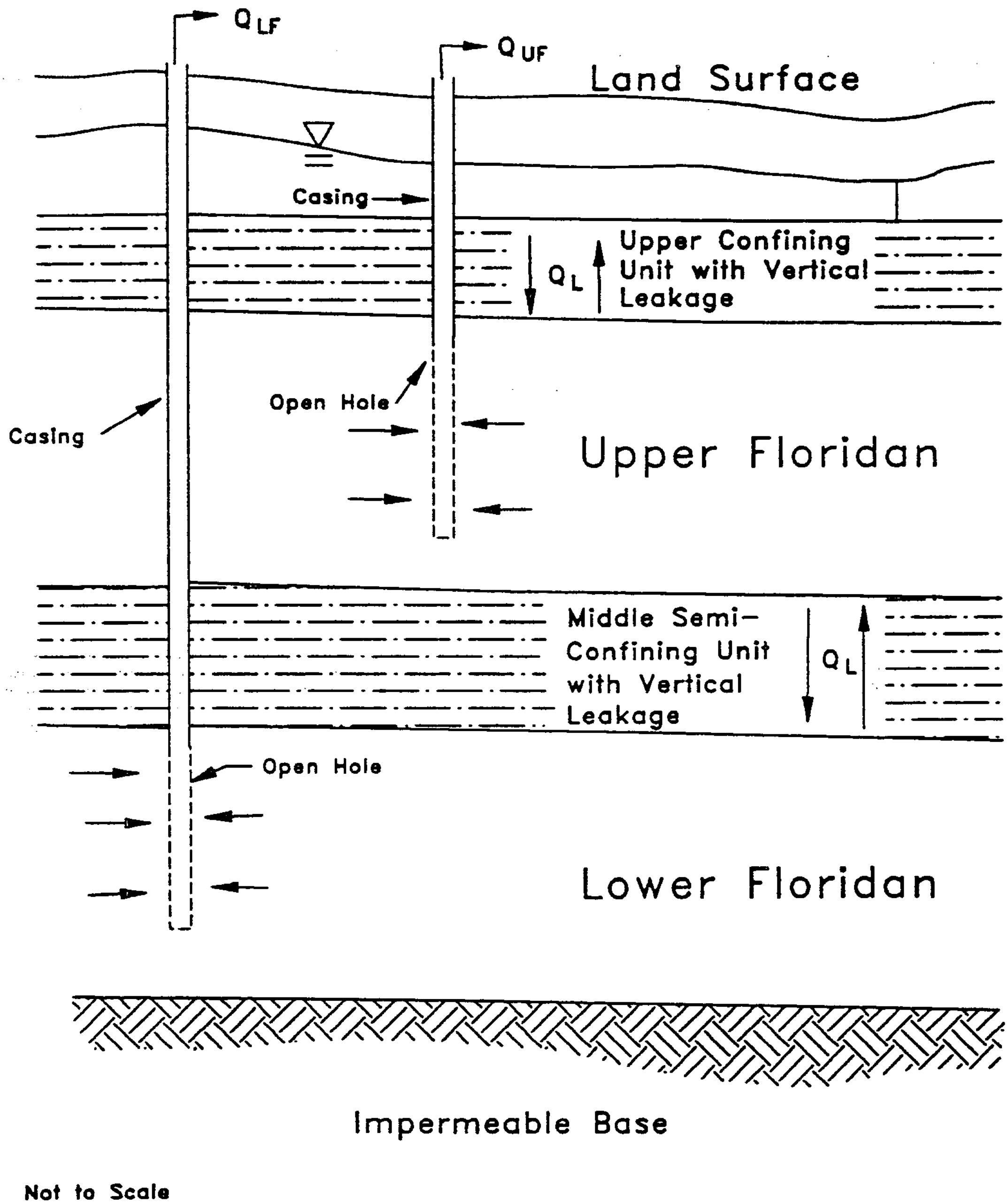


Figure 4.1 Conceptual model for modeling ground-water flow and solute transport within the Floridan aquifer system in east-central Florida.

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). However, in the vicinity of the Cocoa well field, chloride concentrations have been increasing gradually since the first wells were put on-line. It is important that the calibrated model have the ability to simulate the increase in chloride concentrations with time at the Cocoa well field, particularly in the Upper Floridan, from which the water supplies are obtained.

4.4 Model Domain

The Phase III model domain, outlined in Figure 3.1, 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, 1992).

- The model domain has to include the ERWF, the Cocoa well field, and the proposed expansion of the Cocoa well field. These existing and proposed well fields play a critical role in the prediction scenarios for ground-water flow and solute transport in eastern Orange County for the 20 year planning horizon.

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

The final model domain used in the analysis is 41 miles in the east-west direction and 27 miles in the north-south direction. The active model domain did not include this entire region, however, as is discussed in Section 4.6. In general, the model domain extends in an east-west direction from Orlando in Orange County to about the middle of Merritt Island in Brevard County, and in a north-south direction from Oviedo in Seminole County to Kissimmee in Osceola County. In State Plane coordinates, the lower-left-hand corner of the Phase III study area (model grid) is located at x = 385,825.5 ft and y = 1,440,873.0 ft.

Moving from west to east, the active model domain begins to curve up in a northeasterly direction starting at about the East Cocoa well field. This configuration of the active model domain is consistent with the conceptualized ground-water flow and chloride boundary conditions. The estimated predevelopment and average 1988 potentiometric surfaces portray regional flow in eastern Orange 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

The finite element mesh used for the Phase III model simulations is presented in Figure 4.2. The mesh consists of 63,802 nodal points and 58,320 hexahedral brick elements, of which only 40,793 nodal points and 36,612 elements are active due to the configuration of the boundary conditions. In plan view (x-y plane) there are 46 gridline rows and 73 gridline columns. In the vertical dimension there are 19 nodal layers.

In the horizontal (x-y) plane the discretization (cell size) varies from 2,640 ft (½ mile) to 5,610 ft (1.0625 miles) in the x-direction, and is a uniform 3,168 ft (0.6 mile) in the y-direction. The finest discretization was used where the largest variations in chloride concentrations were expected, and larger cell sizes were used in the western region of the model domain where concentration variations were expected to be relatively small.

The DSTRAM orthogonal curvilinear mesh option was used to discretize the model domain in the vertical (z) dimension. A curvilinear mesh is one where the gridline columns and/or rows do not remain parallel over their entire length. This option permits a grid to be developed that conforms to the changing geometry of the various hydrogeological units. This option was invoked because 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. The vertical curvilinear grid for two representative cross sections (one east-west and one north-south) is illustrated in Figure 4.3. Note in Figure 4.3 that the fault along the St. Johns River (see Figure 3.3a) is incorporated into the mesh as a smooth increase (over a short distance) in Upper Floridan aquifer thickness. This approach was followed to reduce the number of model nodes and the degree of effort involved in constructing the grid; treating the fault in this manner rather than replicating a sharp contrast, as was done in the Phase II study (Blandford, 1991), has a negligible influence upon the model simulation results.

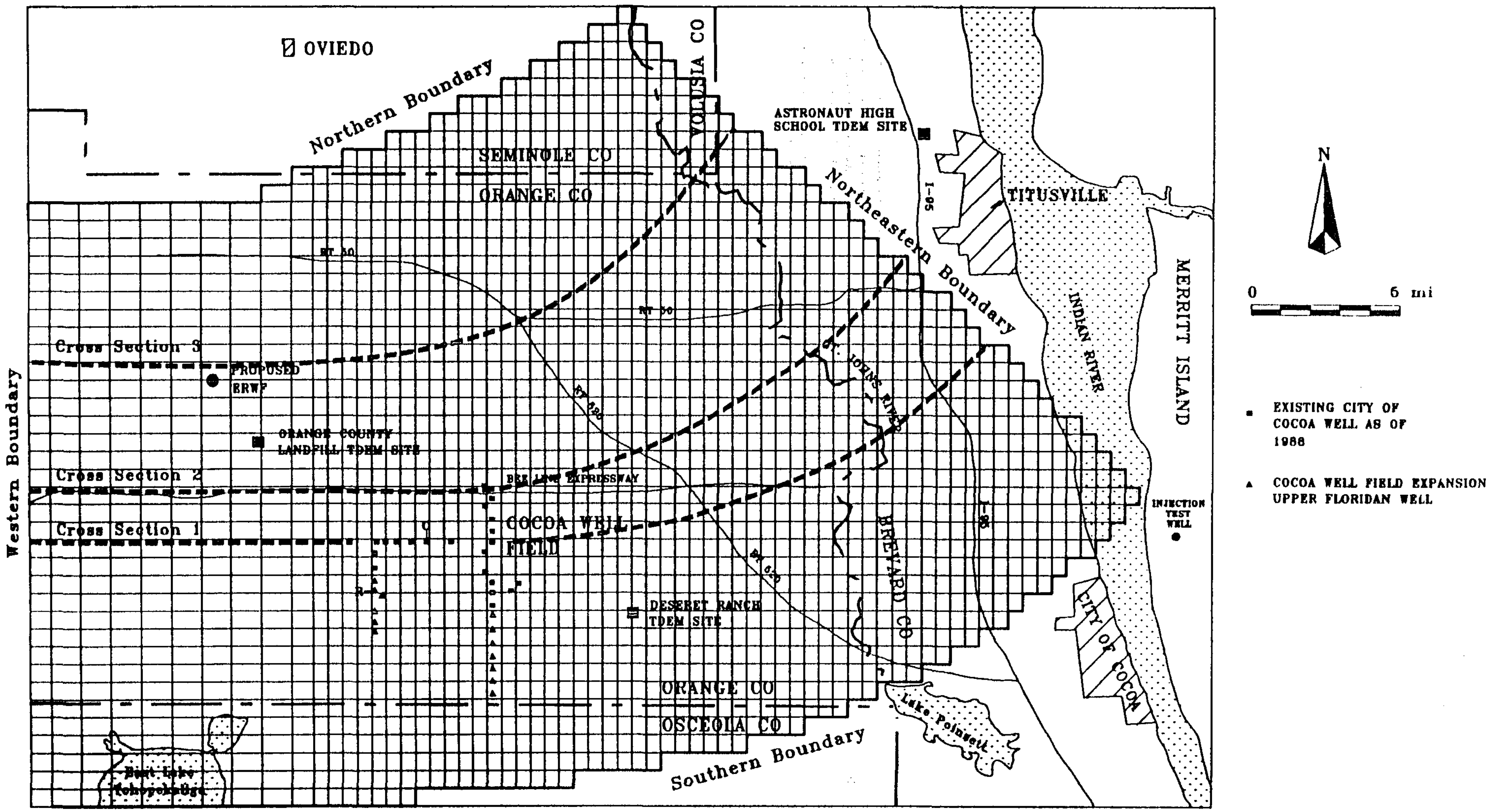


Figure 4.2 Finite element mesh used for three-dimensional, density-dependent ground-water flow model calibration and location of three standard cross sections used to display simulation results.

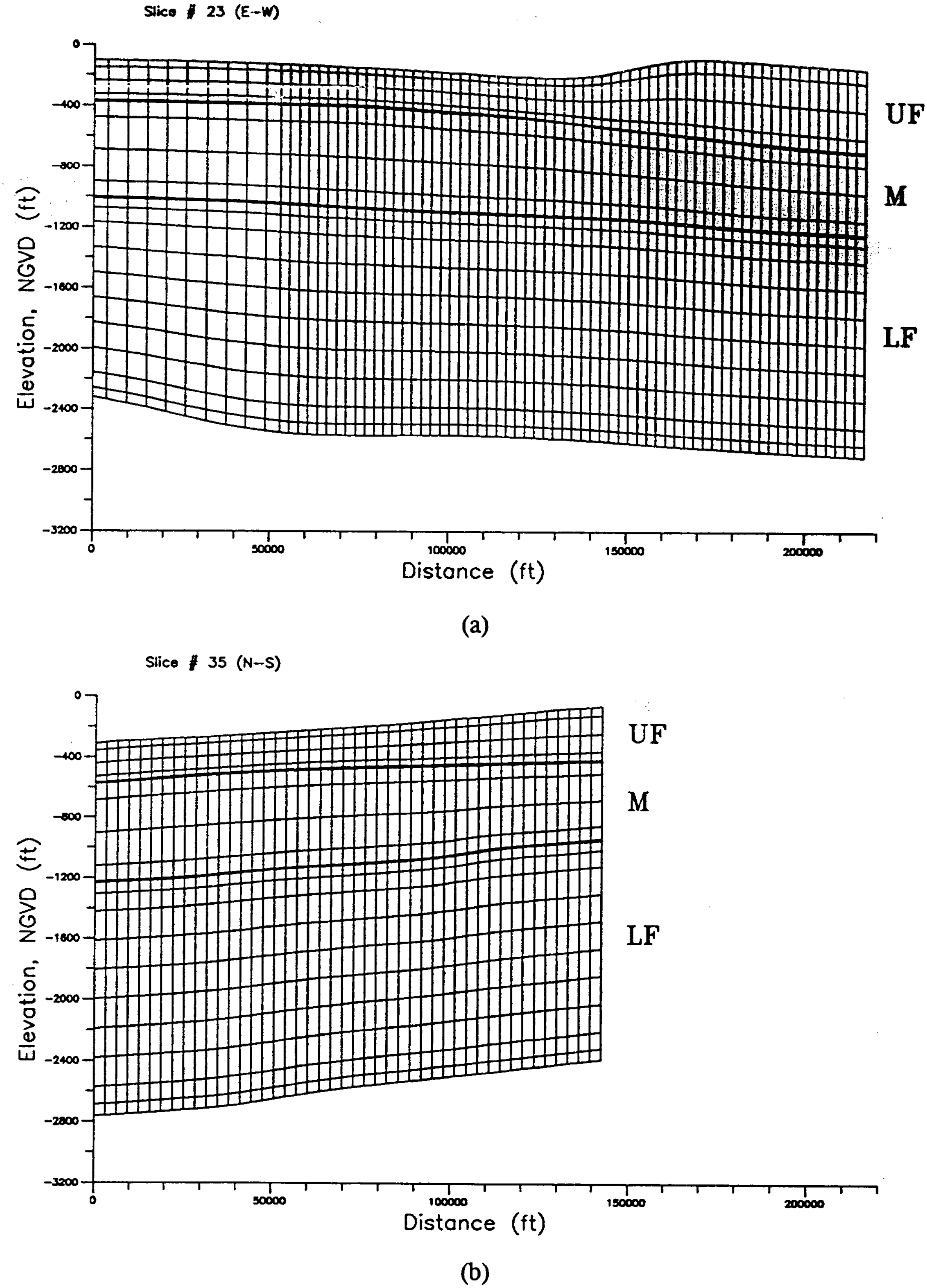


Figure 4.3 Vertical discretization used for model calibration along middle row (a) and middle column (b) of finite element mesh.

4.6 Model Boundary Conditions

This section describes the boundary conditions that were used for both ground-water flow and chloride concentrations at the bottom, top, and sides of the three-dimensional model domain. A conceptual diagram of the boundary conditions applied along cross section 1 is presented in Figure 4.4 for reference purposes. Many of the boundary conditions are dependent upon the Phase IV modeling results documented in Blandford and Birdie (1992), herein referred to simply as the Phase IV model. The lateral boundary conditions are labelled in Figure 4.2.

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 ÷ 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 (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.

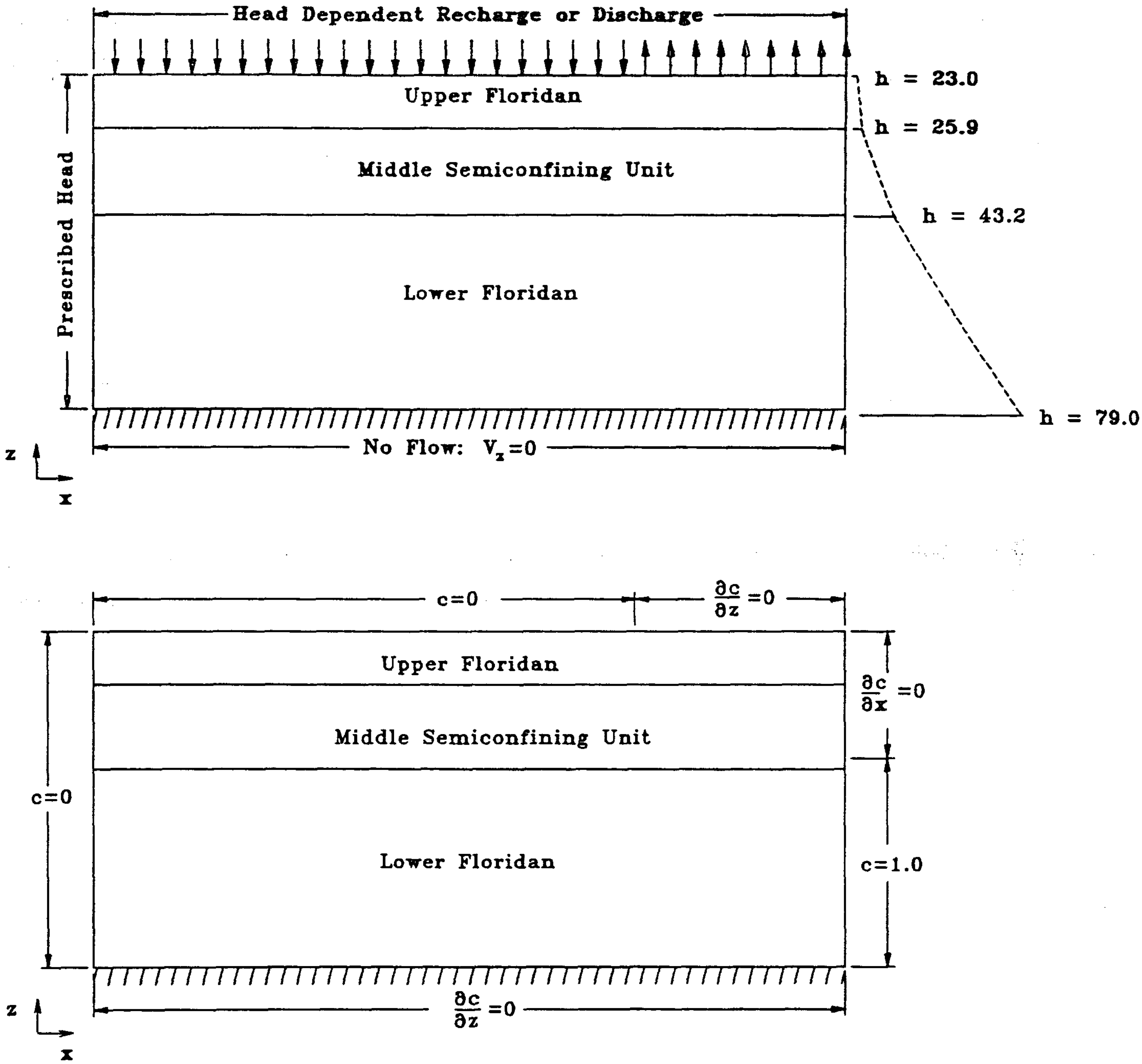


Figure 4.4 Schematic diagram of top, bottom, western and eastern boundary conditions applied along cross section 1 (variable thicknesses of hydrogeologic units not reproduced).

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). This boundary was 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. At this location, 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 (Chapter 3). This conceptualization was adopted in numerous other modeling studies, and is consistent with the Phase IV regional model.

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. This approach is preferable to that of adding an additional model layer of prescribed nodal head values because computational storage requirements are significantly reduced. 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, h_s is the water-table elevation in the surficial aquifer, h_u is the hydraulic head at the top of the Upper Floridan, 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 system. 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. 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 lateral model boundary is oriented north-south and is located in the vicinity of Orlando, about 6 miles west of ERWF. Nodal heads along this boundary were prescribed based upon the regional Phase IV modeling results. Chloride concentrations at the western boundary nodes were set equal to zero. This approach is consistent with the results of the ERWF testing (Jammal and Associates, 1990), in which chloride concentrations in the Upper Floridan, the middle semiconfining unit and the upper one-sixth of the Lower Floridan were found to be very low. Also, at the Sand Lake Road injection test well, about 5 miles due west of this boundary, chloride concentrations are very low throughout the Floridan aquifer system, with the possible exception of the very bottom of the Lower Floridan, where chloride concentrations may reach 250 mg/l or more (Geraghty and Miller, 1977). Although it is possible that chloride concentrations on the order of 250 mg/l or more may exist near the base of the Lower Floridan in the vicinity of this boundary, there is an insufficient amount of observed data to quantify the chloride distribution. Furthermore, if chloride concentrations of 250 mg/l or so were prescribed at the bottom of the Lower Floridan along the western boundary, it is doubtful that any significant changes in the major simulated isochlors would be observed.

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 the Merritt Island injection test well to about the south end of Lake Harney 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. Although the Merritt Island injection test well is located near the southeastern tip of this boundary, chloride concentrations observed at the test well are probably not indicative of concentrations along the entire boundary.

Figures in Tibbals (1990) indicate that chloride concentrations in the top 100 ft of the Upper Floridan are generally higher along most of this boundary than those observed at the Merritt Island well. Presumably, chloride concentrations at depth would be higher as well. At the Astronaut High School TDEM site, about 4½ miles east of the northeastern model boundary in the vicinity of Titusville, TDEM test results indicated high chloride water (greater than 10,000 mg/l) in the Upper Floridan. Samples listed in the SJRWMD chloride database indicate that Upper Floridan chloride concentrations range from 1,500-6,000 mg/l in the vicinity of this boundary, although most of these samples are probably not representative of the entire Upper Floridan thickness.

In view of the uncertainty regarding the specification of this boundary condition, and given the fact that sufficient data is not available to construct a detailed picture of the chloride distribution (particularly with depth) along the length of this boundary, it was decided that a general conceptualization of the boundary condition would be implemented at the onset of the Phase III modeling. During the model calibration process, conditions prescribed along this boundary were treated as calibration parameters. The final boundary specification along the northeastern boundary, arrived at through analysis of the observed data and model calibration, is presented in Figure 4.5.

Along the entire boundary, equivalent freshwater head was prescribed based upon the Phase IV model results and assumed chloride concentrations; equivalent freshwater head was calculated using equation 4.6 (rearranged to solve for h) and the density values presented at the beginning of this section. The 10,000 mg/l isochlor was assumed to lie at 500 ft below msl along the entire extent of the northeastern boundary, as is indicated by Figure 3.7. Along the boundary, this depth roughly corresponds to the top one-quarter of the middle semiconfining unit (northwest end) or the bottom one-third of the Upper Floridan (southeast end). As the result of some initial sensitivity analysis and model calibration , 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

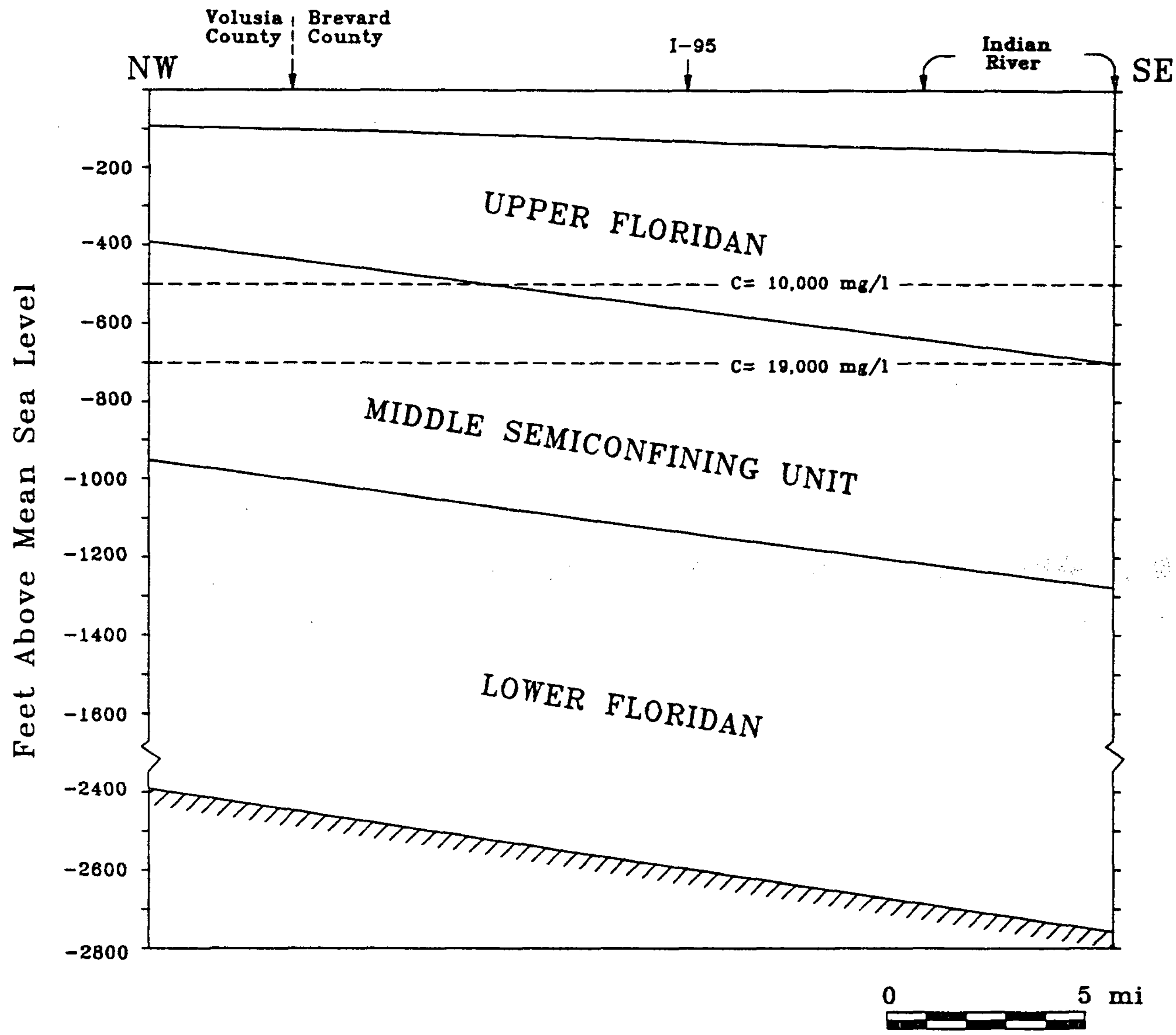


Figure 4.5 Schematic diagram of chloride concentrations assumed along the eastern lateral boundary in order to compute equivalent freshwater head.

3 was estimated using the data in Table 3.3. The 19,000 mg/l isochlor thus positioned lies about midway into the middle semiconfining unit at the northwest end of the boundary, and at about the top of the middle semiconfining unit at the southeast end of the boundary. At the Merritt Island test well, the 19,000 mg/l isochlor was observed to lie within the middle semiconfining unit about 350 ft deeper than it was specified at the southeastern tip of the northeastern boundary. This discrepancy could be due in part to local heterogeneities in the hydrogeologic system, and it is probably also due to simplifying assumptions that must be made during the modeling process.

Between the 10,000 mg/l and the 19,000 mg/l isochlors, the average chloride concentration was assumed to be 14,500 mg/l. Above the 10,000 mg/l isochlor, average concentrations were assumed to be 2,400 mg/l and 6,900 mg/l at the northwest and southeast ends of the boundary, respectively. These values are in reasonable agreement with Tibbals (1990); samples documented in the SJRWMD chloride database; and observed data from the Merritt Island test well, at which chloride concentrations of 2,200 mg/l were observed within the top one-quarter of the Upper Floridan.

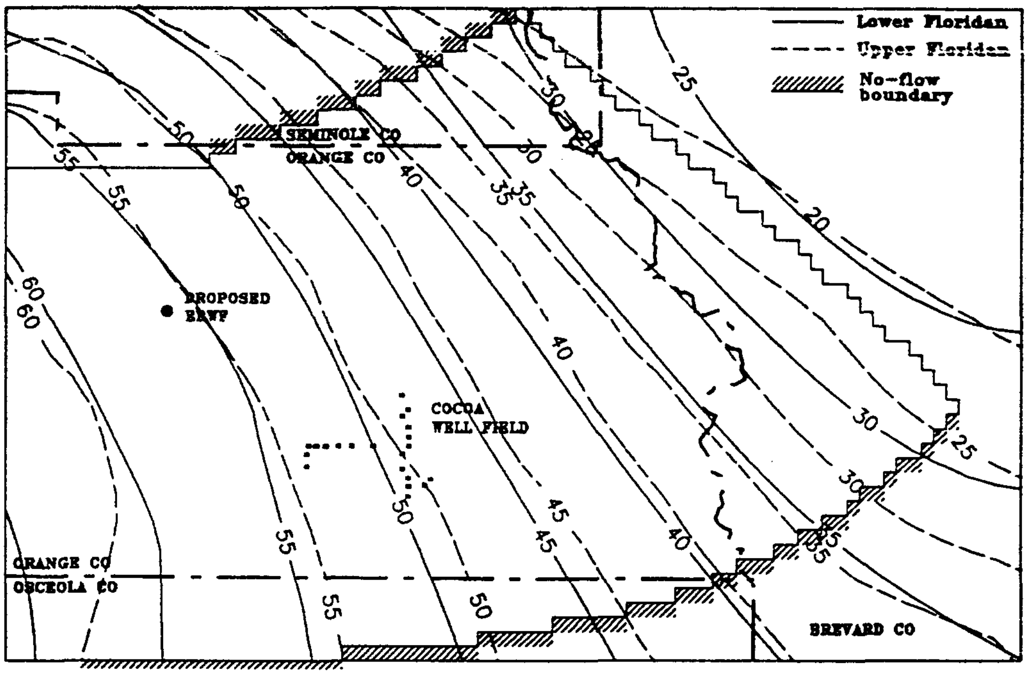
It should be noted that there is some inherent error incorporated into the model in using the Phase IV model heads, in conjunction with estimated chloride concentrations, to derive the northeastern boundary condition (the Phase IV model heads were used as a rough approximation to H, or true head, in 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

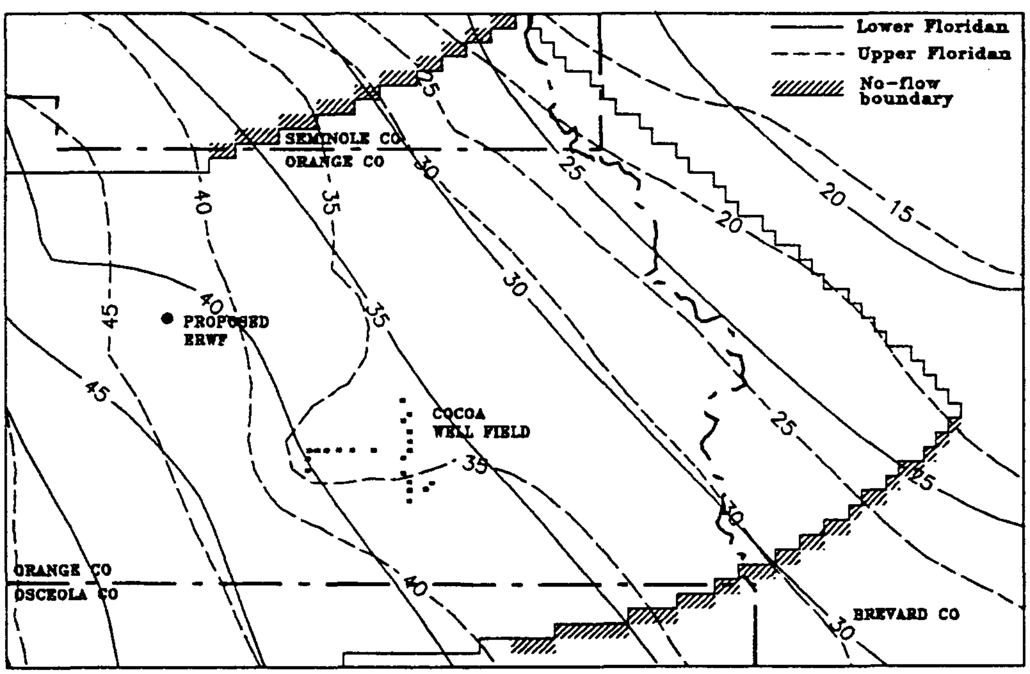
The northern and southern lateral model boundaries are oriented along regional ground-water flow pathlines for both the Upper and Lower Floridan aquifers. The locations of the pathlines selected are very similar for predevelopment and average 1988 conditions, and consequently the locations of the lateral boundaries were not altered between calibration periods (Figure 4.6). 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 3.7.

The location of the northern and southern lateral boundaries were selected very carefully in the above manner so that they could be conceptualized in the three-dimensional model as zero flux (with respect to ground water and solutes) boundary conditions along the major portion of their extent. 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 Orange County and the portion of west-central Brevard County that is adjacent to Orange 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. This relationship is clearly demonstrated for the Upper Floridan by figures presented in Tibbals (1990) and Toth (1988). 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 3.7, 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 in southeastern Seminole County presented in Blackhawk Geosciences (1992).

Finally, for some distance along the western-most portion of both the north and the south lateral boundaries, a prescribed head boundary condition was implemented (Figure 4.6). This was done



(a)



(b)

Figure 4.6 Upper Floridan and Lower Floridan potentiometric surfaces obtained from the Phase IV model for the predevelopment (a) and average 1988 (b) calibration periods and the selected Phase III model lateral boundary conditions.

at these locations because the boundary orientation did not replicate closely enough the locations of the selected bounding ground-water flow pathlines. It the Lower Floridan, the boundary condition type did not change between the predevelopment and 1988 simulation periods. In the Upper Floridan, however, the region of prescribed head along the southern boundary was extended from grid column 4 for the predevelopment simulations to column 30 for the average 1988 simulations. This approach was required because the location of the southern boundary due south of the Cocoa well field does not sufficiently mimic the position of a regional ground-water flow pathline for average 1988 conditions (Figure 4.6). The western and central sections of the southern boundary, therefore, are ones of ground-water influx for the average 1988 simulation. The chloride concentration of the ground water flowing into the model domain through the southern boundary was set equal to the predevelopment simulated concentrations along the boundary.

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, it is felt that 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 (1992). 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 confining unit overlying the Upper Floridan. 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.

Although the Phase III model areal discretization is in general finer 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 III study area. This approach was taken for three reasons. First of all, topographic relief (on which the surficial aquifer heads depend) does not vary substantially across the model domain; it ranges from about 75 ft on the west side of the model domain to about 5 ft on the east side of the model domain. Therefore, refining the estimates of surficial aquifer heads would probably not lead to any substantial increase in accuracy. Secondly, data concerning the leakance of the upper confining unit is very limited, and there is really no justification for further refinement of this model parameter. Finally, most of the three-dimensional model domain lies within regions of very low to moderate recharge or discharge, and therefore adjusting the surficial aquifer heads by relatively small amounts would not substantially affect the model results. The prescribed surficial aquifer head values were 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 (1992).

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 nodal spacing throughout the entire aquifer thickness, except in the vicinity of the Cocoa well field where a greater proportion of discharge was assumed to come from near the bottom of the Upper Floridan (see Section 4.7.4). Similarly, recharge due to drainage wells in the vicinity of Orlando was applied throughout the thickness 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. 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 main model calibration parameters were porosity, dispersivities and anisotropy ratio for each hydrogeologic unit; boundary condition inputs such as equivalent freshwater head along the northeastern lateral boundary; vertical hydraulic conductivity of the middle semiconfining unit in the vicinity of the Cocoa well field; and transmissivity of the Upper Floridan.

The Phase III density-dependent ground-water flow and solute transport model was calibrated to predevelopment, as well as postdevelopment (average 1988) conditions. A similar approach was used for the Phase IV regional model. Where required, the Phase III model boundary conditions are calibration-period specific. For example, the head values prescribed along the Phase III 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 (1992). There is 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 much of eastern Orange County, it is a reasonable assumption that essentially natural hydrogeologic conditions prevailed prior to construction of the Cocoa well field. Therefore, 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 32 years or so (the first Cocoa well was completed in 1956). All postdevelopment (average 1988) simulations, therefore, were transient simulations run for a time period of 32 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. The calibration targets 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 32 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 32 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 database for the period 1958-1988 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 Floridan, and the vertical hydraulic conductivity of the middle semiconfining unit, within some regions of the Phase III model domain. These changes were consistently checked to insure that the Phase IV regional model results were not significantly altered.

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 Targets

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

1) Location of the 250 mg/l isochlor in eastern Orange County (Figure 3.5) and in the vicinity of the Cocoa well field. From predevelopment to average 1988 conditions, the 250 mg/l isochlor should move very little or not at all in eastern Orange County. Predevelopment chloride concentrations in the vicinity of the Cocoa well field should be small (about 50 mg/l or less), but they should increase at the East Cocoa well field in the postdevelopment simulation to 200-300 mg/l or so. Also, chloride concentrations at Cocoa wells 7A and 13 should increase by about 150 and 100 mg/l, respectively.

2) Initial (predevelopment) concentrations at the Cocoa C salinity monitoring well sampling zones. From predevelopment to average 1988 conditions, chloride concentrations in sampling zones 3 and 4 in the middle semiconfining unit should remain unchanged, while chloride concentration in the deep zone should increase approximately 1,850 mg/l.

3) Observed and estimated chloride concentrations at depth at other locations such as the ERWF deep test well, the Cocoa R deep test well, and the Deseret and Orange County landfill TDEM sites. Estimates of chloride concentration are available at these sites for present hydrogeological conditions only, although concentrations were probably not much, if any, smaller during predevelopment conditions than they are today.

4) 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 criteria was met, is discussed in the following two sections.

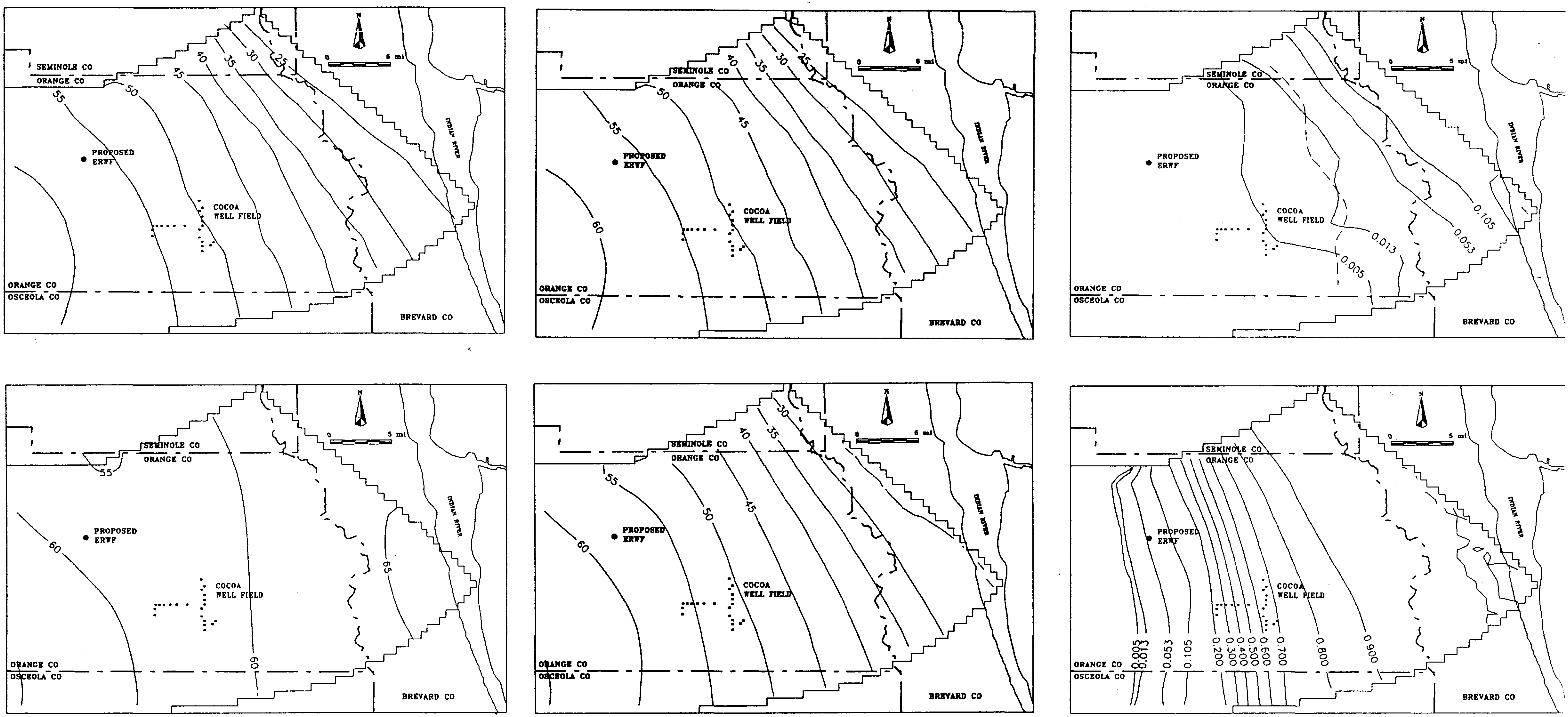
4.7.3 Predevelopment Model Calibration Results

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. Upper or Lower Floridan). The three cross sections presented illustrate simulation results for vertical slices through the three-dimensional domain; the location of each vertical slice is indicated in Figure 4.2. Chloride concentrations are presented as normalized concentration, and hydraulic heads are plotted as equivalent freshwater heads and 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. The definition of true head, environmental head and equivalent freshwater head is provided in Section 4.2. A detailed explanation of each type of head value is provided by Lusczynski (1961). Briefly, equivalent freshwater head defines hydraulic gradients within a horizontal plane, and environmental head defines hydraulic gradients in the vertical direction. Since DSTRAM accounts for density effects, and the regional Phase IV MODFLOW model does not, the simulated head fields obtained from the Phase III 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 (particularly the northeastern boundary), the orientation of the velocity vectors may be erratic due to computational round-off errors within the computer plotting program. The result is that some vector plots for the Lower Floridan indicate that ground-water flow is out of, rather than into, the model domain along the northeastern boundary. The orientation of these "erratic" boundary vectors should be ignored when examining the velocity vector plots.

The predevelopment model calibration results are presented in Figures 4.7-4.10. Figure 4.7 illustrates the simulated equivalent freshwater head, the environmental head, and the normalized chloride concentration distribution for the middle nodal layer of the Upper and Lower Floridan aquifers. Figure 4.8 illustrates the difference between the simulated environmental heads and the observed potentiometric surface in the Upper Floridan. Figure 4.9 presents areal velocity vector plots for the middle layer of the Upper and Lower Floridan, and Figure 4.10 portrays the simulated isochlors and the corresponding velocity vector plots for the three standard cross sections.

A critical comparison of Figures 4.7 and 4.10 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



(a) (b) (c)

Figure 4.7 Simulated predevelopment equivalent freshwater head (a), environmental head (b), and normalized chloride concentration (c) at the middle of the Upper and Lower Floridan. The dashed line in (c) is the estimated location of the 250 mg/l isochlor in the Upper Floridan in eastern Orange County.

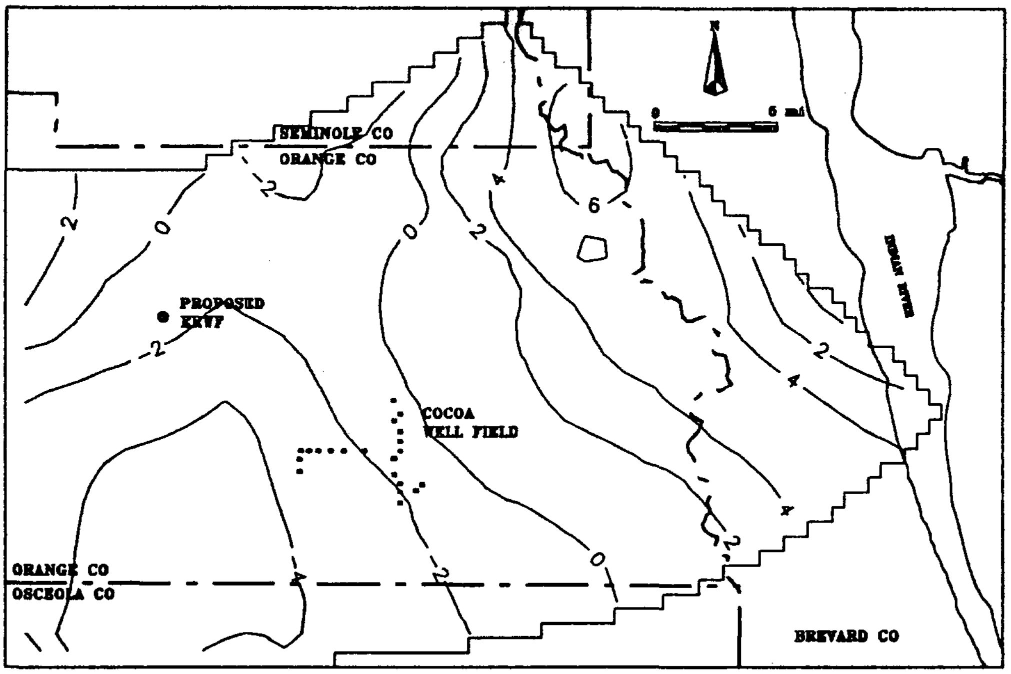
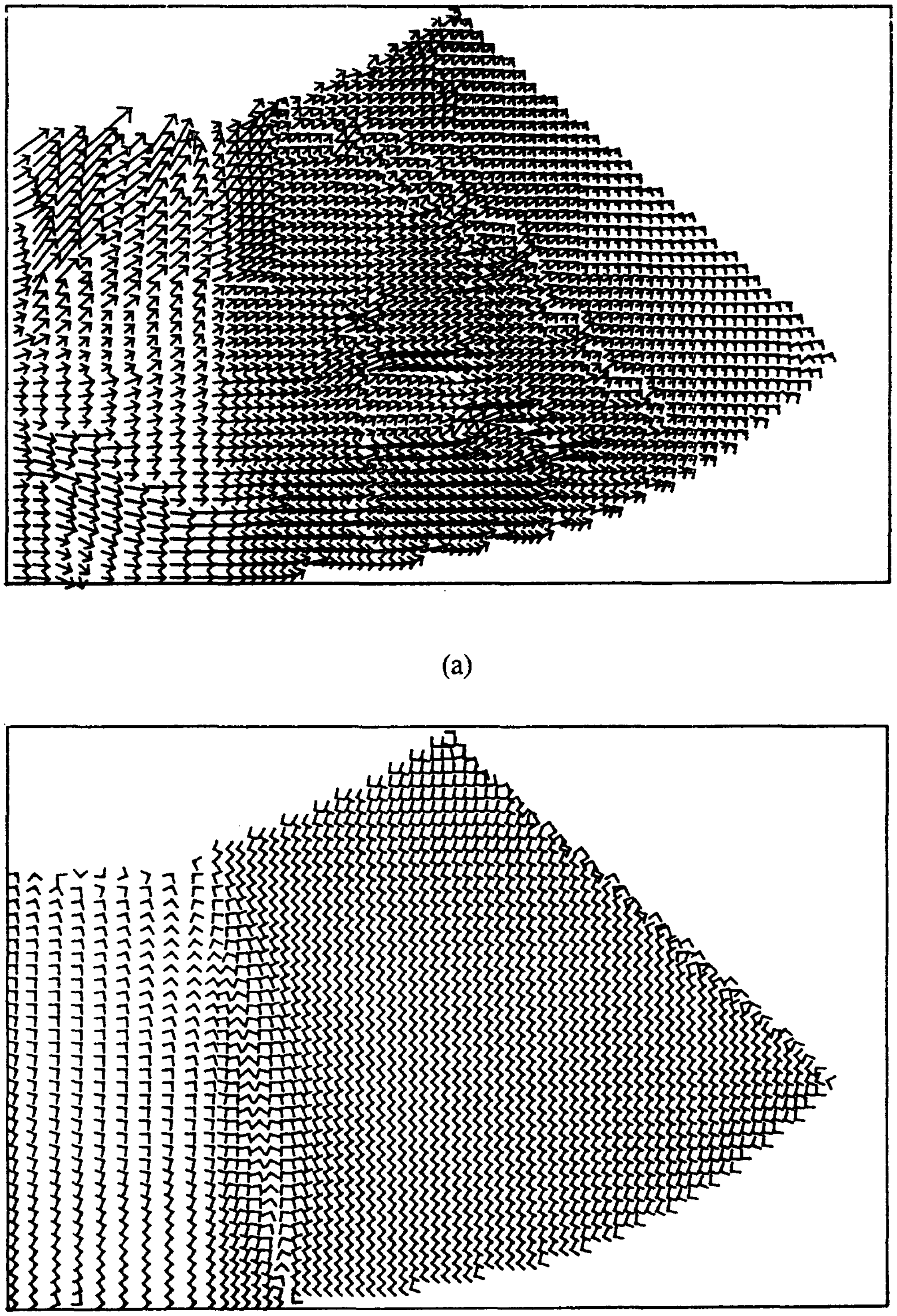


Figure 4.8 Difference between observed and simulated (environmental) potentiometric surface of the Upper Floridan for predevelopment conditions.



(a)

(b)

Figure 4.9 Simulated predevelopment horizontal (x-y) velocity vectors at the middle of the Upper (a) and Lower (b) Floridan.

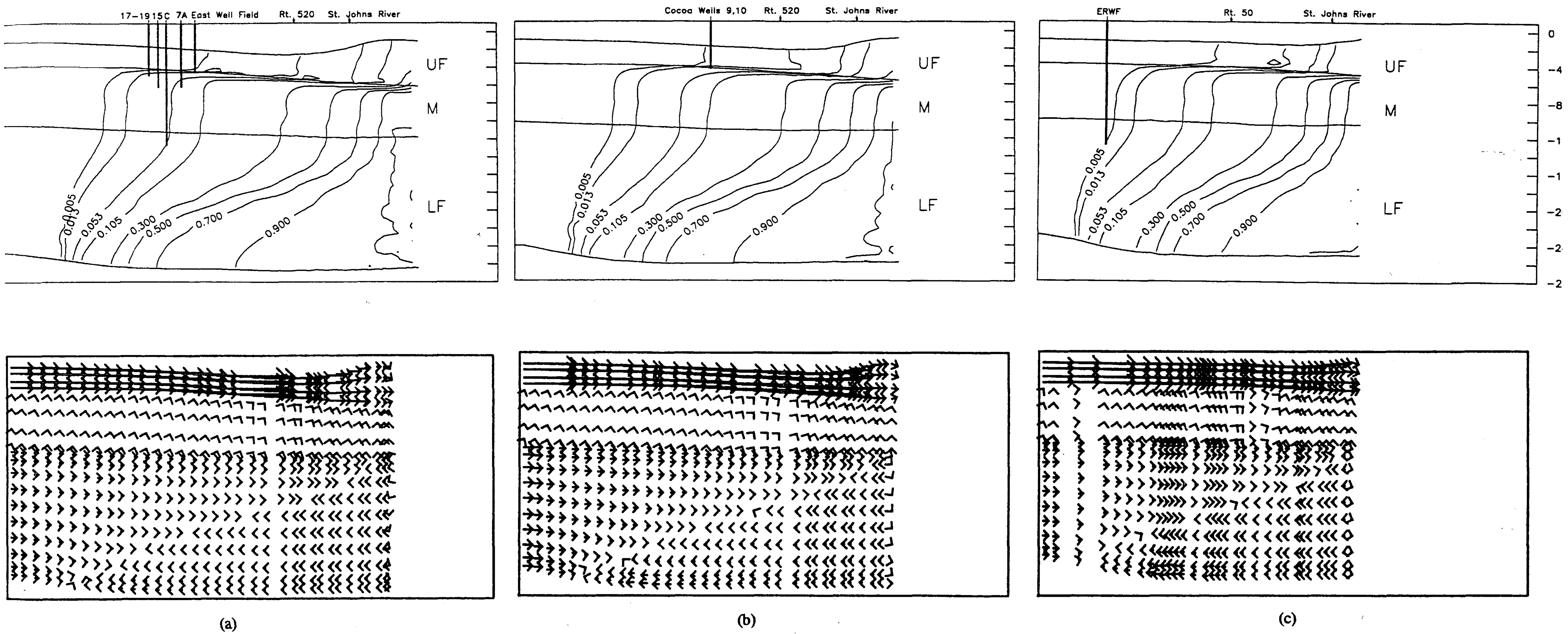


Figure 4.10 Simulated predevelopment normalized chloride concentrations and velocity vectors for cross section 1 (a), cross section 2 (b) and cross section 3 (c). Refer to Figure 4.2 for the cross-section locations.

surface is generally less than 4 ft or so throughout the model domain (Figure 4.8). Along the northeastern boundary, there is a very small region in which the simulated heads are up to 6 ft less than the estimated predevelopment potentiometric surface. The simulated Upper Floridan heads also match well (within 3-4 feet) with the Phase IV MODFLOW computed heads. The same is true for western regions of the Lower Floridan where chloride concentrations are not particularly high. Differences between Phase IV model (MODFLOW) heads and equivalent freshwater heads in the Upper Floridan and in low chloride regions of the Lower Floridan in the DSTRAM model are due to three reasons: 1) Relatively small chloride concentrations within the aquifer (say 2,000 mg/l) can cause larger equivalent freshwater heads of 1-2 ft depending upon aquifer thickness; 2) The selected boundary conditions for the Phase III simulations (particularly the no-flow northern and southern lateral boundaries) may cause moderate (up to several feet) changes in the simulated head field in certain regions; and 3) A significant portion of the Floridan aquifer system contains saltwater of substantial chloride concentration which is accounted for explicitly in the DSTRAM simulations, but was implicitly neglected during the MODFLOW simulations. Such regions of high chloride concentrations can significantly affect the equivalent freshwater head in regions of low chloride concentrations in some instances.

The areal concentration plots in Figure 4.7 indicate that the general northwest-southeast trend of the Upper and Lower Floridan isochlors in eastern Orange County is reproduced by the model. In the Upper Floridan, the 250 mg/l isochlor (0.013 normalized concentration) is simulated quite well except in the southern portion of the model domain where the simulated isochlor lies several miles to the east of the estimated location. Indeed, this region of the model was particularly difficult to calibrate, and although significant effort was expended it was not possible to improve the 250 mg/l isochlor calibration in this area. Given the inherent uncertainties in the model boundary conditions, physical parameters and chloride observation data (or lack thereof), the simulated 250 mg/l isochlor as presented herein is deemed reasonable.

The 1000 mg/l and 2000 mg/l isochlors (normalized concentration 0.053 and 0.105, respectively) in the Upper Floridan also match well with observed data in that they occur in the vicinity of the St. Johns River and regions further east. However, the simulated chloride concentrations of about 500 mg/l in the extreme southeastern tip of Orange County, in the vicinity of Lake Poinsett, are somewhat lower than the observed values of about 1,000 mg/l.

Figure 4.9 presents simulated areal velocity vector plots for the middle layer of the Upper and Lower Floridan aquifers. In the Upper Floridan, velocities are generally oriented east or northeast. The highest velocities occur in the western region of the model domain where the aquifer is thinnest (300 ft or less) and the hydraulic conductivities are highest. The smallest velocities occur in the far eastern portions of the model domain where the aquifer is thicker (400-500 ft or so) and the hydraulic conductivities are smaller. Velocity variations indicated in the Upper Floridan velocity field are primarily a function of aquifer heterogeneity.

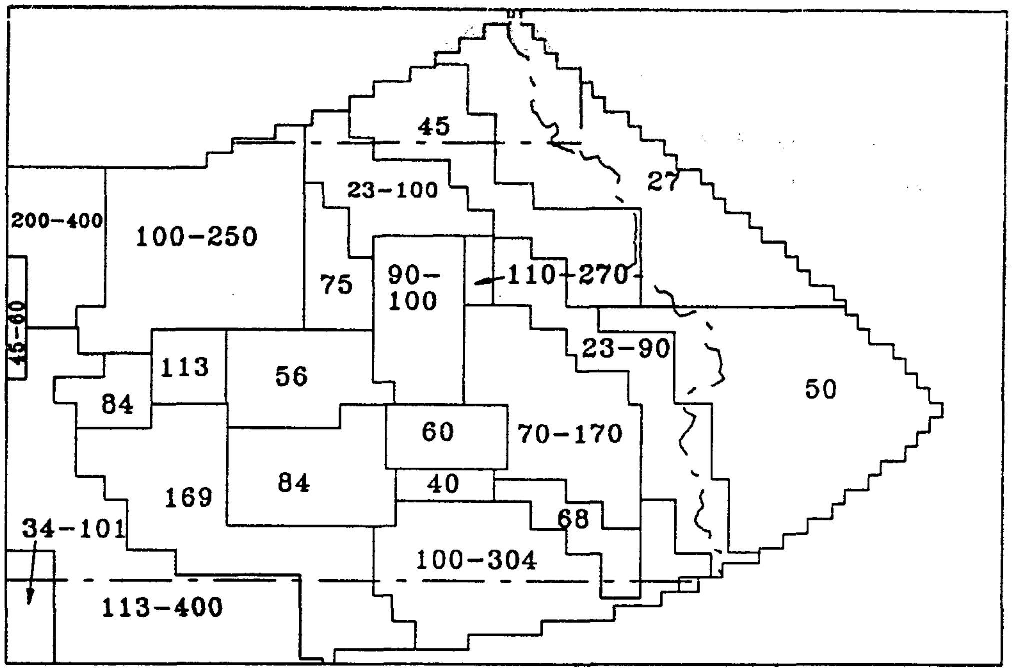
In the Lower Floridan, the simulated areal velocities are much more uniform than in the Upper Floridan due to the nearly uniform hydraulic conductivities. In the Lower Floridan, the ground water flow field is significantly affected by the density-dependent flow of ground water with high chloride concentration. High chloride water from the northeastern model boundary generally moves west or slightly southwest within the model domain. Fresh ground water entering the model domain along the western model boundary generally moves east or northeast. Low chloride water entering the Lower Floridan from the western model boundary must either exit the Lower Floridan by moving vertically through the middle semiconfining unit or laterally out of the model domain. Water that does not exit the Lower Floridan will eventually come into contact with higher chloride water and be incorporated into the zone of mixing, in which case its flowpath will be determined by a complex set of factors, including density-driven flow.

Some water in the Lower Floridan exits the model domain along the straight section of the northern boundary that is not specified as no-flow. This behavior is not surprising, since the simulated potentiometric surface from the Phase IV regional model indicated a northeastern component of ground-water flow in the Lower Floridan in the vicinity of this boundary. A portion of this discharge is concentrated at the turn in the northern boundary where the boundary condition changes from prescribed head to no-flow. As is indicated in the Lower Floridan potentiometric surface maps (Figure 4.7), this region is one of decreased potentiometric head.

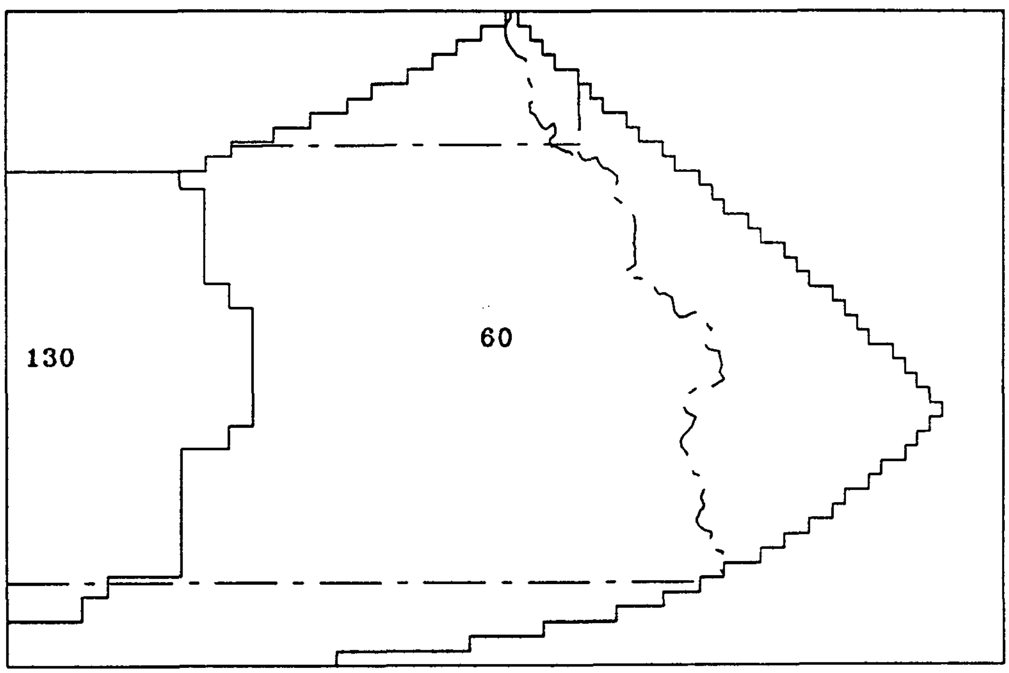
The degree to which the prescribed boundary conditions locally affect the potentiometric surface in this region is unknown. Uncertainty in the prescribed boundary conditions undoubtedly affects the simulated potentiometric surface and isochlors in the vicinity of this boundary to some extent, but it is not believed that the effects are substantial within the interior portions of the model domain.

Figure 4.10 illustrates the simulated chloride concentrations and velocity vectors for three model cross sections. The simulated chloride distribution in the vertical dimension is also quite reasonable. Cross sections 1 and 2 indicate that in the vicinity of the Cocoa well field, predevelopment chloride concentrations are generally less than 100 mg/l, except in the northern part of the East Cocoa well field, where they are slightly greater than 100 mg/l (see Figure 4.7 also). The simulated predevelopment chloride concentrations at the Cocoa C well are about 1,000 mg/l for sampling zone 1 and about 900 mg/l for zones 3 and 4. The simulated concentration for sampling zone 1 agrees reasonably well with the observed initial chloride value of 750 mg/l. The simulated chloride concentrations for sampling zones 3 and 4, however, are significantly higher than the observed respective concentrations of 81 mg/l and 40 mg/l. At the ERWF deep test well, simulated chloride concentrations are under 100 mg/l, as would be expected since low chloride concentrations were observed at this well when it was first sampled in 1989.

The calibrated model parameters are presented in Figures 4.11 and 4.12. The transmissivities of the Lower Floridan are the same as those used in the Phase IV study; the transmissivities of the Upper Floridan are the same as those used in the Phase IV study except for the south-central region of the model domain, where some adjustments were made during the DSTRAM model calibration. The leakances of the middle semiconfining unit are the same as in the Phase IV study throughout the model domain except in the vicinity of the East Cocoa well field, where the Phase IV model leakance was increased three-fold to simulate enhanced hydraulic connection between the Upper Floridan and zones of higher chloride water at depth. The leakance of the upper confining unit is identical to that used in the Phase IV model. Note that although transmissivities and leakances are presented in Figures 4.11 and 4.12, horizontal hydraulic

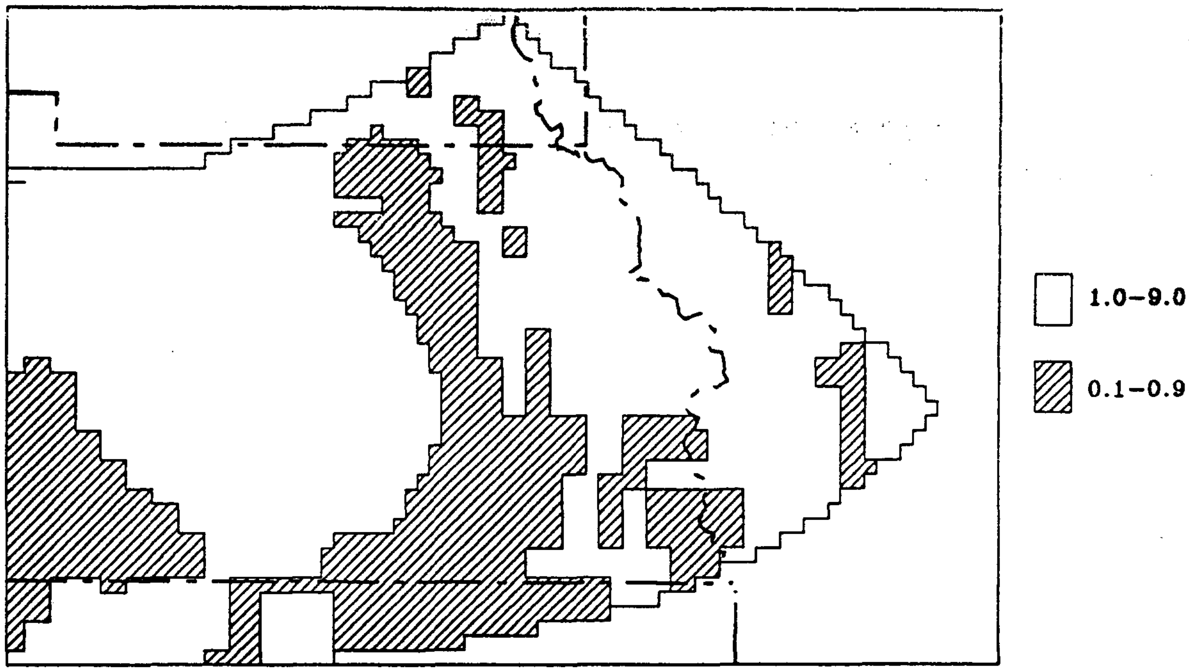


(a)

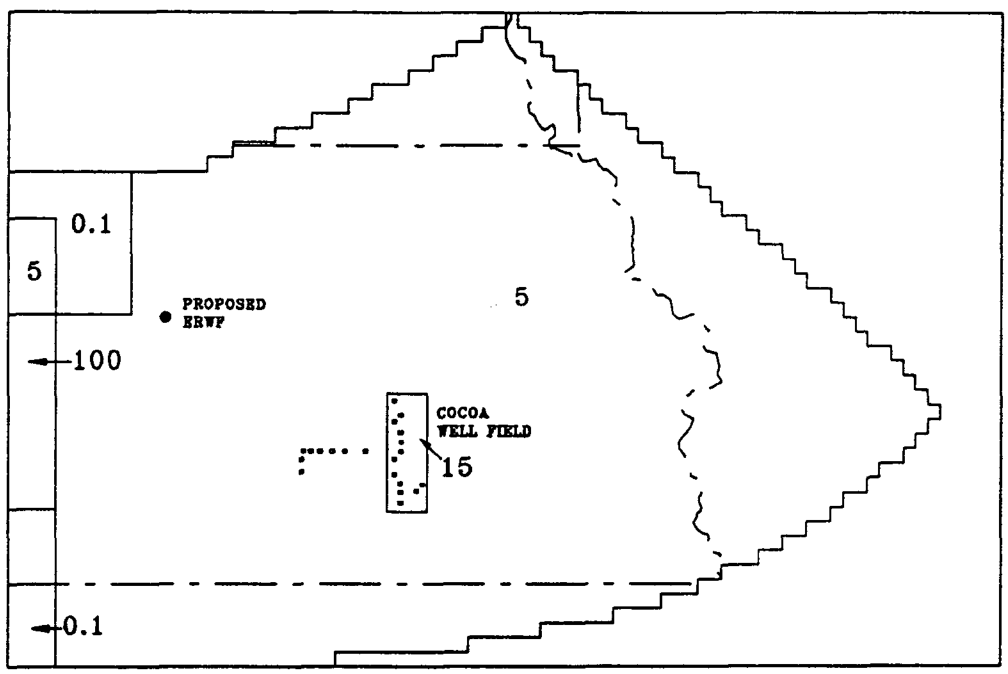


(b)

Figure 4.11 Transmissivity of the Upper Floridan (a) and Lower Floridan (b) aquifers in thousands of ft^2/d.



(a)



(b)

Figure 4.12 Leakance of the upper semiconfining unit (a) and the middle semiconfining unit (b) times 10^{-5} d^{-1}.

conductivities for the Upper and Lower Floridan can be obtained by dividing the transmissivity by the appropriate aquifer thickness. Vertical hydraulic conductivity of the middle semiconfining unit may be obtained by multiplying the leakance value by the thickness of the unit. Table 4.1 summarizes the various model input parameters.

The high middle semiconfining unit leakance used in the vicinity of the East Cocoa well field (Figure 4.12b) is discussed in detail in the next section (Section 4.7.4). The justification for the inclusion of this local zone of high leakance is based upon a conceptual model derived from observations of the physical system at the Cocoa well field (Tibbals and Frazee, 1976). Although they could not be identified during this study due to a lack of field data, it is highly likely that there are other (possibly numerous) zones or regions of higher leakance throughout the model domain.

The calibrated effective porosities are 0.25 for the Upper Floridan, and 0.1 for the Lower Floridan and the middle semiconfining unit. These values are in reasonable agreement with numerous other studies. Conceptually, it is realistic that the Upper Floridan be assigned an effective porosity larger than that of the Lower Floridan or the middle semiconfining unit. This is because the ability of the Floridan aquifer to transmit water is primarily a function of secondary porosity, such as solution cavities and fractures. Since the ground-water flow system is substantially more vigorous (in terms of flow velocities and volumes of water passed through the aquifer) in the Upper Floridan than in the Lower Floridan, the effective porosity of the Upper Floridan should be larger than the other hydrogeological units due to the increased solution activity.

The anisotropy ratio of vertical to horizontal hydraulic conductivity is 1:30 for both the Upper and Lower Floridan aquifers. 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). Within the middle semiconfining unit, the horizontal hydraulic conductivity is 0.1 ft/d throughout most of the model domain, but it is 0.6 ft/d within a region of high leakance near the western model boundary (Figure 4.12). The resulting anisotropy ratio within the middle semiconfining unit

Table 4.1 Summary of calibrated model input parameters.

Parameter		High	Low
Transmissivity (ft^2/d)	Upper Floridan	400,000	27,000
	Lower Floridan	130,000	60,000
Upper Confining Unit Leakance (d^{-1})		9×10^{-5}	1×10^{-6}
Middle Semiconfining Unit Leakance (d^{-1})		1×10^{-3}	1×10^{-6}
Porosity	Upper Floridan	0.25	0.25
	Lower Floridan	0.10	0.10
	Middle Semiconfining Unit	0.10	0.10
Dispersivity longitudinal/transverse (ft)	Upper Floridan	50/5	50/5
	Lower Floridan	50/5	50/5
	Middle Semiconfining Unit	50/5	50/5
Anisotropy Ratio	Upper Floridan	1:30	1:30
	Lower Floridan	1:30	1:30
	Middle Semiconfining Unit	1:5	1:3
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}

ranges from about 1:3 - 1:5. Although these ratios are larger than those of the Upper and Lower Floridan, they are not unreasonable. Conceptually, solutioning activity in the middle semiconfining unit should tend to increase the vertical hydraulic conductivity, rather than the horizontal hydraulic conductivity, of the unit since ground-water flow through the unit is predominately in the vertical direction. This observation suggests that larger anisotropy ratios (more isotropic conditions) in the middle semiconfining unit, relative to the Upper and Lower Floridan, might be expected in the field.

The final calibrated longitudinal dispersivity 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 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 resulted in a more disperse chloride concentration distribution in the middle semiconfining unit.

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 4.13-4.16. Figure 4.13 illustrates the simulated equivalent freshwater head, the environmental head, and the chloride concentration distribution for the middle nodal layer of the Upper and Lower Floridan aquifers. Figure 4.14 illustrates the difference between the simulated (environmental) heads and the observed potentiometric surface in the Upper Floridan. Figure 4.15 presents areal velocity vector plots for the middle layer of the Upper and Lower Floridan, and Figure 4.16 portrays the distribution of chlorides and the corresponding velocity vector plots for the three standard cross sections. The average 1988 simulation results were obtained by conducting a transient simulation from predevelopment (1956) conditions to 1988 (simulation period of 32 years). A time step of 8 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.

A comparison of Figures 4.13 and 4.16 with the observed data and the predevelopment simulation results (Figures 4.7-4.10) 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 2 ft throughout the model domain (Figure 4.14). The simulated Upper Floridan heads also match well (within two feet) with the Phase IV MODFLOW computed heads, and the same is true for western regions of the Lower Floridan where chloride concentrations are not particularly high. Differences between Phase IV model (MODFLOW) heads and equivalent freshwater heads in

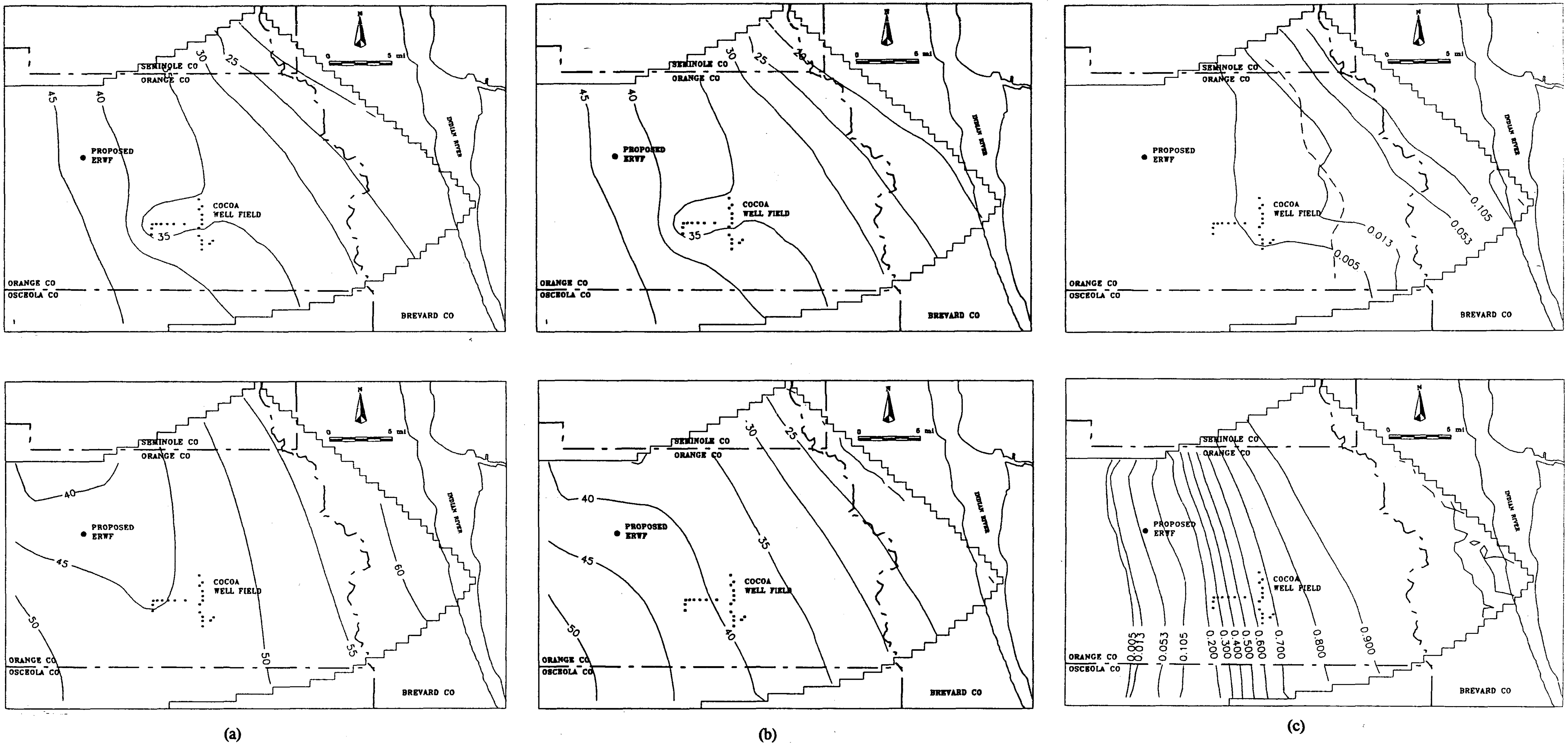


Figure 4.13 Simulated average 1988 equivalent freshwater head (a), environmental head (b), and normalized chloride concentration (c) at the middle of the Upper and Lower Floridan. The dashed line in (c) is the estimated location of the 250 mg/l isochlor in the Upper Floridan in eastern Orange County.

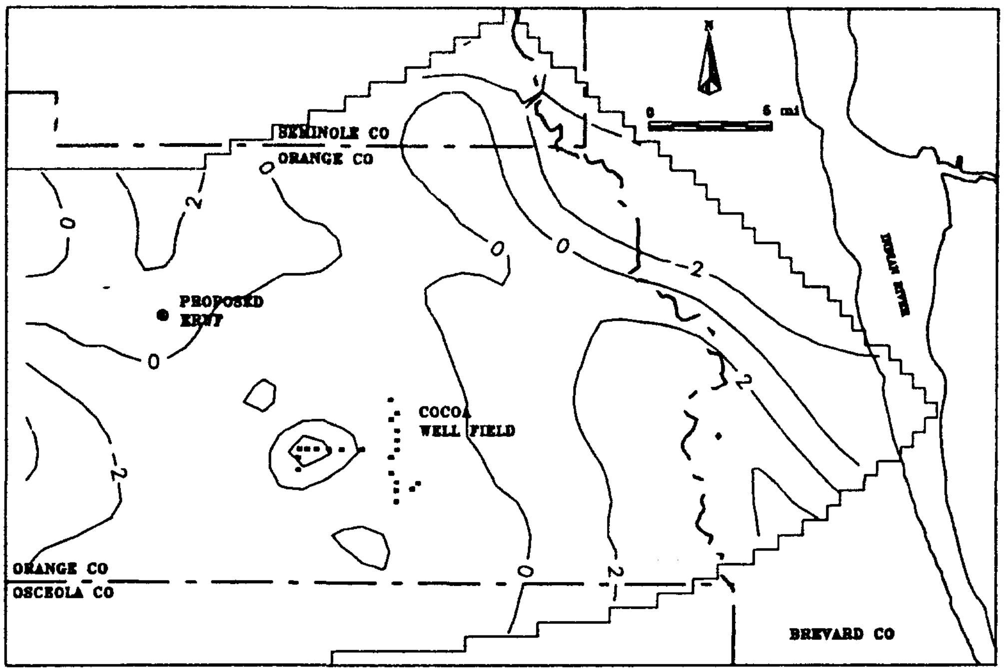
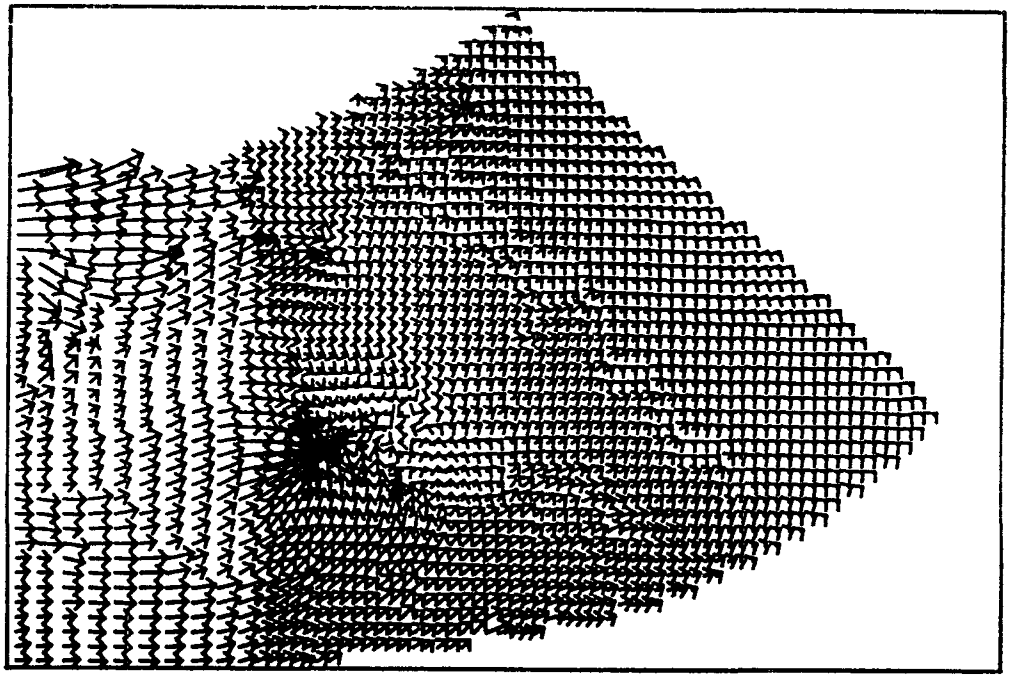
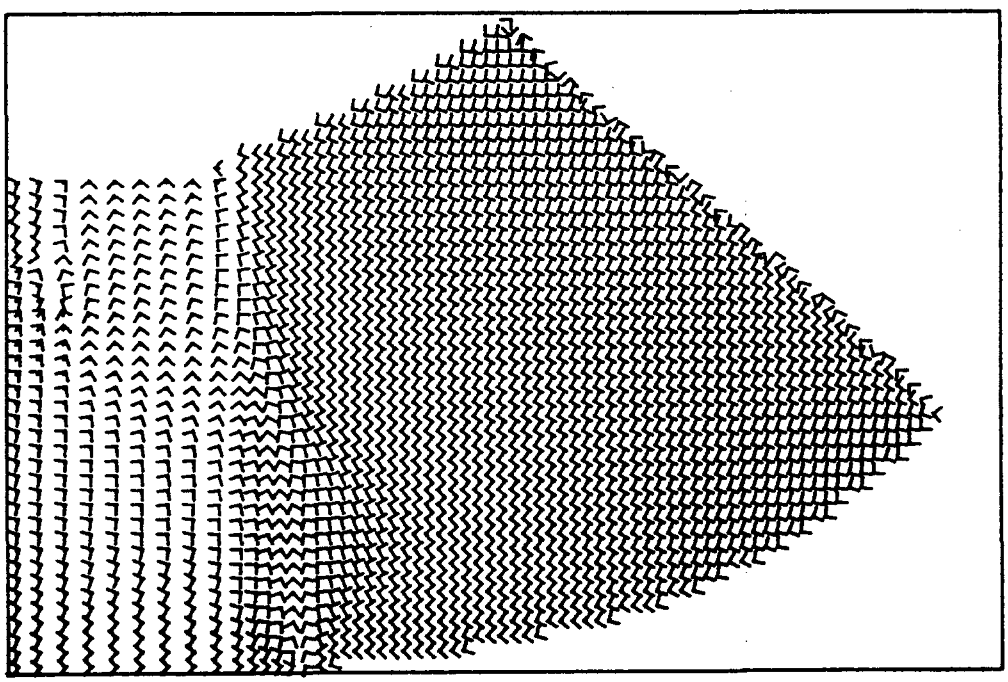


Figure 4.14 Difference between observed and simulated (environmental) potentiometric surface of the Upper Floridan for average 1988 conditions.



(a)



(b)

Figure 4.15 Simulated average 1988 horizontal (x-y) velocity vectors at the middle of the Upper (a) and Lower (b) Floridan.

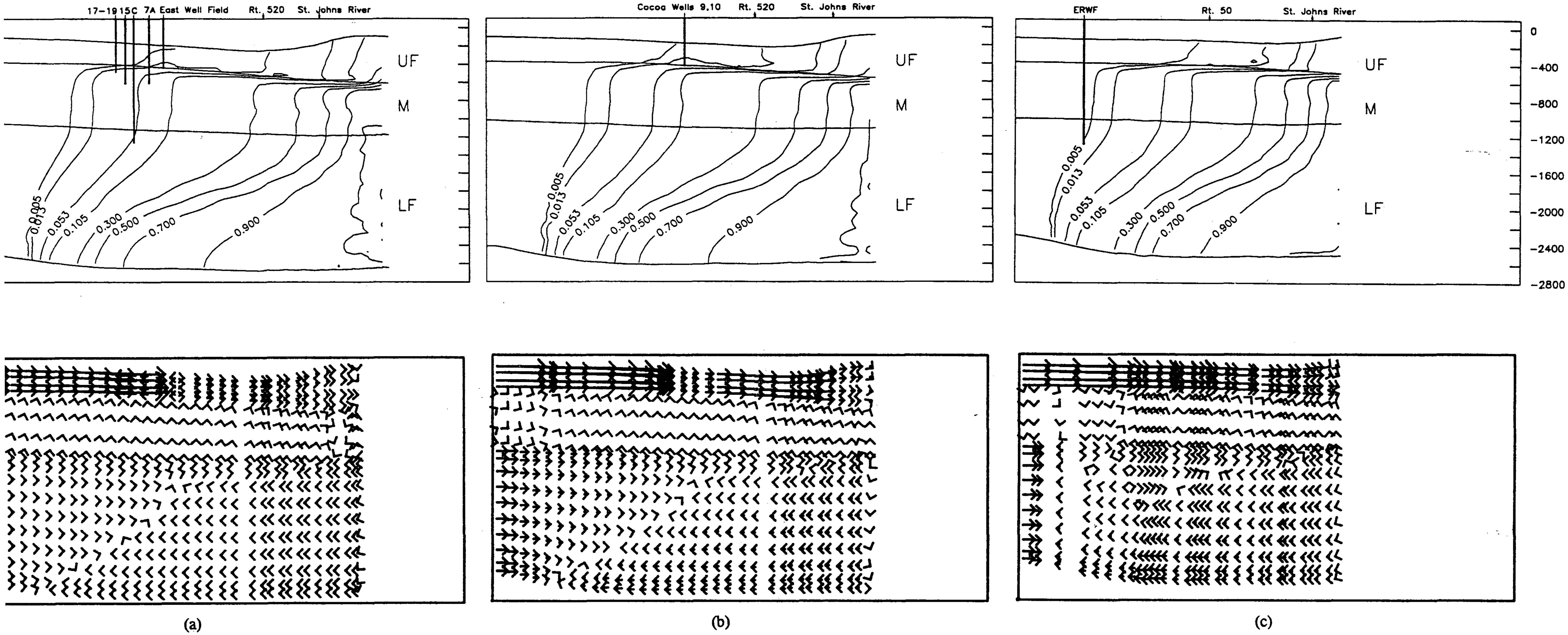


Figure 4.16 Simulated average 1988 normalized concentrations and velocity vectors for cross section 1 (a), cross section 2 (b) and cross section 3 (c).

the Upper Floridan and low chloride regions of the Lower Floridan are due to the same reasons outlined in the previous section. In the Upper Floridan, all of the isochlors have remained essentially unchanged from predevelopment to 1988, except for the 100 mg/l isochlor (0.005 normalized concentration) which has moved a substantial distance to the south and west in the vicinity of the Cocoa well field (Figure 4.13). In the Lower Floridan, the isochlors moved very slightly to the west, as would be expected (Figure 4.13c).

The simulated areal velocity vector plots at the middle of the Upper and Lower Floridan (Figure 4.15) are very similar to the predevelopment vector plots, particularly in the Lower Floridan. In the Upper Floridan, the flow of ground water towards various pumping centers, and in particular the Cocoa well field, is clearly evident. Within a small region due east of the Cocoa well field area, the regional ground-water flow direction has been reversed by well field pumping, and ground water flows west towards the well field, rather than northeastward towards the coast. Note, however, that in the vicinity of the regional 250 mg/l isochlor in eastern Orange County, the original (predevelopment) direction of ground-water flow has not been altered substantially, and hence there has been little movement of the 250 mg/l isochlor from predevelopment to postdevelopment conditions.

Figure 4.16 illustrates the normalized chloride concentration distribution and the velocity vector plots for the standard set of vertical cross sections. In cross section 1, which passes through the center of the Cocoa well field, the upconing of the 250 mg/l isochlor (normalized concentration 0.013) in the vicinity of the East Cocoa well field is clearly evident. Upconing of the 250 mg/l isochlor is also evident in cross section 2, which passes through the north end of the East Cocoa well field in the vicinity of Cocoa wells 9 and 10.

The simulated and observed chloride concentrations at the relevant Cocoa wells for predevelopment and 1988 conditions are listed in Table 4.2. The simulated chloride concentrations in Table 4.2 are flux-averaged values for the appropriate nodes that represent the Cocoa wells. In general, the agreement between observed and simulated chloride concentrations is quite reasonable. In order to obtain (and justify) a significantly improved match between

Table 4.2 Observed and simulated chloride concentrations at the Cocoa well field for average predevelopment and 1988 hydrologic conditions.

Well No.	Predevelopment Chloride Conc. (mg/l)		Postdevelopment Chloride Conc. (mg/l)	
	Observed	Simulated	Observed	Simulated
2	NA	101	450	302
3	30	87	350	283
4	NA	68	225	207
7A	25	55	185	180
8	NA	114	350	310
9	30	114	250-260[a]	310
10	NA	141	190[b]	321
11	NA	55	190	108
12A	NA	82	350	150
12B	160[c]	82	220	150
13	36[c]	36	140	103
14	38[c]	30	105	89
15	54[c]	27	60	74
16	55[c]	21	55	53
17	55[c]	20	50	29
18	NA	19	60	27
19	NA	19	58	27

Note: Postdevelopment chloride concentration is the approximate average concentration for the mid to late 1980's

[a] Average concentration prior to plugging well back from a depth of 525 ft to 385 ft in 1984.
[b] Average concentration prior to plugging well back from a depth of 506 ft to 350 ft in 1986.
[c] Well completed after some other Cocoa wells were already in operation.

simulated and observed chloride concentrations at the Cocoa wells, it would be necessary to construct a local-scale model encompassing the Cocoa well field that would be capable of incorporating local-scale aquifer heterogeneities. Such an effort is not warranted at the present time, however, due to the lack of detailed field data on aquifer characteristics.

In order to achieve a reasonable calibration it was necessary to 1) increase the middle semiconfining unit leakance in the vicinity of the East Cocoa well field by a factor of three, and 2) skew the discharge attributed to the Cocoa wells towards the model nodes near the bottom of the Upper Floridan. The selected region of increased leakance is outlined in Figure 4.12; this modeling approach is consistent with Tibbals and Frazee (1976), who surmise that the vertical hydraulic connection between aquifer units is better in the East well field than it is in the West well field. Assigning the discharge of the Cocoa wells to the bottom three nodes (lower half) of the Upper Floridan is justified because the majority of the water pumped from the Cocoa wells is derived from a cavity zone near the bottom of the Upper Floridan about 500 ft or so below land surface (Kevin Bral, CH2M Hill, personal communication, 1992). Although some of the Cocoa wells, such as well 7A, penetrate the top of the middle semiconfining unit, due to the low permeability of this unit it was assumed that none of the well discharge was derived from it.

The average 1988 calibration results are also in reasonable agreement with other key chloride observations within the model domain such as the ERWF deep test well, the Cocoa R salinity test well, and the Orange County Landfill and Deseret Ranch TDEM sites (Table 4.3). As with the predevelopment calibration, however, the simulated concentrations at the Cocoa C well do not match well with those observed. The trend of no increase in concentrations from predevelopment to postdevelopment conditions at sampling zones 3 and 4 within the middle semiconfining unit is generally replicated by the model, but the simulated concentrations are about 850 mg/l too high. The simulated predevelopment chloride concentration for the deep Cocoa C monitor zone (zone 1) is reasonable, but from predevelopment to postdevelopment conditions the simulated increase in chloride concentration is only 159 mg/l, whereas an actual increase of about 1,850 mg/l has been observed (Table 4.3).

Table 4.3 Observed and simulated chloride concentrations at various locations within the Phase III model domain.

Site Description	Predevelopment Conc. (mg/l)		Postdevelopment Conc. (mg/l)	
	Observed	Simulated	Observed	Simulated
ERWF - Lower Floridan Test Well	NA	<50	<50	<50
Cocoa C - Zone 1 (1351-1357 ft bls)	750[a]	1,000	2,600	1,159
Cocoa C - Zone 3 (1218-1224 ft bls)	82[a]	900	82	944
Cocoa C - Zone 4 (1044-1050 ft bls)	40[a]	880	40	885
Cocoa R (1,098-1,205 ft bls)	NA	625	352	630
Deseret Ranch TDEM Site (1,292 ft below msl)	NA	4,417	3,270[b]	4,436
Orange County Landfill TDEM Site (2,304 ft below msl)	NA	4,180	2,880[b]	4,180

[a] Observed concentrations as of 1967, approximately 10 years after first Cocoa well was completed and utilized.

[b] Chloride concentrations in excess of the tabulated value is expected. Porosity of 25% was assumed to obtain this value; observed concentrations would be higher if porosity of 0.1 (as was used in the Lower Floridan) was used.

It is not clear why the observed chloride concentrations at the Cocoa C well are so difficult to simulate; although it is certainly due in part to a lack of knowledge of local-scale aquifer parameters. For example, observed chloride concentrations in the deep monitor zone could be increasing faster than was simulated due to the presence of highly transmissive fracture zones or solution cavities near the top of the Lower Floridan. Since so little data is available concerning the hydraulic characteristics of the Lower Floridan, however, it is difficult to justify the implementation of such speculations into a model. The simulated chloride concentrations in the middle semiconfining unit in the vicinity of the Cocoa C well are also somewhat higher than those observed; it would seem, therefore, that the simulated isochlors in the middle semiconfining unit should actually fall some distance to the east of their present location. However, the simulated isochlors in the Upper and Lower Floridan in the vicinity of the Cocoa well field are quite reasonable. It is not clear how, given the available data and modeling framework presented herein, simulated chloride concentrations in the middle semiconfining unit beneath the west Cocoa well field could be reduced, while at the same time maintaining the present locations of the simulated isochlors in the Upper and Lower Floridan.

The calibrated model presented in this chapter is suitable for the prediction of regional scale trends in chloride concentrations over the long term (decades). The model has been demonstrated to possess the ability to simulate the time-variation of chlorides in eastern Orange County, particularly in the Upper Floridan. The model simulations conform well to the conceptual model of the ground-water flow system, and the simulation results match well with observed hydraulic heads and chloride concentrations. The only calibration targets that were not met particularly well in the simulations are the concentrations in the middle semiconfining unit at the Cocoa C well, and the observed increase in chloride concentration from predevelopment to postdevelopment conditions in the deep (Lower Floridan) Cocoa C sampling zone. Given the absence of data concerning aquifer characteristics in the vicinity of the Cocoa C well deep sampling zones, however, it is doubtful that an improved calibration could be obtained in this region without making arbitrary and unjustifiable (in terms of observed data) changes to the model. Furthermore, it is not clear from a conceptual standpoint how the model could be altered to shift the isochlor positions in the middle semiconfining unit about Cocoa C, yet maintain the simulated isochlors as they now exist in the Upper and Lower Floridan.

4.8 Model Sensitivity Analysis

A series of nine 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 and Lower Floridan aquifers; the vertical hydraulic conductivity of the middle semiconfining unit; the longitudinal dispersion coefficient; the Lower Floridan anisotropy ratio; and the effective porosity of the Upper and Lower Floridan. A sensitivity run was also conducted for the northeastern model boundary by assuming a modified chloride concentration distribution in the Upper Floridan along that boundary. Except for the effective porosity 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 (except for vertical hydraulic conductivity of the middle semiconfining unit) 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 Figure 4.7 and the transient sensitivity model runs should be compared against Figure 4.13. A summary overview of each sensitivity analysis is provided in Table 4.4.

4.8.1 Hydraulic Conductivity

A series of four sensitivity runs were conducted which involved changes in the calibrated model hydraulic conductivity. In the first run, the hydraulic conductivity in the Upper Floridan was increased by one order of magnitude (10 times). This change had only a minimal effect on the equivalent freshwater heads and the chloride concentrations in the Lower Floridan; changes were

Table 4.4 Summary of Phase III model sensitivity analysis.

Sensitivity Run No.	Description of Change	Summary of Results[a]
1	Upper Floridan hydraulic conductivity increased 10 times	Concentrations in the Upper Floridan substantially decreased. Concentrations in the Lower Floridan essentially unchanged.
2	Lower Floridan hydraulic conductivity increased 10 times	Upper Floridan 250 mg/l isochlor moved west to the Cocoa well field. Saltwater wedge in the Lower Floridan "flattened" so concentrations at the top of the Lower Floridan decreased.
3	Middle semiconfining unit vertical hydraulic conductivity increased 10 times	Isochlors in Upper Floridan moved to the east; isochlors in Lower Floridan essentially unchanged.
4	Middle semiconfining unit vertical hydraulic conductivity decreased to form a 1:30 anisotropy ratio.	Very minor changes in Upper and Lower Floridan isochlors.
5	Longitudinal dispersivity increased from 50 to 250 ft, and transverse dispersivity increased from 5 to 25 ft.	Minor changes in Upper and Lower Floridan isochlors. Isochlors in middle semiconfining unit became more disperse and moved a significant distance to the west.
6	Lower Floridan vertical hydraulic conductivity reduced to form anisotropy ratio of 1:10 (original ratio was 1:30)	No change throughout most of the system. Lower Floridan isochlors moved a small distance to the east.
7[b]	Upper Floridan effective porosity decreased from 0.25 to 0.1	Isochlors in the Upper Floridan moved a significant distance to the west; 250 mg/l isochlor in the vicinity of Cocoa well field. Minor change in Lower Floridan isochlors.
8[b]	Lower Floridan effective porosity decreased from 0.1 to 0.05	Upper Floridan isochlors unchanged; Lower Floridan isochlors moved slightly west.
9	Equivalent freshwater heads increased along the northeastern boundary to account for higher chloride concentrations at shallower depths	Isochlors in Upper Floridan moved slightly (½ mile or so) to the west; isochlors in Lower Floridan unchanged.

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

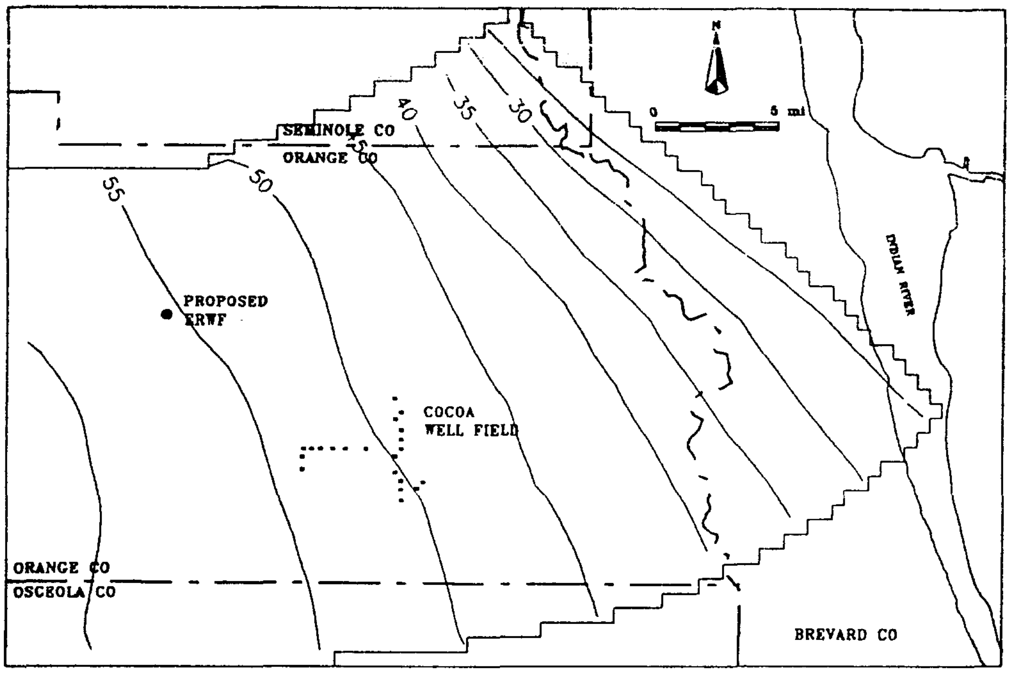
[b] Sensitivity run conducted for transient, postdevelopment conditions rather than steady-state conditions

more substantial, however, in the Upper Floridan (Figure 4.17). Heads in the Upper Floridan increased about 1-2 ft in the western regions of the model domain, and they decreased about 3-4 ft in the eastern portions of the model domain relative to the calibrated model results. The 100 and 250 mg/l isochlors 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.

In the second sensitivity run, the hydraulic conductivity in the Lower Floridan was increased an order of magnitude. The results of this simulation indicate substantial changes in chloride concentrations in both the Upper and Lower Floridan aquifers (Figures 4.18 and 4.19). In general, heads in the Upper Floridan are very similar to the calibrated model simulation and heads in the Lower Floridan increased several feet. The isochlors in the Lower Floridan moved a significant distance (up to several miles) to the east, relative to the calibrated model results (Figure 4.19). The saltwater wedge, however, ends at about the same location in the western model domain (i.e. the 100 and 250 mg/l isochlors have not moved substantially). These results indicate that the saltwater wedge in the Lower Floridan tends to be "flattened out" when the Lower Floridan hydraulic conductivity is increased. In the Upper Floridan, however, the isochlors generally moved to the west (Figure 4.18).

In the third sensitivity run, the vertical hydraulic conductivity of the middle semiconfining unit was increased by an order of magnitude. This parameter change had a very minor effect on chloride concentrations in the Lower Floridan, and equivalent freshwater heads in the Lower Floridan changed by about a foot or less. In the Upper Floridan, there was no significant change in equivalent freshwater heads, but there was some change in the simulated isochlors (Figure 4.20).

In the forth sensitivity run, the vertical hydraulic conductivity of the middle semiconfining unit was decreased such that an anisotropy ratio of 1:30 within the unit was maintained. The 1:30 anisotropy ratio is the same as that used for the Upper and Lower Floridan aquifers. For this sensitivity run, there were no significant changes in the simulated hydraulic heads or isochlors within the system.



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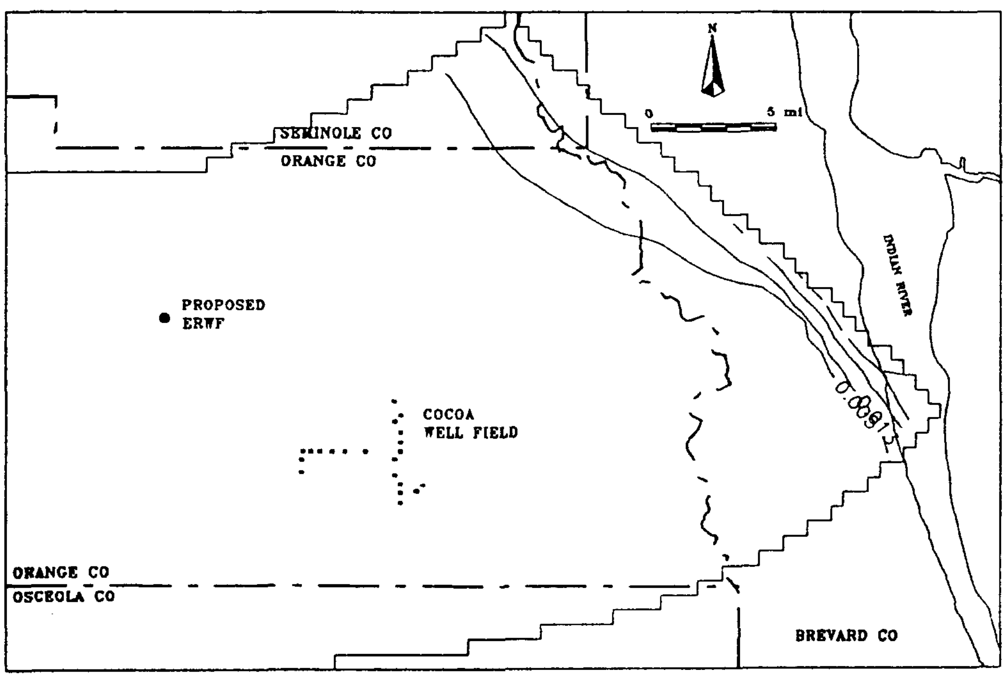
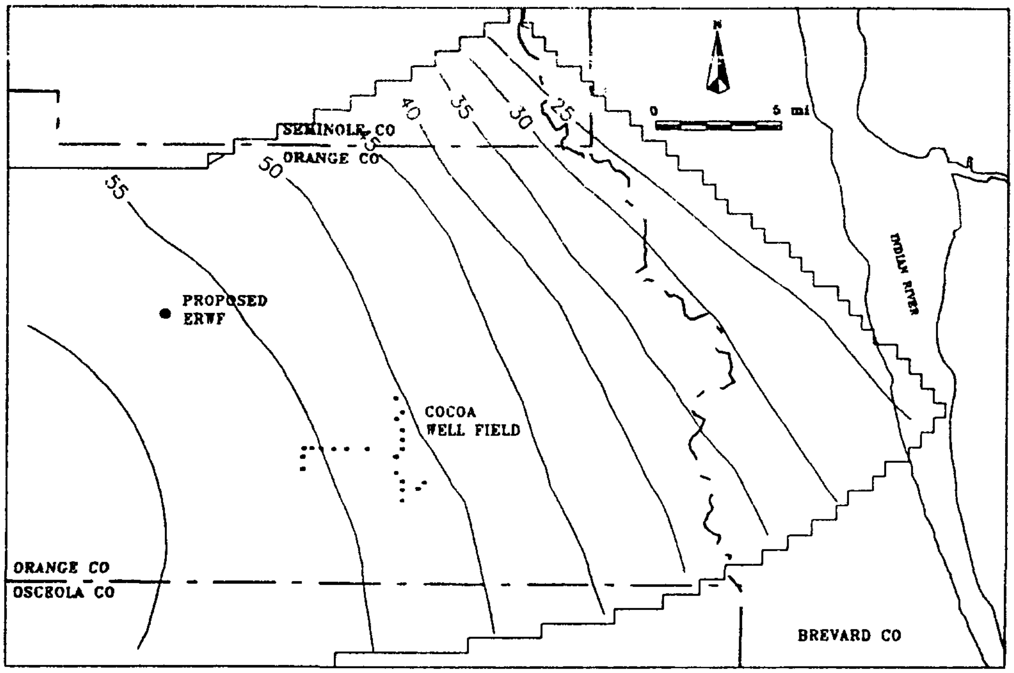


(b)

Figure 4.17 Equivalent freshwater head (a) and normalized chloride concentrations (b) for the Upper Floridan for sensitivity run 1, hydraulic conductivity increased by 10 times in the Upper Floridan.



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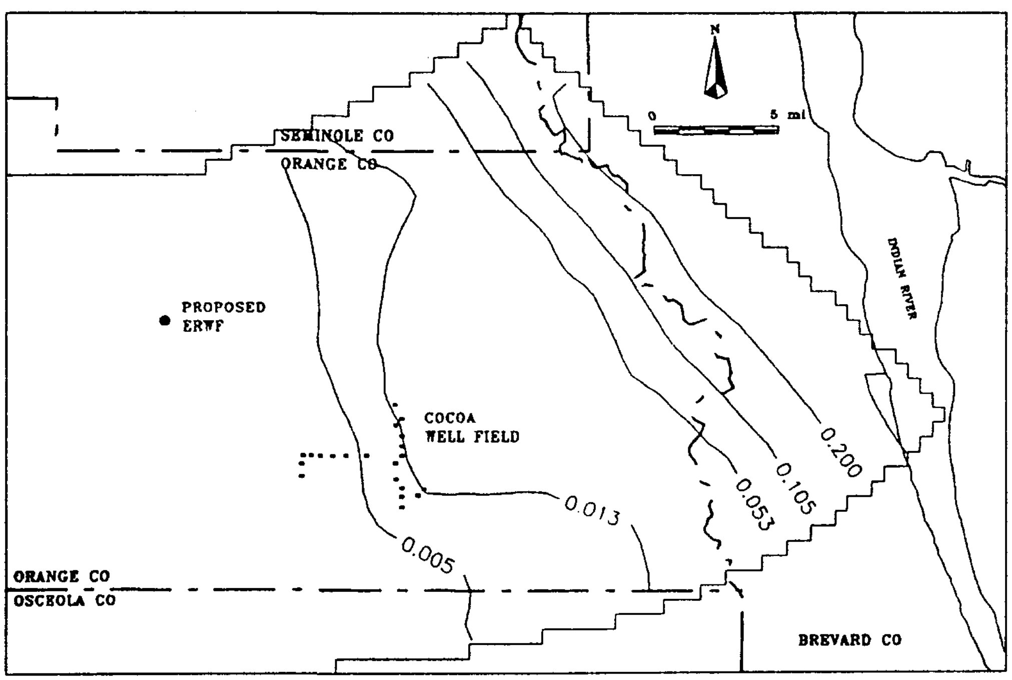
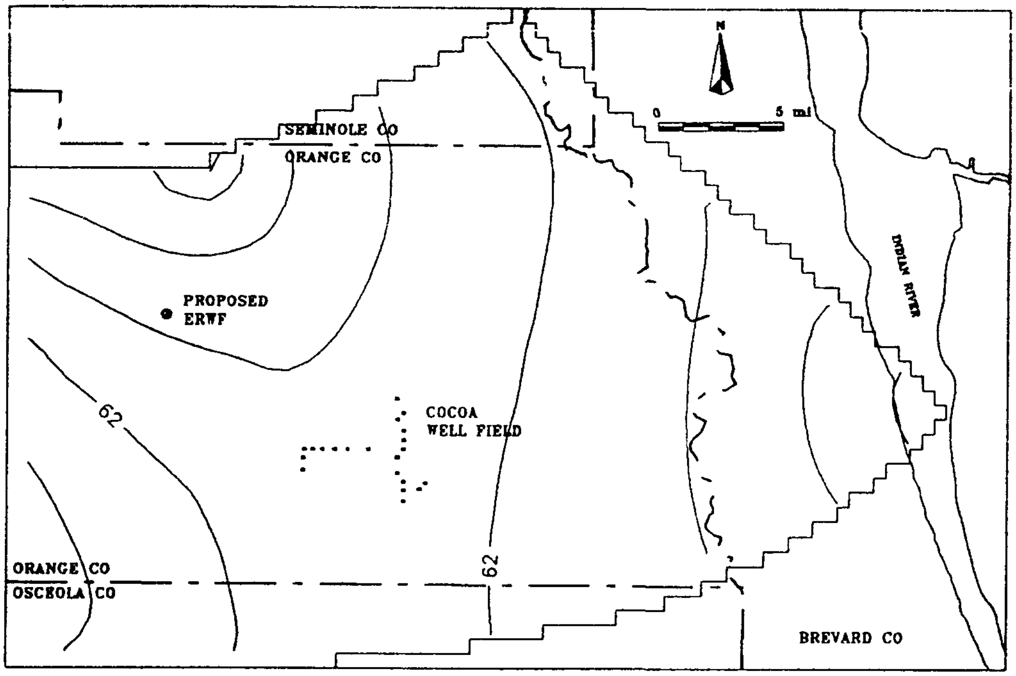


(b)

Figure 4.18 Equivalent freshwater head (a) and normalized chloride concentrations (b) for the Upper Floridan for sensitivity run 2, hydraulic conductivity increased by 10 times in the Lower Floridan.



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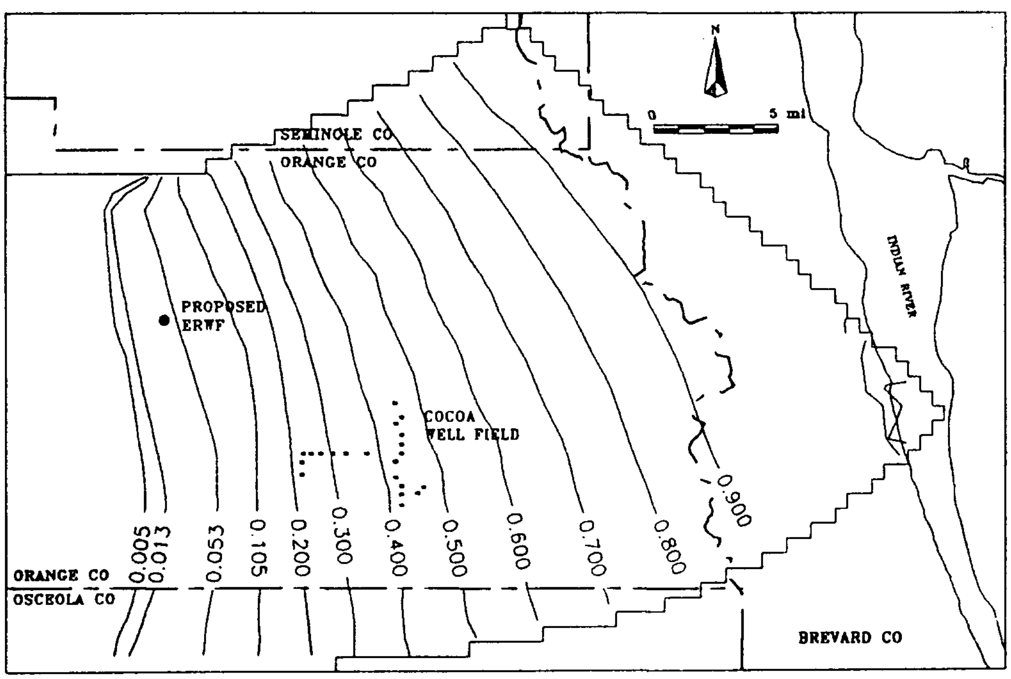
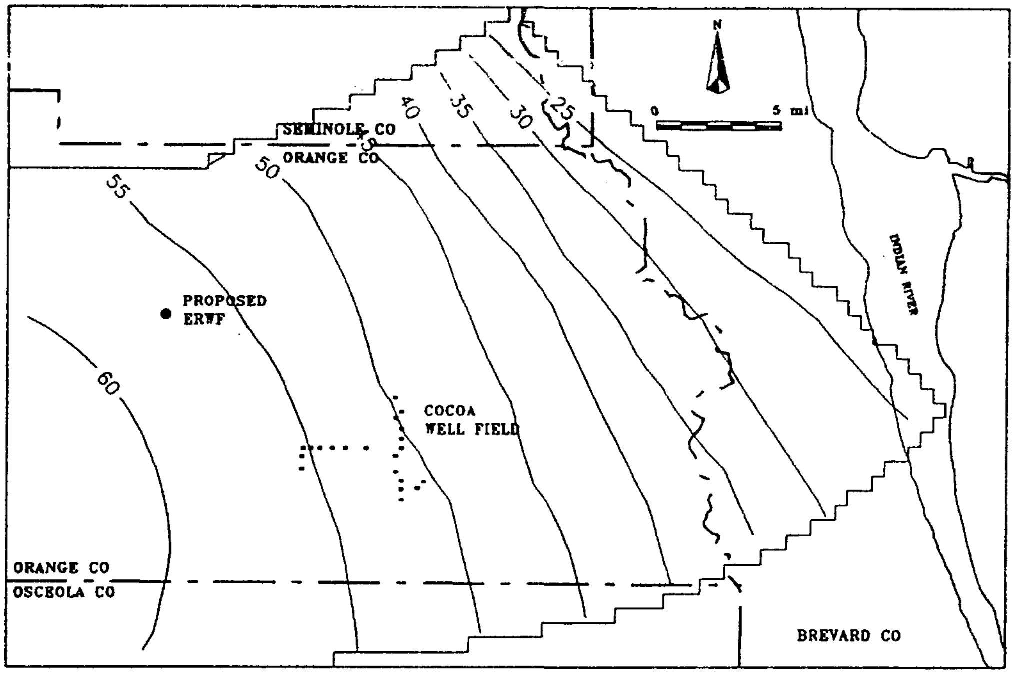
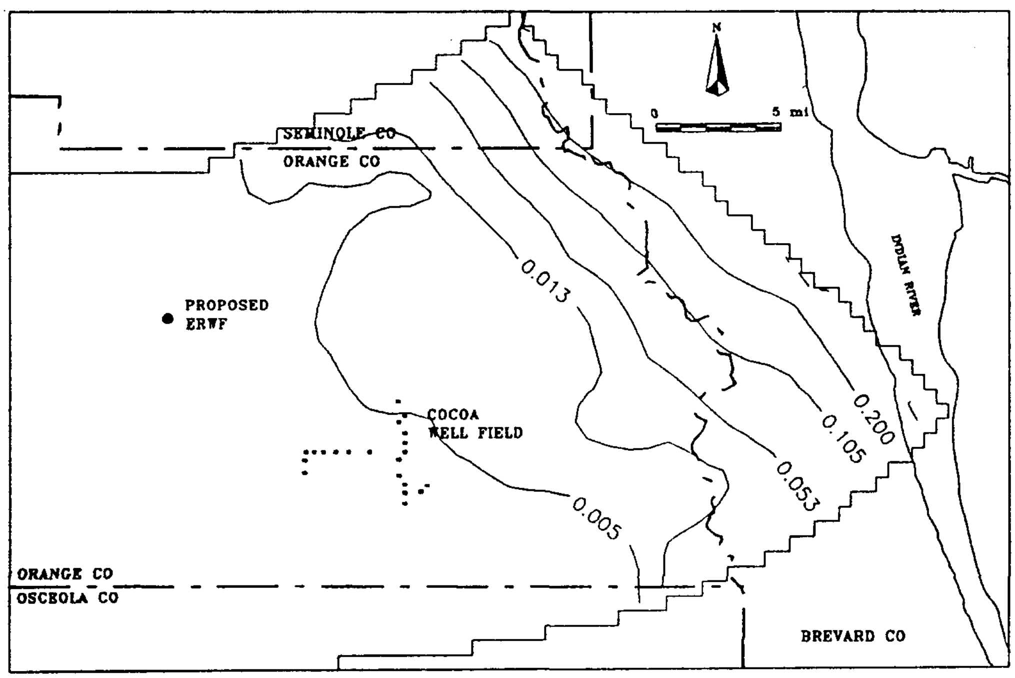


(b)

Figure 4.19 Equivalent freshwater head (a) and normalized chloride concentrations (b) for the Lower Floridan for sensitivity run 2, hydraulic conductivity increased by 10 times in the Lower Floridan.



(a)



(b)

Figure 4.20 Equivalent freshwater head (a) and normalized chloride concentrations (b) for the Upper Floridan for sensitivity run 3, vertical hydraulic conductivity increased by 10 times in the middle semiconfining unit.

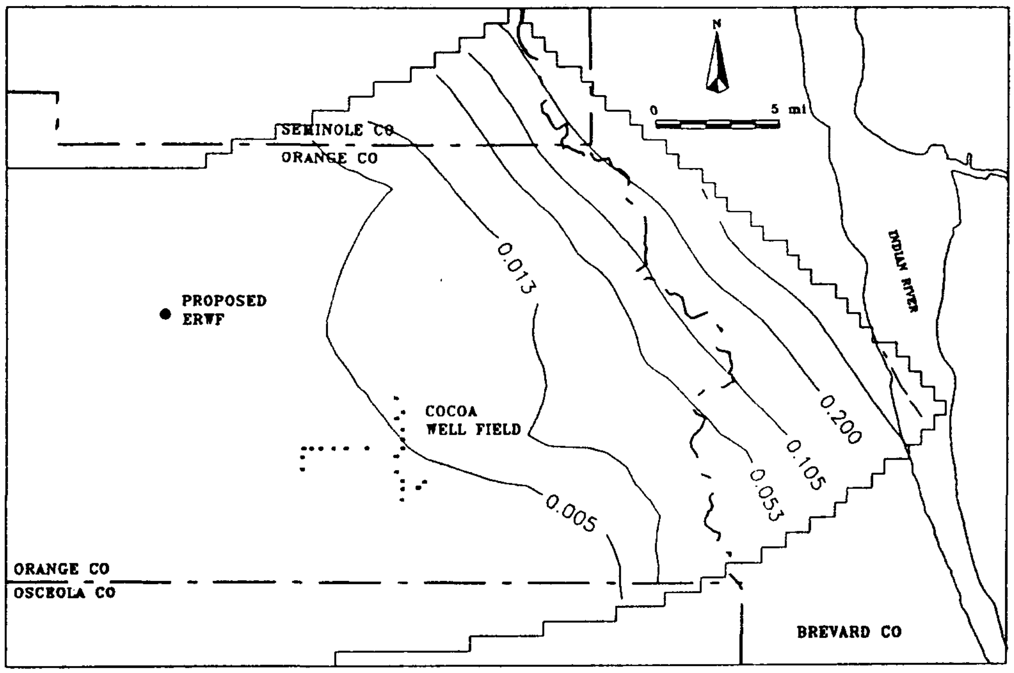
4.8.2 Longitudinal Dispersivity

In the fifth sensitivity run, the longitudinal dispersivity was increased from 50 ft to 250 ft, and the transverse dispersivity was increased from 5 ft to 25 ft. For this run, the equivalent freshwater heads at the middle of the Upper Floridan were identical to the predevelopment calibration, and the chloride isochlors were very similar to the predevelopment calibration except that the 1,000 mg/l and higher isochlors moved slightly to the west (Figure 4.21). At the middle of the Lower Floridan, equivalent freshwater heads and chloride concentrations were nearly identical to the predevelopment calibration simulation. However, for this particular sensitivity run, examining only the areal plots for the middle of the Upper and Lower Floridan can be deceiving; an examination of cross section 1 (Figure 4.21) indicates that chloride concentrations have increased significantly in the middle semiconfining unit and the top of the Lower Floridan due to increased spreading caused by the larger dispersivity.

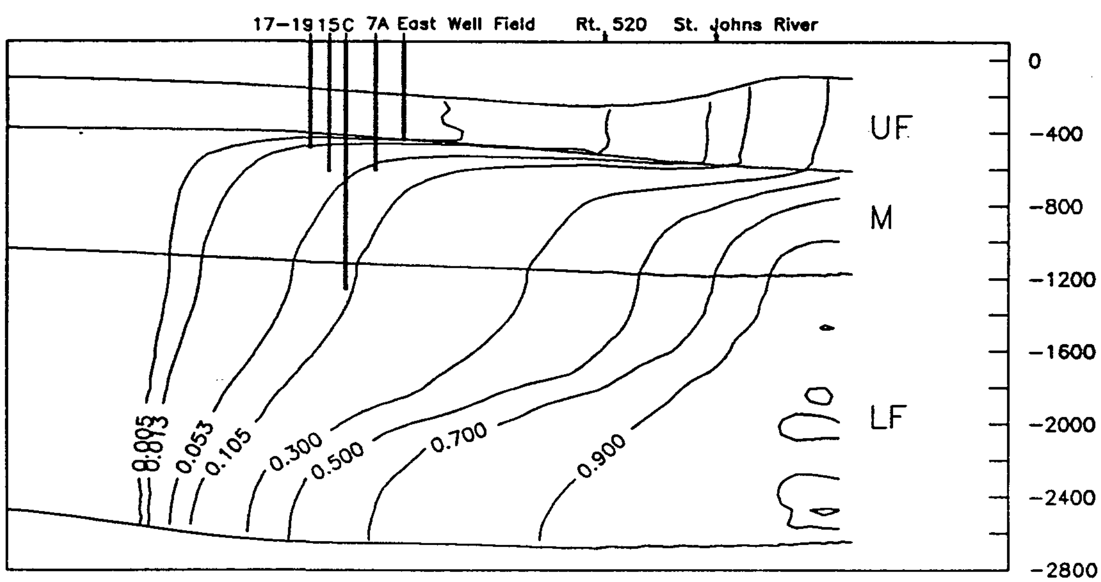
For cases where molecular diffusion is small compared to advection, the grid Peclet number may be defined as

$$P_e = \frac{\Delta x}{\alpha_L}$$

where Δx is the length of the finite element in the x-direction. During the model calibration, the Peclet number was on the order of 50 (i.e., 2,640 ft/50 ft), which is substantially larger than the Peclet number of 10 or so that is required to achieve stable numerical results (Huyakorn and Pinder, 1983). Consequently, the upstream weighting option of DSTRAM was utilized, and the upstream weighting procedure introduced an unknown degree of numerical (or artificial) dispersion into the simulation results. For this sensitivity run, however, the Peclet number is about 10 (2,640 ft/250 ft), and there should be little, if any, numerical dispersion embedded in the simulation results. A comparison of this sensitivity run with the calibrated model results provides, therefore, a crude methodology by which the effects of upstream weighting (numerical dispersion) may be assessed. Application of the reasoning outlined above leads to the following observations:



(a)



(b)

Figure 4.21 Normalized chloride concentrations for the middle of the Upper Floridan (a) and cross section 1 (b) for sensitivity run 5, longitudinal dispersivity of 250 ft.

1) The simulated isochlors in the Upper Floridan, and most of the Lower Floridan, are not significantly affected by numerical dispersion.

2) The simulated isochlors within the middle semiconfining unit and isochlors near the top of the Lower Floridan are more disperse and are located further west in the sensitivity run. It can be surmised, therefore, that although this middle (in cross section) region of the model domain is affected somewhat be numerical dispersion, the "equivalent" model dispersivity (input dispersivity of 50 ft plus some unknown numerical dispersion) is something significantly less than 250 ft.

4.8.3 Lower Floridan Anisotropy

The sixth sensitivity run, also conducted for steady-state predevelopment conditions, involved changing the Lower Floridan anisotropy ratio from 1:30 to 1:10. The simulated results were very insensitive to changes in this ratio. The equivalent freshwater heads in both the Upper and Lower Floridan were unchanged, and the simulated isochlors in the Lower Floridan moved only a very small distance (several hundred feet or so) to the east.

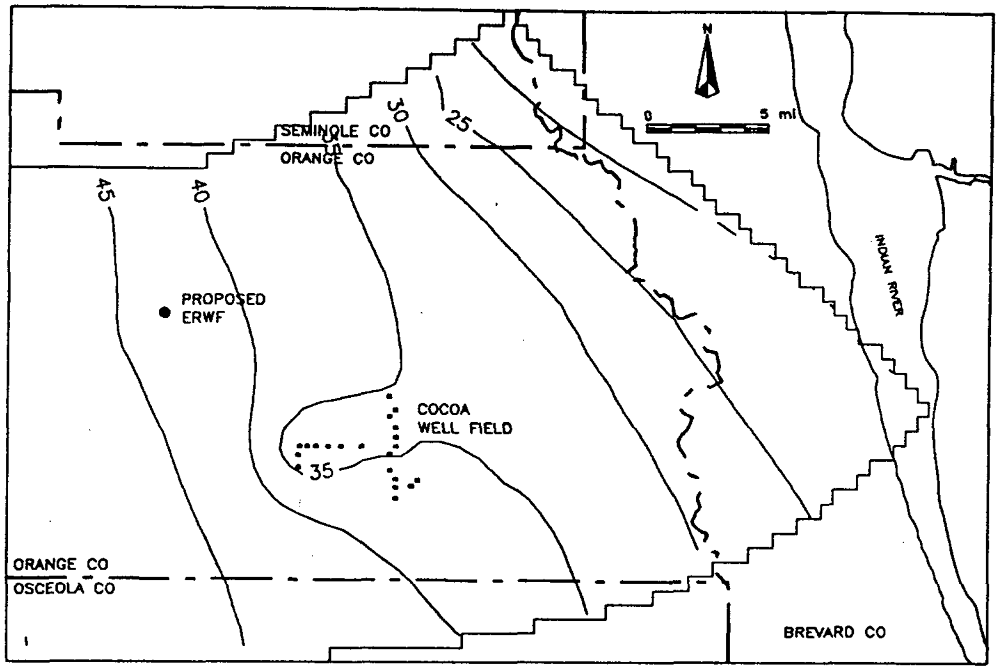
4.8.4 Effective Porosity

The next two sensitivity runs involved decreasing the effective porosity for both the Upper and Lower Floridan aquifers. These transient model runs (32 years) simulate the change in heads and chlorides from predevelopment to average 1988 conditions. Transient simulations were conducted because effective porosity has only a minor influence on steady-state (predevelopment) model results.

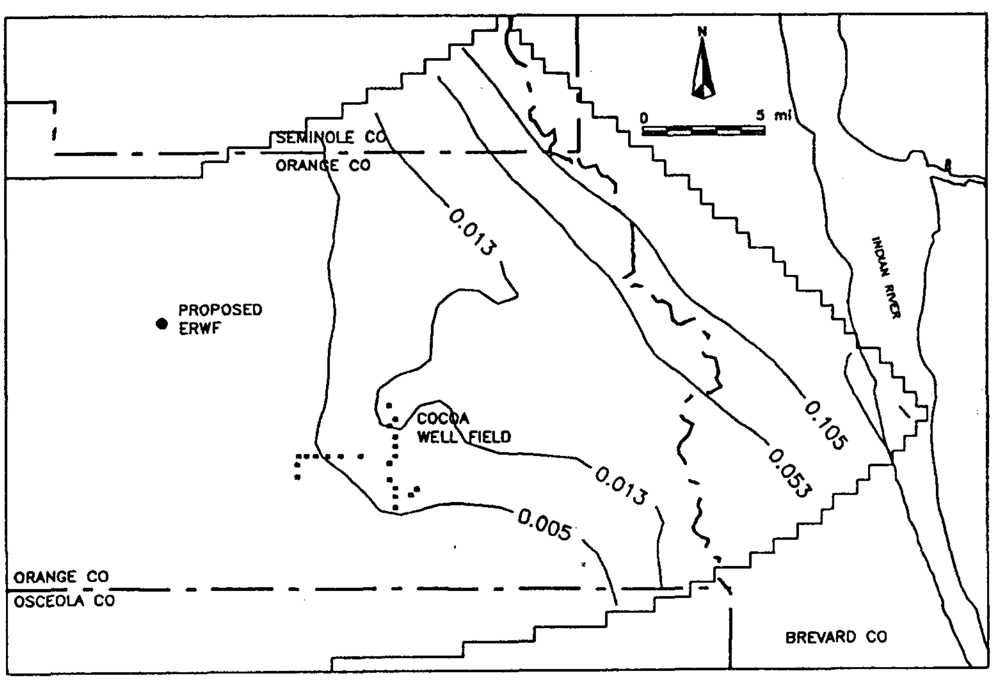
In sensitivity run 7, the effective porosity of the Upper Floridan was decreased from 0.25 to 0.1, and in sensitivity run 8 the effective porosity in the Lower Floridan was decreased from 0.1 to 0.05. The results of both sensitivity simulations indicated only very minor changes in Upper and Lower Floridan equivalent freshwater heads. For run 8, the isochlors in the Upper Floridan were unchanged and the isochlors in the Lower Floridan moved very slightly towards the west. The only significant change observed for the effective porosity sensitivity runs was chloride concentrations in the Upper Floridan when porosity was decreased in the Upper Floridan (Figure 4.22). The 250 mg/l isochlor in eastern Orange County moved a significant distance west towards the Cocoa well field when the Upper Floridan effective porosity was set to 0.1 for the postdevelopment simulation.

4.8.5 Northeastern Model Boundary Condition

The final sensitivity run involved adjusting the chloride concentrations and equivalent freshwater heads along the northeastern boundary to reflect the potential for higher chloride concentrations at the northern tip of this boundary (Figure 4.23). The prescribed isochlors along the boundary were also tilted to mimic the dip of the Floridan aquifer system (compare Figure 4.23 with Figure 4.5). The results of this sensitivity run were the same as, or showed only minor deviations from, the results of the predevelopment simulation. The most significant change was that the 250 mg/l isochlor moved slightly eastward (less than 1 mi) in the region to the northeast of the Cocoa well field.



(a)



(b)

Figure 4.22 Equivalent freshwater head (a) and normalized chloride concentrations (b) for the Upper Floridan for sensitivity run 6, effective porosity in the Upper Floridan decreased from 0.25 to 0.1.

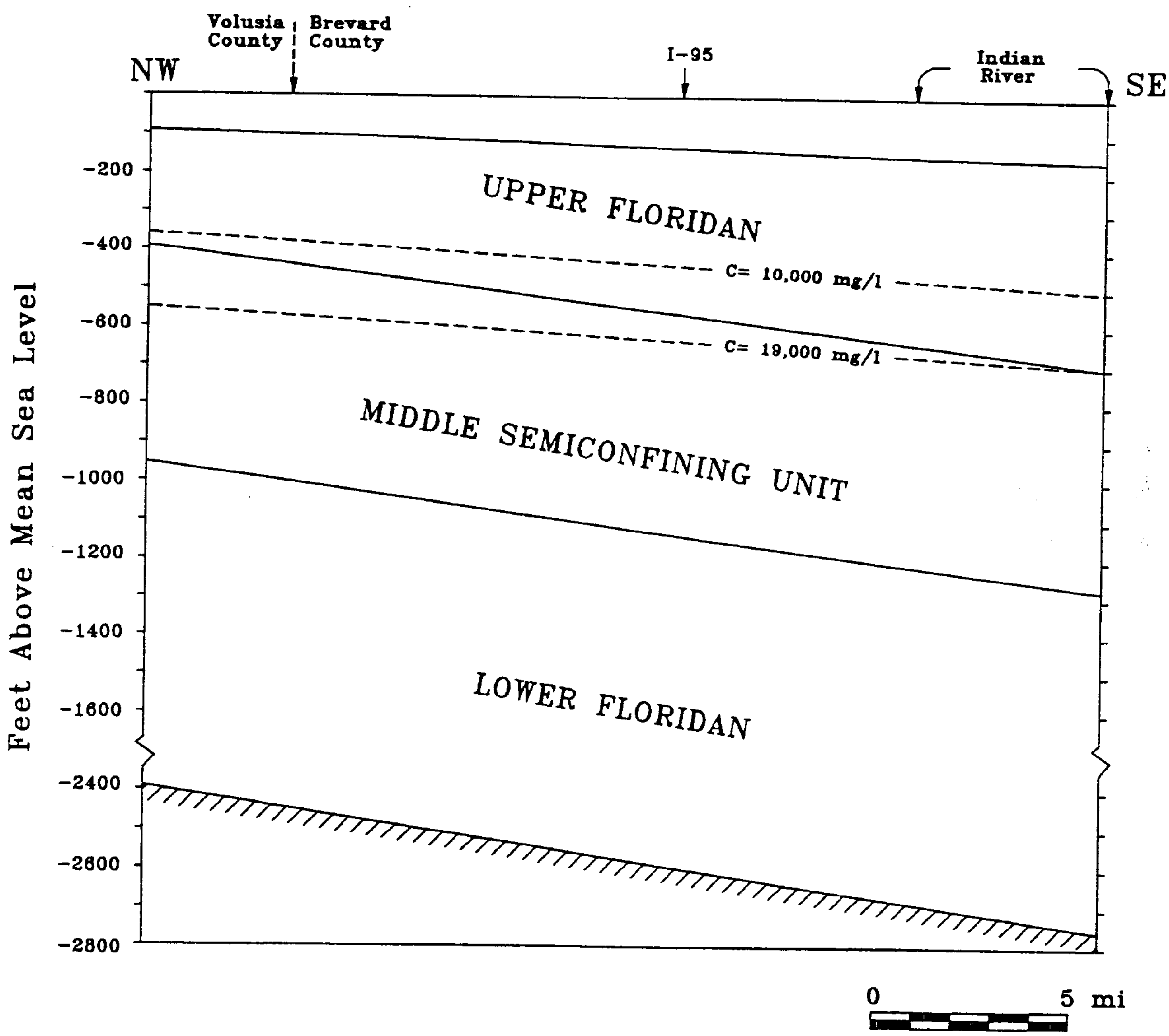


Figure 4.23 Schematic diagram of chloride concentrations assumed along the northeastern lateral boundary in order to compute equivalent freshwater head for the northeastern boundary sensitivity run.

5 PREDICTIVE SIMULATIONS

5.1 Background

Using the calibrated Phase III model, a series of 5 predictive simulations were performed. The first, or base-case, simulation incorporated the actual estimated 2010 pumpage at the ERWF, the Cocoa well field, and at all other withdrawal points within the model domain. The four additional simulations are various permutations of the first based upon projected 2010 demand. The purpose of these simulations 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. Of particular interest is the potential for increased chloride concentrations in the vicinity of the Cocoa well field, since this well field is vulnerable to the upconing and lateral 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, 1992); refer to the Phase IV report for a detailed explanation of the methods and sources of information used. Projected pumping increases were only derived for municipal supplies obtained from the Upper and Lower Floridan; 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.

The Phase IV modeling results indicated that substantial drawdowns from average 1988 conditions would occur in eastern Orange County in response to the projected 2010 pumping rates. Much of the simulated drawdown was attributable to Orange County's proposed ERWF, at which about 30 ft of drawdown for 2010 was simulated. Simulated drawdown at the Cocoa well field varied from about 15 ft at the West well field to about 10 ft at the East well field (see Figure 5.1a). Even when pumping due to ERWF was eliminated, wide-spread drawdowns of over 10 ft were simulated for much of eastern and central Orange County.

For the base-case 2010 predictive simulation, the 2010 pumping estimates used in the current model were the same as those used in the Phase IV predictive simulation. Orange County's ERWF had a projected 2010 withdrawal rate of 45.4 million gallons per day (MGD), and the Cocoa well field had a projected withdrawal rate of 28 MGD (the projected total withdrawal for the Cocoa well field is actually 31 MGD, but 3 MGD is supposed to be obtained from the intermediate aquifer that overlies the Upper Floridan, and thus was neglected in the model). The increased Cocoa well field pumping for 2010 conditions was distributed among the Cocoa wells that existed in 1988, and among a series of new wells in both the West and East well fields (Figure 3.1), some of which were being constructed as of the writing of this report. A detailed outline of the estimated 2010 pumping assigned to each Cocoa well is presented in Appendix A. The total projected 2010 average daily flow (ADF) required by the City of Cocoa is actually 48.2 MGD, but 17.2 MGD of this total is expected to be obtained from the Taylor Creek Reservoir, which is several miles south of the City of Cocoa's Dyal Water Treatment Plant. Furthermore, due to the vulnerable nature of the East Cocoa well field, the current well field consumptive use permit (CUP) limits total discharge from the East well field to 5.2 MGD, and it limits the completion depth of the new wells in the East well field (Cocoa wells 38-44) to about the upper one-third or so of the Upper Floridan. These conditions and restrictions were taken into account in developing the 2010 pumping estimates for the Cocoa wells.

Each of the four additional predictive simulations (referred to as simulations A, B, C and D), are founded upon the base-case scenario, but certain withdrawals were varied among well fields to observe the potential effects of distributing pumping in a different manner. Each scenario was specified by the District. The premise of each of the four predictive scenarios is outlined below:

Scenario A - All projected 2010 Cocoa average daily flow (ADF), 48.2 MGD, was withdrawn from the Upper Floridan at the Cocoa well field, except for 3 MGD which is assumed to come from the intermediate aquifer and was neglected in this study. The balance of the projected increase in ADF (17.2. MGD) was distributed between the new Cocoa wells and the existing West well field wells (nos. 13-19). All other withdrawals were unchanged.

Scenario B - Same as scenario A, except the balance of the projected increase in ADF (17.2 MGD) was distributed among all the existing and planned Cocoa wells based upon well capacity.

Scenario C - The pumping at Orange County's ERWF was reduced from 45.4 MGD to 15.4 MGD. The balance of 30 MGD was withdrawn from the Lower Floridan at Orange County's Orangewood well field, which is located southwest of Orlando in the vicinity of the Sand Lake Road test well. The Orangewood well field was considered to be off-line in the base-case simulation. All other withdrawals were unchanged.

Scenario D - Same as Scenario C, except that ADF at the ERWF was 32.6 MGD (= 15.4 MGD + 17.2 MGD); the additional 17.2 MGD is Cocoa's projected increase in ADF.

Scenarios A and B are designed to examine potential impacts if Cocoa's additional demand past 1995 could not be supplied by the Taylor Creek Reservoir. Scenario C is designed to examine the potential benefits of moving some of the large ERWF projected demands to another, possibly better suited, location in the county. Scenario D is a hybrid management scenario of the other three simulations. A summary of the predictive simulation scenarios is provided in Table 5.1, and the predicted drawdown from simulated 1988 potentiometric surface levels in the Upper Floridan is illustrated for each scenario (except B) in Figure 5.1. Scenario B is not included in Figure 5.1 because the simulated drawdown in nearly identical to that of Scenario A.

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

1) The Phase IV MODFLOW regional model was run for steady-state, estimated 2010 pumping conditions.
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 each predictive simulation, equivalent freshwater head and normalized chloride

Table 5.1 Summary of predictive simulations.

Predictive Simulation	Comments	Predictive Simulation Withdrawal in million gallons per day		
		Cocoa Well Field	ERWF*	Orangewood Well Field
Base-Case		28.0	45.4	0.0
A	Increased withdrawal at Cocoa well field (relative to base case) distributed among new wells and existing wells 13-19, regardless of well capacity	45.2	45.4	0.0
B	Increased withdrawal at Cocoa well field (relative to base case) distributed among all existing and planned wells based upon well capacity	45.2	45.4	0.0
C	Withdrawal at Orangewood from the Lower Floridan aquifer	28.0	15.4	30.0
D	Withdrawal at Orangewood from the Lower Floridan aquifer	28.0	32.6	30.0

* Orange County planned Eastern Regional Well Field

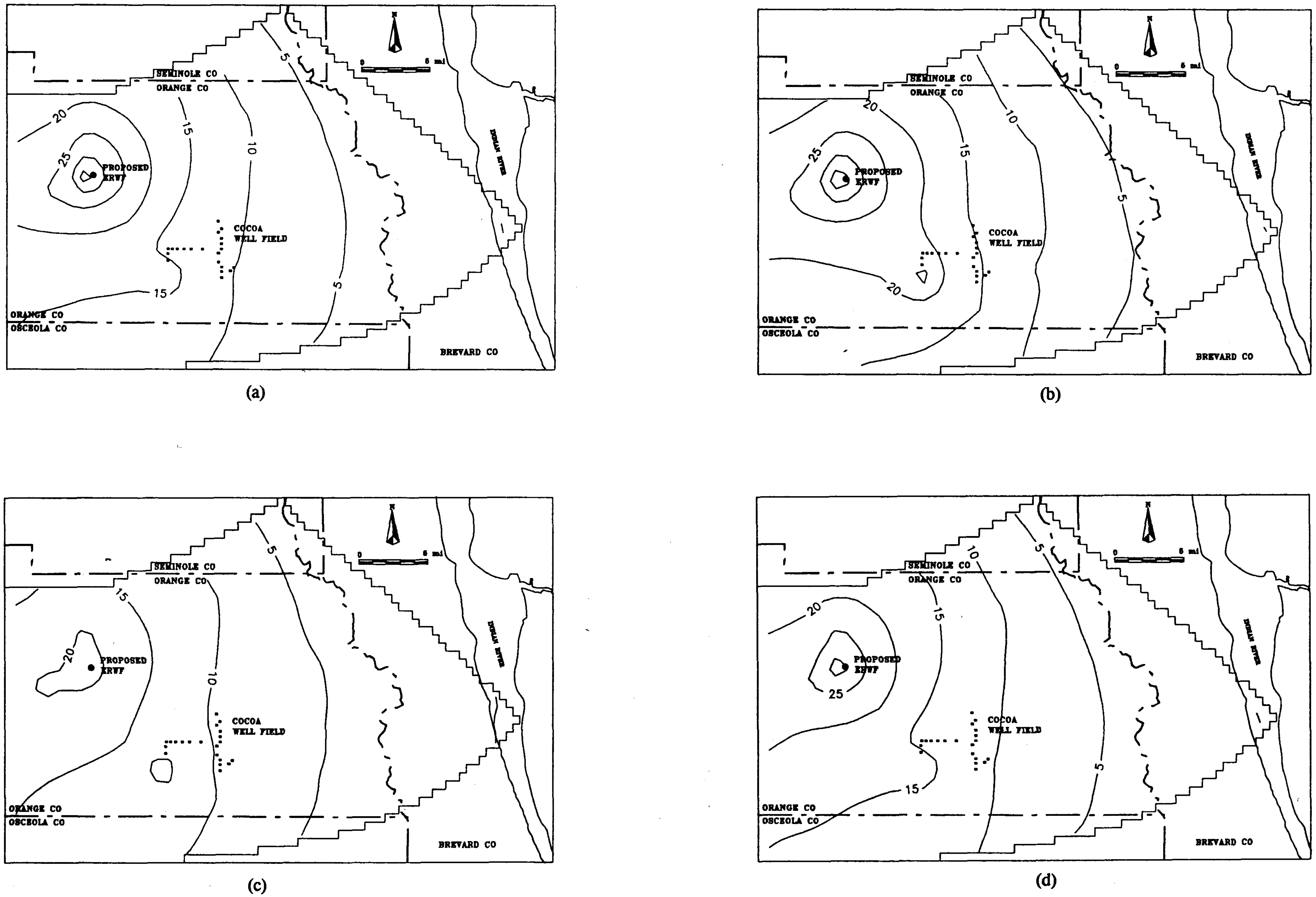


Figure 5.1 Simulated drawdown (environmental head) from simulated 1988 conditions in Upper Floridan for base-case predictive scenario (a), and predictive scenarios A (b), C (c), and D (d).

concentration was prescribed along all lateral Phase III model boundaries; this is in contrast with the average 1988 calibration where significant portions of the northern and southern boundaries are no-flow.

3) The new set of 2010 boundary conditions developed in step 2 were implemented, and a 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).

In each of the predictive simulations, Upper Floridan pumping attributed to Cocoa wells 1, 5, 7, 9, 10 and 38-44 was assigned to the upper one-half of the Upper Floridan either because they were plugged back from their original depth (existing wells), or because they will not penetrate the entire thickness of the Upper Floridan when they are constructed (new wells).

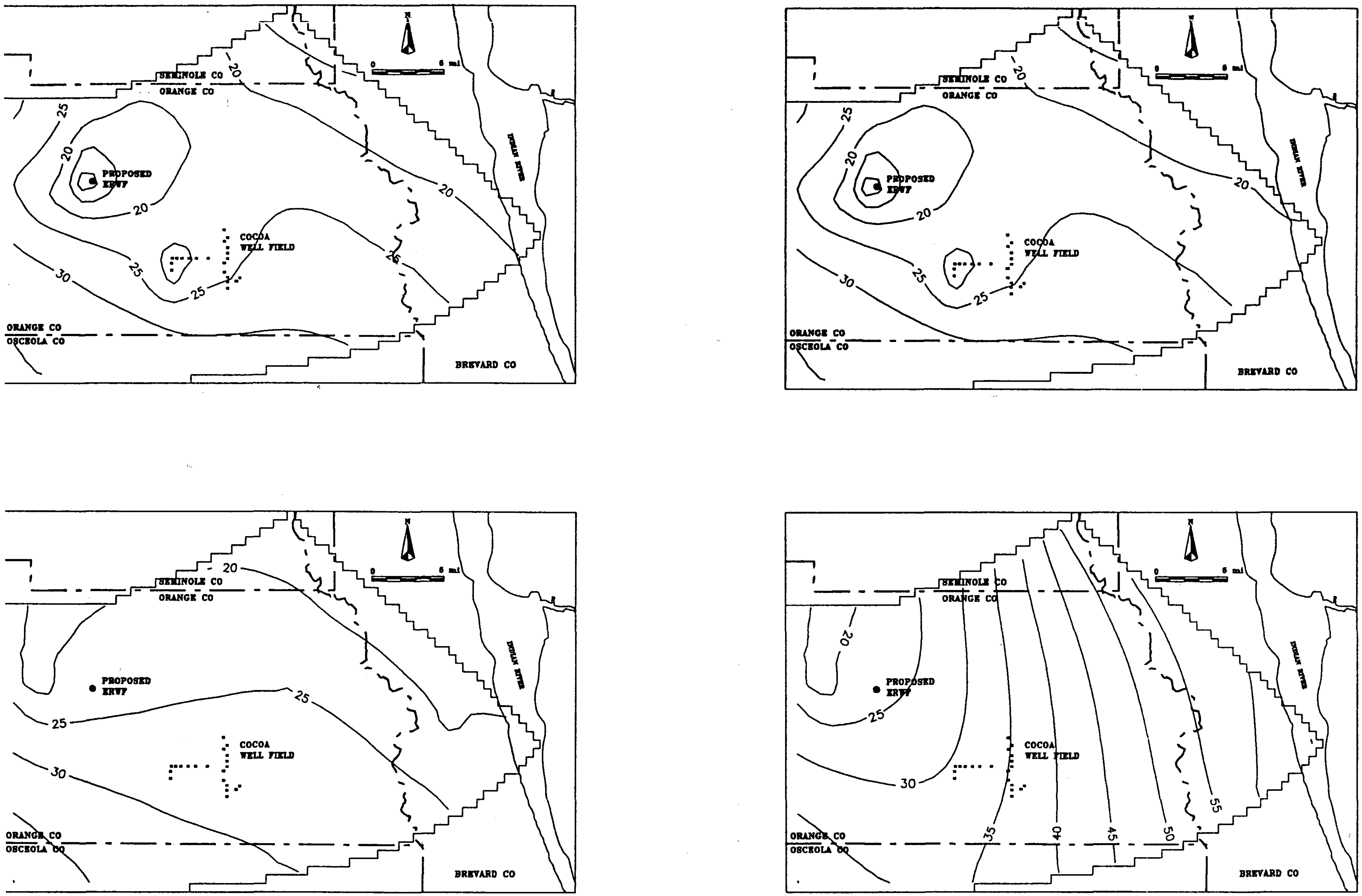
The approach of using a step change in the predictive simulation boundary conditions from average 1988 conditions is both reasonable and conservative. The approach is reasonable due to the large response time of the chloride concentrations relative to changes in the hydrogeologic system. Since the simulated 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 in a linear fashion or some other manner.

In the following sections, the results of the base-case predictive simulation and each of the four predictive scenarios are presented. The results of each of the predictive simulations A-D are discussed relative to the results of the base-case predictive scenario, rather than 1988 conditions. Only the simulated potentiometric surfaces of the Upper and Lower Floridan aquifers for the year 2010 are presented in the figures; this is because the change in simulated head values from 2010 to 2060 and 2110 is minor. Unless otherwise identified, the simulated heads presented in this chapter are environmental heads, rather than equivalent freshwater heads.

5.2 Base-Case Predictive Simulation

The results of the base-case predictive simulation are presented in Figures 5.2-5.5. Figures 5.2 and 5.1a indicate that substantial drawdown from 1988 water levels (about 30 ft in the vicinity of ERWF and about 10 ft in the vicinity of the Cocoa well field) will occur in the Upper Floridan by the year 2010 in response to the large estimated withdrawals. In the Upper Floridan, high chloride water (chloride concentration greater than 250 mg/l) will continue to upcone at the East Cocoa well field and migrate laterally to the West well field (Figure 5.3). Although chloride concentrations increased steadily at Cocoa wells 13, 14, 15, 16 and 17 through the simulation period (122 years), the simulated chloride concentrations at these wells and other wells in the West well field remained below 250 mg/l in the predictive simulation. At the middle of the Upper Floridan, the simulated 100 mg/l isochlor migrated from between Cocoa wells 7A and 13 in the 1988 simulation to Cocoa well 14 by 2010, and to Cocoa well 17 by 2110. Figure 5.3 also indicates that by 2110 the 250 mg/l isochlor could migrate a substantial distance westward relative to 1988 conditions in eastern Orange County north and northeast of the Cocoa well field.

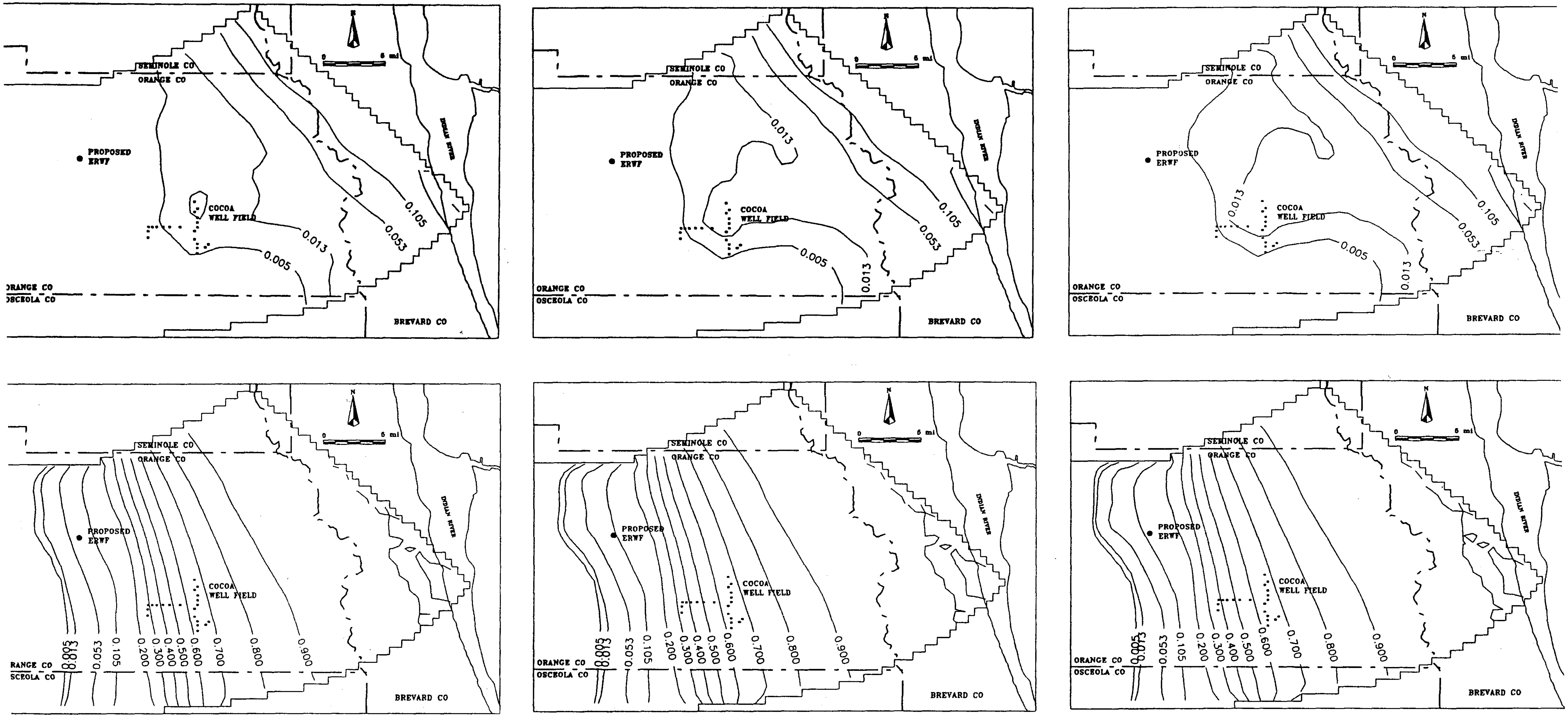
The 2010 simulation results, however, indicate only minor movement of the regional 250 mg/l isochlor in eastern Orange County. The 250 mg/l isochlor does enclose the northern half of the East Cocoa well field in the 2060 and 2110 simulation results, but it does so due to the combined effects of upconing and lateral movement of high chloride water. The westward migration of the regional 250 mg/l isochlor in eastern Orange County is primarily due to the combined effects of increased pumping from ERWF and the Cocoa well field.



(a)

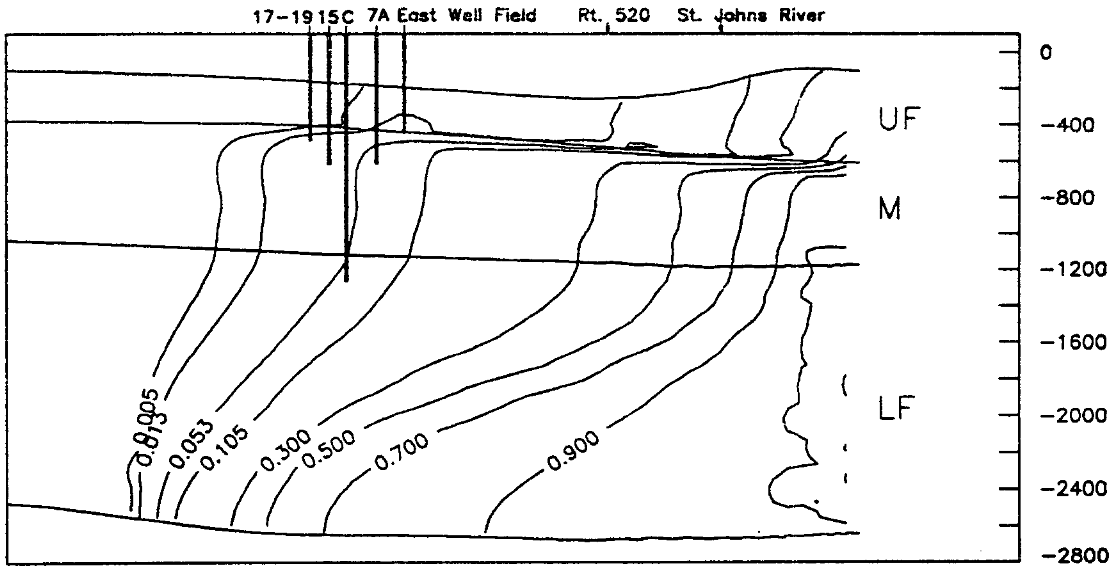
(b)

Figure 5.2 Base-case simulated environmental head (a) and equivalent freshwater head (b) at the middle of the Upper and Lower Floridan for 2010.

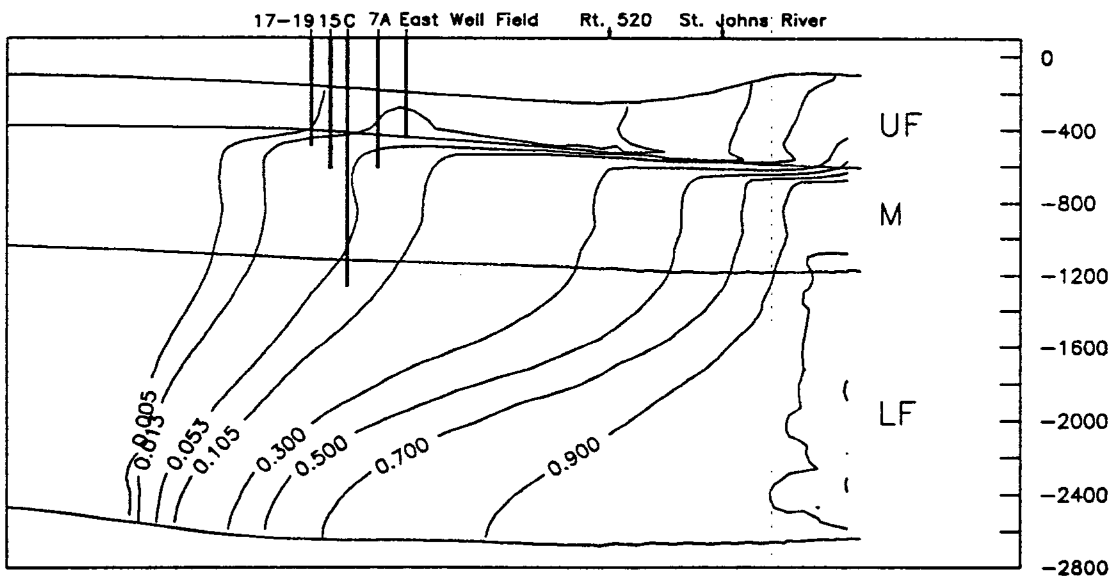


(a) (b) (c)

Figure 5.3 Base-case simulated normalized chloride concentrations at the middle of the Upper and Lower Floridan for 2010 (a), 2060 (b) and 2110 (c).



(a)



(b)

Figure 5.4 Base-case simulated normalized chloride concentrations for cross section 1 for 2010 (a) and 2060 (b).

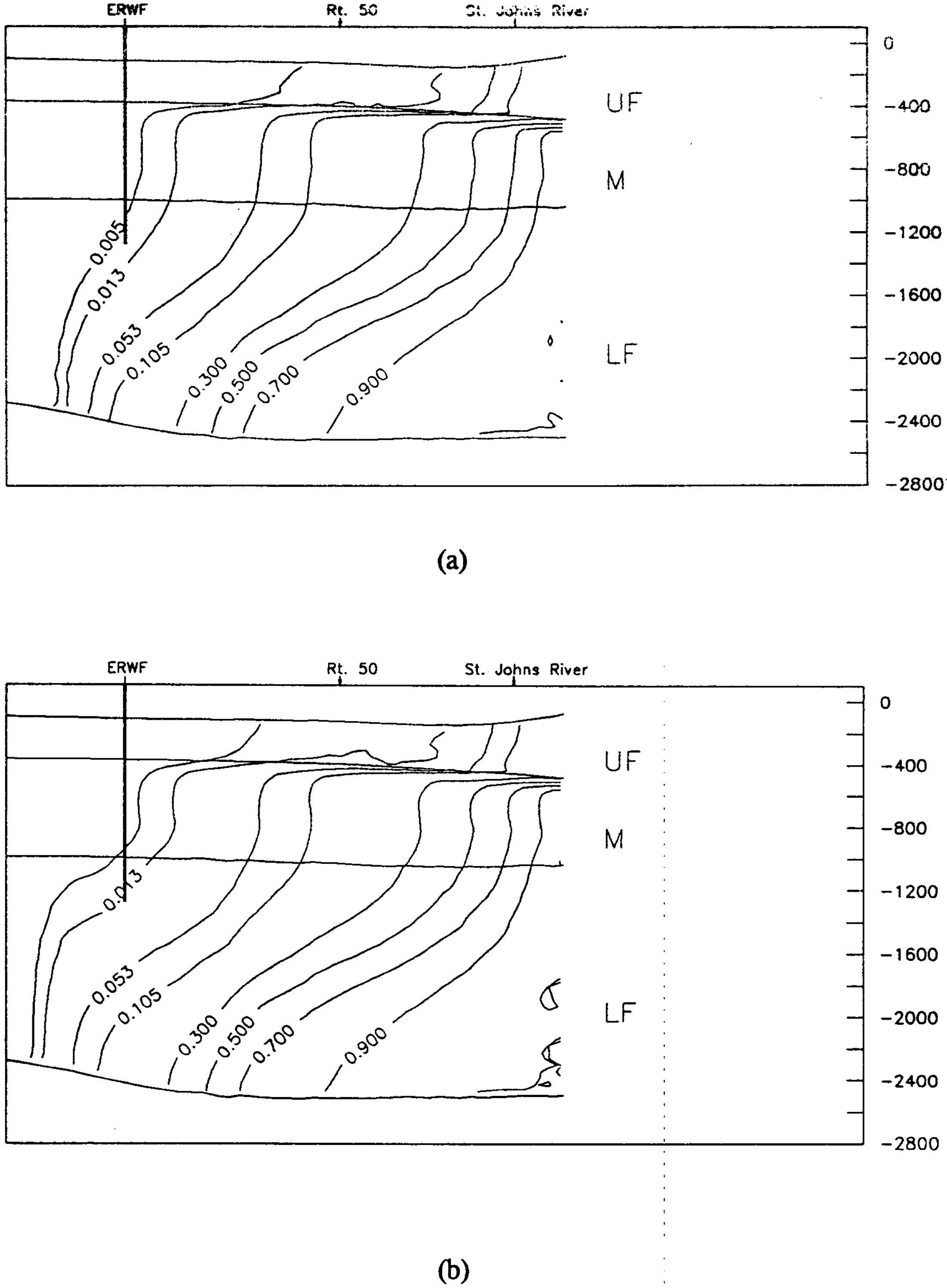


Figure 5.5 Base-case simulated normalized chloride concentrations for cross section 3 for 2010 (a) and 2060 (b).

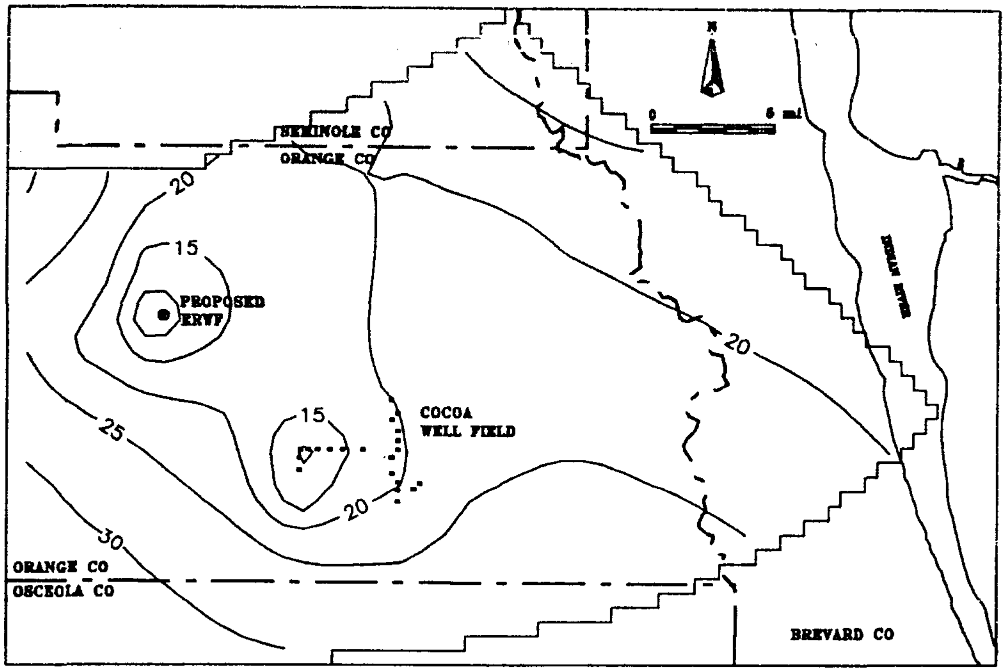
Figure 5.2 indicates that substantial drawdowns in the Lower Floridan (up to 20 ft in the vicinity of Orlando) may also be expected in response to the estimated 2010 withdrawal rates. These drawdowns are due primarily to increased pumping in the Lower Floridan in the vicinity of Orlando. Although the predictive simulation results show that chloride concentrations in the Lower Floridan will increase somewhat throughout the study area, there is a substantial increase in chloride concentrations in the northwest portion of the model domain in the vicinity of Orlando. In fact, the simulated concentrations in this region of the model are probably artificially low due to the proximity of the western and northern model boundaries (Figure 5.5). Figures 5.3 and 5.5 indicate that by the year 2110, the 250 mg/l isochlor may move 4 miles or more towards Orlando throughout much of the Lower Floridan.

5.3 Predictive Simulation A

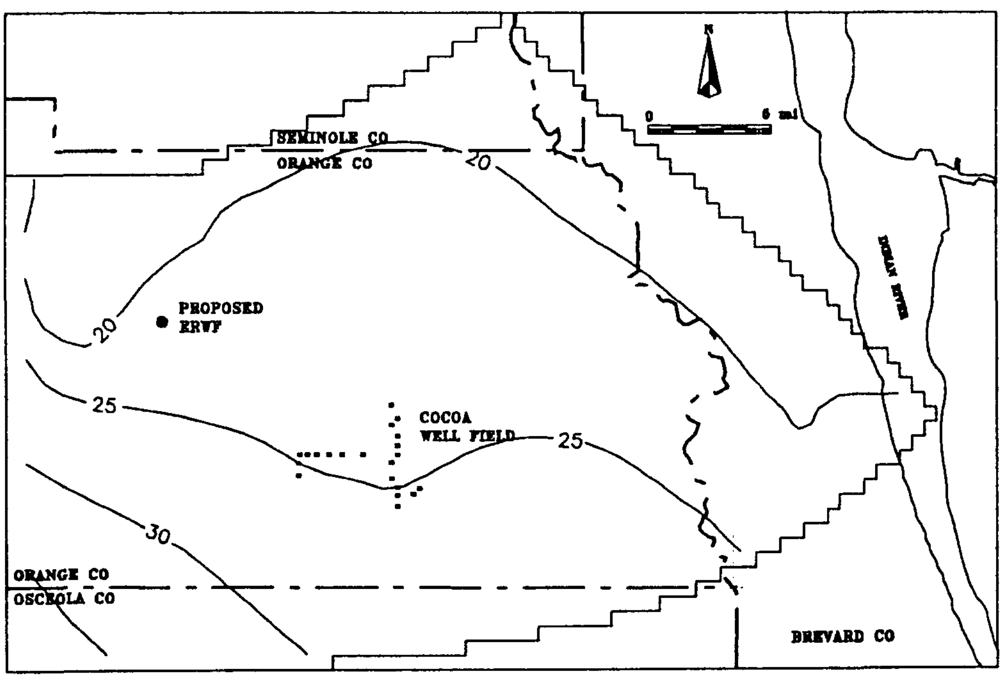
In predictive simulation A, 17.2 MGD of discharge was distributed among the new Cocoa wells and the existing West Cocoa well field wells (nos. 13-19) in addition to the existing 2010 base-case discharge estimates. All other withdrawals were unchanged from the base-case simulation. The results of this simulation are presented in Figures 5.6-5.8.

Figures 5.6 and 5.1b indicate that increased drawdowns (relative to the base-case scenario) of about 5 ft and 2 ft were simulated in the vicinity of the Cocoa well field and the ERWF, respectively. In the Lower Floridan, simulated heads decreased by about 1-3 ft throughout most of the model domain.

Figure 5.7 illustrates that although the simulated isochlors in the Lower Floridan for simulation A are nearly the same as those of the base-case simulation, the same cannot be said of the Upper Floridan isochlors. In the Upper Floridan in the vicinity of the Cocoa well field, the simulated 2010 100 mg/l isochlor has moved farther west to Cocoa well 15, and there is significantly greater upconing of 250 mg/l water in the northern region of the East Cocoa well field. In addition, the simulated 250 mg/l isochlor in eastern Orange County moved westward about 2-3 miles in an area just to the northeast of the Cocoa well field. The 2060 simulation results



(a)



(b)

Figure 5.6 Simulated 2010 environmental head at the middle of the Upper (a) and Lower (b) Floridan for predictive simulation A.

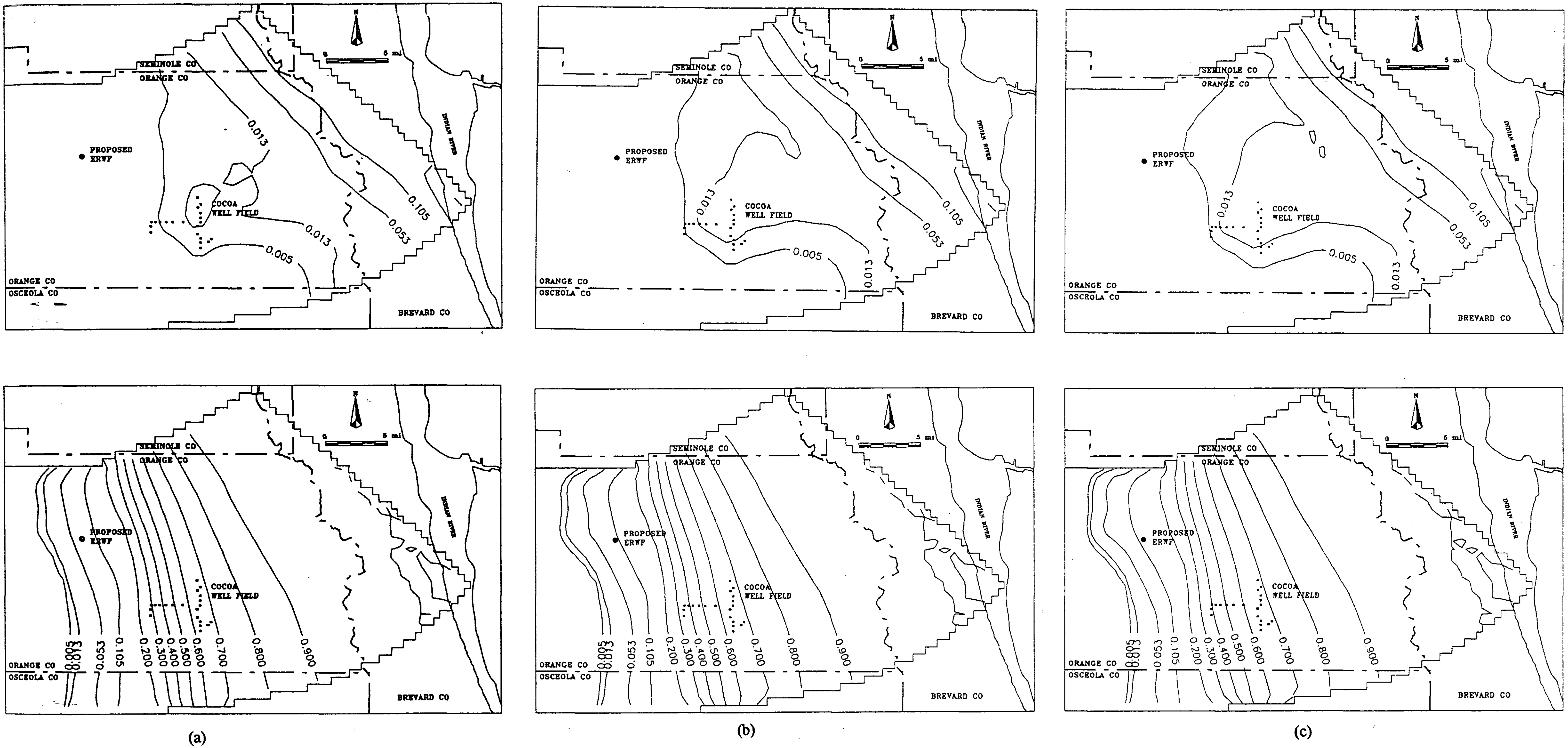
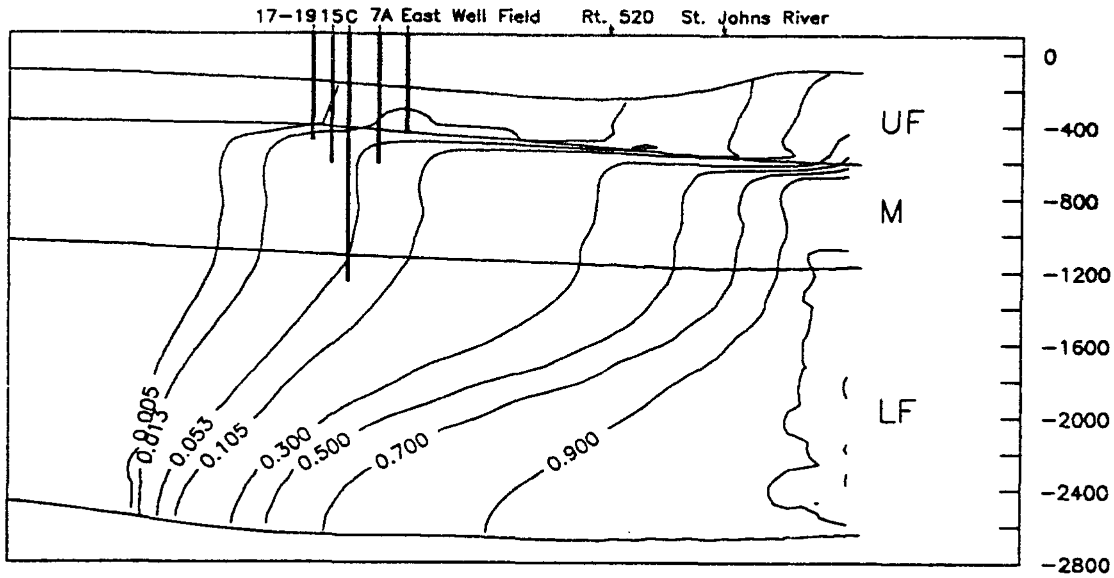
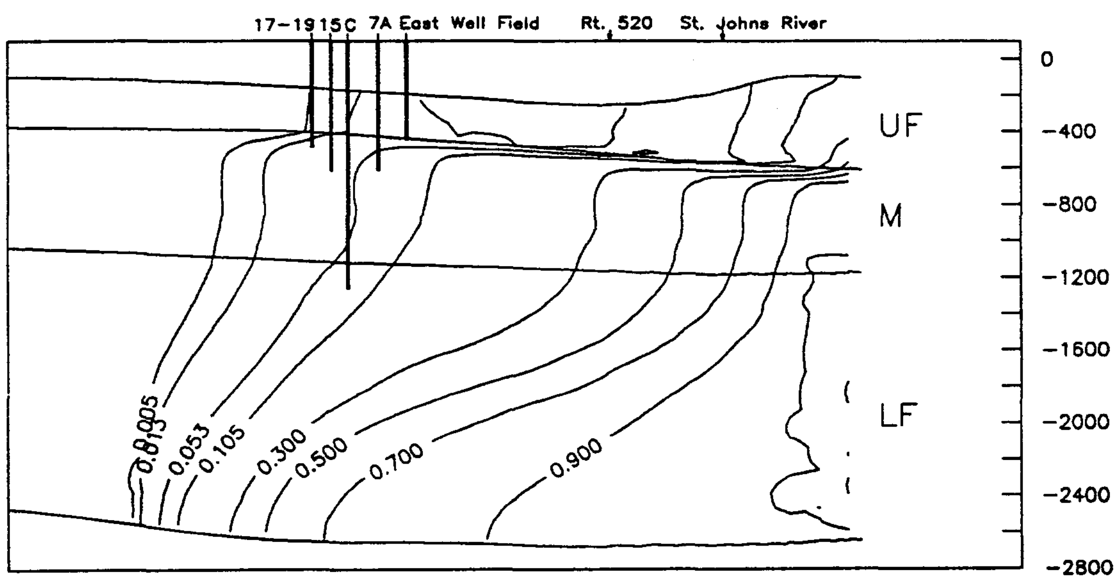


Figure 5.7 Simulated normalized concentration at the middle of the Upper and Lower Floridan for 2010 (a), 2060 (b) and 2110 (c) for predictive simulation A.



(a)



(b)

Figure 5.8 Normalized chloride concentrations for cross section 1 for 2010 (a) and 2060 (b) for predictive simulation A.

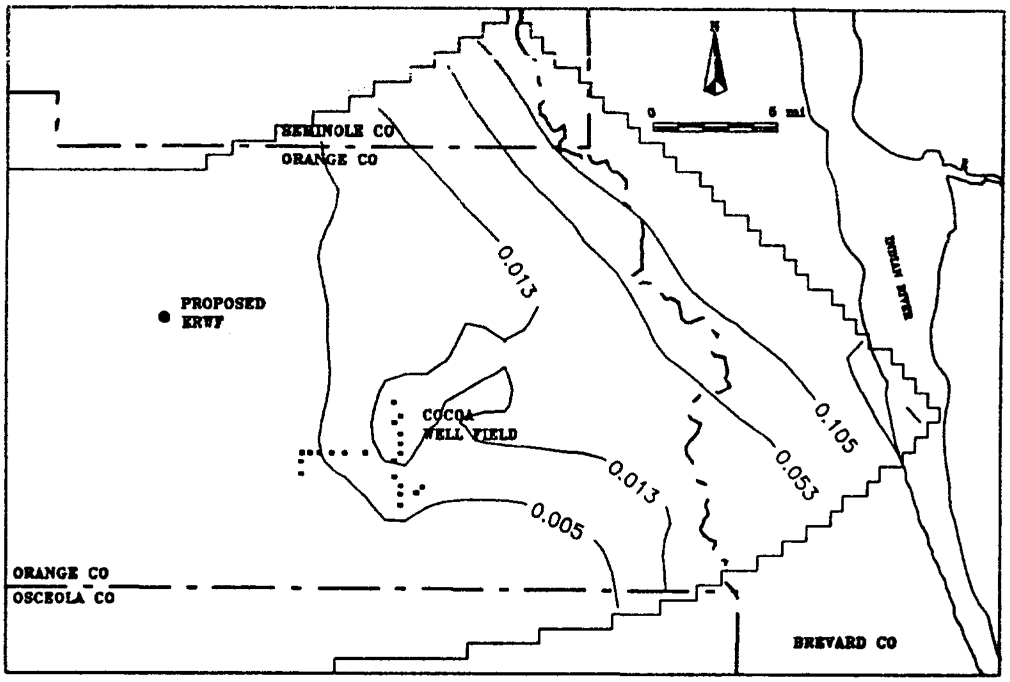
indicate that the high chloride water upconing within the northern portion of East Cocoa well field combines with the 250 mg/l water migrating laterally westward, and by 2110 there is a large region of the Upper Floridan in the center of the model domain with 250 mg/l or greater ground water.

Figure 5.8 portrays the simulated isochlors along cross section 1 for 2010 and 2060. Relative to the base case simulation, the 100 mg/l isochlor has moved about 0.75 miles to the west within the Cocoa well field, and the bulb of 250 mg/l water in the Upper Floridan at the East Cocoa well field continued to grow. By 2060, water with chloride concentrations of 250 mg/l or greater exists throughout the Upper Floridan in the vicinity of the East Cocoa well field, and the 250 mg/l isochlor has moved laterally east and west away from the East Cocoa well field. From 2060 to 2110 (not shown), the position of the 100 mg/l isochlor in the upper Floridan is unchanged, but the 250 mg/l isochlor continued to migrate about three quarters of a mile due east and west from its 2060 location.

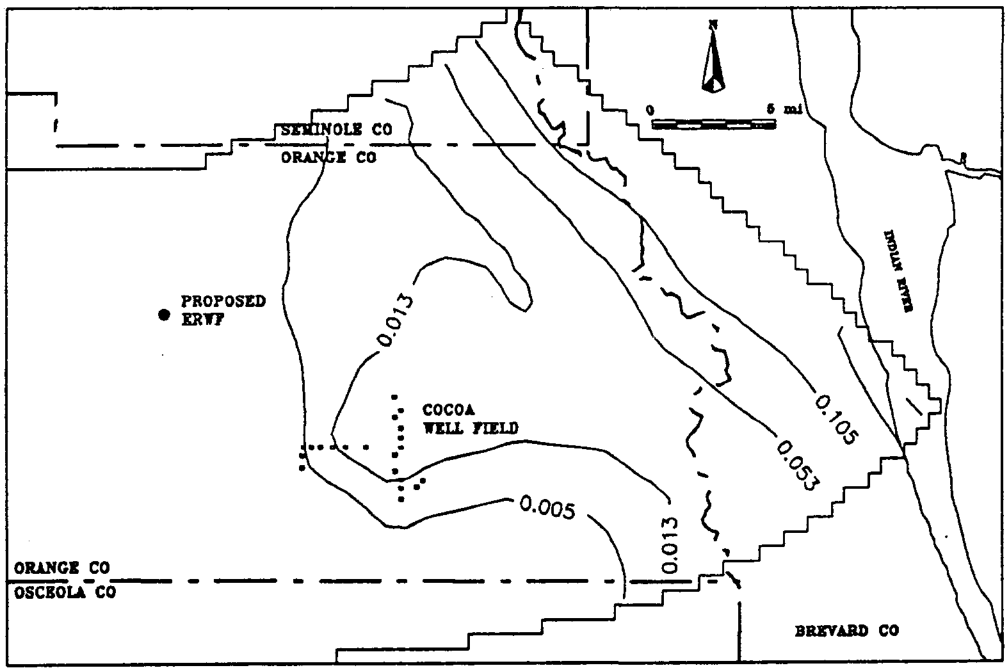
5.4 Predictive Simulation B

The only difference between predictive simulation B and predictive simulation A is that the 17.2 MGD of increased pumping at the Cocoa well field was distributed among all of the existing and planned Cocoa wells based upon well capacity, rather than only among the new and west well field wells. For this scenario, the simulated equivalent freshwater heads in the Upper and Lower Floridan, the simulated chloride concentrations in the Lower Floridan, and the simulated chloride concentrations along cross section 1 were the same, or nearly the same, as in simulation A, and therefore are not presented in this section.

Figure 5.9 presents the simulated chloride concentrations in the Upper Floridan at 2010 and 2060 for predictive simulation B. Although the simulated isochlors for 2060 and 2110 (not shown) in the Upper Floridan are almost the same as those obtained for Scenario A, the 2010 results differ slightly in that the zone of 250 mg/l water in the northern portion of the East Cocoa well field has joined with the 250 mg/l isochlor to the northwest of the Cocoa well field



(a)



(b)

Figure 5.9 Normalized chloride concentrations in middle of Upper Floridan for 2010 (a) and 2060 (b) for predictive simulation B.

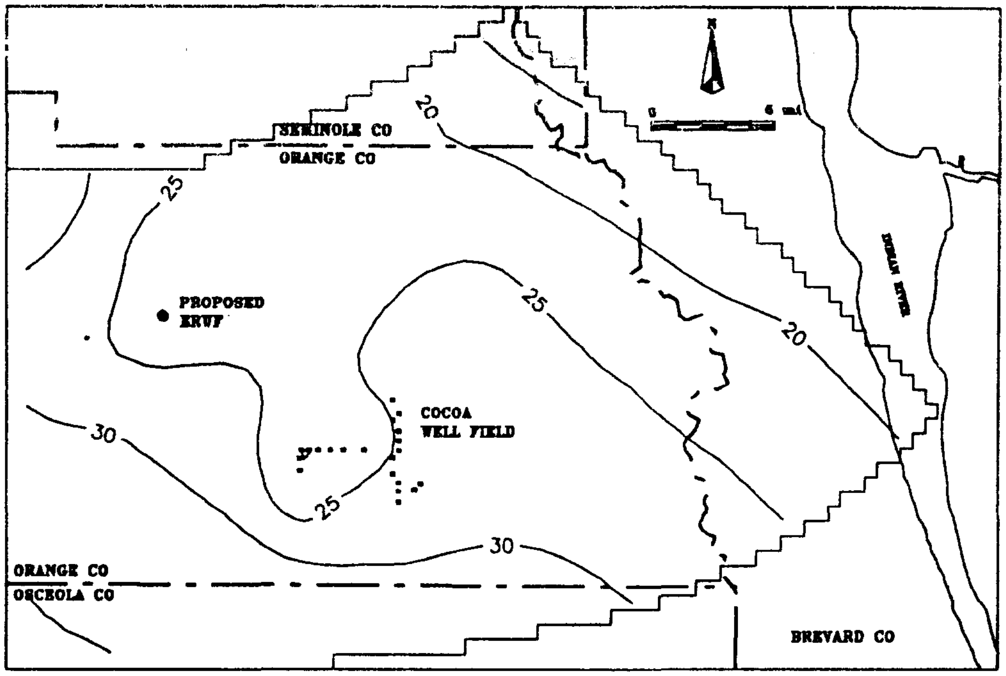
(compare Figure 5.9a with Figure 5.7a). This difference occurred due to the increase pumping in the East Cocoa well field for simulation B relative to simulation A.

5.5 Predictive Simulation C

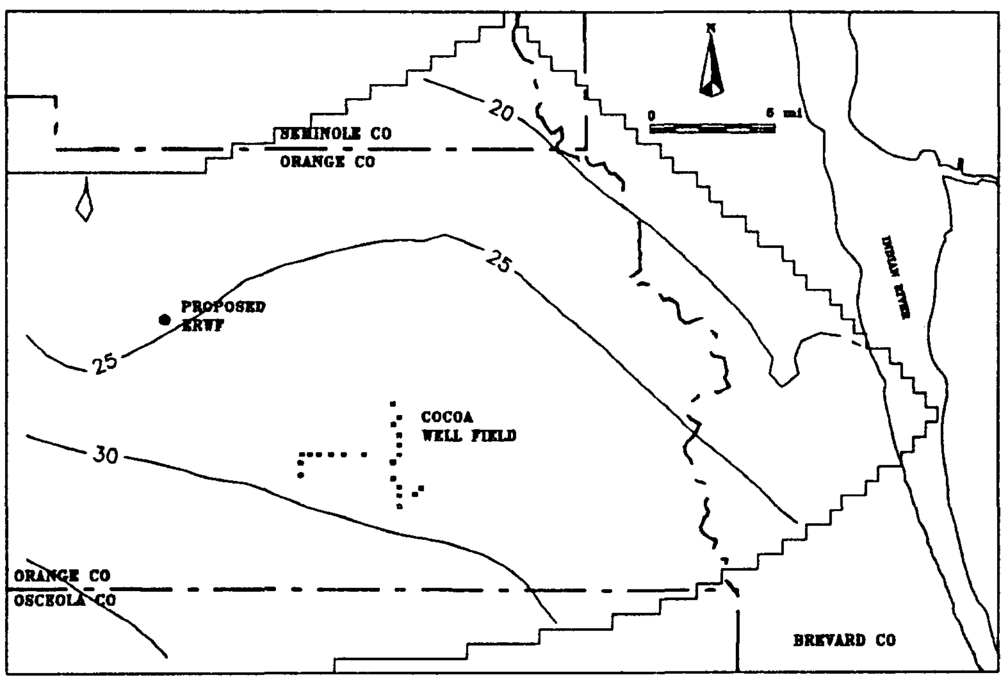
In predictive simulation C, pumping at ERWF was reduced from 45.4 MGD to 15.4 MGD. The balance of 30 MGD was withdrawn from the Lower Floridan at Orange County's Orangewood well field, which is about 5 miles due west of the western Phase III model boundary in the vicinity of the Sand Lake Road test well; the Orangewood well field was considered to be off-line in the base-case simulation. All other withdrawals were unchanged from the base-case simulation. The results of the this simulation are presented in Figures 5.10-5.13.

Figures 5.10 and 5.1c indicate that drawdowns in the Upper Floridan were reduced by about 5 ft and 15 ft in the vicinity of the Cocoa well field and ERWF, respectively, due to moving some ERWF discharge to the west. In the Lower Floridan, drawdowns were reduced throughout much of the model domain by 1-3 ft due to the decreased pumping at ERWF. Drawdowns in the Lower Floridan within the study area did not increase in simulation C, even though more pumping was prescribed within the Lower Floridan. This is because the increased pumping was specified outside the Phase III model domain, and was incorporated into the predictive simulation through the prescribed boundary heads in the Lower Floridan as described in Section 5.1. In the regional Phase IV model, the Orangewood well field is located within a zone of high transmissivity (130,000 ft^2/d) in the Lower Floridan and within a region of high leakance (1.0×10^{-3} d^{-1}) of the middle semiconfining unit. These two factors tended to minimize the simulated drawdowns at the western Phase III model boundary. Also, since drawdowns were substantially reduced the vicinity of the ERWF, conditions are more favorable over the northwest corner of the model domain for downward leakage from the Upper Floridan to the Lower Floridan aquifer.

Figure 5.11 illustrates the predicted normalized chloride concentrations at the middle of the Upper Floridan for the years 2010 and 2060; there was little change in the simulated isochlors

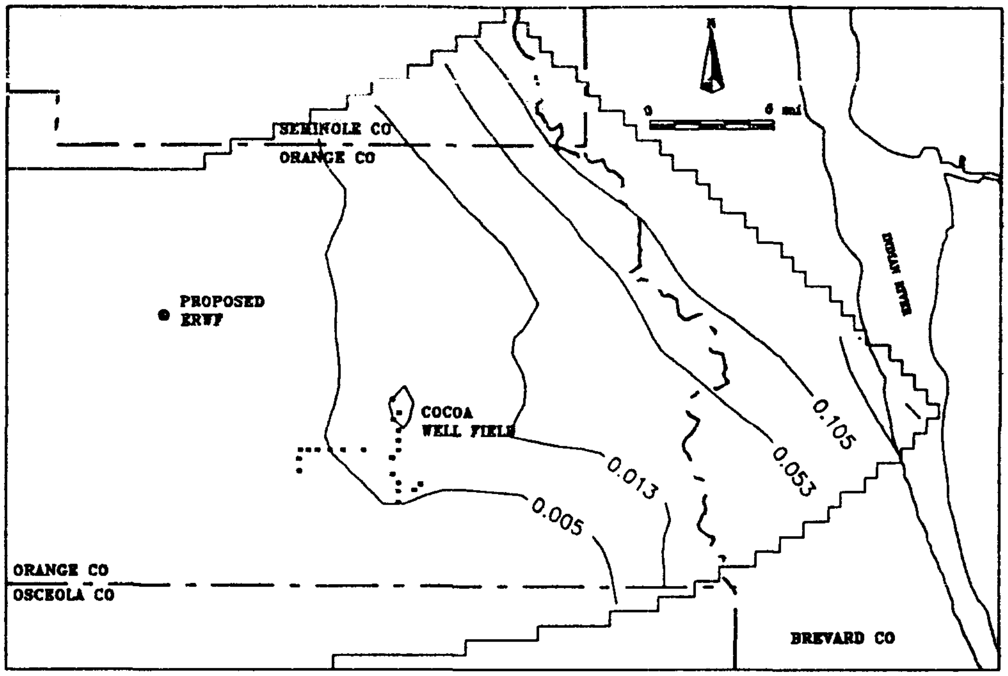


(a)

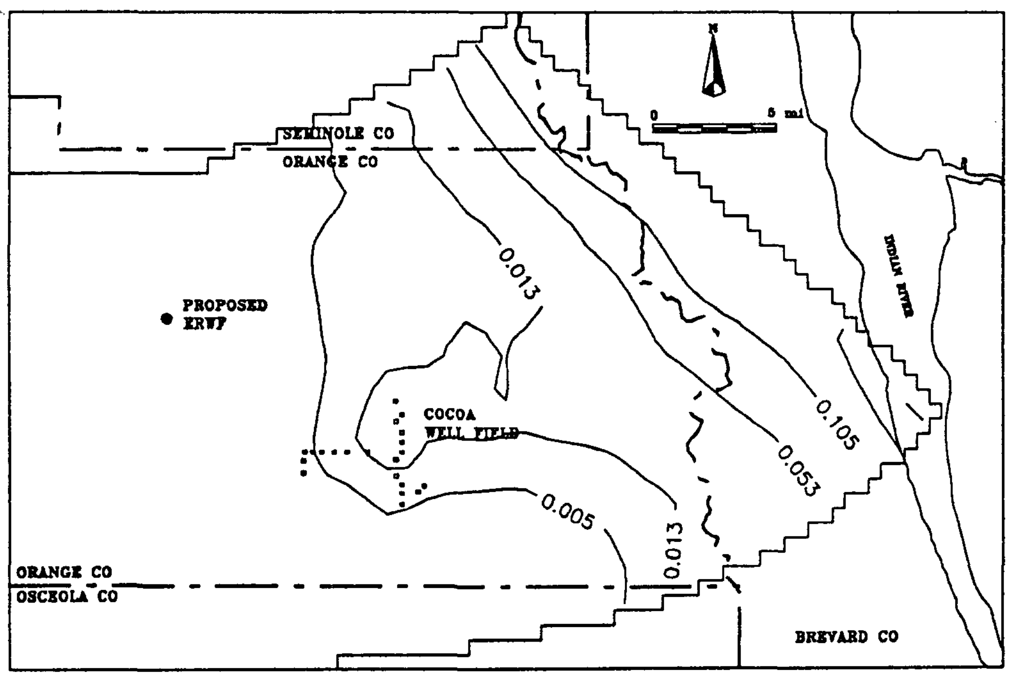


(b)

Figure 5.10 Simulated 2010 environmental head at the middle of the Upper (a) and Lower (b) Floridan for predictive simulation C.



(a)



(b)

Figure 5.11 Normalized chloride concentrations in middle of Upper Floridan for 2010 (a) and 2060 (b) for predictive simulation C.

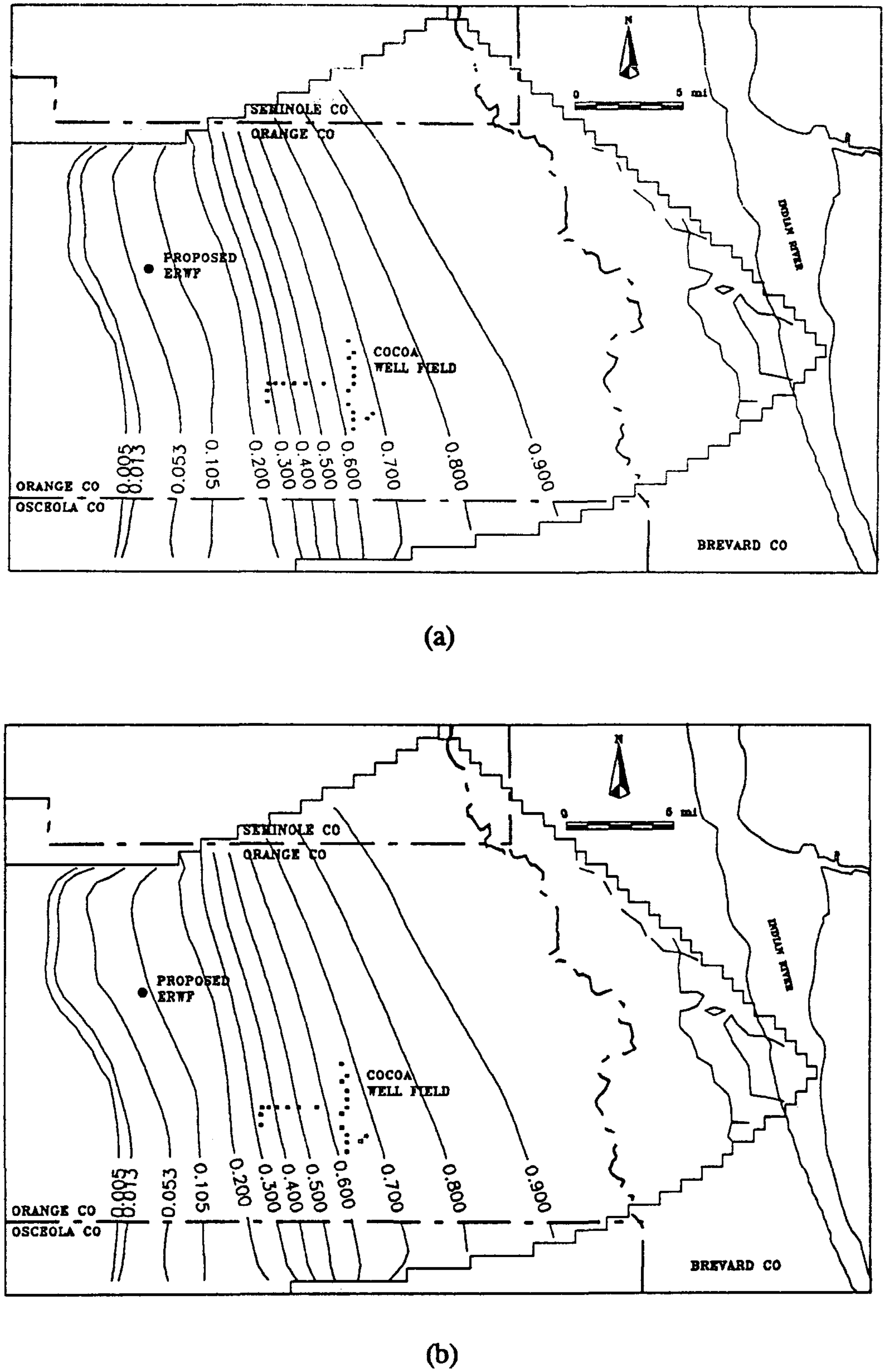
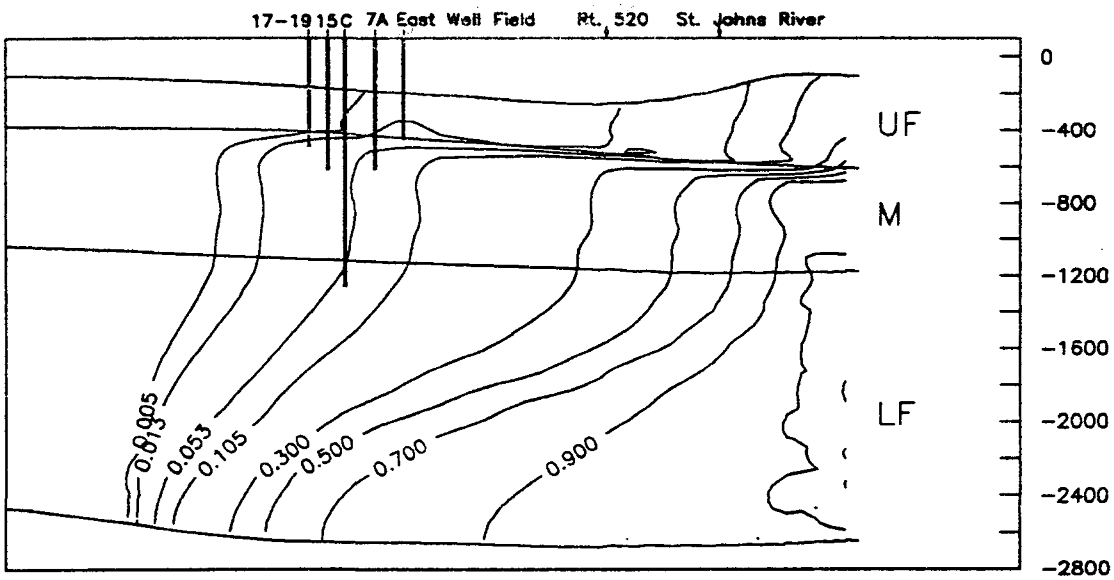
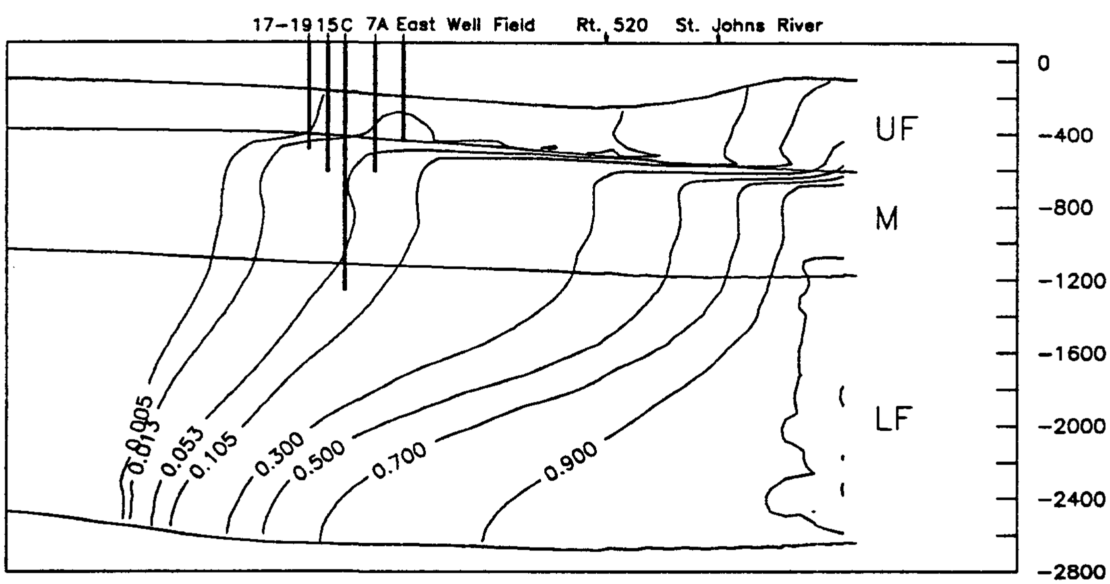


Figure 5.12 Normalized chloride concentrations in middle of Lower Floridan for 2010 (a) and 2060 (b) for predictive simulation C.



(a)



(b)

Figure 5.13 Normalized chloride concentrations for cross section 1 for 2010 (a) and 2060 (b) for predictive simulation C.

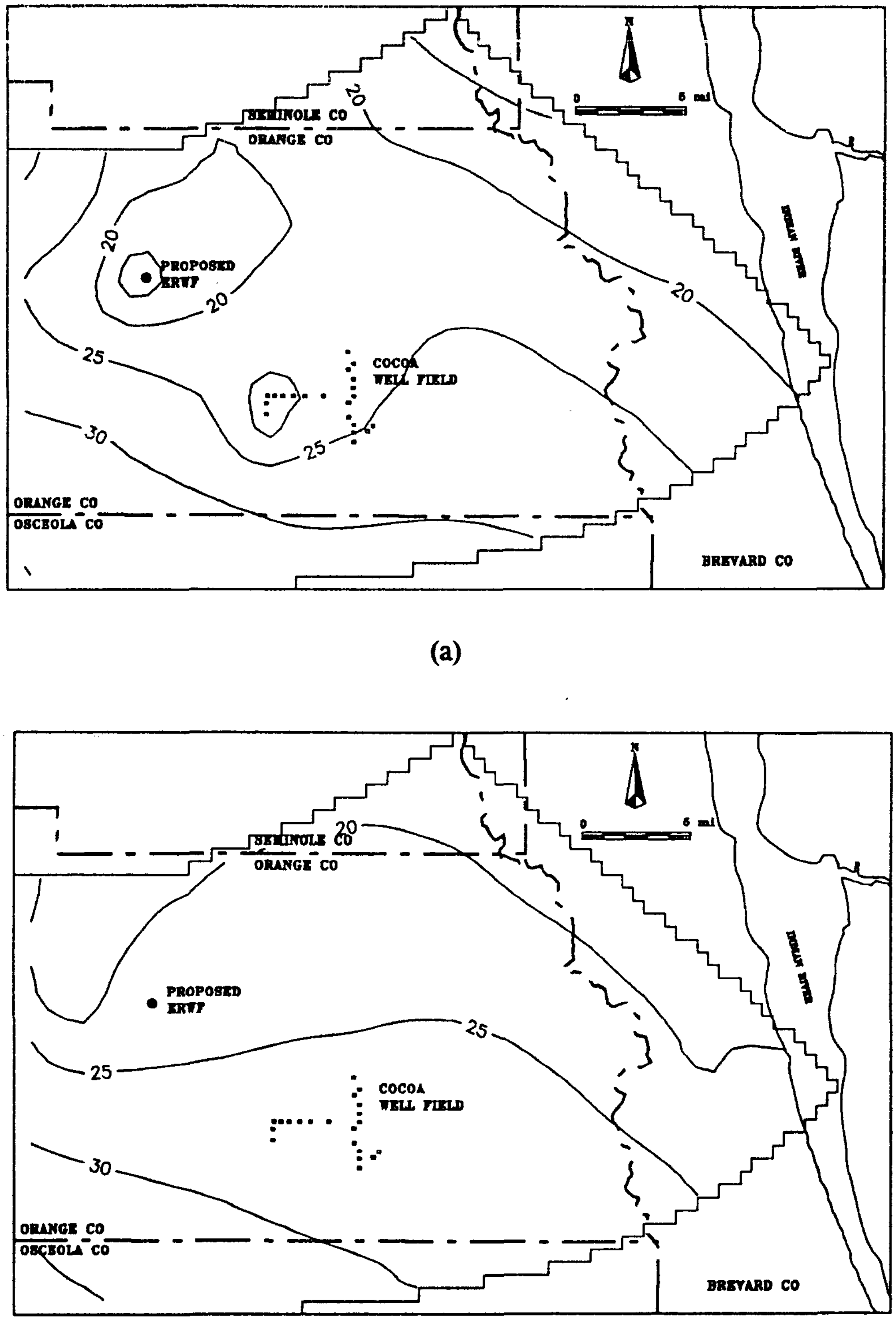
from 2060 to 2110. Figure 5.11 indicates that for 2010, the extent of upconing of poor quality water in the northern portion of the East Cocoa well field is slightly less, and the regional 250 mg/l isochlor is the same as in the base-case simulation. In the northern half of the model domain, the 100 mg/l isochlor moved a small distance (less than a mile) to the west relative to the base-case simulation. For the year 2060, the simulated 100 and 250 mg/l isochlors in the northern portion of the model domain enclose a smaller area for simulation C than in the base-case scenario. The same isochlors in the southern portion of the domain, however, are unchanged between the two simulations.

Figures 5.12 and 5.13 illustrate the simulated normalized concentration at the middle of the Lower Floridan and along cross section 1, respectively. Chloride concentrations in the Lower Floridan are only slightly less for simulation C than those predicted in the base-case simulations. The simulated concentrations along cross section 1 are nearly identical to those of the base case simulation, indicating that in the vicinity of this cross section the upconing and lateral migration of high chloride water is due primarily to pumping and hydrogeologic conditions at the Cocoa well field, rather than withdrawals at ERWF.

5.6 Predictive Simulation D

The modeling scenario for predictive simulation D is similar to that of predictive simulation C; the only difference is that a total of 32.6 MGD was withdrawn from the ERWF, rather than 15.4 MGD. The increased withdrawal of 17.2 MGD is equal to the City of Cocoa's projected increase in average daily flow for 2010. The results of this simulation are presented in Figures 5.14 and 5.15; the predicted chloride concentrations in the Lower Floridan and along cross section 1 are nearly identical to those of simulation C, and are therefore not presented.

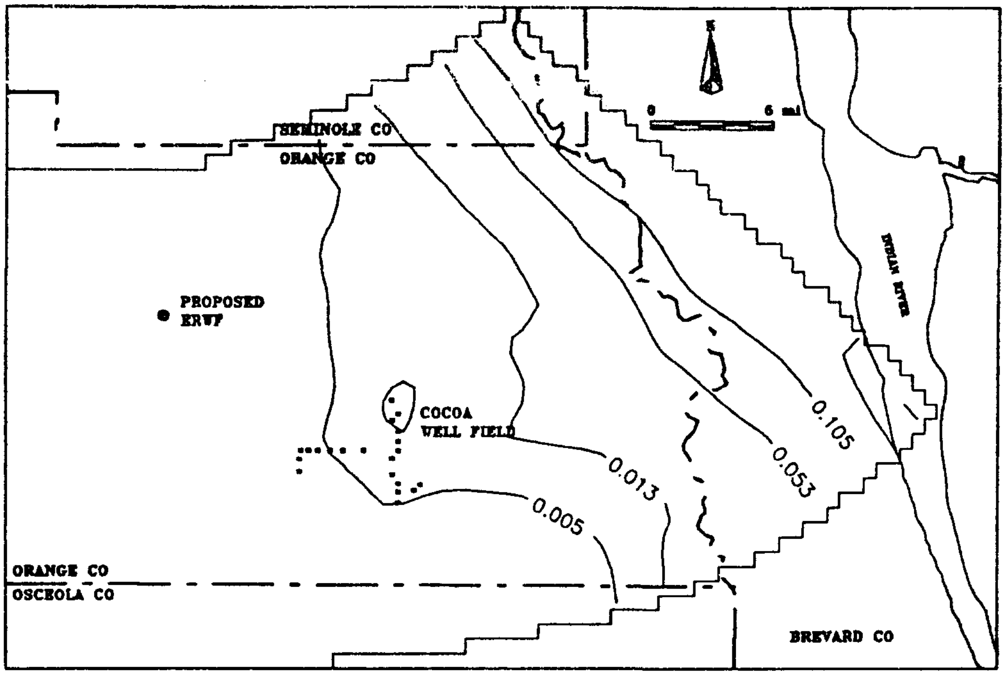
Figures 5.14 and 5.1d indicate that in the Upper Floridan, simulated drawdowns in the immediate vicinity of ERWF are decreased by about 5 ft relative to the base-case scenario. The simulated potentiometric surface in the vicinity of the Cocoa well field is nearly identical to that of the base-case simulation. In the Lower Floridan, the simulated drawdown is slightly greater



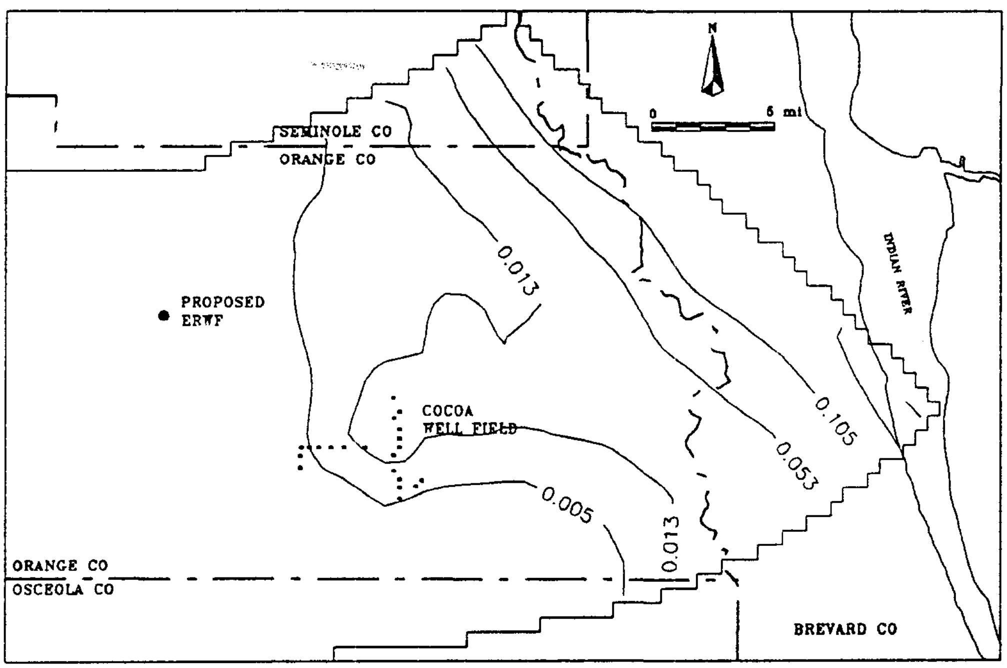
(a)

(b)

Figure 5.14 Simulated 2010 environmental head at the middle of the Upper (a) and Lower (b) Floridan for predictive simulation D.



(a)



(b)

Figure 5.15 Normalized chloride concentrations in middle of Upper Floridan for 2010 (a) and 2060 (b) for predictive simulation D.

(1 ft or less) relative to the base-case scenario due to the substantial withdrawal assigned to the Lower Floridan Orangewood well field.

Figure 5.15 indicates that the simulated chloride concentrations in the Upper Floridan are nearly identical to those of simulation C for 2010; the only difference is that the 100 mg/l isochlor has moved a little farther west in simulation D due to the increased pumping at ERWF. For 2060, the simulated chloride concentrations for the Upper Floridan in the north-central region of the model domain lie in between those of the base-case simulation and simulation C, as would be expected.

6 SUMMARY AND CONCLUSIONS

The primary purpose of this (Phase III) 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 eastern Orange County and immediately adjoining regions. Of particular importance is the potential for the degradation of fresh ground-water resources in the vicinity of the Cocoa well field and Orange County's proposed Eastern Regional well field (ERWF). To accomplish this task, a model calibration was performed for average predevelopment and 1988 (postdevelopment) hydrologic conditions using the DSTRAM computer code. The Phase III model calibration was performed for a subregion of the Phase IV regional model domain (Blandford and Birdie, 1992). The Phase IV modeling results formed the basis for many of the aquifer parameters and boundary conditions used in this study.

The Phase III model was successfully calibrated to predevelopment and average 1988 conditions and is suitable for the prediction of regional scale trends in chloride concentrations over the long term (decades). The model simulations conform well to the conceptual model of the ground-water flow system, and the simulation results match well with observed hydraulic heads (generally within 2 ft) and chloride concentrations. The only calibration targets that were not met particularly well in the simulations are the observed chloride concentrations in the middle semiconfining unit at the Cocoa C well, and the observed increase in chloride concentration from predevelopment to average 1988 conditions in the deep (Lower Floridan) Cocoa C sampling zone. Given the absence of data concerning aquifer characteristics in the vicinity of Cocoa C, however, it is doubtful that an improved calibration could be obtained in this region without making arbitrary and unjustifiable (in terms of observed data) changes to the model.

Although the Phase III 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

2) Observed potentiometric head in the Lower Floridan

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

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

Due to the above data constraints, the model can not be considered to be rigorously calibrated with respect to the Lower Floridan. This has potential implications for the simulation results within the Upper Floridan since the Lower Floridan is the major source of salt for this unit. At present, the simulated chloride concentrations in the Lower Floridan are in reasonable agreement with observed chloride concentrations at the Sand Lake Road test well, the Merritt Island injection test well, the ERWF deep test well, the Cocoa R test well, and the Orange County Landfill and Deseret Ranches geophysical test sites. However, taken as a whole with respect to the size of the modeled area, these calibration (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.

Using the calibrated model, a series of five predictive simulations were performed. The first, or base-case, predictive simulation is based upon the estimated 2010 pumping rates for the regional (Phase IV) study area; the other four predictive simulations are based upon the first, but pumping was added to, or subtracted from, the ERWF or the Cocoa well field to simulate various demand scenarios. For all of the predictive scenarios, the Phase IV regional (MODFLOW) model was run for steady-state conditions subject to the estimated 2010 withdrawals. The hydraulic heads predicted using MODFLOW were then used in conjunction with the simulated average 1988 chloride concentrations along the Phase III model boundary to prescribe the necessary boundary conditions (equivalent freshwater head and chloride concentration) for the predictive simulations. Each Phase III predictive modeling scenario was conducted as a transient simulation, with results obtained for 2010, 2060 and 2110. A summary of the predictive simulation scenarios is provided in Table 6.1.

The procedure used to develop the predictive simulation boundary conditions has two potentially significant, although unavoidable, limitations. First of all, the chloride concentration prescribed at inflow nodes is maintained at 1988 simulated values throughout the predictive simulation. This approach may tend to restrict the migration of saltwater within the model domain in response to pumping, since chloride concentrations outside of the model domain, as well as inside it, would be expected to increase in the future. This limitation is believed to have a relatively minor effect on the predicted chloride concentrations throughout most of the model domain. If the lateral intrusion of high-chloride water into freshwater regions of the aquifer system was significantly retarded during the predictive simulations due to the imposed boundary conditions, the simulated isochlors would show sharp breaks in the vicinity of the prescribed boundary conditions. In general, this condition was not observed in the predictive scenario results.

Secondly, the 2010 steady-state boundary heads predicted using MODFLOW implicitly neglect the density effects of dissolved solutes. Although density effects are accounted for by computing the equivalent freshwater head based upon the simulated average 1988 chloride concentrations along the model boundaries, the equivalent freshwater head computed in this manner could be in error by several feet or more. This is primarily a potential problem in the Lower Floridan only, since chloride concentrations in the Upper Floridan are not substantial with respect to density effects. However, the error incurred due to this approach is not believed to substantially affect the simulation results, particularly those for the Upper Floridan. In general, the Lower Floridan environmental heads computed using DSTRAM during the Phase III subregional modeling lie within 2½ ft or so of the hydraulic heads computed using MODFLOW during the regional Phase IV modeling. Simulated vertical fluxes between the Upper and Lower Floridan are therefore similar between the two models. Finally, despite the potential drawbacks of determining the boundary conditions for the predictive simulations in this manner, the only

Table 6.1 Summary of predictive simulations.

Predictive Simulation	Comments	Predictive Simulation Withdrawal in million gallons per day		
		Cocoa Well Field	ERWF*	Orangewood Well Field
Base-Case		28.0	45.4	0.0
A	Increased withdrawal at Cocoa well field (relative to base case) distributed among new wells and existing wells 13-19, regardless of well capacity	45.2	45.4	0.0
B	Increased withdrawal at Cocoa well field (relative to base case) distributed among all existing and planned wells based upon well capacity	45.2	45.4	0.0
C	Withdrawal at Orangewood from the Lower Floridan aquifer	28.0	15.4	30.0
D	Withdrawal at Orangewood from the Lower Floridan aquifer	28.0	32.6	30.0

* Orange County planned Eastern Regional Well Field

alternative, which is to model the entire Phase IV regional area using a density-dependent ground-water flow model, is infeasible given the computational requirements.

Overall, the predictive simulation results are believed to be reasonably accurate and appropriate for regional-scale water resources planning purposes. Greater confidence should be placed in the Upper Floridan simulation results since there is a substantial amount of observed data available for this model layer, and since this is the only hydrogeological unit that is considered to be rigorously calibrated. Furthermore, greater confidence should be placed on the predictive simulation results in the central portions of the model domain (2-3 miles from the model boundaries), since the simulated isochlors away from the boundaries are less likely to be affected by errors in the boundary specifications. There is one region in the Upper Floridan in which the simulated isochlors of the calibrated model do not match the observed isochlors particularly well; this region is along the southern model boundary to the south and southeast of the Cocoa well field (see Figure 4.7). In this region the simulated chloride concentrations are less than those observed. It is not believed, however, that the calibration error in this region significantly affects the predictive simulation results, since a northeastern direction of ground-water flow along the southern boundary is maintained in each predictive simulation scenario.

The base-case predictive simulation indicated that poor quality water will continue to upcone at the East Cocoa well field, and lateral intrusion of poor quality water into the West Cocoa well field will continue to occur. However, as of the year 2010, all of the Cocoa production wells in the West well field continued to produce water with chloride concentration less than 250 mg/l, and the same was indicated for the year 2110 with the exception that Cocoa well 7A produced water in excess of 250 mg/l. The regional 250 mg/l isochlor in eastern Orange County moved a relatively small distance to the west towards the Cocoa well field by 2010, but by the year 2060 this isochlor moved a significant distance west and combined with the 250 mg/l isochlor formed by upconing in the northern half of the East Cocoa well field.

The results of the base-case predictive simulation also indicate that there is the potential for substantial lateral intrusion of poor quality water in the Lower Floridan in the vicinity of the east side of Orlando and Winter Park. There is the potential that the Orlando Utility Commission's (OUC) Conway Plant will be adversely effected. Simulated drawdowns from 1988 conditions in the Lower Floridan in the vicinity of Orlando are about 20 ft. However, it must again be emphasized that the Lower Floridan aquifer was not rigorously calibrated in this study, and additional hydrologic data and aquifer properties need to be obtained before highly certain predictions of drawdowns and chloride concentrations may be made for the Lower Floridan.

In predictive simulations A and B, 17.2 MGD of additional pumping was added to the estimated 2010 Cocoa well field withdrawal. The additional pumping represents the balance of the City of Cocoa's projected 2010 demand, which is planned to be obtained from the Taylor Creek Reservoir. In predictive simulation A, the increased withdrawal was distributed among the existing West Cocoa well field wells and the new Cocoa well field wells. In predictive simulation B, the additional pumping was distributed among all of the existing and proposed Cocoa wells based upon well capacity.

The results of predictive simulations A and B are very similar. The increased withdrawals caused additional drawdowns in the Upper Floridan of about 5 ft in the vicinity of the Cocoa well field, and of about 2 ft in the vicinity of ERWF. Simulated chloride concentrations in the Lower Floridan are nearly the same as for the base-case predictive simulation, but chloride concentrations in the Upper Floridan in the vicinity of the Cocoa well field increased significantly relative to the base-case simulation. By the year 2010, simulated chloride concentrations at Cocoa well 7A are in excess of 250 mg/l, and by the year 2060 simulated chloride concentrations reach 250 mg/l at Cocoa well 14. Also, from about Cocoa well 14 to a location slightly east of the East Cocoa well field, simulated chloride concentrations throughout the Upper Floridan equal or exceed 250 mg/l.

In predictive simulation C, pumping at ERWF was reduced from 45.4 MGD to 15.4 MGD. The balance of 30 MGD was withdrawn from the Lower Floridan at Orange County's Orangewood well field, which is about 5 miles due west of the western model boundary in the vicinity of the

Sand Lake Road test well; the Orangewood well field was considered to be off-line in the base-case simulation. All other withdrawals were unchanged from the base-case simulation.

The results of this predictive simulation indicate that drawdown in the Upper Floridan would be reduced by about 15 ft in the vicinity of ERWF and by about 5 ft in the vicinity of the Cocoa well field. Despite the decreases in simulated drawdowns, however, the predicted chloride concentrations in the Upper Floridan are very similar to those of the base-case scenario. This result indicates that to a large degree, the degradation of water quality at the Cocoa well field is due primarily to pumping at the well field, rather than increased drawdown caused by simulated withdrawals at ERWF. Simulated chloride concentrations in the Lower Floridan are slightly less than those of the base-case scenario, since the potentiometric surface of the Lower Floridan increased by several feet in response to the decreased pumping at ERWF.

The modeling scenario for predictive simulation D is similar to that of predictive simulation C; the only difference is that a total of 32.6 MGD was withdrawn from the ERWF, rather than 15.4 MGD. The increased withdrawal of 17.2 MGD is equal to the City of Cocoa's projected increase in average daily flow for 2010. The results of this simulation are very similar to those of predictive simulation C and the base-case scenario, with the exception that the simulated potentiometric surface in the vicinity of ERWF is about 5 ft higher than in the base-case simulation. In terms of chloride concentrations, there is no substantial difference between predictive simulations C and D and the base-case predictive simulation, particularly in the vicinity of the Cocoa well field.

In addition to the predictive simulation modeling results, a number of conclusions can be based upon the modeling study. First of all, the model simulations indicate that the upconing and lateral migration of high chloride water in the immediate vicinity of the Cocoa well field is due primarily to pumping and local hydrogeologic conditions at the well field. This is despite the fact that predicted pumping at ERWF contributes to predicted drawdowns at the Cocoa well field by about five feet. The simulated westward migration of the regional 250 mg/l isochlor in eastern Orange County (dashed line in Figure 3.5) is not substantial as of 2010, but there is significant movement by 2060; the westward migration of this isochlor is due primarily to the combined effects of pumping at the Cocoa well field and ERWF. The Cocoa H monitoring well would be a good existing well to sample on a regular basis (perhaps annually) to document the westward movement of the 250 mg/l isochlor if it does in fact occur.

The modeling results also indicate that the movement of chlorides in the Lower Floridan is relatively independent of pumping in the Upper Floridan. In the predictive scenarios, there was a substantial lateral migration of 250 mg/l water in the Lower Floridan towards the cone of depression caused by Lower Floridan pumping in the vicinity of Orlando. In fact, the migration of the salty water was most likely inhibited by the proximity of the western and northern Phase III model boundaries. The extent of the lateral movement of saltwater in the Lower Floridan did not change appreciably between the various predictive scenarios, which differed primarily due to the prescribed pumping in the Upper Floridan. It must be noted, however, that historically significant increases in chloride concentrations at the Cocoa C well in the Lower Floridan have been observed; the concentrations presumably increased in response to pumping at the Cocoa well field. As noted earlier, the model simulations are not highly accurate with respect to the observed chloride concentrations at the shallow Cocoa C sampling zones (those in the middle semiconfining unit), or the increase in chloride concentrations with time at the deep Cocoa C sampling zone (top of the Lower Floridan).

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 scale. The model is not suitable for the prediction of chloride concentrations on a local scale at individual wells. Furthermore, greater emphasis should be placed upon the 2010 predictive simulation results rather than the 2060 and 2110 results, since hydrologic conditions, available data and the calibrated model itself may well change substantially prior to the later simulation dates. In order to more accurately predict local-scale ground-water chloride concentrations in the Upper Floridan, it might be necessary to conduct detailed hydrogeologic mapping of the lithologic units to locate structural anomalies and zones of increased hydraulic permeability and porosity. This information could then be incorporated into a local-scale model constructed about the region of interest. The local-scale model could be constructed as a subregion of the Phase III model, much in the way the Phase III model was constructed as a subregion of the Phase IV model.

As with all models used for predictive purposes, the model formulation and simulation results should be periodically evaluated and reassessed as additional data (at existing and new observation points) becomes available. New data and conceptualizations of the ground-water flow system should be incorporated into the modeling framework as required. For example, the predictive simulations presented in this report may already be partially outdated since Orange County does not currently expect to obtain flows of 45 MGD from ERWF, but rather plans to use other well fields to supplement ERWF production (Review Comments of David MacIntyre submitted to Rob Teegarden, October 7, 1992). 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 have additional data on hydraulic parameters of the Lower Floridan and the middle semiconfining unit; chloride observations in the Lower Floridan and the middle semiconfining unit; and water level elevations in the Lower Floridan. The major sources of error in the Phase III model stem directly from the lack of data available for the Lower Floridan aquifer.

To address the need for more information, a data collection program should be established to characterize the chloride and water level distributions within the Lower Floridan. This program should include a series of monitoring wells placed along at least one, and preferably two or three, lines that intersect the saltwater wedge at right angles (in eastern Orange County this would be a line of wells in approximately west-east orientation, rather than a north-south orientation). It would be advantageous if there were an Upper Floridan monitoring well in close proximity to each Lower Floridan monitoring well so that the direction of vertical ground-water flow between the Upper and Lower Floridan aquifers could be determined. The major purpose of the monitoring program would be to:

1) Characterize the lateral and vertical distribution of chloride concentrations in the Lower Floridan.

2) Characterize vertical ground-water flow between the Upper and Lower Floridan.

3) Monitor changes in Lower Floridan chloride concentrations, particularly in the freshwater-saltwater (chloride concentrations greater than 250 mg/l) transition zone resulting from natural and/or anthropogenic causes.

4) Develop baseline data against which future effects may be evaluated

The information gained from such a program could be used to evaluate the accurateness and adequacy of the current modeling approach and simulation results. If necessary, the new data could be used to update and recalibrate the model, and improve its reliability for predicting the impact of stresses (such as increased pumping) on the hydrologic system.

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APPENDIX A

Estimated 2010 Discharge for
City of Cocoa Wells

Cocoa Well ID	Estimated Base-Case 2010 Discharge (ft^3/d)
Cocoa well 1	32003.00
Cocoa well 2	31785.83
Cocoa well 3	31785.83
Cocoa well 4	32003.00
Cocoa well 4A1	32003.00
Cocoa well 5	32003.00
Cocoa well 7	32003.00
Cocoa well 7A	34548.30
Cocoa well 8	32003.00
Cocoa well 9	32003.00
Cocoa well 10	19838.10
Cocoa well 11	32003.00
Cocoa well 12A	32003.00
Cocoa well 12B	32003.00
Cocoa well 13	159453.50
Cocoa well 14	221962.30
Cocoa well 15	235811.50
Cocoa well 16	235811.50
Cocoa well 17	233191.40
Cocoa well 18	249286.50
Cocoa well 19	249286.50
New Cocoa well 20	249286.50
New Cocoa well 21	249286.50
New Cocoa well 22	249286.50
New Cocoa well 31	249286.50
New Cocoa well 32	249286.50
New Cocoa well 33	249286.50
New Cocoa well 38	32003.00
New Cocoa well 39	32003.00
New Cocoa well 40	32003.00
New Cocoa well 41	32003.00
New Cocoa well 42	32003.00
New Cocoa well 43	32003.00
New Cocoa well 44	32003.00

APPENDIX B

VERTICAL CROSS-SECTIONAL MODELING ANALYSIS OF GROUNDWATER FLOW AND SALTWATER TRANSPORT IN ORANGE AND BREVARD COUNTIES, FLORIDA

Prepared for

St. Johns River Water Management District
Orange County Public Utilities Division
City of Cocoa

Prepared by

HydroGeoLogic, Inc.
Herndon, VA

July 1991

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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 eastern-most Orange County, however, the Floridan aquifer contains water with chloride concentrations that exceed the EPA recommended limit of 250 mg/l for public supplies. Freshwater for central Brevard County is obtained from the Cocoa well field in eastern Orange County. Increased demands on the Floridan aquifer in Orange and Osceola counties, along with anticipated increases in water demand in the rapidly growing urban areas of western Orange and northwestern Osceola counties, have demonstrated the need for regional water resource management efforts.

The study described in this report is a portion of an ongoing program to address the pressing need for a long-term, environmentally sound, water resources management policy, under joint funding by the St. Johns River Water Management District (SJRWMD), the City of Cocoa, and the Orange County Public Utilities Division (OCPUD). The primary purpose of this study is to provide the technical basis needed to determine the optimal allocations of groundwater resources in eastern Orange County. The major emphasis is on the Floridan aquifer system.

It was decided that the best technical approach to address the given problem would be a series of three, mutually dependent, numerical modeling studies that incorporate the large amount of hydrogeological data available for the east-central Florida region. The first phase involved the development of a regional, three-dimensional groundwater flow model encompassing all of Orange and Seminole counties and significant portions of Lake, Volusia, Brevard, Osceola and Polk counties as technical considerations warranted. 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 second phase involves the development of a vertical cross-section model extending in an east-west direction through the Cocoa well field in eastern Orange County. The purpose of this phase of the study is to assist with the conceptualization of the flow system using density-dependent groundwater flow and solute transport simulations. The third and final phase of the study involves the construction of a three-dimensional, density-dependent flow and transport model for a sub-regional area in eastern Orange County. The second phase of this study, hereafter referred to as Phase II, is the topic of this report.

1.2 Purpose and Scope of Work

The primary purpose of the Phase II modeling effort is to obtain a preliminary analysis of the groundwater flow system in the vicinity of the freshwater/saltwater interface and to determine the physical parameters that exhibit the greatest influence on the position of the interface. This goal was to be achieved through the construction and calibration of a two-dimensional, cross-sectional, density-dependent groundwater flow and solute transport model. The scope of work for the Phase II modeling effort includes the following activities:

- Review existing published and unpublished hydrogeologic data concerning the project area, with particular emphasis on hydrostratigraphy and water quality.

- Construct and calibrate a two-dimensional vertical cross-sectional model for predevelopment, steady-state conditions.

- Conduct a sensitivity analysis on the calibrated cross-sectional model to determine the model input parameters that exert the greatest influence upon the model results.

It should be emphasized that, due to the nature of the simplifying assumptions required to model groundwater flow and solute transport in vertical cross section (two-dimensions), the results of this study must be considered preliminary. The major purpose of this phase of the overall project is to provide some initial insights with regard to the physical system, and to guide the initial construction of the Phase III fully three-dimensional model.

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 in the vicinity of the cross section and water quality. Chapter 4 provides the specifics of the groundwater modeling effort, including the details of model construction and calibration. Chapter 5 is devoted to an extensive sensitivity analysis, and Chapter 6 consists of technical conclusions.

2 TECHNICAL APPROACH

2.1 Overall Approach

The overall technical approach for Phase II of the current study consisted of four major steps. First, the relevant hydrogeological literature for the study area was reviewed, with particular emphasis placed on water quality observations and vertical hydrostratigraphy. This step included the review of unpublished as well as published reports, and a number of geophysical well logs were analyzed. Secondly, the location of the cross section was determined based upon the conceptual model of the region, and a hydrogeological cross section was developed using data collected during the first step. The hydrogeological section was subsequently discretized, and the initial model input parameters and boundary conditions were determined. Some of the initial input parameters were obtained from the Phase I regional model (Blandford et al., 1991). Finally, the cross-sectional model was calibrated to estimated predevelopment conditions, and an extensive sensitivity analysis was performed on the calibrated model results.

2.2 Code Selection

The computer code DSTRAM was selected for use during this study. 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 (groundwater) 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). DSTRAM has also been verified against problems with known solutions.

- 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 was provided in Chapter 3 of the Phase I report (Blandford et al., 1991). 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 II 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 Formation, which consists of marine interbedded sands and clays that are often phosphatic. The Hawthorn Formation 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 groundwater 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 a value perhaps as high as 100 ft. The primary

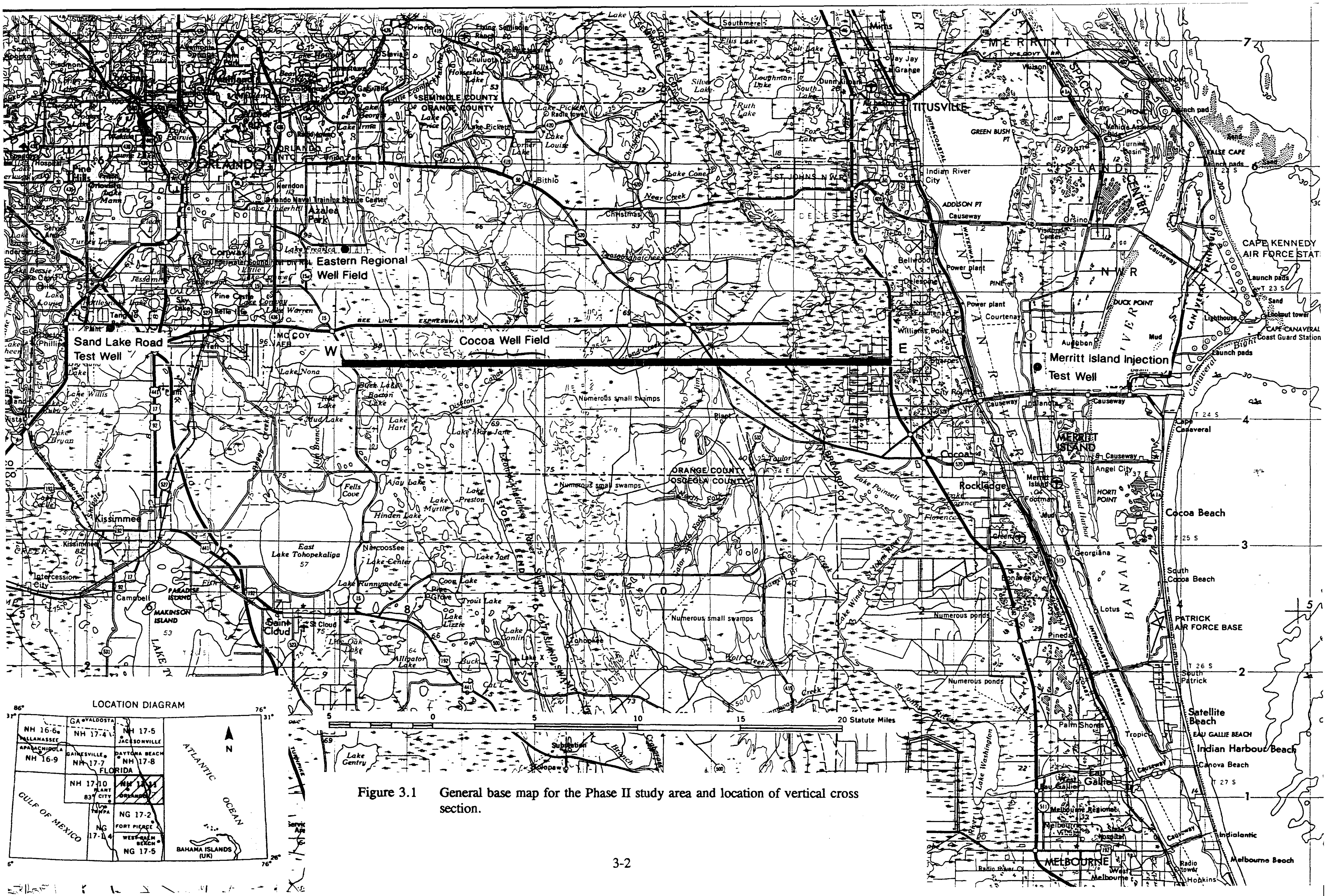


Figure 3.1 General base map for the Phase II study area and location of vertical cross section.

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 Formation	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

- Surficial 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), and McKenzie-Arenberg and Szell (1990).

hydrologic function of the surficial aquifer on a regional scale is to either recharge the underlying Upper Floridan aquifer, or to discharge groundwater 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 productive 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 the vicinity of the Cocoa well field, 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 (CH2M-Hill, 1988 and Tibbals and Frazee, 1976). 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 groundwater 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 ranges from about 2,000 - 2,800 ft in east-central Florida. 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 thickness of the Upper Floridan is approximately 300 - 400 ft throughout the study area.

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 thickness of the middle semiconfining unit ranges from about 100 ft at the western edge of the study area to about 800 ft in the central and some far eastern portions of the study area (Miller, 1986). The flow of groundwater 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 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. These beds have very low permeability due to high amounts of gypsum and anhydrite.

3.3 Predevelopment Potentiometric Surface Map

Figure 3.3 illustrates the potentiometric surface of the Upper Floridan within the study area prior to groundwater development. This figure was adapted from Tibbals (1981), who had in turn adapted it from a multistate potentiometric map of the entire Tertiary limestone aquifer presented by Johnston et al. (1980). Tibbals (1981) states

> "This map is a composite of many other maps: recent potentiometric surface maps in areas where pumping has been light; and older maps or modifications of them where ground-water development has been extensive. The map is intended to show the best estimate that can be made with available data of the 'average' potentiometric surface as it existed prior to development."

Since groundwater flows from areas of high potentiometric surface levels to areas of low potentiometric surface levels, the predevelopment regional groundwater flow in the Upper

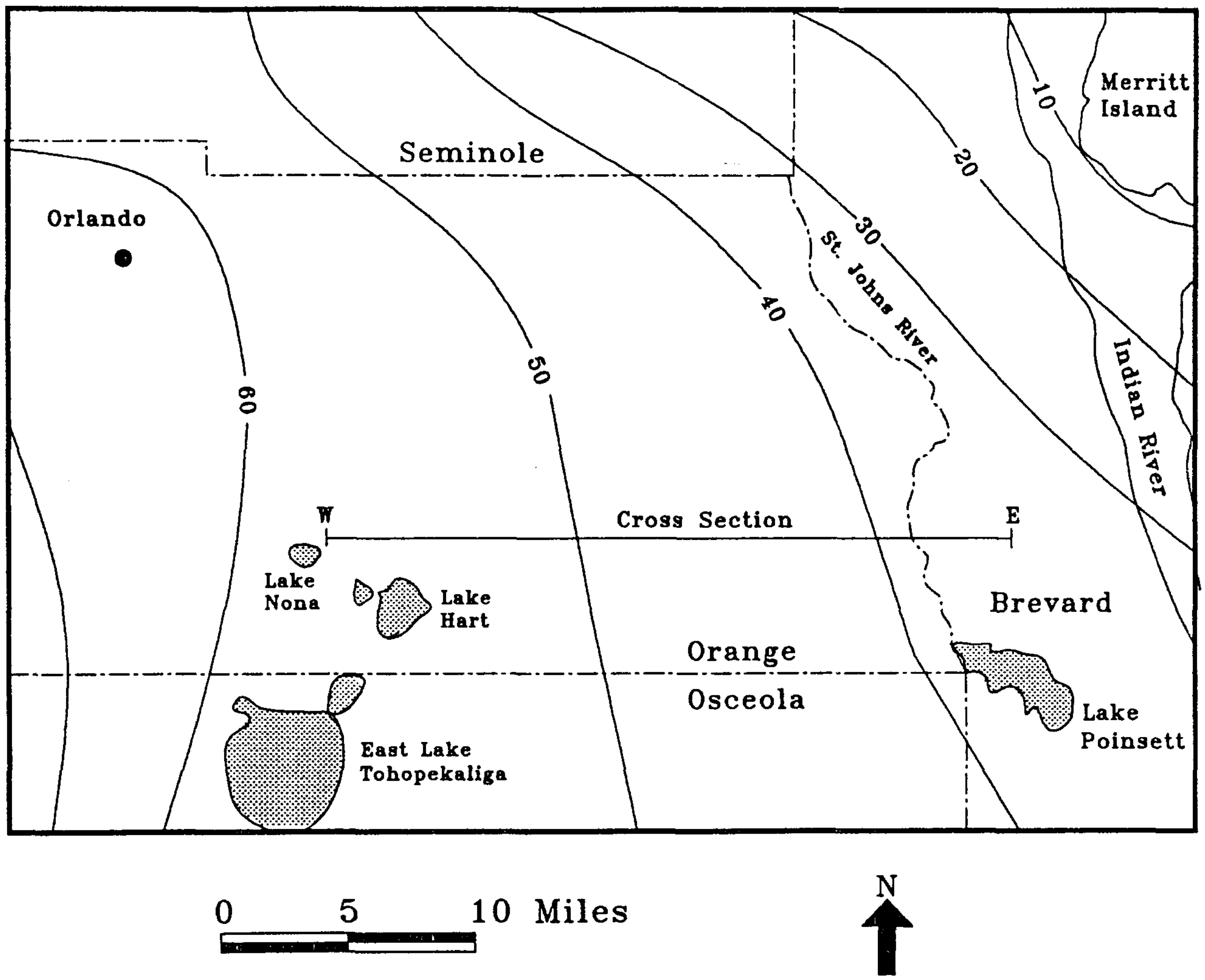


Figure 3.3 Average potentiometric surface of the Upper Floridan aquifer in feet above msl prior to significant groundwater development.

Floridan in the vicinity of the cross section was generally from west to east, although a component of northeasterly flow did exist in eastern Orange County and western Brevard County.

No information is available for the potentiometric surface of the Lower Floridan prior to groundwater development, but it is generally believed that regional groundwater flow directions in the Lower Floridan tend to mimic those in the Upper Floridan.

3.4 Hydrostratigraphy

In the Phase I regional groundwater 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 was reasonable for the regional characterization of groundwater flow.

This Phase II modeling effort, however, examines the two-dimensional flow of groundwater and the associated movement of dissolved salts within a vertical cross section. The flow of groundwater 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 vertical extent and variation of the pertinent hydrogeological units in the vicinity of the cross section. 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 SJRWMD (Brian McGurk, pers. comm.).

The hydrogeological cross section developed for the Phase II modeling effort is illustrated in Figure 3.4. Note on the figure that control points derived from individual well logs are differentiated from control points taken from hydrogeological maps. The control points obtained from well logs should be more accurate than those obtained from the maps because the latter are regional in scale and are probably somewhat generalized. The methodology followed to construct the cross section in Figure 3.4 is outlined below.

1) A general cross section was developed using the hydrogeological maps in Tibbals (1990) and Miller (1986).

2) Lithologic and geophysical well logs supplied by SJRWMD that were in the vicinity of the cross section were identified and, where there was no technical analysis or written report accompanying the logs, the logs were analyzed in an attempt to identify the major hydrogeological units penetrated.

3) If the vertical extent of a given hydrogeological unit (i.e. the Upper Floridan, Lower Floridan, or middle semiconfining unit) as determined from a well log was different than that determined from the maps in Tibbals (1990) or Miller (1986), the value was revised to reflect the well log data.

Two points should be noted concerning the development of the cross section. First, the two areas of the cross section where vertical stratigraphy was obtained using well logs rather than the hydrogeological maps are 1) the Cocoa well field and 2) the west end of the section. At the west end of the section, the hydrostratigraphy information obtained during exploration of Orange County's proposed Eastern Regional well field (ERWF) site (Jammal & Associates, 1990) was utilized. This was deemed appropriate since the ERWF lies only five miles due

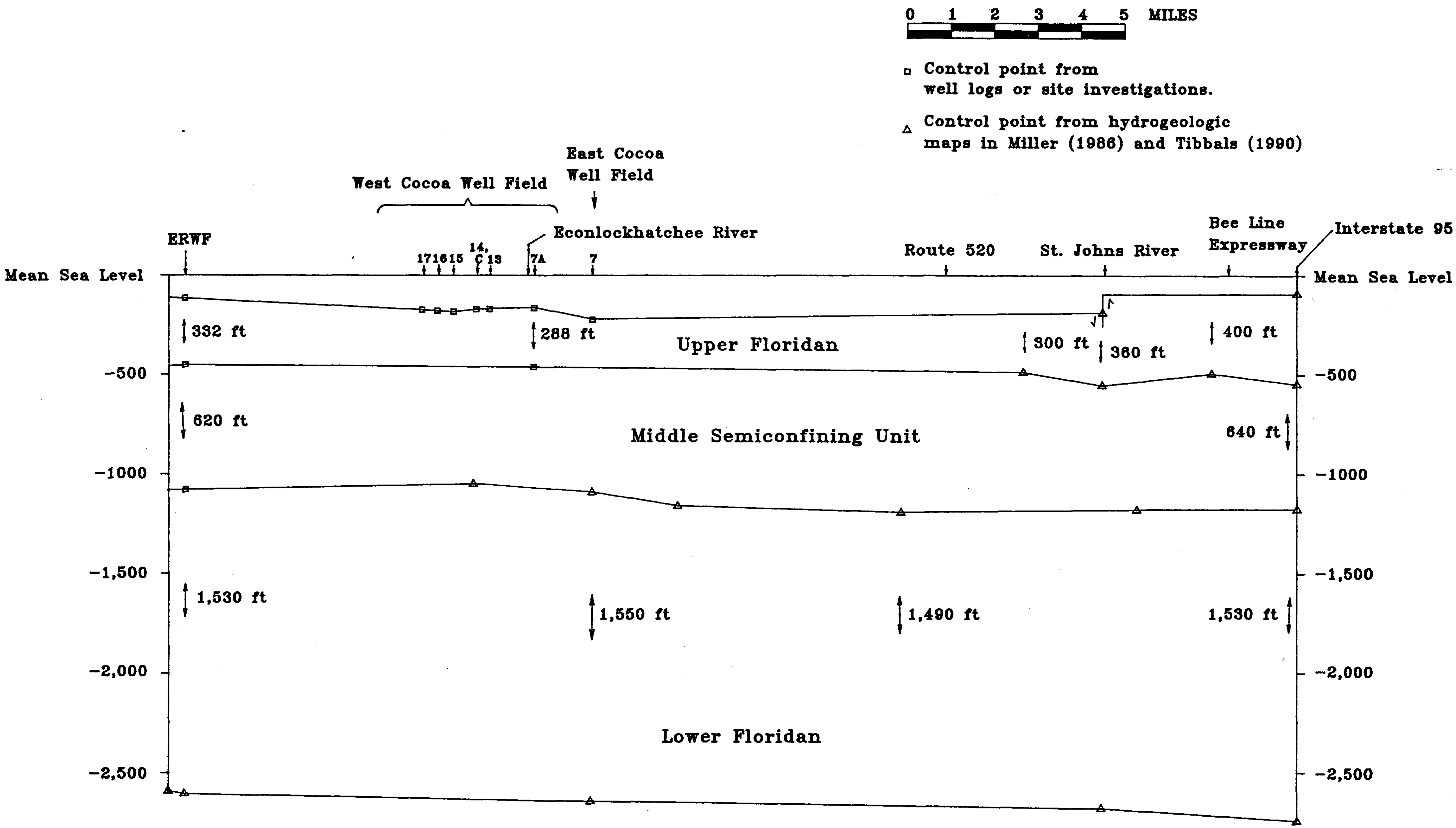


Figure 3.4 Hydrogeological cross section developed for the vertical cross-sectional modeling study.

north of the west cross section boundary.

Secondly, the hydrogeological maps in Tibbals (1990) and Miller (1986) were checked wherever possible, both in the vicinity of the cross section and at various points some distance away. These maps were found to be quite accurate; no major discrepancies were uncovered between the map values and those obtained from well logs or other sources.

Figure 3.4 shows that the Lower Floridan and the middle semiconfining unit are approximately 1,500 and 600 ft thick throughout the section, respectively. The Upper Floridan varies in thickness from approximately 300 ft west of the St. Johns River to about 400 ft east of the St. Johns River. The sudden change in thickness at the river is due to a fault which has offset the carbonate rocks that form the Upper Floridan. This fault may also cause large (relative to adjoining areas) vertical hydraulic conductivities in the vicinity of the St. Johns River, which may be one contributing factor to the high salinity of the groundwater in the Upper Floridan in the vicinity of the St. Johns River.

3.5 Water Quality

This section provides an overview of the water quality in the Upper and Lower Floridan aquifers in the vicinity of the cross section. 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.

3.5.1 Upper Floridan

Both Toth (1988) and Tibbals (1990) provide extensive discussions concerning water quality in the Upper Floridan, and to some degree the Lower Floridan, within the vicinity of the cross section. In general, the dissolved solids content of the groundwater decreases from east to west in both the Upper and Lower Floridan (Figure 3.5). The poor quality water at the east end of the cross section is attributed to the presence of relict seawater, which

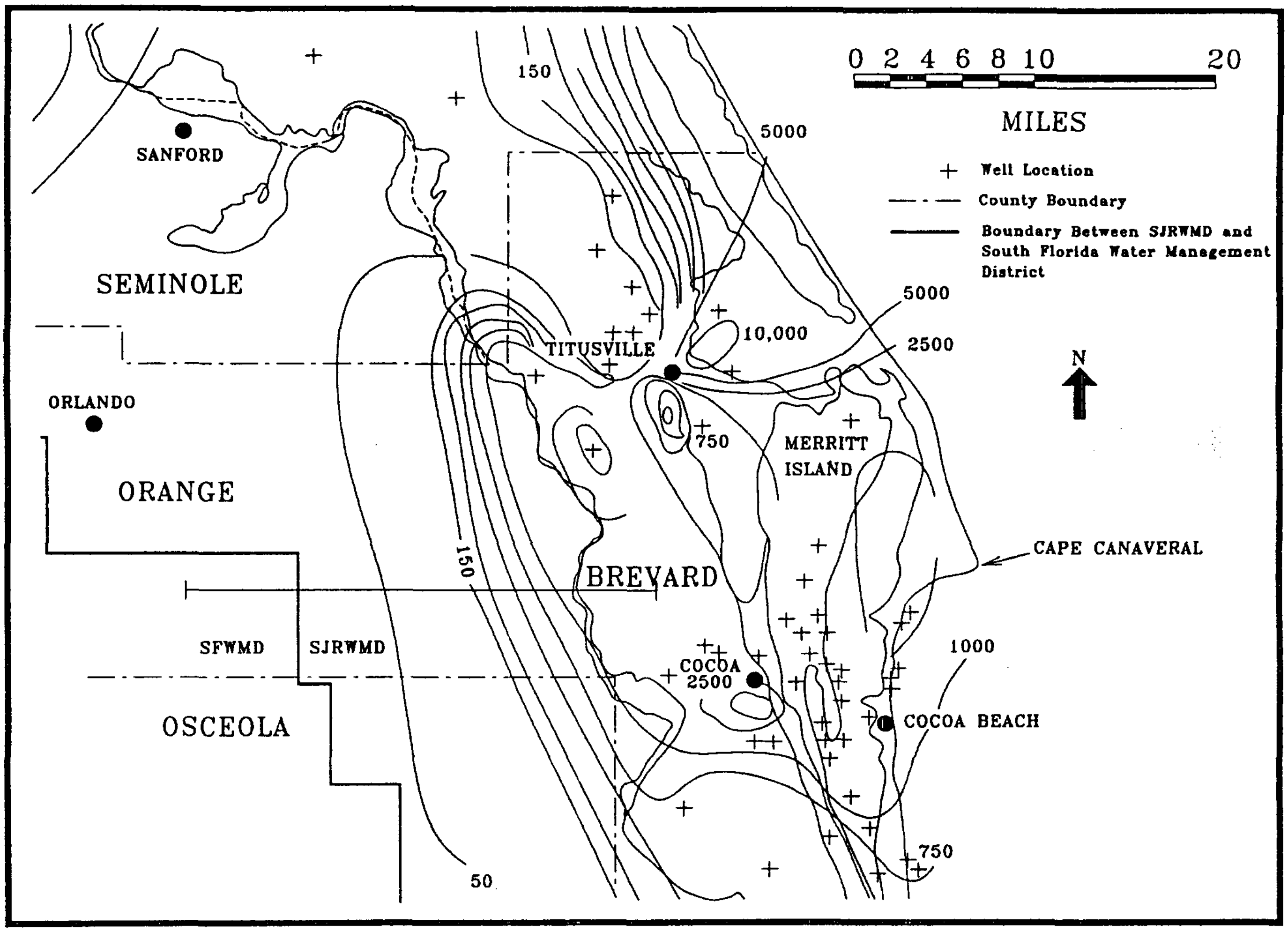


Figure 3.5 Contour map showing chloride concentrations in mg/l for the Upper Floridan (adapted from Toth, 1988).

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.

During the early phases of this study, SJRWMD supplied a base map illustrating the locations of wells that had been sampled for chloride concentrations within the study area, and the relevant portion of their digital data base that corresponded to the same area. A summary of the available data for wells near the east end of the cross section is provided in Table 3.1, and a listing of all recorded chloride data for these wells is provided in Appendix A.

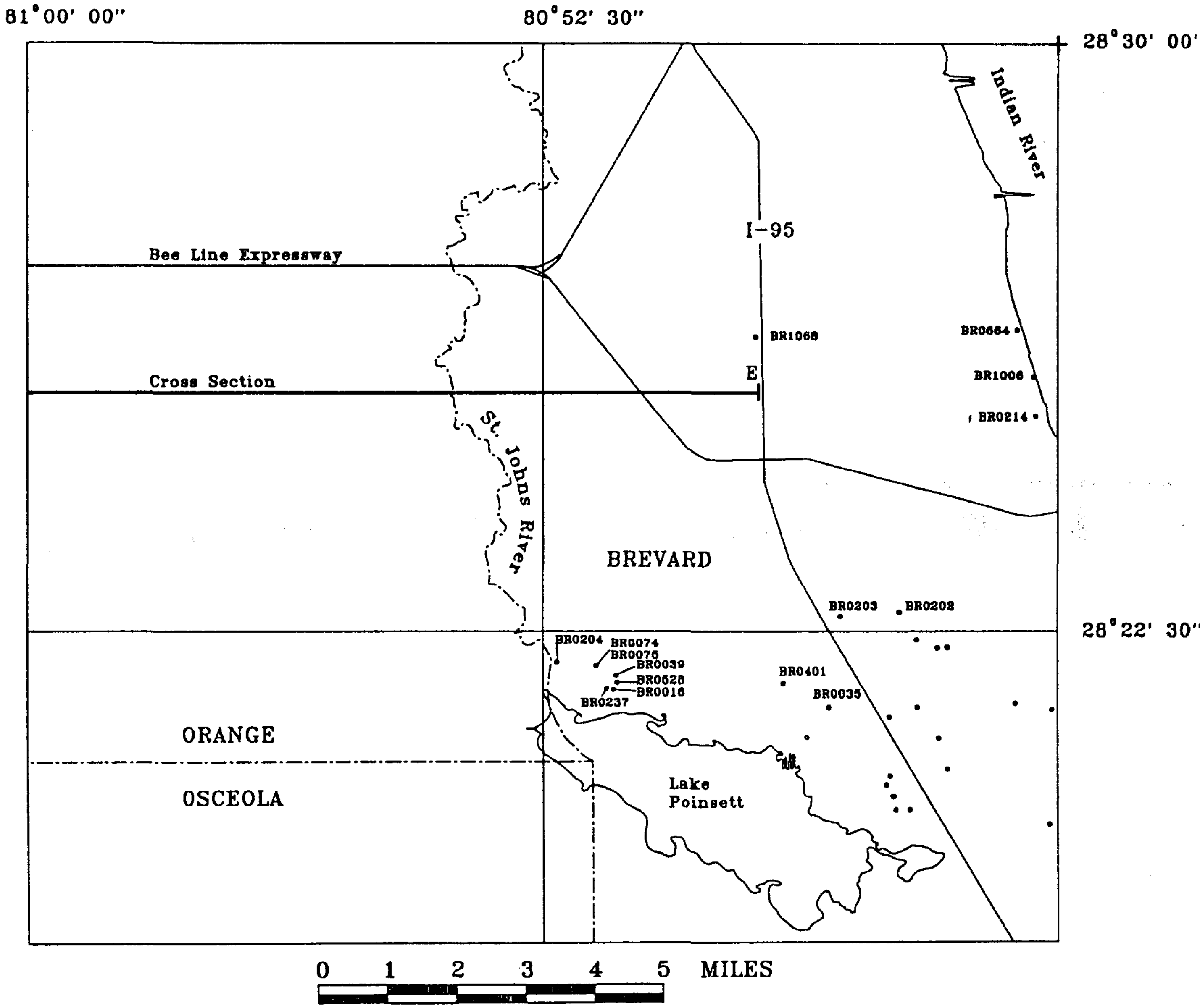
All of the wells listed in Table 3.1 except for BR0214 and BR0664 are located approximately 3 - 4 miles south of the east end of the cross section in the vicinity of the city of Cocoa in Brevard County (Figure 3.6). The lowest and highest chloride concentrations observed in these wells were 1,490 and 2,634 mg/l, respectively, but in general the concentrations average about 2,200 to 2,400 mg/l. A chloride concentration of 4,220 mg/l was recorded in well BR0664, which is due east of the east end of the cross section on the shore of Indian River. Well BR0214 is also on the shore of the Indian River, but samples from this well were not deemed representative of the Upper Floridan because it has a total depth of only 100 ft.

The data presented in Table 3.1 agree reasonably well with the contour map developed by Toth (Figure 3.5), except that Toth's map does not reflect the presence of chloride concentrations greater than 1,000 mg/l near well BR0664. The observed concentration of 4,220 mg/l at well BR0664 may be an anomaly since east of this well, at the Merritt Island Exploratory Well, chloride concentrations in the Upper Floridan were found to be only 2,200 mg/l (Geraghty & Miller, Inc. 1984).

Table 3.1 Summary of chloride concentration data for selected wells in the SJRWMD data base.

Well ID	Casing Depth (ft)	Well Depth (ft)	Number of Samples	Average Conc. (mg/l)	High Conc. (mg/l)	Low Conc. (mg/l)
BR0035	-	180	1	1,900	-	-
BR0401	-	-	2	2,244	2,285	2,203
BR0528	-	-	1	2,112	-	-
BR0039	-	-	1	2,400	-	-
BR0074[a]	138	495	11	2,403	2,500	2,270
BR0075[a]	530	553	11	2,482	2,634	2,400
BR0204	-	-	11	2,097	2,188	2,010
BR0203	-	-	4	2,272	2,129	2,505
BR0202	114	129	14	1,594	1,750	1,490
BR0214[b]	-	100	2	1,145	1,300	990
BR0664	-	-	1	4,220	-	-
BR0016	no data					
BR0237	no data					
BR1006	no data					
BR1068	no data					

[a] Same location
[b] May be in secondary artesian aquifer



• **Well location from SJRWMD chloride observation data base**

BR0204 **Identification number for selected wells**

Figure 3.6 Locations of selected wells in the vicinity of the east end of the cross section for which chloride concentration data is available in the SJRWMD data base.

Wells BR0074 and BR0075 compose a well nest, and they provide some information about chloride variation with depth. Well BR0074 is open hole from 138 to 495 ft below land surface (bls) and therefore samples obtained from this well should be composite or average values of chloride concentration for the entire thickness of the Upper Floridan at that point. Well BR0075 is open to the aquifer in the interval 530 - 553 ft bls, and therefore provides chloride information from the zone slightly below the bottom of well BR0074. Based upon the maps presented in Tibbals (1990), well BR0075 should sample the very bottom of the Upper Floridan, the very top of the middle semiconfining unit, or some combination of these two hydrogeological units.

Table 3.1 shows that well BR0074 has an average chloride concentration of about 2,400 mg/l, while well BR0075 has an average chloride concentration of about 2,480 mg/l. These data illustrate the expected trend of increasing chloride concentration with depth. The increase, however, is not substantial over the intervals sampled. At wells BR0074 and BR0075, the freshwater/saltwater interface (chloride concentration of about 10,000 mg/l) must exist at a depth significantly below the bottom of the Upper Floridan, probably at some point within the middle semiconfining unit.

3.5.2 Lower Floridan

Observed data concerning the variation of chloride concentrations in the Lower Floridan are very limited. In the vicinity of the Phase II cross section, there are four deep test/monitor wells that penetrate all or portions of the Lower Floridan and which provide useful water quality data. These wells are the Merritt Island injection test well located near the center of Merritt Island; the Sand Lake Road injection test well located just south of Orlando; the Cocoa C salinity monitoring well at the Cocoa well field; and the Lower Floridan exploratory well at Orange County's ERWF site. The data obtained from each of these wells is summarized below.

The Merritt Island injection test well is located on Merritt Island about 8 miles due east of the east end of the cross section (Figure 3.1). The construction and testing of this well was performed in 1984 and is documented in Geraghty & Miller (1984). The well was drilled to a total depth of 2,701 ft 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 3.2 lists observed values of chloride concentration versus depth at the Merritt Island test well. This table shows that the average chloride concentration within the Upper Floridan at this point is about 2,200 mg/l, and the freshwater/saltwater interface occurs between 340 and 950 ft bls, probably within the middle semiconfining unit. Chloride concentrations in the Lower Floridan are approximately equal to that of seawater (19,000 mg/l).

The Sand Lake Road injection test well, completed in 1977, is located just south of Orlando and about 9 miles due west of the west end of the cross section (Figure 3.1). The construction and testing of this well is documented in Geraghty & 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 & 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 was extremely low (1 mg/l or less). However, since the volume of water that moved

Table 3.2 Chloride and total dissolved solids concentrations for various depth intervals at the Merritt Island deep injection test well (Geraghty & 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.

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 groundwater 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.

The Cocoa C salinity monitoring well was constructed in 1965. This well was originally completed with five sampling zones (numbered from the bottom up), but Zone 2 was subsequently plugged. The remaining sampling zones are open to the intervals indicated in Table 3.3. Zone 1 samples the Lower Floridan; Zone 4 samples the middle semiconfining unit; and Zone 5 samples the Upper Floridan and the middle semiconfining unit. Zone 3 lies very close to the contact between the top of the Lower Floridan and the bottom of the middle semiconfining unit, but is probably open to the middle semiconfining unit since chloride concentrations have not changed significantly in time for this sample location, while chloride concentrations in Zone 1 have increased from about 750 mg/l in 1967 to approximately 2,600 mg/l in 1989. Chloride concentrations have remained relatively stable in monitoring Zones 3 and 4 over the period 1967 - 1989 at about 81 mg/l and 40 mg/l, respectively (Table 3.3).

Table 3.3 Depth intervals and abbreviated chloride concentration history for Cocoa C salinity monitoring well sampling zones (Fayard, 1989).

Zone No.	Depth Interval (ft bls)	Chloride Concentration History
1	1,351 - 1,357	Initially 750 mg/l in 1967. Increased to about 2,600 mg/l by 1989.
3	1,218 - 1,224	Relatively stable at about 81 mg/l from 1967 - 1989.
4	1,044 - 1,050	Relatively stable at about 40 mg/l from 1967-1989.
5	248 - 1,004	No data available.

In the vicinity of the Cocoa C monitoring well, chloride concentrations are relatively low within the Upper Floridan and the middle semiconfining units, but the water quality quickly becomes non-potable (chloride concentrations greater than 250 mg/l) in the Lower Floridan. However, since the deepest sampling zone only penetrates about the upper one-sixth of the Lower Floridan, the nature of the vertical transition of chloride throughout the remainder of the Lower Floridan is unknown.

Finally, as part of the aquifer testing and well field evaluation project conducted by Orange County for their proposed ERWF, a Lower Floridan exploratory well was constructed at that site in 1989 (Jammal & Associates, 1990). The ERWF site is located about seven miles east of Orlando, and about five miles due north of the west end of the cross section (Figure 3.1). This well was completed to a total depth of 1,385 ft, and penetrates about 235 ft (the upper one-sixth) of the Lower Floridan. The water quality at this site in both the Upper and Lower Floridan aquifers is excellent. The maximum chloride concentration measured in the Lower Floridan was 10 mg/l.

4 TWO-DIMENSIONAL CROSS-SECTIONAL MODEL

4.1 Introduction

In this chapter, the rationale behind the placement, discretization, and assignment of aquifer parameters and boundary conditions to the cross section are discussed. The modeling methodology and the predevelopment, steady-state model results are also explained. However, prior to presenting the details of the cross-sectional 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 (groundwater) 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 groundwater flow and solute transport, the code solves two coupled partial differential equations: one for density-dependent fluid flow and one for the transport of dissolved solutes.

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 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

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

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

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

$$\frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial c}{\partial x_j}\right] - V_i\frac{\partial c}{\partial x_i} = \phi R\left[\frac{\partial c}{\partial t} + \lambda c\right], \tag{4.7}$$
$$i,j = 1,2,3$$

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 ($\lambda = 0$). Equations (4.1) and (4.7) 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 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 hence 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". Nonlinear problems arise when there are two or more dependent variables that must be solved for at the same time. 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 not converged or nonconverged.

4.3 Conceptual Model and Modeling Assumptions

The conceptual model adopted for the quantitative analysis of groundwater flow and salt transport in east-central Florida is illustrated in Figure 4.1. The basic model 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 confining unit that provides areally distributed recharge or discharge directly to the Upper Floridan. In recent postdevelopment conditions, pumpage occurs in both aquifers. However, since this study was conducted for steady-state predevelopment conditions, pumpage was not specified in either aquifer.

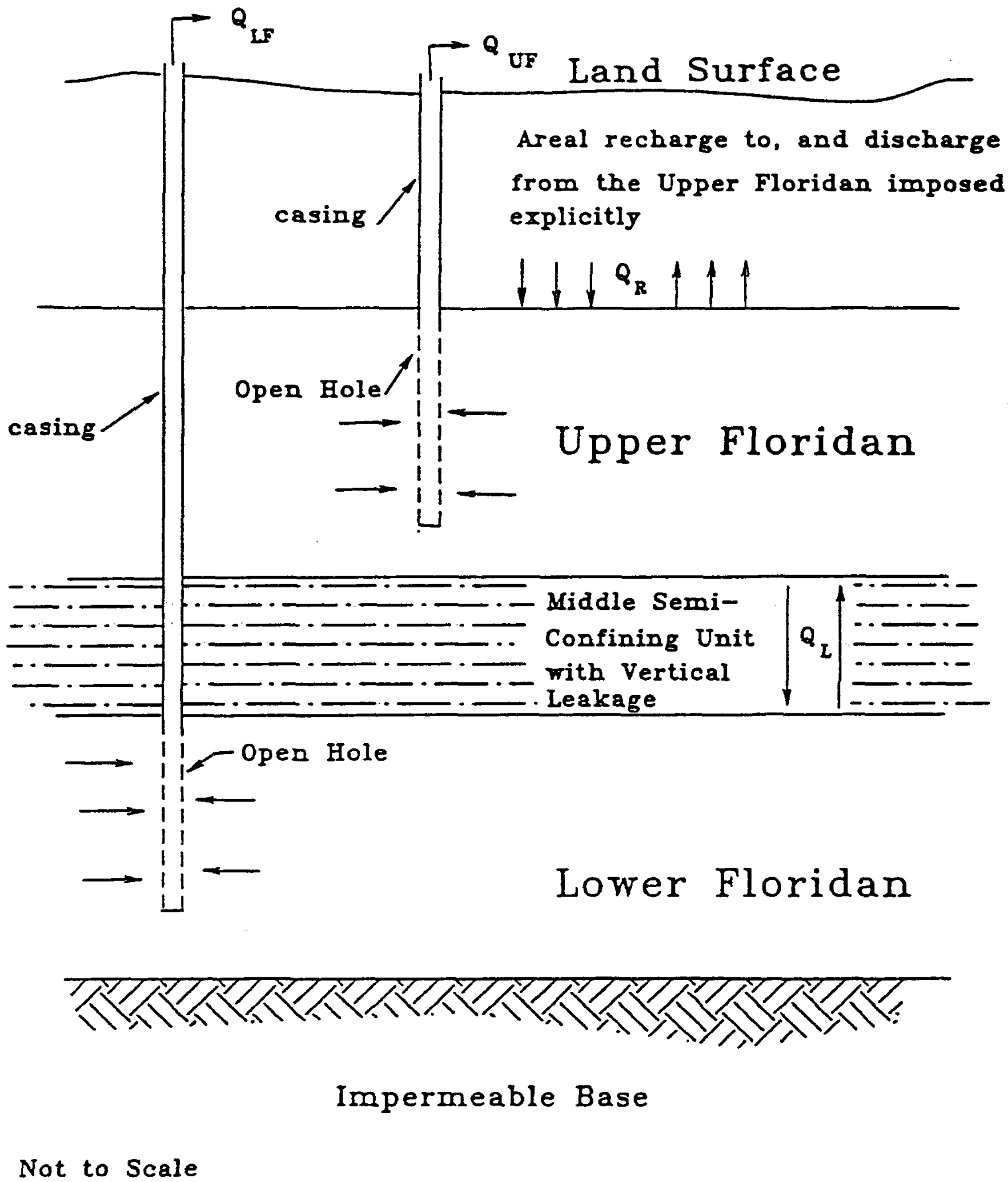


Figure 4.1 Conceptual model for modeling groundwater flow and solute transport within the Floridan aquifer system in east-central Florida.

The fundamental assumption of vertical cross-sectional modeling is that the concentration distribution in the vertical plane of the selected cross section is governed by two-dimensional flow of water and chloride transport in that plane. The effects of advection and dispersion across the plane are neglected. Typically, the cross section is conceptualized to be of unit width (e.g. 1 ft), and subsequently all calculations of flux are computed as "per unit width of aquifer".

In many previous modeling studies of regional groundwater flow in east-central Florida, the Floridan aquifer system was divided into two distinct producing zones separated by a semiconfining unit (see, for example, Tibbals (1990) or Blandford et al. (1991)). In this approach, only the vertical leakage of water (up or down) through the middle semiconfining unit is simulated; horizontal groundwater 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) must be discretized into multiple layers to reasonably account for density-dependent groundwater flow and transport processes that occur in the vertical direction, since both the flow of groundwater and the distribution of chlorides is of primary importance.

Recharge to, and discharge from the Upper Floridan is specified directly in the model. In reality, groundwater that flows vertically to or from the Upper Floridan must pass through the upper semiconfining unit and into, or out of, the surficial aquifer. Areal recharge (note that discharge is simply negative recharge) is a function of the hydraulic head in the surficial aquifer (h_s), the hydraulic head in the Upper Floridan (h_u), the hydraulic conductivity of the upper semiconfining unit (K') and the thickness of the upper semiconfining unit (b'). As outlined in Blandford et al. (1991), the approach of specifying recharge directly, rather than modeling the flow of water through the upper semiconfining unit explicitly, is valid because of the steady-state flow field assumption.

Another assumption concerns the estimated Upper Floridan predevelopment potentiometric surface. It is assumed that the potentiometric surface map constructed by Johnston et al. (1980) is representative of observed conditions throughout the model domain, even though it was constructed from observed data collected prior to development in some areas and estimated in other areas.

The final assumption concerns the relationship of chloride concentration in the groundwater to the 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 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 throughout the model domain.

4.4 Model Domain

Vertical cross-sectional modeling is generally conducted along a groundwater flowpath, because the resulting mathematical computations are conducted on a per unit width of aquifer basis (Section 4.3). This constraint, combined with the modeling goal of obtaining a preliminary assessment of the distribution of chloride concentrations in the vicinity of the Cocoa well field, led to the east-west orientation of the cross section presented in Figures 3.1 and 3.3. The east-west orientation of the cross section also made it easier to transfer the initial aquifer parameters from the Phase I regional model (Blandford et al. 1991) to the cross-sectional model. One can see from Figure 3.3 that the cross section is, in general, oriented along a predevelopment groundwater flowpath. However, at the east end of the section, there are significant components of flow in a north-east, as well as an easterly direction. It is felt that, given the goals of the Phase II study, this error may be regarded as insignificant.

The length of the cross section (26.5 miles) was selected after careful consideration of the available data on boundary conditions and pertinent hydrogeological features. Configuration of the Phase III model grid, which will be limited by computer storage and computational requirements, was also an important consideration in designing the cross section. The cross section was extended west of the Cocoa well field to an end point due south of the ERWF. At this point, the Floridan aquifer was believed to contain water of very low chloride concentrations, except, possibly, at great depth. Furthermore, data recently obtained from the ERWF tests (Jammal & Associates, 1990) could be used to define the hydrostratigraphy at this boundary.

The cross-section was extended east of the Cocoa well field to near Interstate 95 (I-95), which is located roughly half-way between the St. Johns and Indian Rivers. This end point was selected for two major reasons. First, the hydrologic effects of a possible zone of high vertical hydraulic conductivity (relative to adjoining areas) underlying the St. Johns River due to faulting was to be assessed. The east boundary, therefore, had to extend a significant distance beyond the St. Johns River so that the zone of sensitivity would not lie at the boundary. Secondly, the Merritt Island injection test well due east of the cross section, and the monitoring wells in the vicinity of Cocoa in the SJRWMD database, provided a reasonable amount of data to determine the chloride concentration boundary conditions.

The vertical domain of the cross section was defined by the hydrogeological cross section presented in Chapter 3 (Figure 3.4). The top of the cross section corresponds to the top of the Upper Floridan, and the bottom of the cross section corresponds to the base of the Floridan aquifer system (bottom of the Lower Floridan). The physical boundary conditions at the top, bottom and sides of the cross section are discussed in Section 4.6.

4.5 Finite-Element Mesh Design

The finite-element mesh used for the Phase II model simulations is presented in Figure 4.2. The mesh consists of 2,240 nodal points and 2,109 quadrilateral finite elements. The top line in Figure 4.2 corresponds to a horizontal line 100 ft below sea level, which is the datum used throughout this report. The horizontal (plan view) extent of the cross section is exactly 26.5 miles (139,920 ft); the location of the cross section is illustrated in Figure 3.1. The cross section is set along row 31, with the end points corresponding to columns 23 (west end) and 44 (east end) of the Phase I regional model grid (Blandford et al., 1991).

The DSTRAM orthogonal curvilinear mesh option was used to discretize the hydrogeological cross section presented in Chapter 3 (Figure 3.3). A curvilinear mesh is one where the gridline columns and/or rows do not remain parallel over their entire length. This option allows a grid to be developed that conforms to the changing geometry of the various hydrogeological units. This option was invoked because, although the thickness of the individual hydrogeological units do not change appreciably across the section, there is a significant dip to the bottom of the system. The elevation gradient of the bottom of the Floridan aquifer system is, in fact, larger than the regional, predevelopment hydraulic gradient. This condition could potentially have a significant influence upon the density-dependent groundwater flow simulations, and therefore the sloping bottom condition was incorporated directly into the modeling domain. The sloping aquifer bottom condition should tend to inhibit the landward (western) migration of higher density saltwater.

The horizontal discretization (cell size) varies from 1,000 ft throughout most of the cross section to 5,280 ft (1 mile) at the west end of the section. The finest discretization was used where the largest variations in concentrations were expected, and larger cell sizes were used where concentration variations were expected to be relatively small. For cases where diffusion is small compared to advection, the grid Peclet number may be defined as where Δx is the length of the grid cell in the x-direction and α_L is the longitudinal dispersivity. For flow parallel to the x-axis, therefore, the Peclet number over most of the

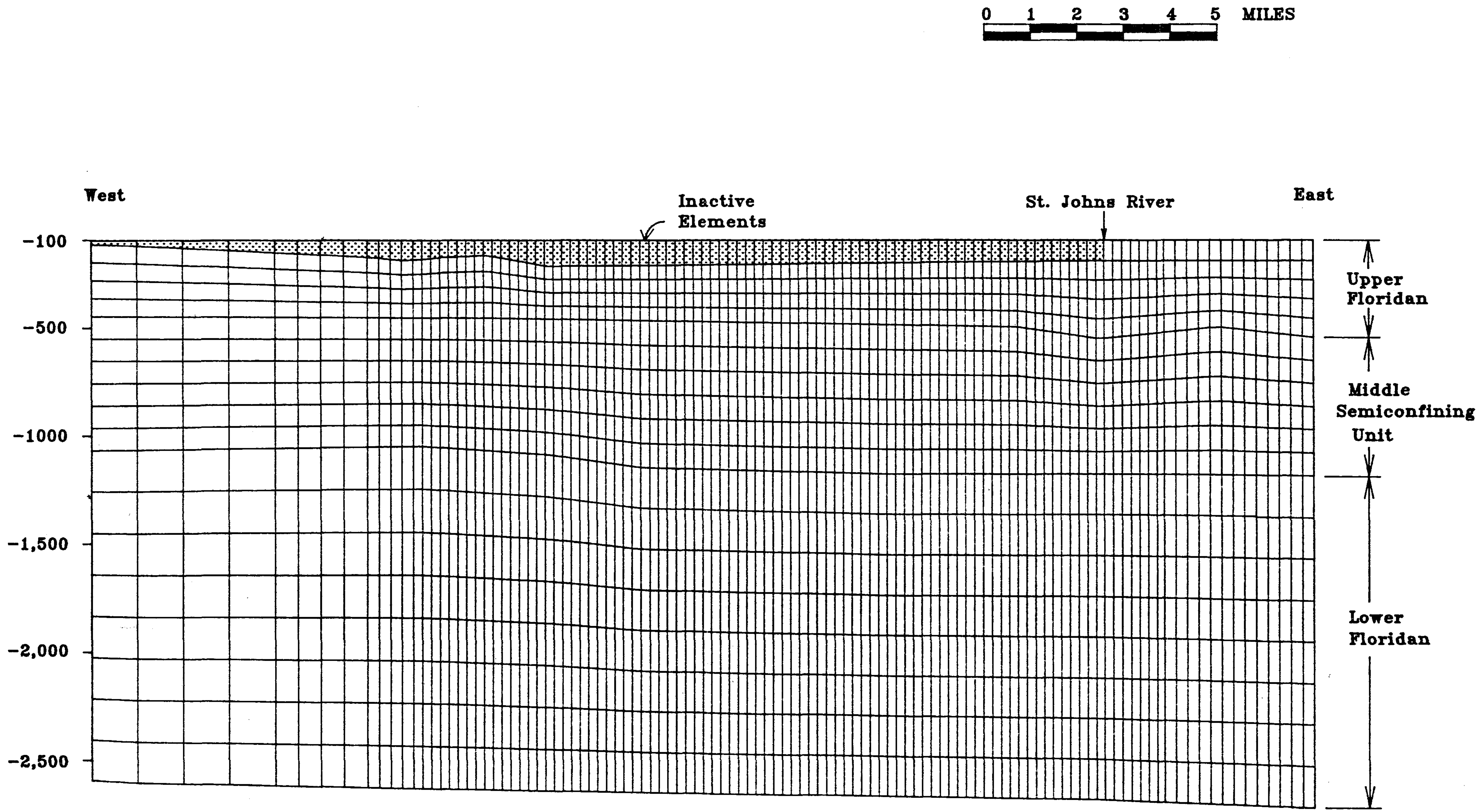


Figure 4.2 Curvilinear finite element mesh used for vertical cross-section modeling.

$$P_e = \frac{\Delta x}{\alpha_L} \tag{4.8}$$

domain is 10, since α_L used in the simulations was 100 ft. This condition lies well within the solution capabilities of DSTRAM.

In the vertical (z) direction, the Floridan aquifer system was divided into a total of 19 layers. The Lower Floridan was divided into eight layers ($\Delta z \approx$ 190 ft), the middle semiconfining unit was divided into six layers ($\Delta z \approx$ 100 ft), and the Upper Floridan was divided into four layers west of the St. Johns River, and five layers east of the St. Johns River ($\Delta z \approx$ 80 ft).

A portion of the elements in the top row of the mesh were designated as inactive model cells. This was done to incorporate the structural discontinuity within the Upper Floridan that is believed to exist at the St. Johns River (Tibbals, 1990). West of the St. Johns River, therefore, the first active elements occur one row down from the top of the mesh. The nodes that form the tops of these elements represent the top of the Upper Floridan. East of the river, the top row of elements is active and the average thickness of the Upper Floridan increases from 300 ft to 400 ft.

4.6 Model Boundary Conditions

This section describes the boundary conditions that were imposed for both groundwater flow and chloride concentrations at the bottom, top, and sides of the vertical cross sectional model domain. A conceptual diagram of the cross-sectional model boundary conditions is presented in Figure 4.3.

In this section, reference is 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 ÷

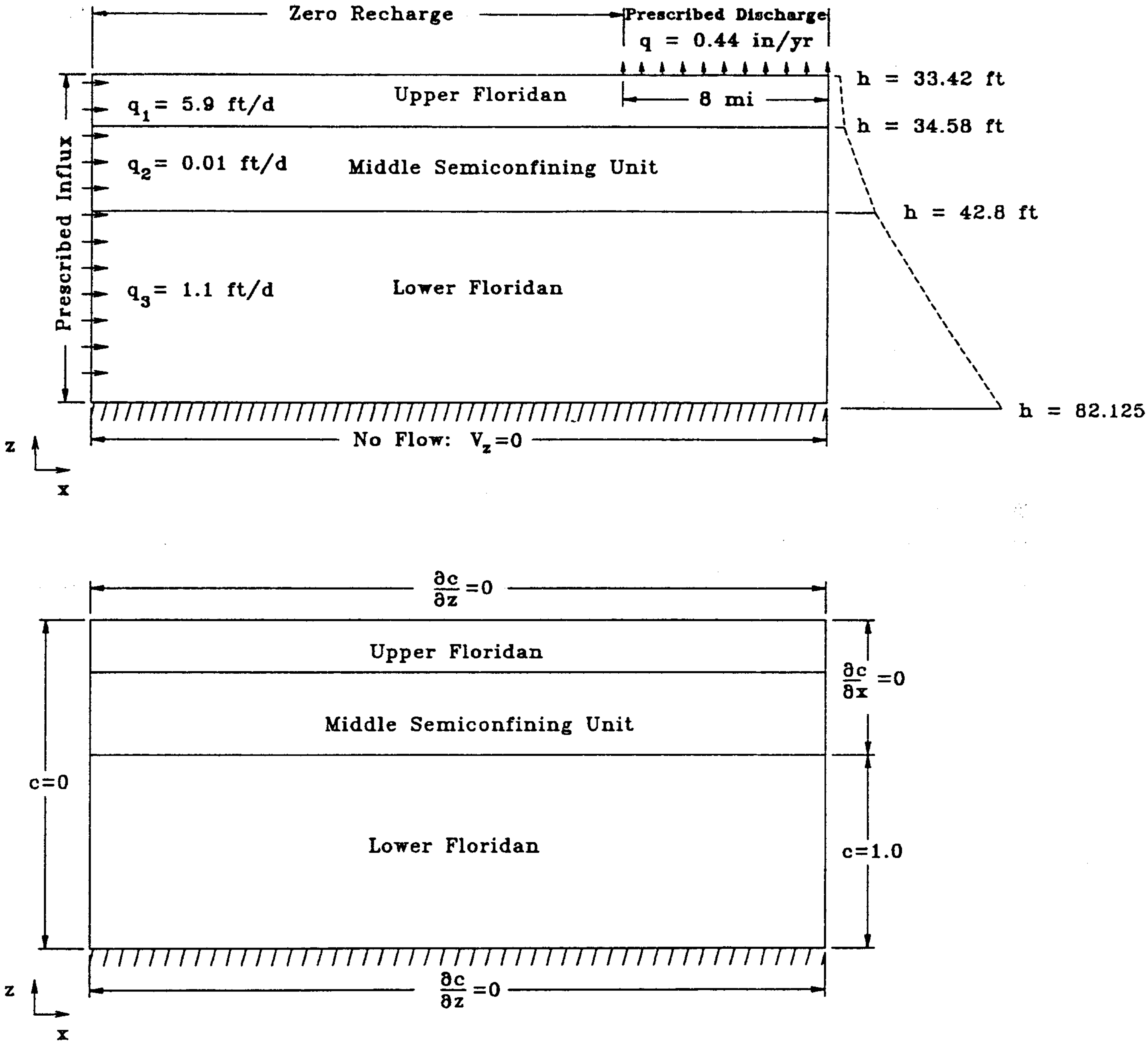


Figure 4.3 Imposed boundary conditions for density-dependent flow and solute transport vertical cross sectional model.

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_0) of the water was taken as 0.997 g/cm^3 (Drever, 1982) and the maximum density of the saltwater (ρ_s) was taken as 1.02261 g/cm^3 (de Marsily, 1986). These density values are based upon an average groundwater temperature of 25°C.

4.6.1 Bottom Boundary

The bottom boundary of the cross section corresponds to the base of the Floridan aquifer system. This boundary was 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. At this location, 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 (Chapter 3). The same conceptualization was adopted in numerous other modeling studies.

4.6.2 Top Boundary

The top boundary of the cross section corresponds to the top of the Upper Floridan. Recharge to, and discharge from, the Upper Floridan at this boundary was specified directly. Recharge water was assigned a chloride concentration of zero, and the chloride concentration in discharging water was determined by DSTRAM as an advective solute flux exiting the model domain. The initial values of recharge and discharge along the cross section were taken from the Phase I regional model study (Blandford et al., 1991), but they were adjusted during the calibration process.

4.6.3 West Boundary

At the west boundary, groundwater influx was prescribed at all of the active nodes along gridline column 1 (19 nodes). The initial flux values were calculated using the predevelopment hydraulic gradient in the vicinity of this boundary (Figure 3.3) and the hydraulic conductivity values obtained from the Phase I modeling study. As an initial estimate, the predevelopment hydraulic gradient in the Lower Floridan was assumed to be the same as that in the Upper Floridan. This is probably not too bad of an assumption, since flow in both the Upper and Lower Floridan is expected to be predominantly two-dimensional (horizontal) in this region, and, in general, large hydraulic head differences are not observed between the two aquifers. The lateral influxes to the Upper and Lower Floridan were adjusted during the calibration process.

Chloride concentrations at the western boundary nodes were set equal to zero. This approach is consistent with the results of the ERWF testing (Jammal & Associates, 1990), in which chloride concentrations in the Upper Floridan, the middle semiconfining unit and the upper one-sixth of the Lower Floridan were found to be very low. It is possible that at this end of the cross section, near the bottom of the Lower Floridan, chloride concentrations could increase to significant levels (250 mg/l or more). There is simply an insufficient amount of observed data to accurately quantify chloride concentrations with depth in the lower one-third or so of the Lower Floridan at this end of the cross section. If chloride concentrations near the bottom of the Lower Floridan are significant at this boundary, it is believed at this time that they are not so large as to have a major impact upon the position of the major chloride isochlors, such as the freshwater/saltwater interface.

4.6.4 East Boundary

The boundary conditions at the east end of the cross section were the most difficult to quantify because the chloride concentrations vary significantly with depth, while observed concentration data is very limited. For the most part, the chloride concentrations at this boundary were extrapolated from the Merritt Island injection test well eight miles to the east. At that location, chloride concentrations in the Upper Floridan are about 2,200 mg/l, chloride concentrations in the Lower Floridan are about that of seawater (19,000 mg/l), and the 10,000 mg/l isochlor occurs in the lower one-half of the middle semiconfining unit (Table

3.2). Based upon the observed data at the Merritt Island test well and other wells that penetrate the Upper Floridan, the boundary conditions at the eastern boundary were derived in the manner outlined below.

The average chloride concentration in the Upper Floridan was assumed to be 1,900 mg/l, which is consistent with the Upper Floridan chloride concentration maps in Toth (1988) and Tibbals (1990). This value is slightly less than that observed at the Merritt Island test well and at some observation wells in the vicinity of Cocoa to the south. However, since the eastern boundary is eight miles west of the Merritt Island test well site, and since Toth (1988) shows a region of localized high chloride concentrations in the vicinity of Cocoa, the selected concentration is thought to be reasonable.

Given the average concentration of 1,900 mg/l (normalized concentration of 0.1), the next step was to convert from observed hydraulic head to reference head (equation 4.6) assuming vertical hydraulic equilibrium. Observed head (H) at the eastern boundary is 34 ft (Figure 3.3), and the total thickness of the Upper Floridan at this point is 450 ft (Figure 3.4). The reference head variation in the vertical direction due to variable density is, therefore, 1.16 ft (Figure 4.3), and the appropriate reference head values were prescribed at this boundary. A zero normal gradient of chloride concentrations was specified as the boundary condition for the transport equation, since an outward flow of groundwater exists across the boundary in the Upper Floridan. This type of boundary condition neglects the mass flux of chlorides across the boundary that may be present due to diffusion.

In the Lower Floridan, the chloride concentration was assumed to be 19,000 mg/l (normalized concentration of 1.0). This assumption was based upon the observed concentrations in the Lower Floridan at the Merritt Island test well, conceptual illustrations in Tibbals (1990), and upon the overall conceptualization of the groundwater flow system. Unlike the Upper Floridan, the groundwater flow system in the Lower Floridan is rather sluggish. It is not believed that, in the vicinity of the eastern boundary, the flow of freshwater (low chloride water) in the Lower Floridan has significantly altered the dissolved solids composition of the relict seawater. At the Lower Floridan eastern boundary nodes, therefore, a normalized concentration of 1.0 was prescribed with a corresponding linear varying reference head (Figure 4.3).

Since the freshwater/saltwater interface lies within the middle semiconfining unit, reference heads based upon an average concentration of 9,500 mg/l and a thickness of 640 ft were prescribed for this unit (Figure 4.3). Concentrations were not prescribed within this unit for two reasons. First, the vertical distribution of chlorides within this unit is unknown, and it was not believed that a highly accurate extrapolation of chloride concentrations from the Merritt Island test well could be made. Secondly, since the vertical variation of chlorides is not known within the middle semiconfining unit, rather than prescribe some concentration values that may be in error, it is better to let the model simulate the concentrations as they would appear given the overall modeling framework.

Note that along the eastern boundary (Figure 4.3), the reference heads prescribed are hydrostatic; that is, they vary linearly with depth due only to the chloride concentrations believed to be present in the aquifer. It is possible that this approach neglects components of vertical flow that may be present, for example, between the Upper and Lower Floridan. Such would be the case if the eastern boundary of the cross section lies in a major discharge area for the entire Floridan aquifer system. This possibility is investigated in one of the sensitivity runs presented in Chapter 5.

4.7 Calibration Procedure

Due to the very limited amount of data available pertaining to the predevelopment state of the Floridan aquifer system, a rigorous calibration of the steady-state, predevelopment cross-sectional flow and transport model could not be conducted. However, the model may be considered semi-calibrated, since the input parameters were adjusted until a reasonable match was obtained between observed and model calculated hydraulic heads in the Upper Floridan, and observed and model calculated chloride concentrations in the Upper Floridan and portions of the Lower Floridan. Also, considering the fundamental constraints of modeling in two-dimensional vertical sections, as well as the major Phase II modeling objective of identifying the important physical characteristics of the system, it would not be a wise utilization of time or resources to seek a highly accurate calibration.

The sequence of steps involved in the model calibration are as follows:

- The initial aquifer parameters and boundary conditions were derived from available hydrogeological information (Section 4.6) or from the Phase I regional model.

- A series of DSTRAM runs were conducted to evaluate the effects of varying different physical parameters or boundary conditions.

- The input parameters to the computer model were adjusted until a reasonable match between observed and model calculated values was obtained (Section 4.8). At this point, DSTRAM was run in steady-state mode. Some of the solutions did not fully converge, but the reference head and chloride concentration distributions were plotted and used as a general guide to move ahead.

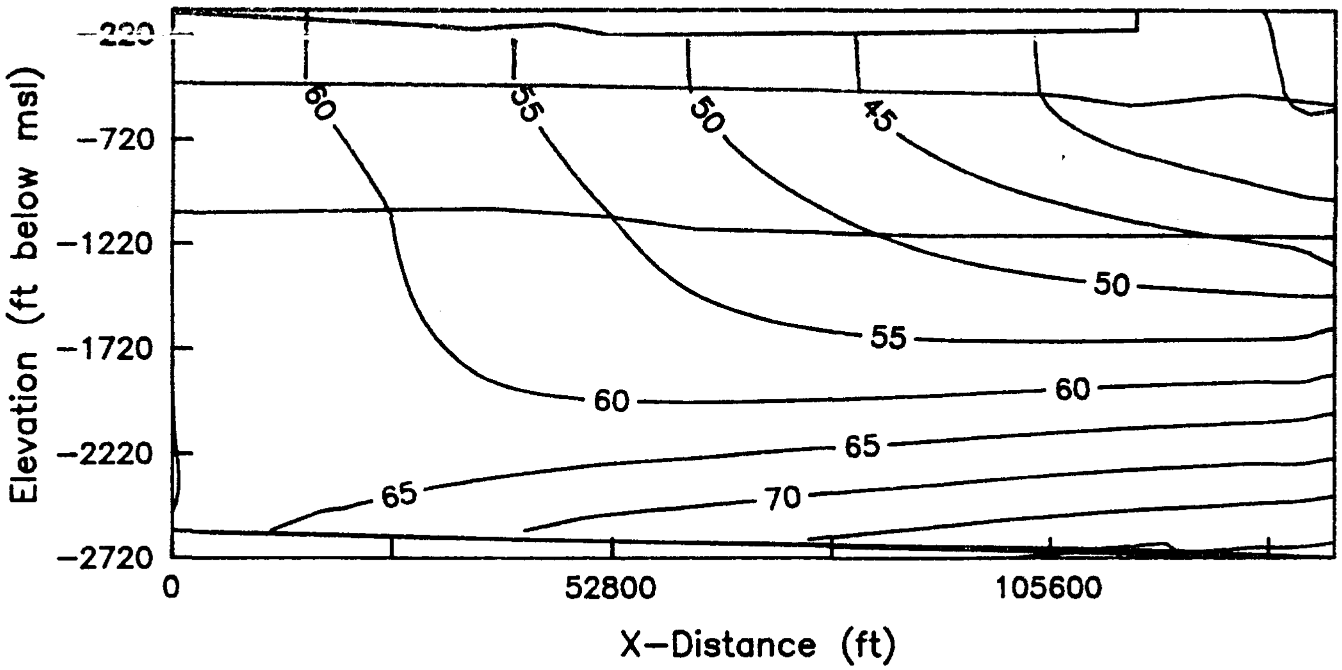
- The best non-converged steady-state solution was used as an initial condition for a transient (time-marching) solution, and DSTRAM was run in transient mode until the calibrated, or "base case", solution presented in Section 4.8 was obtained. A convergence tolerance of 0.01 was used for reference heads and normalized concentrations.

4.8 Cross-Sectional Modeling Results

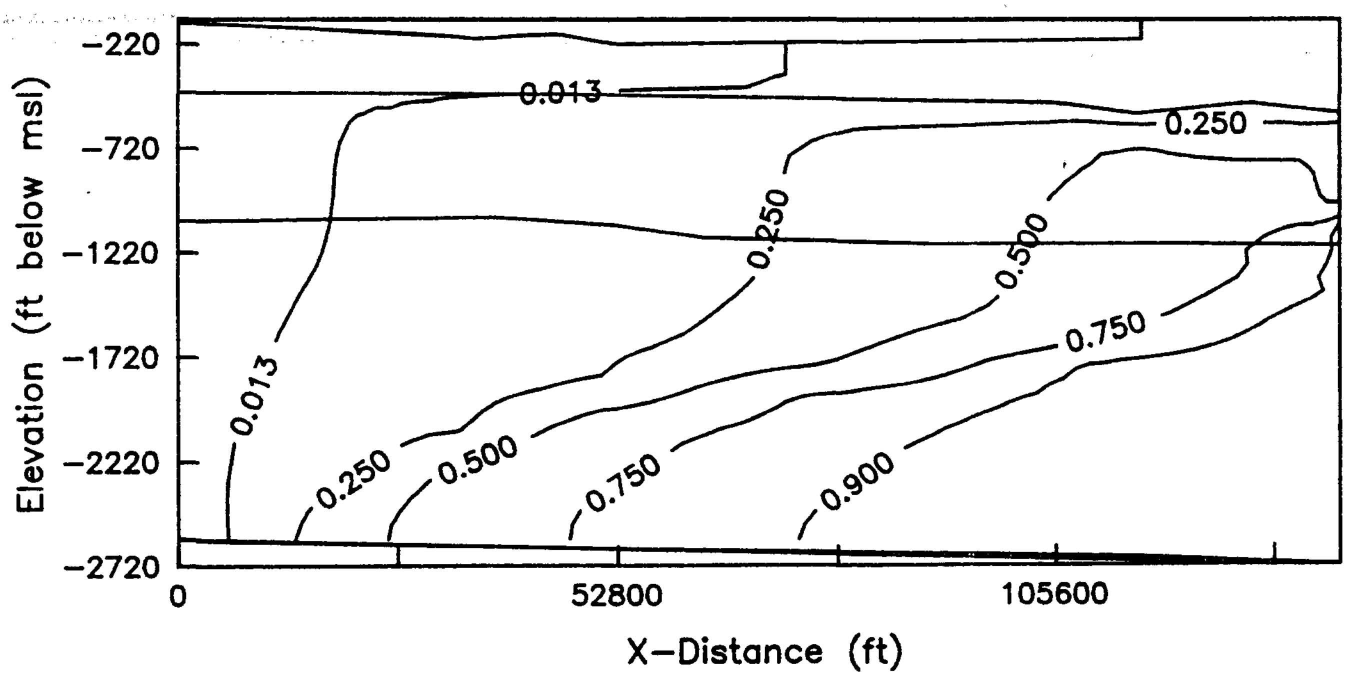
The calibrated model results are presented in Figures 4.4 and 4.5 in terms of the reference head, the velocity field and the distribution of chlorides (in terms of normalized concentration) throughout the domain. The reference head and the chloride concentration were the two main variables compared to observed data during the calibration. The reference head in the Upper Floridan at the west end of the section is about 64 ft, which is six feet higher than indicated on the predevelopment potentiometric surface map (Figure 3.3). This is the greatest known discrepancy between observed and model calculated reference heads in the model domain and, given the simplifications required to model in two-dimensions as well as the inherent uncertainty imbedded within the predevelopment potentiometric surface map, this degree of error is acceptable.

Figure 4.4 indicates that there is an upward vertical hydraulic gradient between the Upper and Lower Floridan across the middle semiconfining unit along the entire cross section. The gradient is relatively small at the west end of the section, and it increases until it becomes relatively large at the east end of the section. For predevelopment conditions, there is no data to substantiate, or invalidate, this modeling result. The east end of the cross section was modeled by Tibbals (1990 and 1981) as a discharge area for the Upper Floridan in postdevelopment and predevelopment conditions. Prior to the cross-sectional model calibration, groundwater flow near the west end of the section was believed to be essentially horizontal (little groundwater flux between the Upper and Lower Floridan).

The simulated chloride concentrations also match well with what is known of the predevelopment chloride levels. Chloride concentrations in the vicinity of the ERWF, in both the Upper and Lower Floridan, are close to zero. In the Lower Floridan in the vicinity of Zone 1 of the Cocoa C salinity monitoring well, chloride concentrations are about 1,300 mg/l, which is slightly higher than the 750 mg/l observed when sampling was initiated in 1967 (Fayard, 1989). Finally, the 250 mg/l contour (normalized concentration 0.0132 line) lies near the bottom of the Upper Floridan in the vicinity of the east Cocoa well field. Since



(a)



(b)

Figure 4.4 Reference head (a) and normalized concentration profile (b) for the calibrated cross-sectional model.

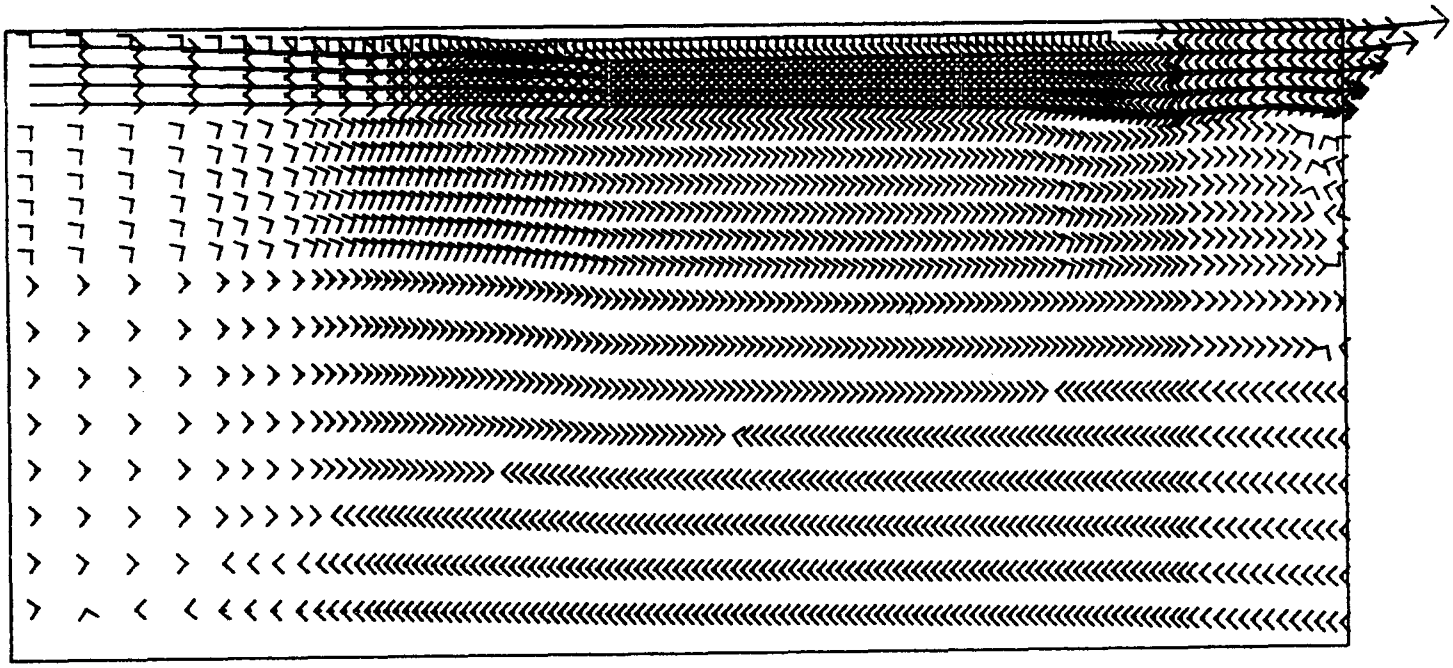


Figure 4.5 Velocity vector plot for the calibrated cross-sectional model.

several wells in the east well field produced water with chloride concentrations greater than 250 mg/l shortly after they were put into production, it is obvious that this contour must lie close to these wells.

The one piece of data that the model results do not match very well are the observed chloride concentrations at Zones 3 and 4 of the Cocoa C well. The initial observed chloride concentrations of 80 mg/l and 40 mg/l for Zones 3 and 4 of the Cocoa C well, respectively, have remained essentially steady through time (Fayard, 1989). The model results, however, indicate chloride concentrations of about 1,200 - 1,300 mg/l within these zones. The clear drop in chloride concentration values between Zone 1 of the Cocoa C well and Zones 3 and 4 was not replicated by the simulation results. The reason for this is unknown, and, due to the high degree of uncertainty concerning the physical parameters in the model domain, it was deemed an inefficient use of resources to try to obtain a more detailed calibration in this region.

Figure 4.5 is a velocity vector plot (velocities were calculated at element centroids) of the calibrated vertical cross-sectional modeling results. 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 groundwater flow, and the length of the tail of each arrow represents the relative magnitude of the velocities (longer tails indicate higher velocities). Groundwater flow velocities are much higher in the Upper Floridan than in the Lower Floridan. The position of the interface between dense, landward moving water and less dense, seaward moving water is delineated in the Lower Floridan by connecting the points at which groundwater flow converges (two velocity vectors point toward one another).

Figure 4.6 illustrates the cross-sectional model calibrated aquifer parameters. As explained in Section 4.7, where possible, the initial aquifer parameters were taken from the Phase I regional model (Blandford et al., 1991). Some of these initial parameters are marked in brackets in Figure 4.6. Although a number of the physical parameters were adjusted during the calibration process, there were two main ones that had to be changed significantly to

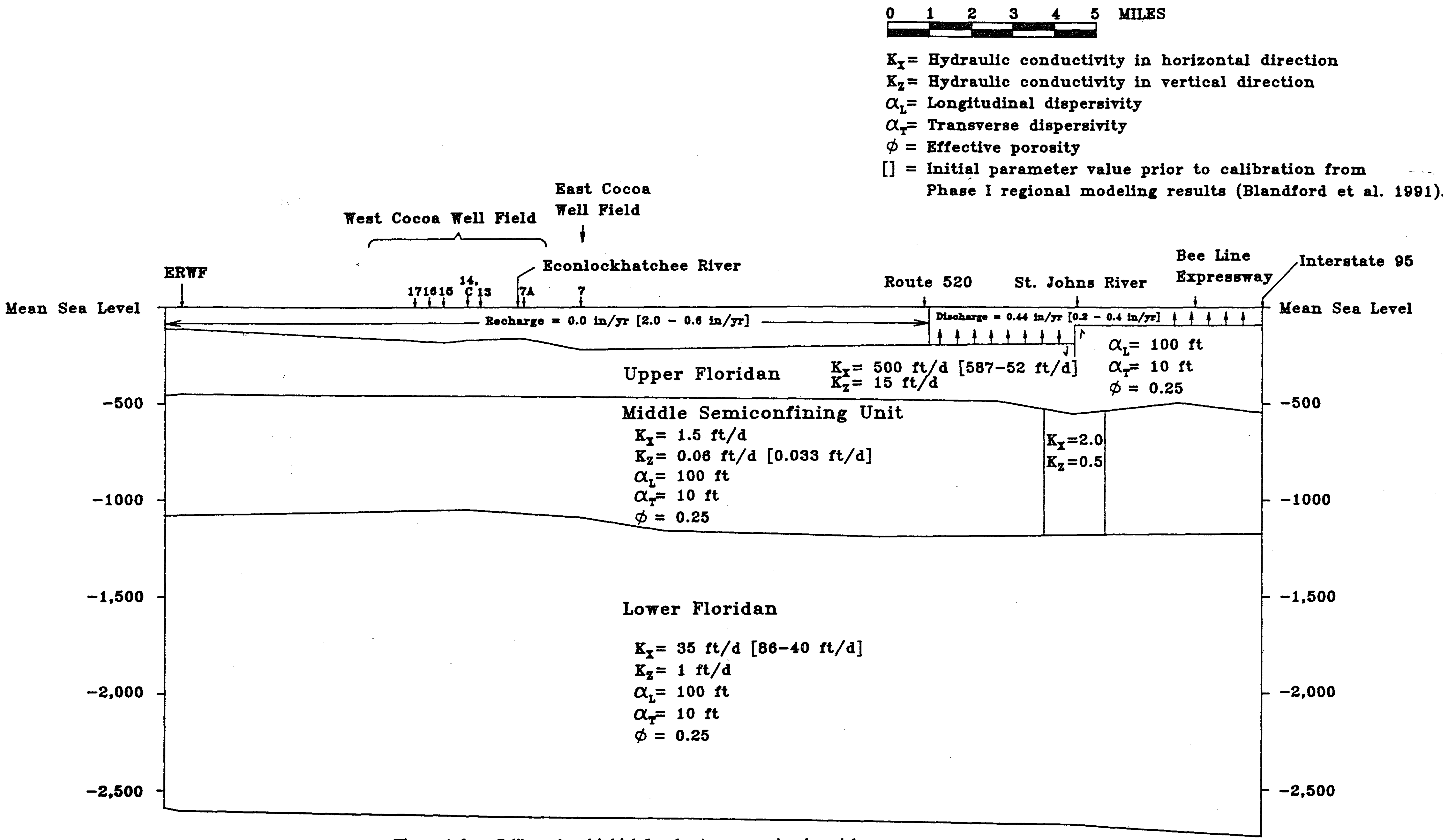


Figure 4.6 Calibrated and initial (brackets) cross-sectional model parameters.

obtain a reasonable calibration; they are prescribed recharge to the top of the Upper Floridan, and the lateral hydraulic conductivity of the Upper Floridan (K_x).

In the Phase I model, recharge applied to the top of the Upper Floridan along the cross section varied from 2.0 to 0.5 in/yr. In the cross-sectional model, this recharge was omitted completely (set to 0.0) due to the following reasons. First, the region of the cross section that had recharge omitted is described as a poor recharge area by Phelps (1989) and Tibbals (1990). Secondly, the Phase I model results, as well as the recharge/discharge maps in Tibbals (1990) and Phelps (1989), are representative of postdevelopment conditions. However, there has been significant drawdown of the potentiometric surface from predevelopment conditions in the vicinity of the Cocoa well field. If, after a substantial increase in the head difference between the Upper Floridan and the surficial aquifer, the recharge rates are still relatively small, then it is not unreasonable to assume that they would have been negligible during predevelopment conditions. A justification for an increase in the Phase I model areal discharge rates can also be made using the same line of reasoning.

When the Phase I model transmissivities along the cross section were divided by the aquifer thicknesses developed during this study (Figure 3.4), the resulting hydraulic conductivity values for the Upper Floridan ranged from 52 ft/d to 587 ft/d, with the lowest values located east of the St. Johns River. During the calibration process, it was observed that when low hydraulic conductivity values were placed at any location within the Upper Floridan, unreasonably high hydraulic gradients were obtained. This result is consistent with the two-dimensional modeling approach, since the majority of the water that moves through the Upper Floridan must, at some point, move through the zone of lowest conductivity. The hydraulic gradients in the Upper Floridan, therefore, must be large enough to pass water through the zone of lowest conductivity. In order to calibrate the cross sectional model, K_x in the Upper Floridan was increased to a uniform value of 500 ft/d. Due to the limiting two-dimensional flow assumption described above, this value could be high for certain regions of the cross section. This value should be considered as an "equivalent" or "averaged" aquifer parameter, the value of which is constrained by the two-dimensional modeling approach as well as the behavior of the physical system.

The aquifer parameters listed in Figure 4.6 that could not be obtained from the Phase I model are the vertical hydraulic conductivity of each unit (K_z), the longitudinal dispersivity (α_L), the transverse dispersivity (α_T), and the porosity (ϕ). The longitudinal dispersivity is 100 ft throughout the model domain. 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, an α_L of 100 feet is not unreasonable for regional scale modeling. A constant α_T of 10 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). In this study, α_T was assumed to be 1/10th of α_L. A porosity of twenty-five per cent was used throughout the domain after Tibbals (1990). The K_z values for each unit were selected based upon the K_x values determined from the regional model and through calibration. Anisotropy ratios (K_x/K_z) of about 1:30 were maintained throughout the domain. Since the true anisotropy ratio within each layer is unknown, the effect of the anisotropy ratio on the simulation results was investigated through sensitivity analysis (Chapter 5). However, in aquifers composed of layered sediments, anisotropy ratios of 1:100 are not uncommon. Anisotropy ratios somewhat less than this value are expected in the Floridan aquifer system due to good vertical connections in the carbonate rocks.

The calibrated cross sectional modeling results, although somewhat limited due to a lack of observed data and the two-dimensional modeling assumptions, represent a reasonable conceptualization of the predevelopment groundwater flow system in the vicinity of the cross section. These results are adequate to form a basis for the most important Phase II modeling objective, which is sensitivity analysis.

5 SENSITIVITY ANALYSIS

5.1 Introduction

A series of 20 sensitivity runs were conducted to determine how sensitive the model results are to variations in the calibrated model parameters. Table 5.1 presents a summary of the parameters varied in each sensitivity run, and the magnitude of the resulting change in the reference head and normalized concentration distributions. The degree of change listed in Table 5.1 is based on a qualitative scale. The spatial plots of reference head and normalized concentration for each sensitivity run were overlaid on the calibrated (or "base case") model results, and the degree of difference between the two plots was noted. If the contours nearly overlay each other, a mark of no change is recorded. If the largest deviation throughout the domain between contours is no more than about 1,000 - 2,000 ft in the x-direction, and about 100 - 200 ft in the z (vertical) direction, the change is reported as moderate. Changes greater than those reported above are reported as significant. In the remaining sections of this chapter, sensitivity plots are only provided for the runs that had a significant change in concentration or reference head distributions.

Each sensitivity run was conducted as a 10,000 year transient simulation, using the steady-state reference head and normalized concentration distributions of the calibrated model as initial conditions. The prescribed tolerance for the convergence of both heads and concentrations is 0.01. The assumption was made that, after a period of 10,000 years, the new model solution would be at steady state. This is a very good assumption for the reference head fields, and, for the sensitivity runs that showed little or no change in concentration fields, it is also a very good assumption. It is possible that, for some of the sensitivity runs that had a dramatic change in the concentration distributions, the concentration distribution at the end of 10,000 years may not be at a true steady state. However, if such is the case, the concentration distributions should be relatively close to their true steady-state locations, and the general model behavior in response to changing a

Table 5.1 Sensitivity of the calibrated model results to changes in selected physical parameters categorized qualitatively as little, moderate or significant change.

Sensitivity Run No.	Description of Adjusted Parameter(s)	Sensitivity					
		Little		Moderate		Significant	
		Heads	Conc.	Heads	Conc.	Heads	Conc.
1*	LF, ↓ K_x from 35 to 20 ft/d, ↓ K_z from 1 to 0.57 ft/d			x	x		
2*	LF, ↑ K_x from 35 to 70 ft/d, ↑ K_z from 1 to 2 ft/d			x			x
3	LF, ↓ K_z from 1 to 0.35 ft/d			x	x		
4	LF, ↑ K_z from 1 to 3.5 ft/d			x	x		
5	MSC1, ↑ K_z from 0.06 to 0.6 ft/d					x	x
6	MSC1, ↓ K_z from 0.06 to 0.006 ft/d					x	x
7	MSC2, ↑ K_z from 0.5 to 5.0 ft/d	x	x				
8	MSC1, MSC2, uniform K_z of 0.06 ft/d	x	x				
9*	UF, ↑ K_x from 500 to 700 ft/d, ↑ K_z from 15 to 21 ft/d					x	x
10*	UF, ↓ K_x from 500 to 300 ft/d, ↓ K_z from 15 to 9 ft/d					x	x
11	UF, ↓ K_z from 15 to 5 ft/d	x	x				
12	UF, ↑ K_z from 15 to 25 ft/d	x	x				
13	WB, ↑ UF lateral influx from 5.9 to 6.5 ft/d			x	x		
14	WB, ↓ UF lateral influx from 5.9 to 5.0 ft/d					x	x
15	WB, ↑ LF lateral influx from 1.1 to 2.0 ft/d					x	x
16	WB, ↓ LF lateral influx from 1.1 to 0.7 ft/d					x	x
17	UF, ↑ areal discharge from 0.44 to 0.88 inches/yr					x	x
18	UF, ↓ areal discharge from 0.44 inches/yr to zero	x	x				
19	UF, added areal recharge of 0.5 inches/yr					x	x
20	EB, ↑ reference head to force vertical flow					x	x

UF = Upper Floridan
LF = Lower Floridan
WB = Western Boundary
EB = Eastern Boundary
↑ = increase
↓ = decrease
MSC1 = Middle semiconfining unit not under St. Johns River
MSC2 = Middle semiconfining unit immediately under St. Johns River

* Original anisotropy ratio maintained.

given parameter is clearly evident.

For each sensitivity run,the magnitude of the change of the given physical input parameter was based upon what was felt to be reasonable for the physical system. In some cases, changes of given parameters were opposite but not equal. For example, in the set of sensitivity runs that examined the effect of the lateral freshwater influx into the Lower Floridan at the west end of the cross section, the influx was increased from the calibrated value (run 15) by 0.9 ft/d, but it was decreased by 0.4 ft/d (run 16).

Some useful generalizations may be made based upon Table 5.1. The groundwater flow system within the vertical cross section is very sensitive to the horizontal hydraulic conductivity in the Upper Floridan, but it is only moderately sensitive to that in the Lower Floridan. The vertical hydraulic conductivity in the Upper Floridan, however, is not a critical parameter. The model results are also highly sensitive to the specified lateral influx of water to each aquifer at the west boundary of the cross section, as well as to any recharge specified along the west and central portions of the section. Also, the model results are sensitive to large variations in the vertical hydraulic conductivities used for the middle semiconfining unit (order of magnitude changes), but they are relatively insensitive to small ones (factor of 2 variations).

Table 5.1 will be used as a guide to calibration during Phase III (the final phase) of this study. As a first-cut analysis, the physical parameters that induced significant changes in the cross-sectional model output will be key calibration parameters in the three-dimensional modeling effort.

5.2 Lower Floridan Hydraulic Conductivity

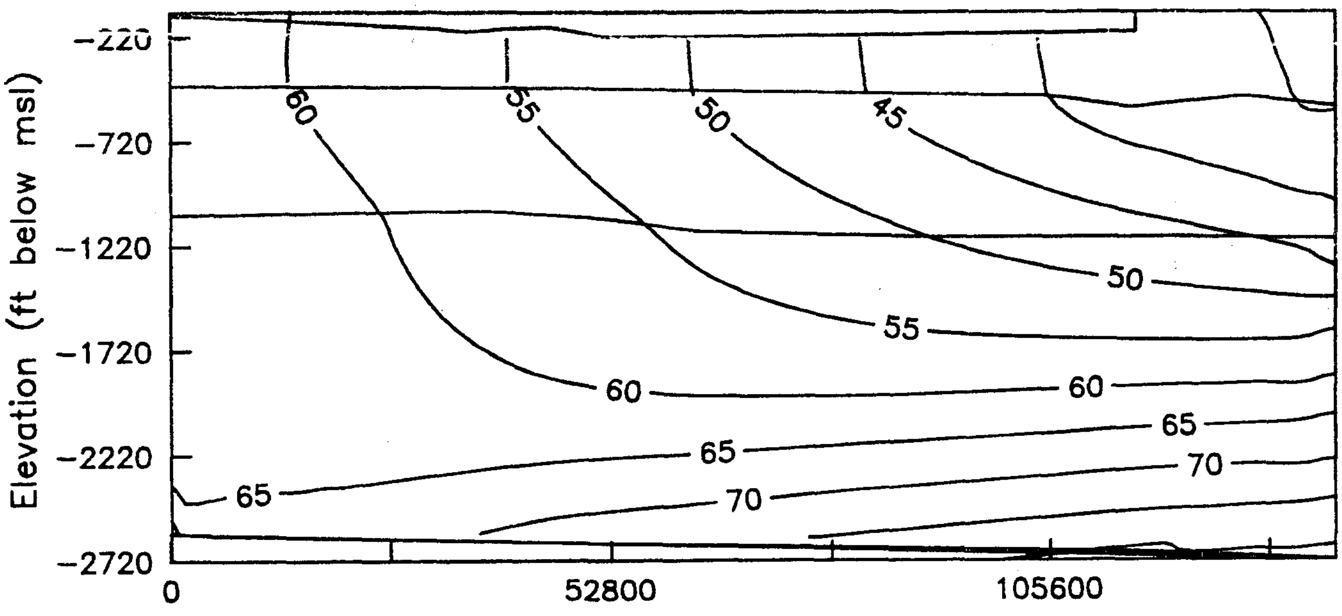
In general, the cross-sectional model results are only moderately sensitive to hydraulic conductivity in the Lower Floridan. This is true even though the bulk of the mass of the total dissolved solids in the system exists in the Lower Floridan. This behavior is due to the "sluggish" nature of flow in the Lower Floridan, as compared to that in the Upper Floridan (Figure 4.5).

Decreasing the horizontal hydraulic conductivity (K_x) in this unit (but maintaining the anisotropy ratio) creates higher hydraulic head gradients across the domain, and the saltwater wedge is consequently moved towards the east. Increasing K_x has the opposite effect of decreasing the hydraulic head gradients, and therefore the lens moves farther towards the western boundary (Figure 5.1). The 250 ppm line comes extremely close to the western boundary where concentrations are set to zero; in this case the boundary condition artificially restrains the movement of chlorides. This constraint of the model is not a significant limitation, however, since the primary objective of the sensitivity analysis is to observe the general trend and magnitude changes in model results, rather than to precisely identify the extent of such changes.

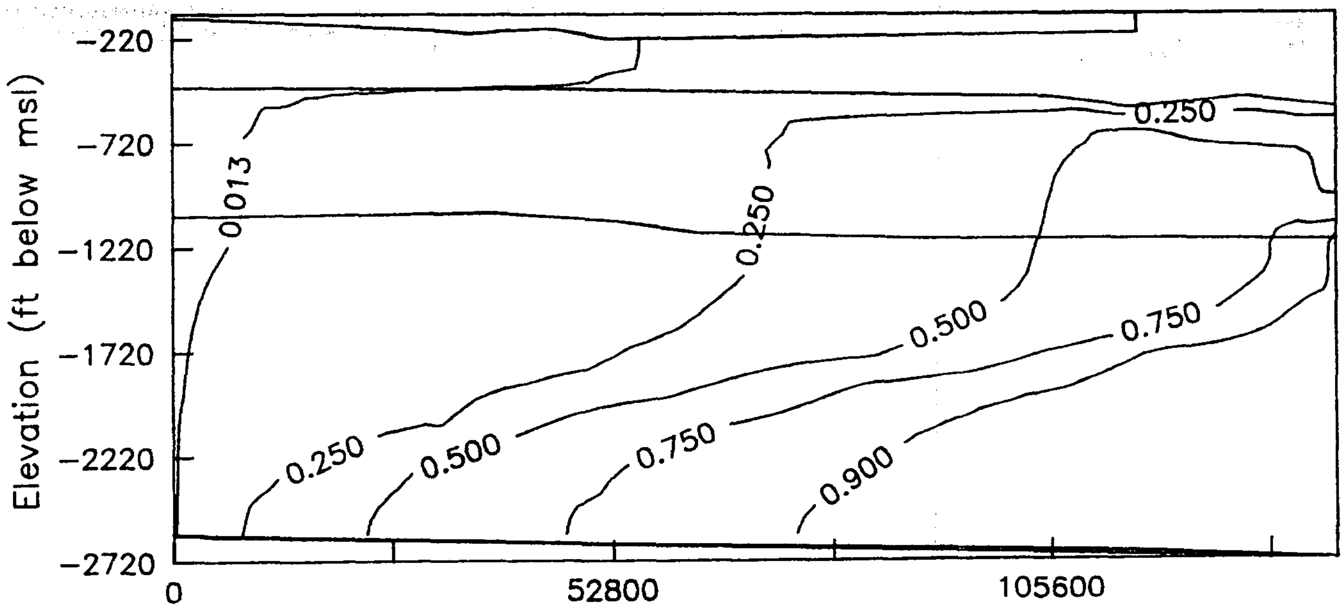
Changing the vertical hydraulic conductivity (K_z) in the Lower Floridan also moderately affected the reference head and chloride distributions. Decreasing K_z forced the chlorides to move more laterally than vertically, and consequently the isochlors moved slightly towards the west. Increasing K_z allowed the chlorides to move more vertically than before, and the isochlors shifted slightly to the east.

5.3 Middle Semiconfining Unit Hydraulic Conductivity

The calibrated model results are quite sensitive to an order of magnitude increase and decrease in the vertical hydraulic conductivity (K_z) of the middle semiconfining unit. Four sensitivity runs were conducted to investigate the effect of this parameter. In runs 5 and 6, K_z was increased to 0.6 ft/d and decreased to 0.006 ft/d, respectively, from the initial value of 0.06 ft/d. In these runs, K_z under the St. Johns River was not changed (Figure 4.6). Increasing K_z in this unit has only a moderate effect on the reference head field, but the isochlors move a significant distance westward (Figure 5.2). Large vertical gradients across this unit are created when K_z is decreased by an order of magnitude, and the isochlors move to the east (Figure 5.3). This behavior is probably due to the fact that more of the lateral influx into the Lower Floridan at the western boundary must initially move through this aquifer unit, rather than move upward through the middle semiconfining unit. It should also be noted that in an initial set of sensitivity runs that are

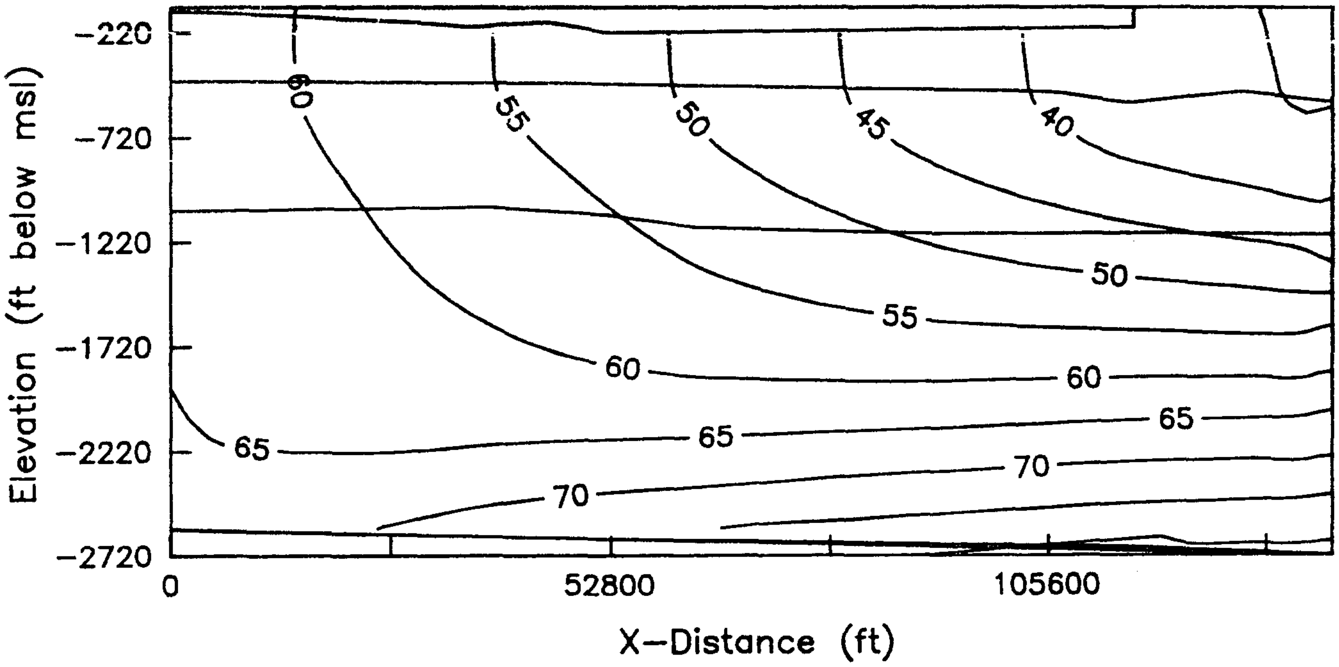


(a)

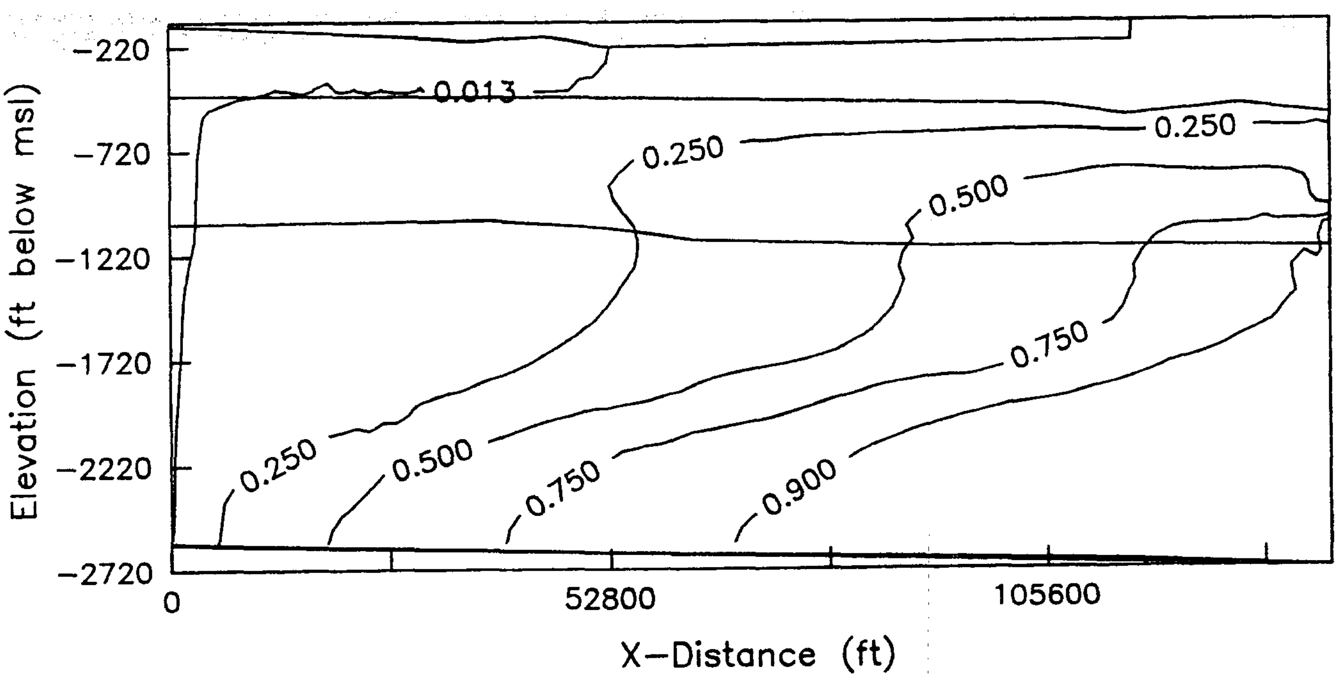


(b)

Figure 5.1 Reference head (a) and normalized concentration (b) distributions for sensitivity run 2; K_x in Lower Floridan increased from 35 to 70 ft/d.

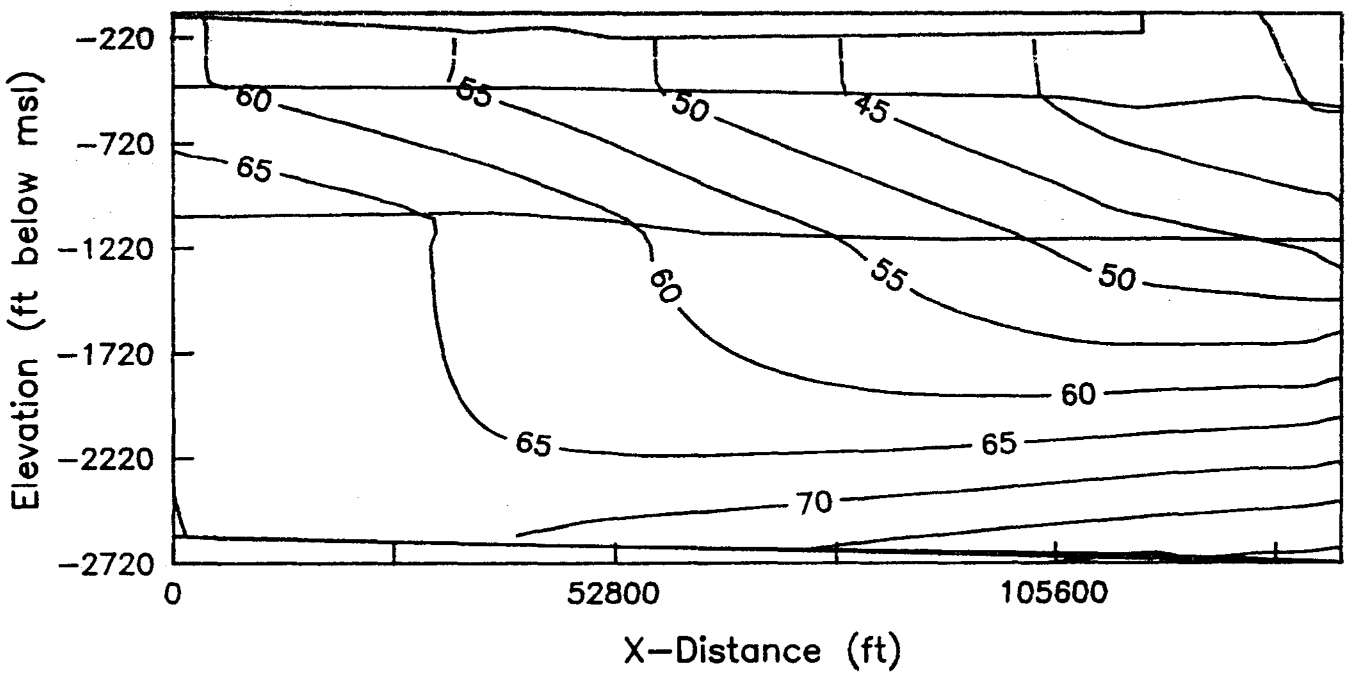


(a)

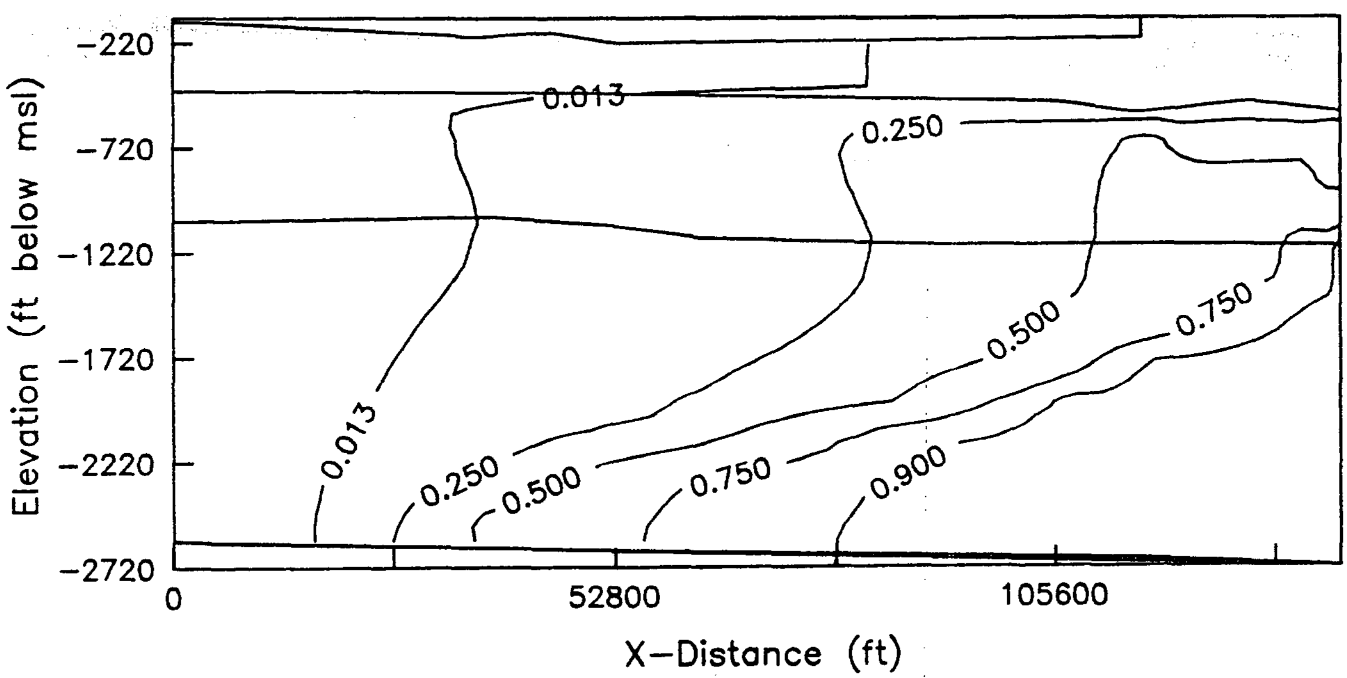


(b)

Figure 5.2 Reference head (a) and normalized concentration (b) distributions for sensitivity run 5; K_z of middle semiconfining unit increased from 0.06 to 0.60 ft/d.



(a)



(b)

Figure 5.3 Reference head (a) and normalized concentration (b) distributions for sensitivity run 6; K_z of middle semiconfining unit decreased from 0.06 to 0.006 ft/d.

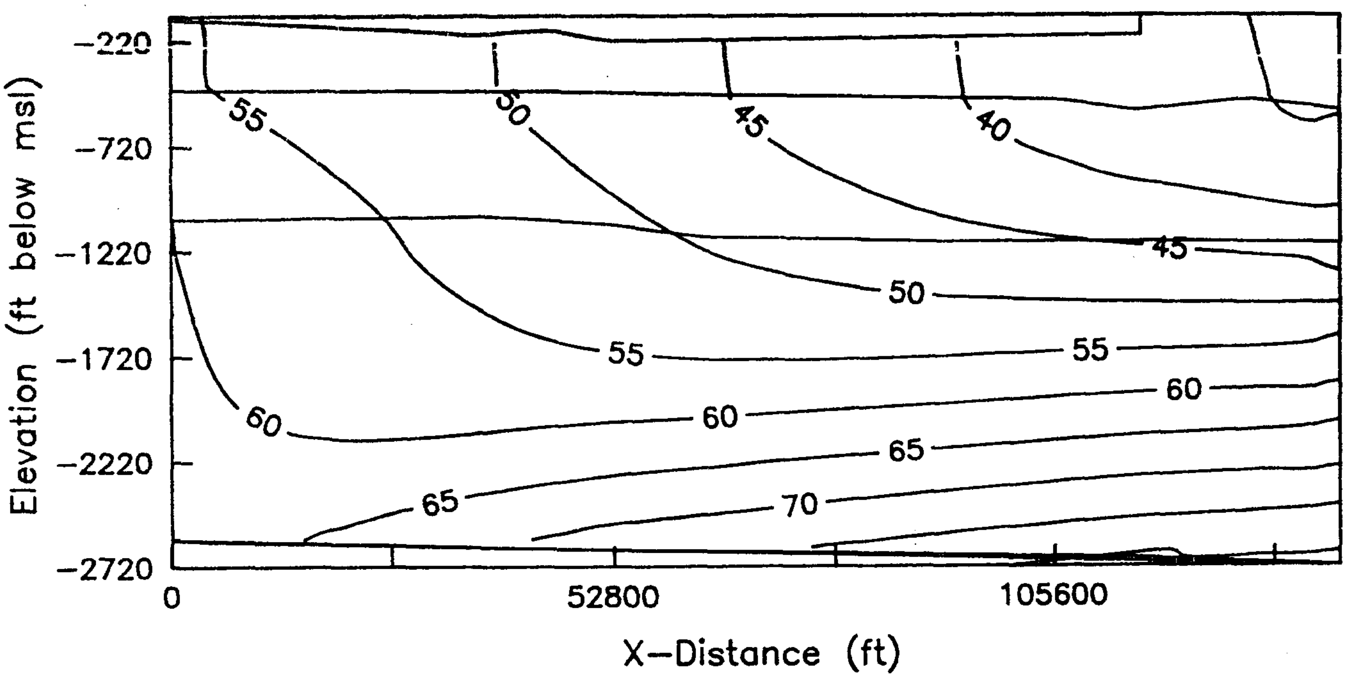
not presented, K_z of the middle semiconfining unit was doubled and reduced by fifty percent, rather than by an order of magnitude. The results of that set of runs were very nearly identical to the calibrated model results, which indicates that the calibrated model results are only sensitive to relatively large changes in this parameter.

Sensitivity runs 7 and 8 investigated the effects of the zone of increased K_z under the St. Johns River (Figure 4.6). In run 7, K_z in this zone was increased from 0.5 to 5 ft/d. In run 8, K_z in this zone was set equal to the K_z throughout the remainder of the middle semiconfining unit (0.06 ft/d). The differences between the results of these runs and the calibrated model results were insignificant. The cross sectional model does not seem to be at all sensitive to the presence of a high conductivity zone in the middle semiconfining unit underlying the St. Johns River.

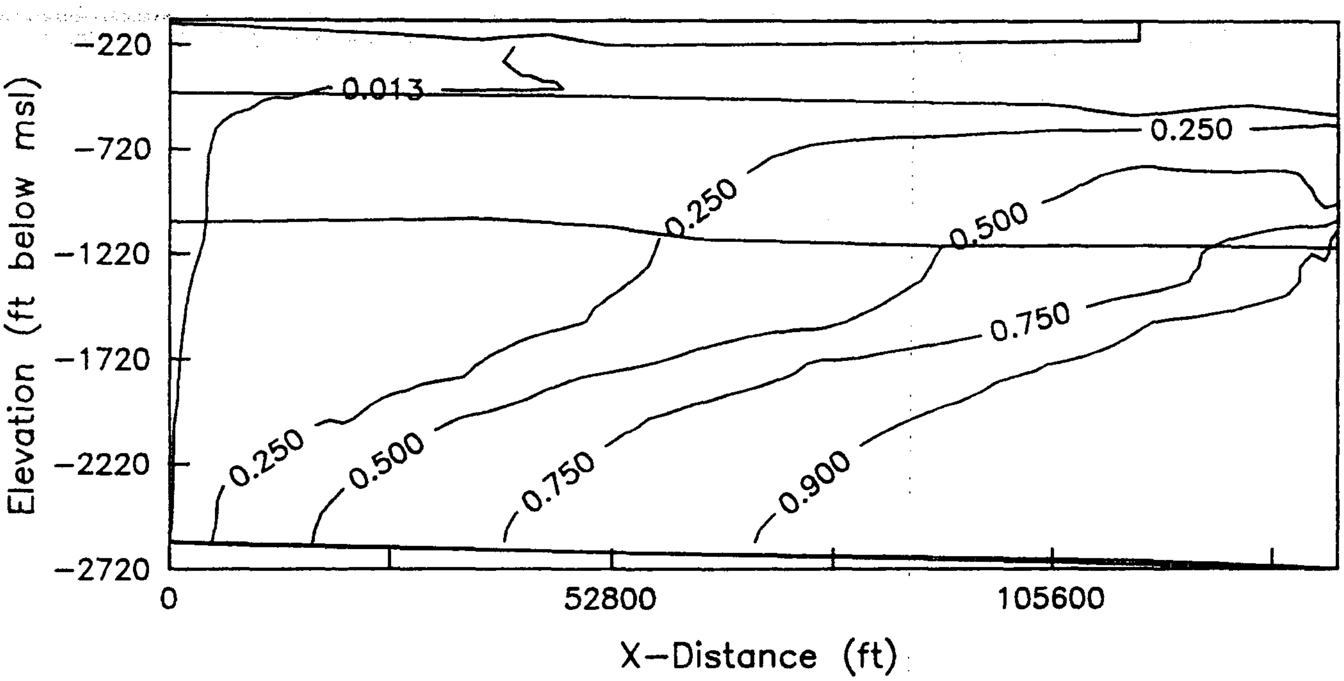
5.4 Upper Floridan Hydraulic Conductivity

The horizontal hydraulic conductivity (K_x) of the Upper Floridan has a very pronounced effect upon hydraulic heads and chloride distributions throughout the entire groundwater system, while the vertical hydraulic conductivity (K_z) of this unit has a negligible effect upon the same variables. Figure 5.4 illustrates the cross-sectional model results obtained when K_x in the Upper Floridan was increased from 500 to 700 ft/d, and Figure 5.5 illustrates the results obtained when K_x was reduced to 300 ft/d. Increasing K_x in the Upper Floridan dramatically decreases the hydraulic head gradient across the entire system, and consequently the chlorides migrate across the entire domain. Vertical hydraulic gradients between the Upper and Lower Floridan were also significantly increased. Decreasing K_x in the Upper Floridan has the opposite effect of dramatically increasing hydraulic gradients across the cross section, and the chloride isochlors are moved significantly to the east. Vertical hydraulic gradients in the western one-third of the cross section are also substantially reduced. These results indicate that, to a large extent, the nature of the groundwater flow system in the Upper Floridan dictates the overall pattern of flow in the entire Floridan aquifer.

The calibrated model results are virtually insensitive to the K_z value used for the Upper Floridan. This is so for two reasons. First, groundwater flow in the Upper Floridan is primarily horizontal,

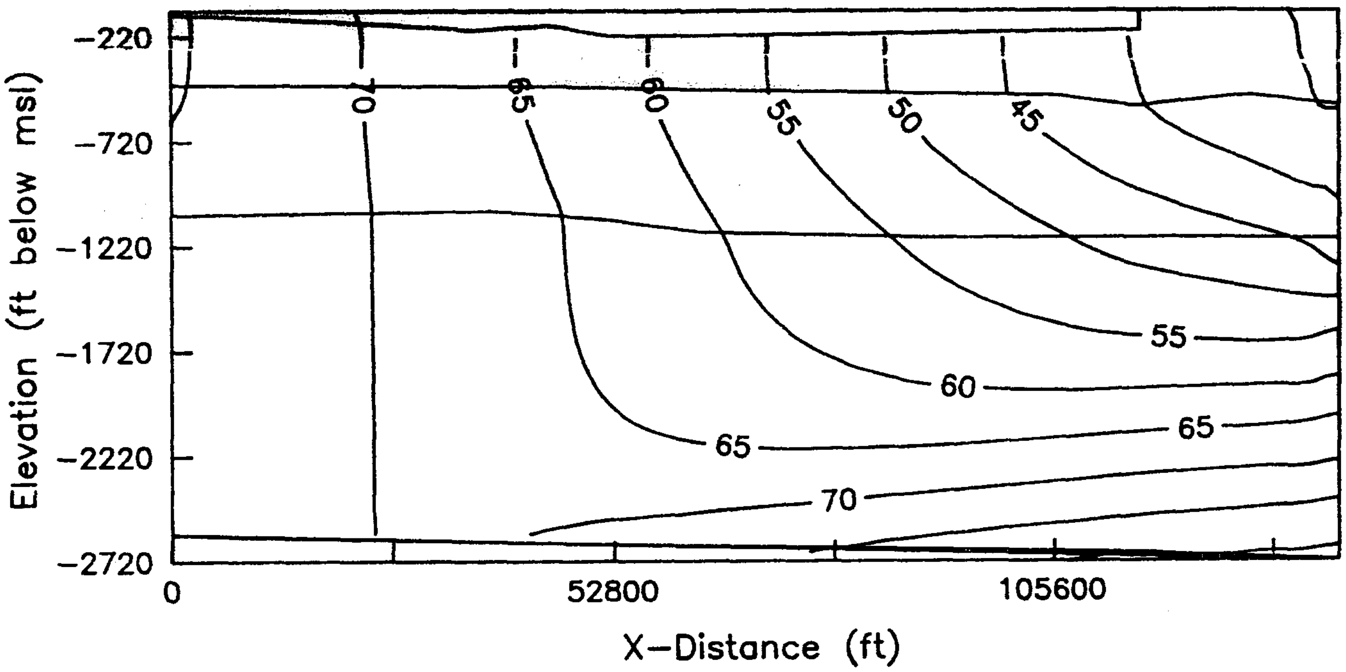


(a)

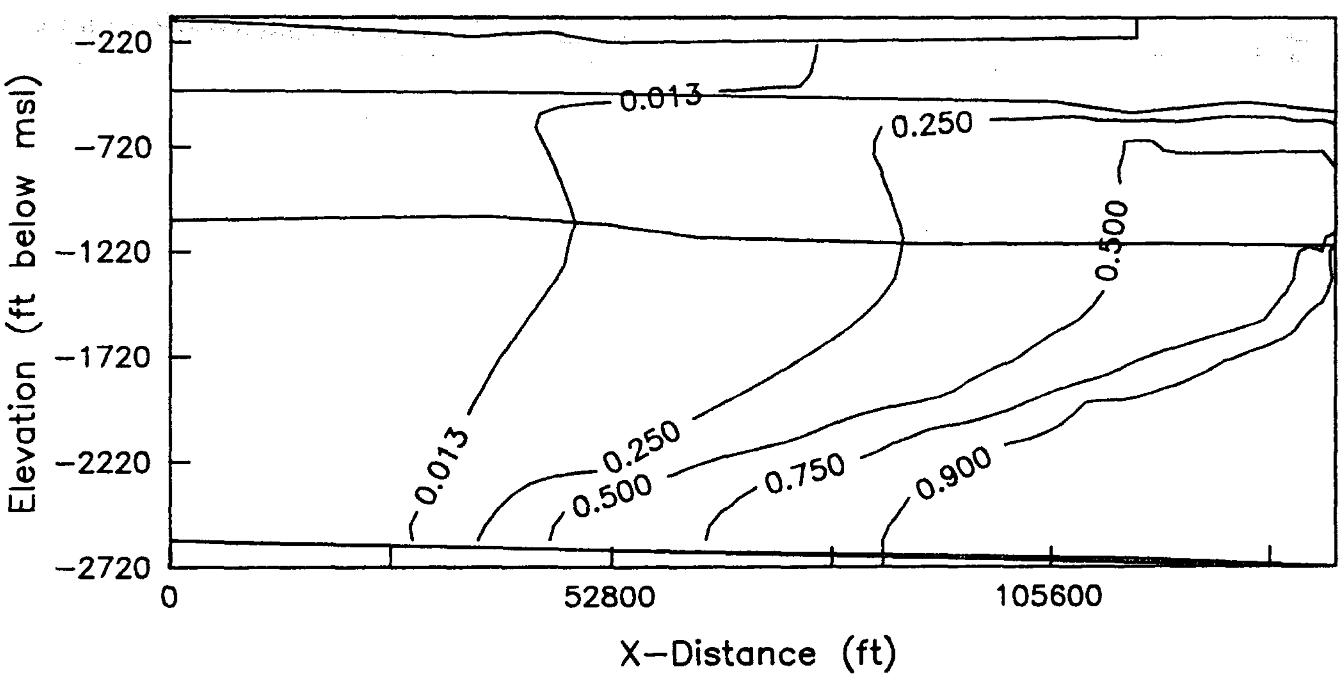


(b)

Figure 5.4 Reference head (a) and normalized concentration (b) distributions for sensitivity run 9; K_x in the Upper Floridan increased from 500 to 700 ft/d.



(a)



(b)

Figure 5.5 Reference head (a) and normalized concentration (b) distributions for sensitivity run 10; K_x in Upper Floridan decreased from 500 to 300 ft/d.

and therefore does not depend upon the vertical component of hydraulic conductivity. Secondly, the largest chloride concentrations exist in the Lower Floridan, and the chloride concentrations in the Upper Floridan are relatively small. Therefore, either the vertical enhancement or retardation of the migration of chlorides in the Upper Floridan will not significantly effect the density-dependent groundwater flow field or the concentration profile.

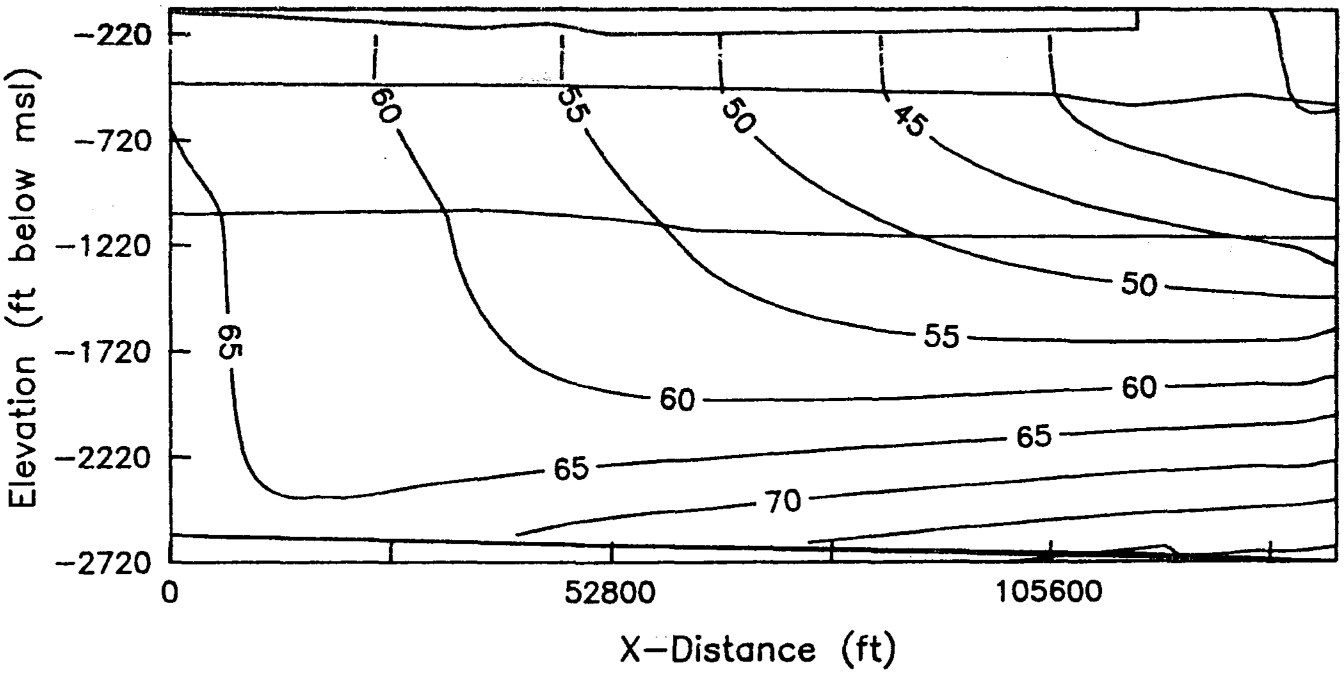
5.5 Western Boundary Lateral Influx

The effects of increasing or decreasing the lateral influx to the Upper and Lower Floridan along the western boundary are analogous to the effects of varying hydraulic conductivity (horizontal) within these units. Increasing the lateral influx causes larger hydraulic head gradients within the model domain to move the additional influx of water (since hydraulic conductivity was not altered), and the increased flux of water and higher flow velocities move the isochlors eastward. Decreasing the lateral influx has the opposite effect of creating smaller hydraulic gradients, and the chlorides consequently migrate farther to the west.

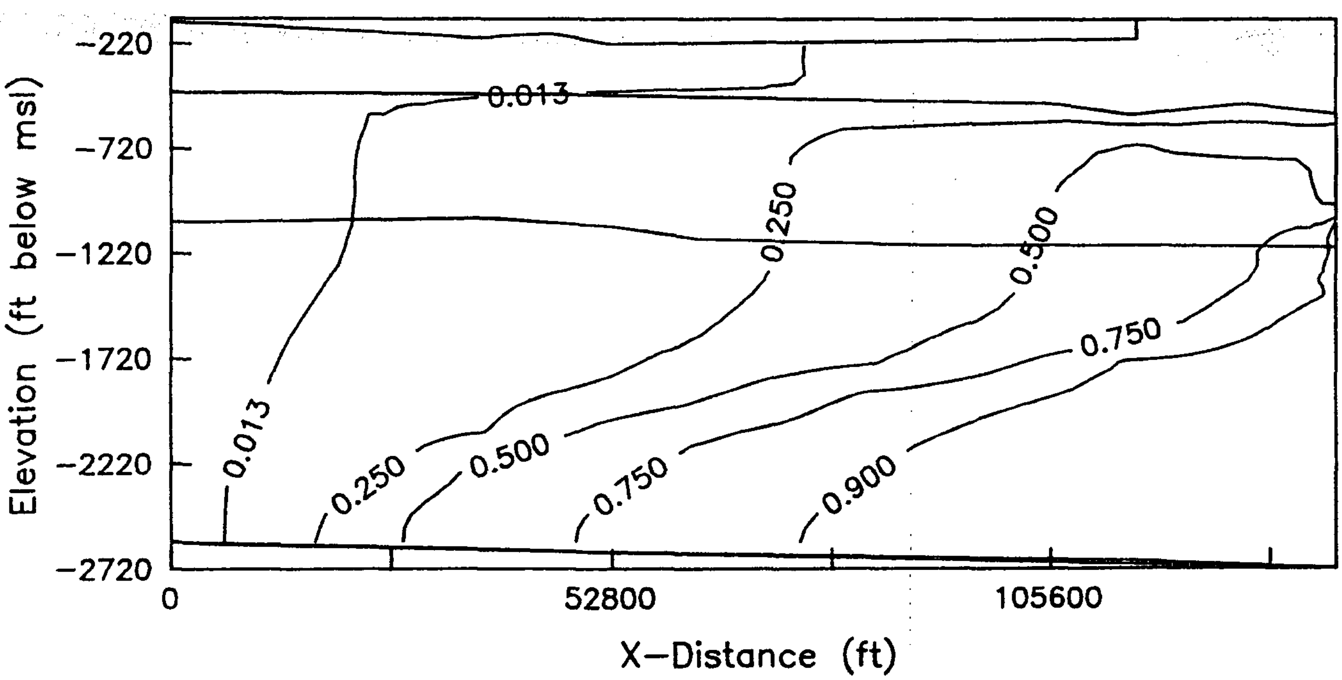
The isochlors only showed a moderate change when lateral influx to the Upper Floridan was increased (Figure 5.6), but they changed significantly when lateral influx to the Upper Floridan was decreased (Figure 5.7), when lateral influx to the Lower Floridan was increased (Figure 5.8), and when lateral influx to the Lower Floridan was decreased (Figure 5.9). As in the hydraulic conductivity sensitivity analysis, the westward movement of the chloride isochlors was probably impeded by the western zero concentration boundary (Figures 5.7 and 5.9). Increasing or decreasing the lateral influx in the Lower Floridan has a greater impact on the isochlor locations than changing the influx in the Upper Floridan.

5.6 Areal Recharge and Discharge

Three sensitivity runs were conducted in which areal recharge to, or from, the top of the Upper Floridan was varied. The regions of recharge to, and discharge from, the top of the Upper Floridan are delineated in Figure 4.6. The cross-sectional modeling results are sensitive to increases in prescribed discharge (Figure 5.10) and prescribed recharge (Figure 5.11), but they are insensitive to decreases in prescribed discharge (Table 5.1). Increasing the prescribed

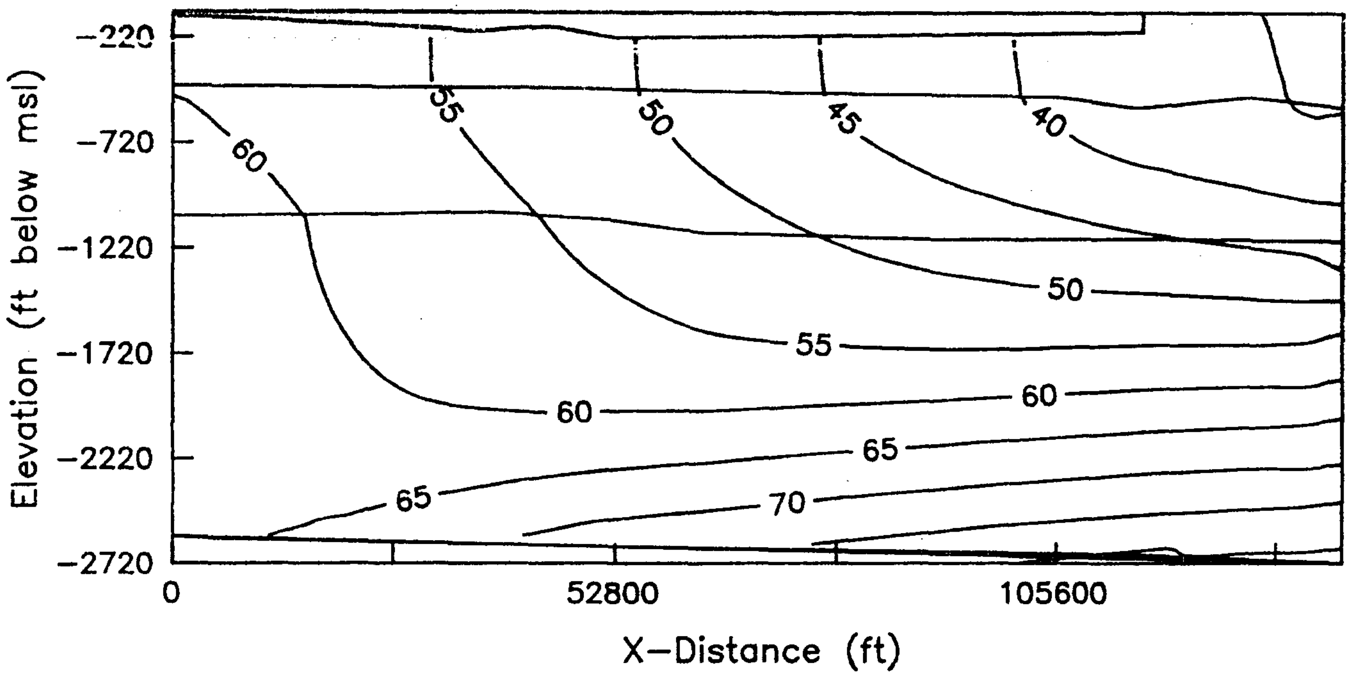


(a)

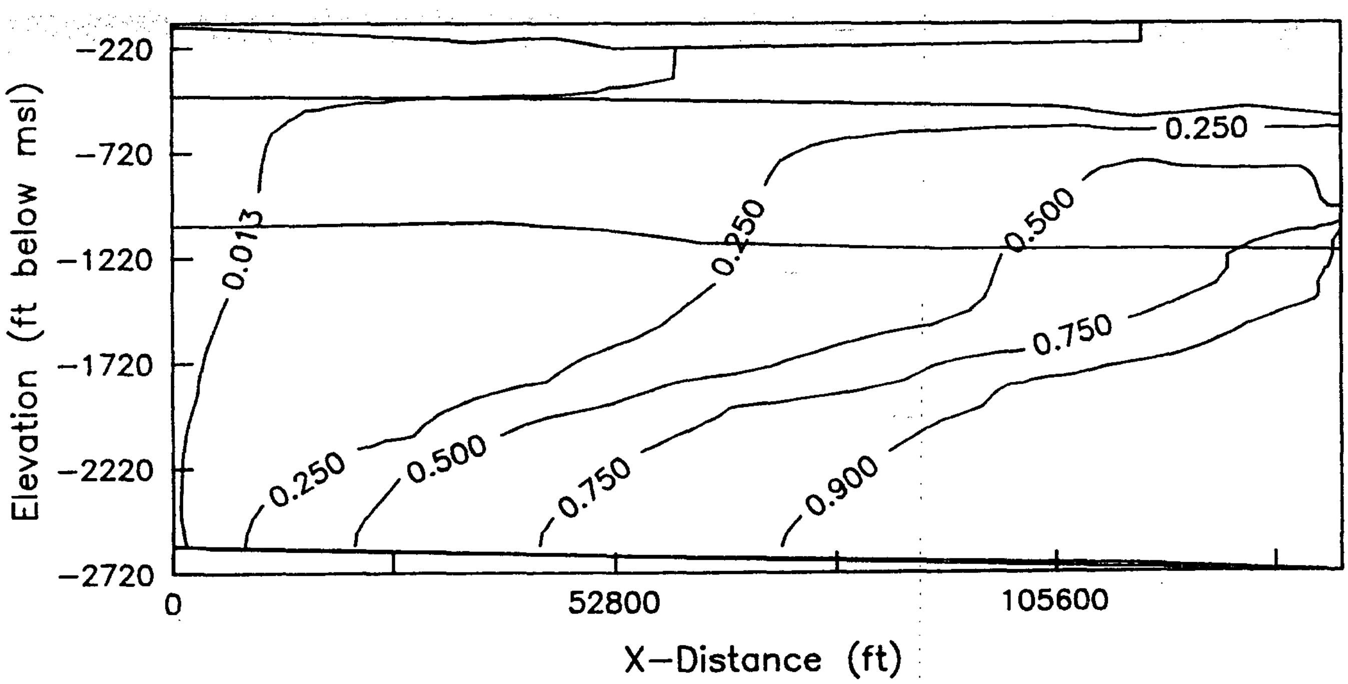


(b)

Figure 5.6 Reference head (a) and normalized concentration (b) distributions for sensitivity run 13; lateral influx to Upper Floridan increased from 5.9 to 6.5 ft/d.

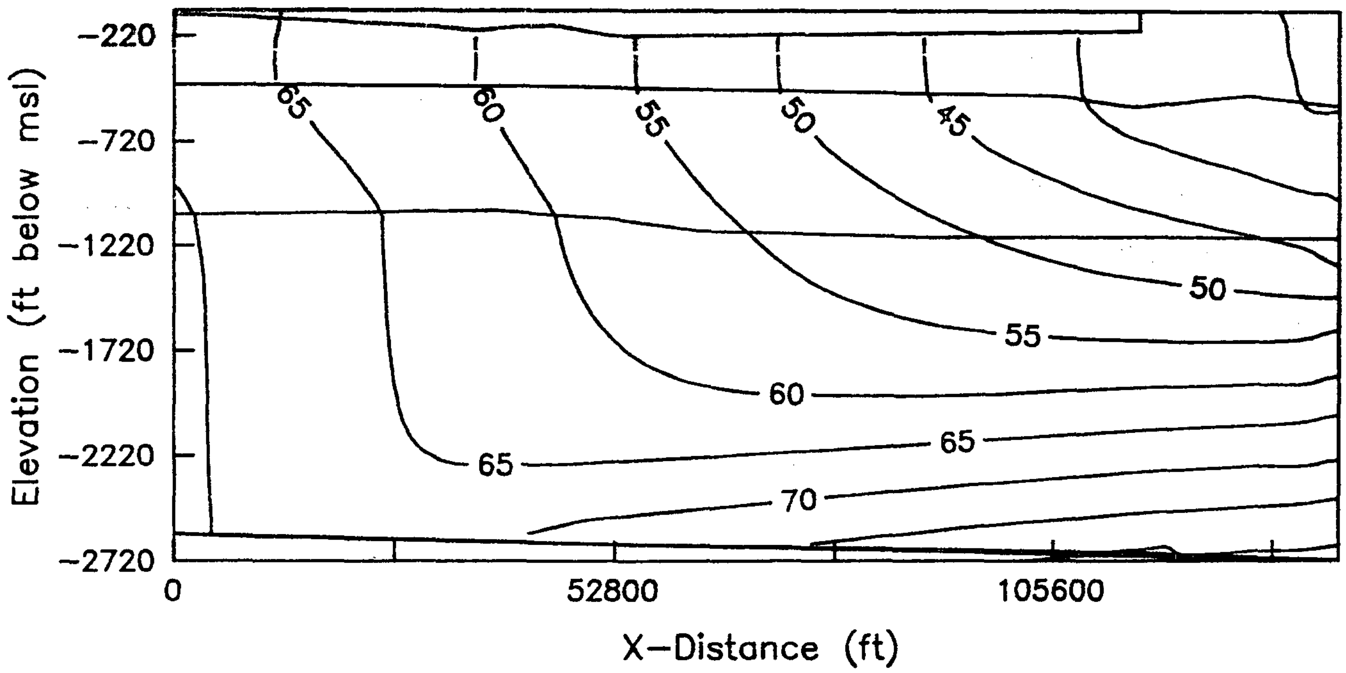


(a)

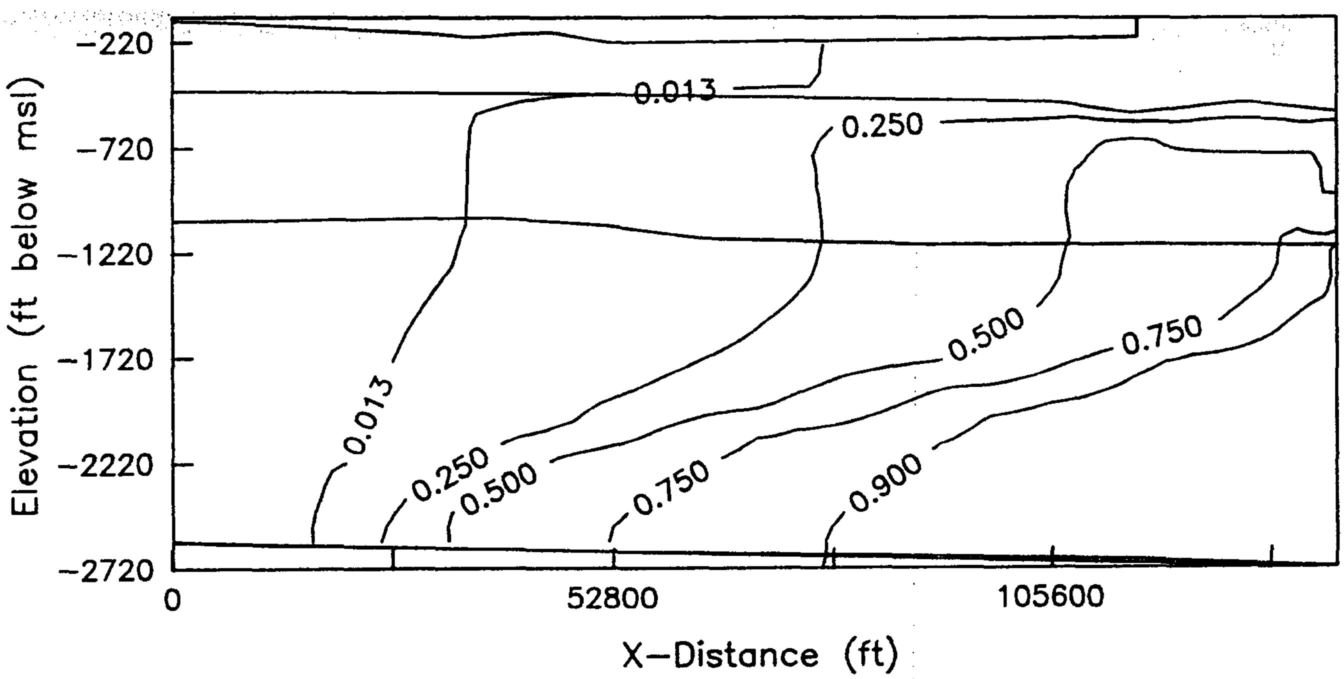


(b)

Figure 5.7 Reference head (a) and normalized concentration (b) distributions for sensitivity run 14; lateral influx to Upper Floridan decreased from 5.9 to 5.0 ft/d.

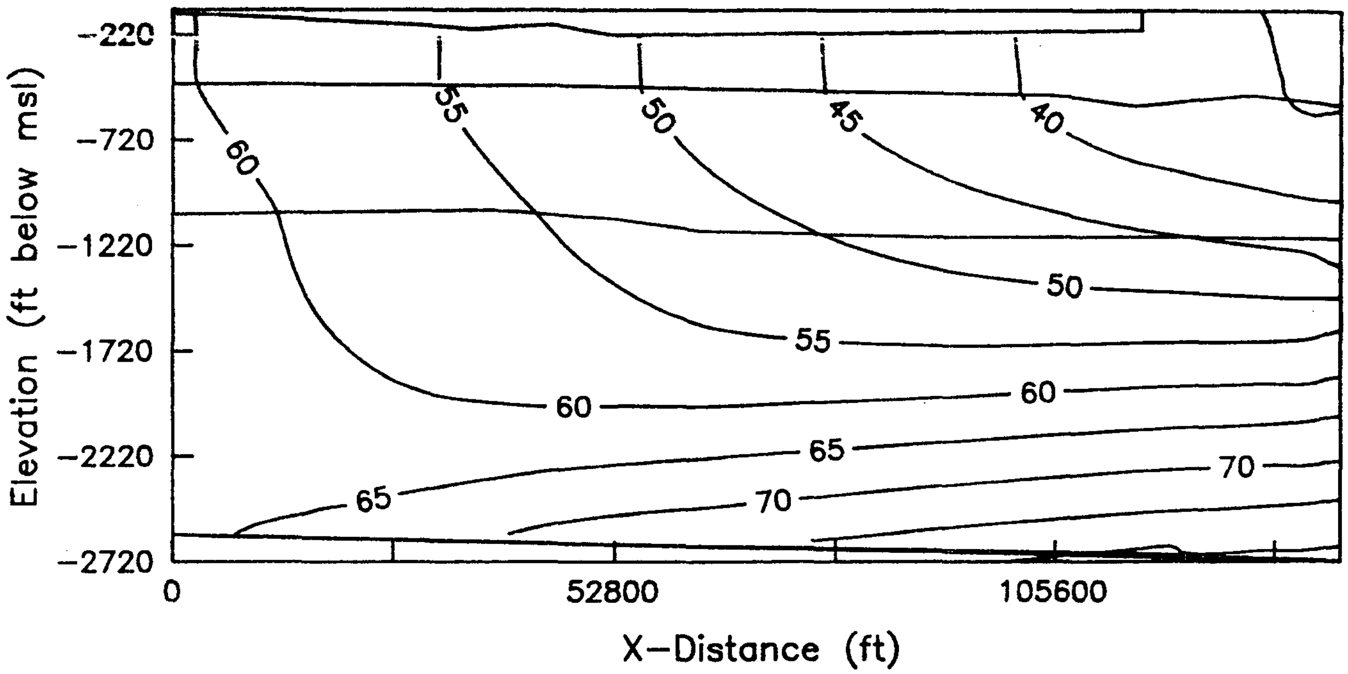


(a)

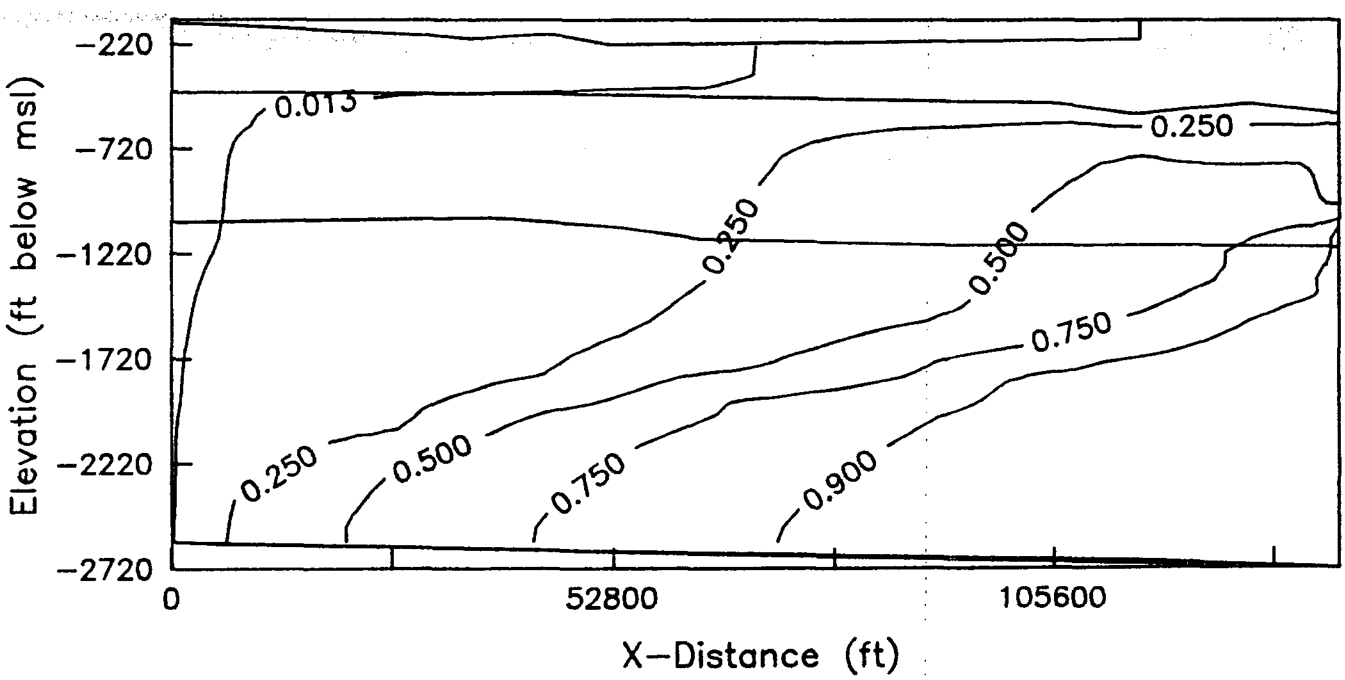


(b)

Figure 5.8 Reference head (a) and normalized concentration (b) distributions for sensitivity run 15; lateral influx to Lower Floridan increased from 1.1 to 2.0 ft/d.

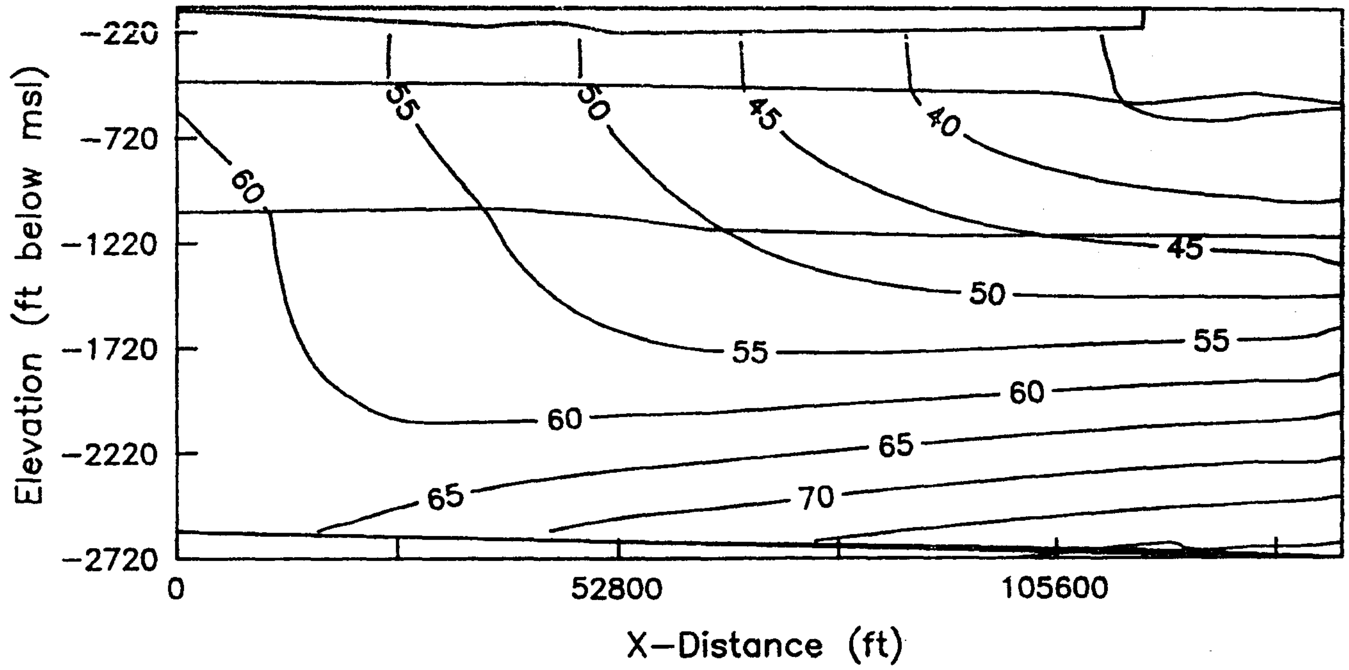


(a)

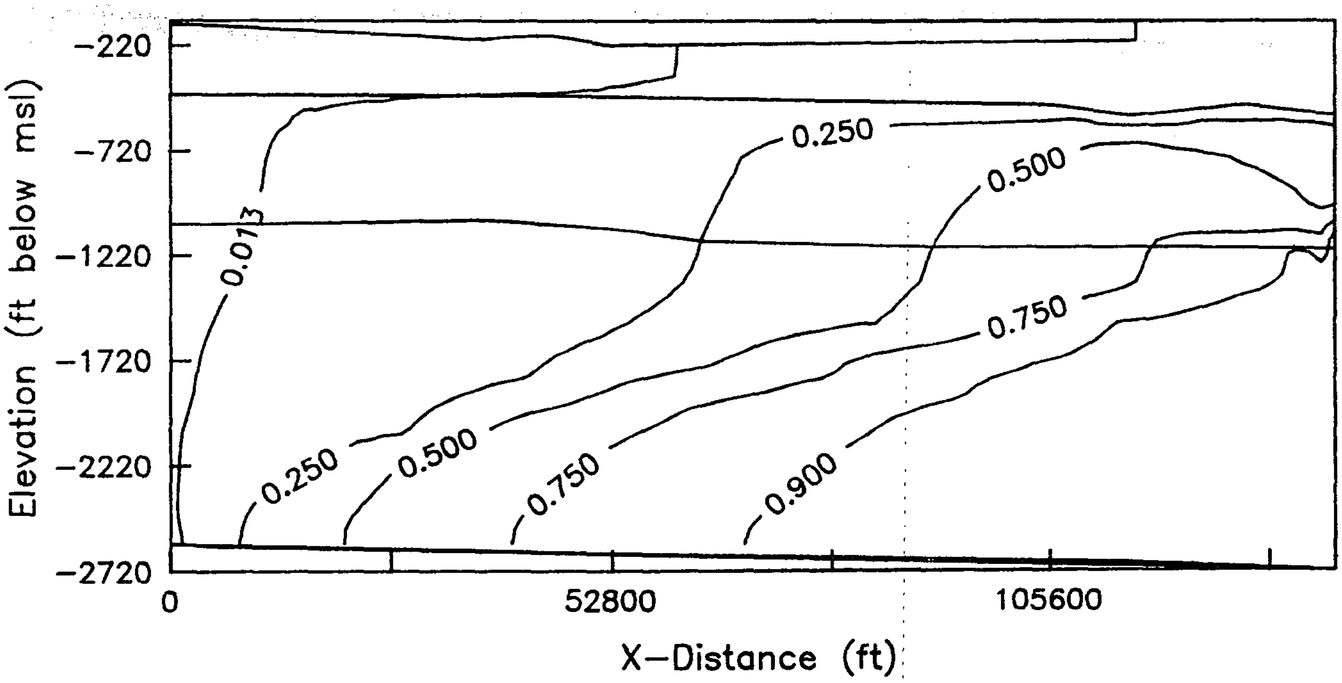


(b)

Figure 5.9 Reference head (a) and normalized concentration (b) distributions for sensitivity run 16; lateral influx to Lower Floridan decreased from 1.1 to 0.7 ft/d.



(a)



(b)

Figure 5.10 Reference head (a) and normalized concentration (b) distributions for sensitivity run 17; prescribed discharge from top of Upper Floridan increased from 0.44 to 0.88 inches/yr.

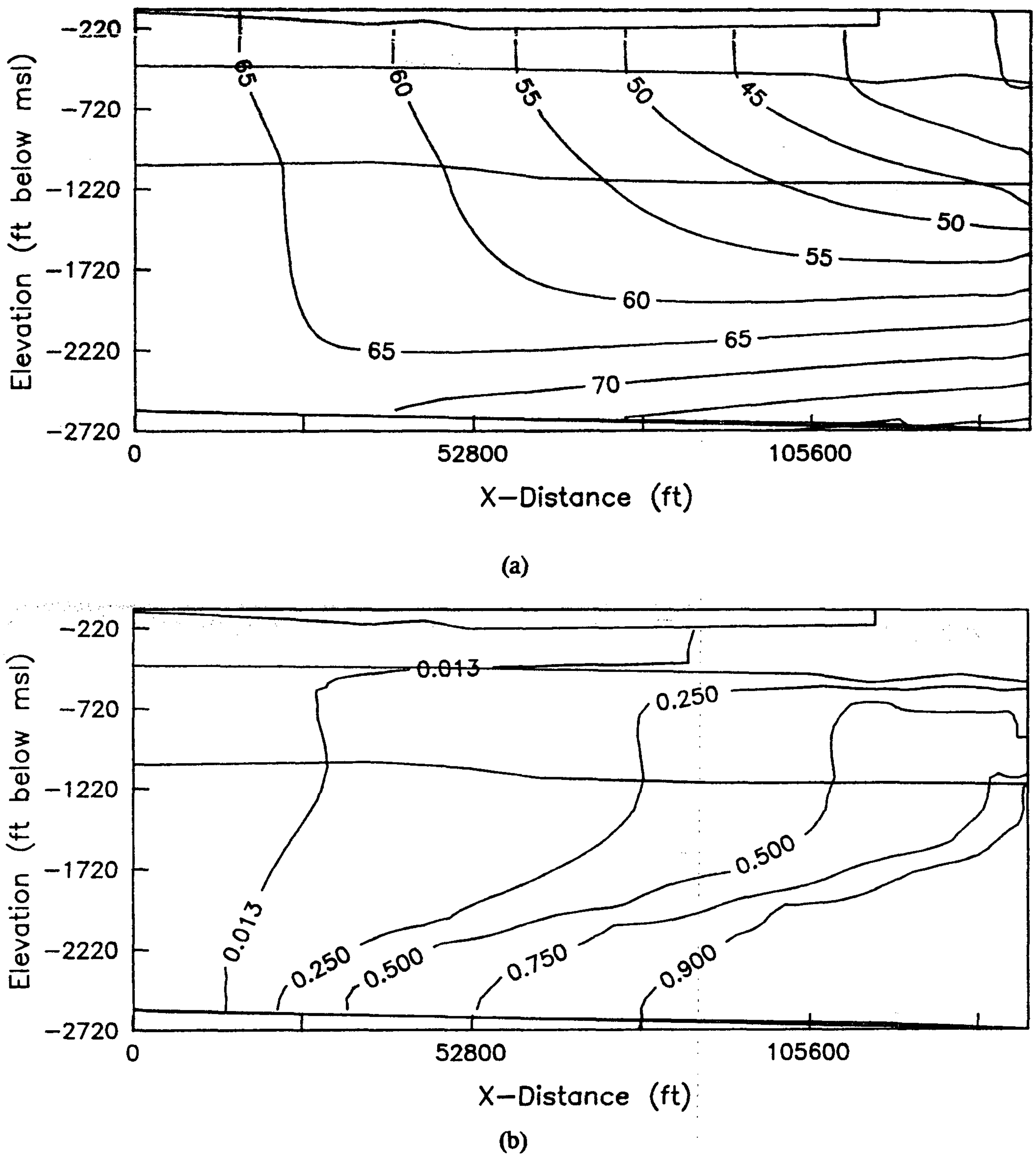
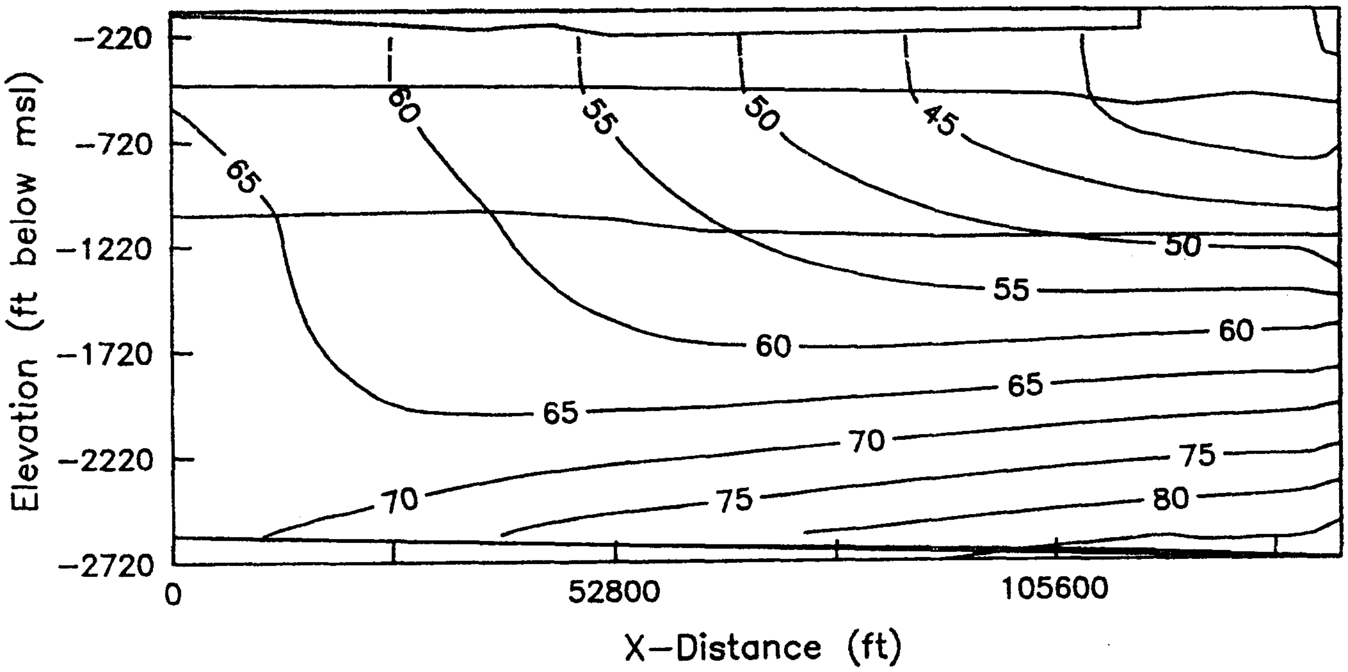


Figure 5.11 Reference head (a) and normalized concentration (b) distributions for sensitivity run 19; prescribed recharge to the top of the Upper Floridan increased from 0.0 to 0.5 inches/yr.

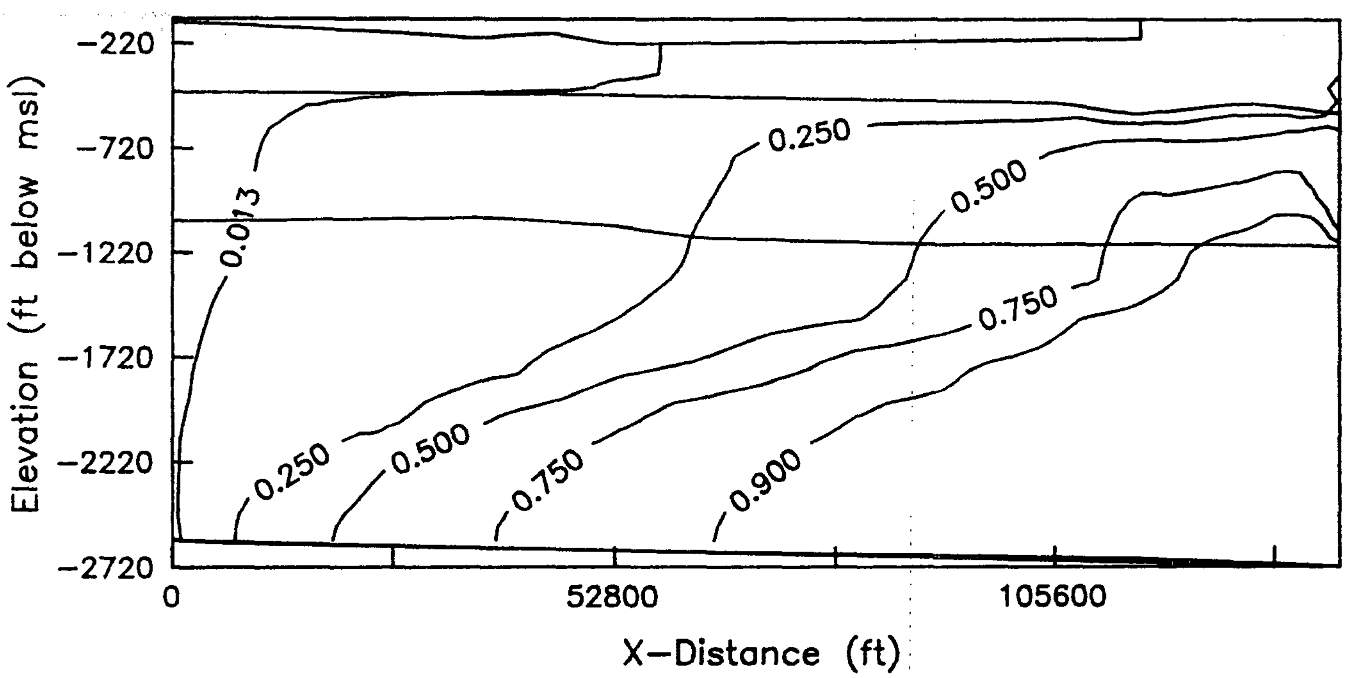
discharge in the eastern portion of the model decreases the hydraulic head gradients within the Upper Floridan across the model domain, and consequently the isochlors migrate toward the western boundary (Figure 5.10). Adding areal recharge to the top of the Upper Floridan in the western and central regions of the domain, where previously there was no recharge (Figure 4.6), causes a general increase in hydraulic gradients, and therefore flow rates, across the system. The resultant effect upon the isochlors is to move them back towards the eastern boundary (Figure 5.11).

5.7 East Boundary Conditions

One sensitivity run was conducted to examine the sensitivity of the calibrated model results to changes in the boundary conditions imposed along the eastern end of the cross section. In run 20, the equivalent freshwater (reference) heads prescribed along the eastern boundary were increased to simulate a preexisting vertical component of groundwater flow. In reference to Figure 4.3, the reference heads prescribed at the top of the upper Floridan, the top of the middle semiconfining unit, the top of the Lower Floridan, and the bottom of the Lower Floridan were 33.5 ft, 36.5 ft, 47 ft and 90 ft, respectively. The results of this run are presented in Figure 5.12. The major effects of changing this boundary condition are that chloride concentrations in the vicinity of the eastern boundary increase within the top of the middle semiconfining unit and the bottom of the Upper Floridan, and the isochlors move farther towards the western boundary.



(a)



(b)

Figure 5.12 Reference head (a) and normalized concentration (b) distributions for sensitivity run 20; reference head along eastern boundary increased to simulate vertical flow.

6 SUMMARY AND CONCLUSIONS

The primary purpose of the Phase II modeling study was to develop a calibrated vertical cross-sectional model for steady-state, predevelopment conditions in the vicinity of the Cocoa well field in eastern Orange County, and to subsequently perform an extensive sensitivity analysis. The results of the Phase II modeling study will be used to guide the development and calibration of the Phase III, fully three-dimensional modeling effort. A hydrogeological profile was developed along the cross section using available published and unpublished data, and the cross section was discretized into orthogonal, curvilinear finite elements. The finite element code DSTRAM (Huyakorn and Panday, 1991) was then used to solve for the density-dependent groundwater flow and solute transport within the cross section. Where possible, the initial input parameters for the cross-sectional model were obtained from the Phase I regional model results (Blandford et al., 1991). The cross-sectional model was calibrated to the limited data available for predevelopment and, in the case of chloride concentrations, early postdevelopment conditions.

The sensitivity analysis indicated that the cross-sectional modeling results are most sensitive to the horizontal hydraulic conductivity in the Upper Floridan, the vertical hydraulic conductivity in the middle semiconfining unit, the lateral influx of water to the Upper and Lower Floridan imposed at the western boundary of the cross section, prescribed areal recharge and the prescribed reference heads at the eastern boundary of the cross section. The model results showed no or little sensitivity to the vertical hydraulic conductivity in the Upper and Lower Floridan, the horizontal hydraulic conductivity in the Lower Floridan, prescribed areal discharge in the Upper Floridan, and the zoning of vertical hydraulic conductivity within the middle semiconfining unit.

The major utility of the cross-sectional modeling results is to guide the development and calibration of the Phase III three-dimensional model. The cross-sectional model results by themselves are considered to be preliminary due to the limitations inherent in two-dimensional cross-sectional modeling. It is possible that, due to the inclusion of the third dimension and additional aquifer stresses (pumping), the Phase III modeling results may vary from those obtained in this study.

The most significant data gap that hinders the density-dependent groundwater flow and solute transport modeling in east-central Florida is the lack of data concerning the spatial distribution of chloride (or total dissolved solids) concentrations, particularly within the Lower Floridan and the middle semiconfining unit. In order to protect the potable water resource in the Upper Floridan in regions of the aquifer that have chloride concentrations approaching 250 mg/l, it is necessary to know what is occurring in other, adjoining portions of the aquifer that already exhibit (or are expected to have) high chloride concentrations. Data such as that collected from the Cocoa C salinity monitoring well is invaluable in assessing the predictive capabilities of regional or sub-regional models. However, the Cocoa C monitoring point is in the middle of the zone that must be protected, and it does little to assist with the assignment of model boundary conditions. Furthermore, this well does not penetrate a significant depth into the Lower Floridan when the entire thickness of that unit is considered. It would be highly desirable to have at least one, and better yet, two additional salinity monitoring wells east of the Cocoa well field. Each well should penetrate as far into the Lower Floridan as feasible.

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APPENDIX A

CHLORIDE CONCENTRATIONS FOR UPPER FLORIDAN WELLS IN THE VICINITY OF THE EAST END OF THE PHASE II CROSS SECTION

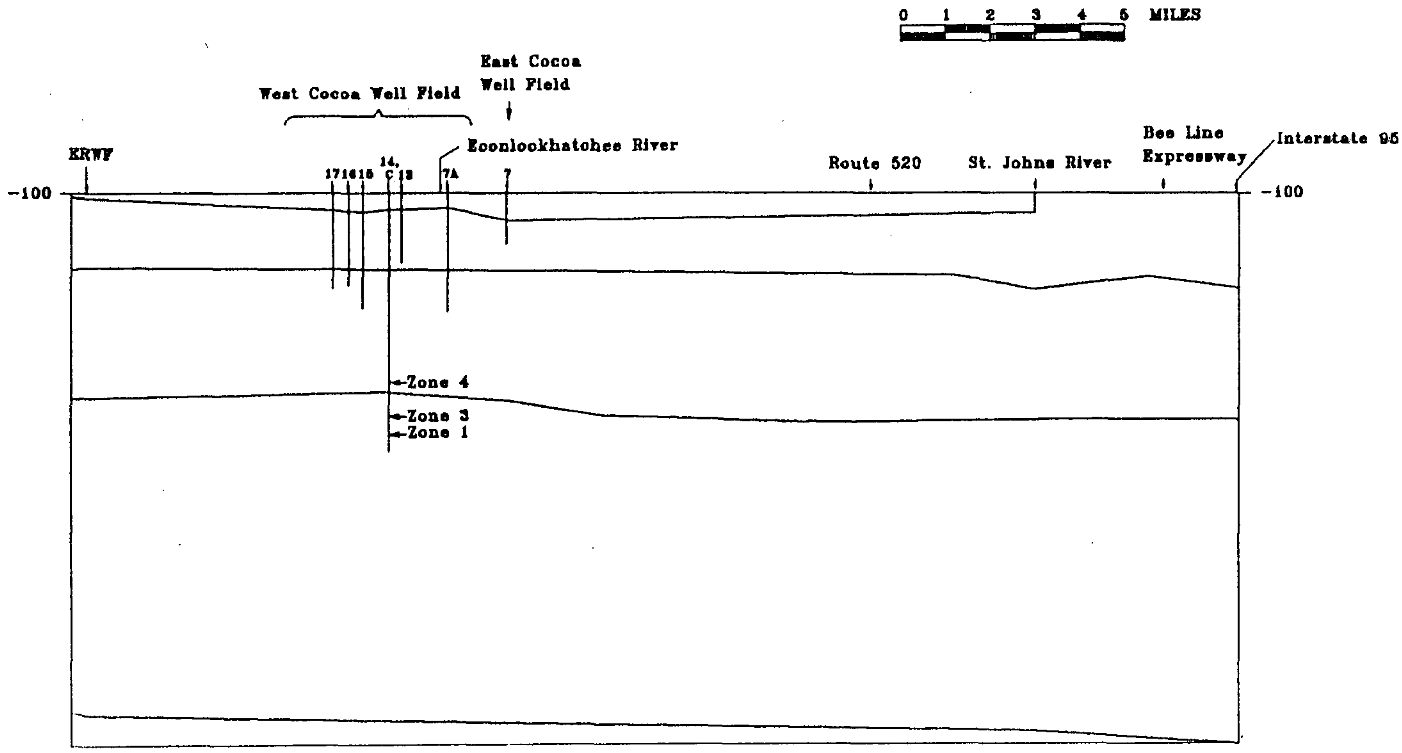
SJRWMD Map No.	Well ID	Casing Depth	Well Depth	Sample History Date	Cl- (mg/l)
16	BR0035	-	180	05/12/75	1,900
21	BR0401	-	-	05/05/81	2,285
				08/27/87	2,203
22	BR0528	-	-	08/27/87	2,112
23	BR0039	-	-	05/12/75	2,400
24	BR0074	138	495	05/05/55	2,270
				05/06/55	2,310
				05/09/55	2,280
				05/11/55	2,380
				05/13/55	2,330
				02/06/62	2,500
				03/06/62	2,500
				04/16/63	2,450
				07/22/63	2,460
				10/01/64	2,450
				03/09/65	2,500
25	BR0075	530	553	05/26/55	2,600
				04/16/63	2,420
				06/22/63	2,480
				07/22/63	2,480
				10/01/64	2,510
				03/09/65	2,500
				06/18/65	2,480
				01/04/67	2,400
				05/16/70	2,400
				11/30/79	2,400
				05/11/83	2,634
26	BR0204	-	-	06/21/54	2,150
				04/16/55	2,050
				01/13/56	2,010
				01/16/57	2,050
				12/05/57	2,050
				05/11/62	2,150
				02/24/66	2,150
				05/24/79	2,040
				09/11/80	2,161
				11/17/80	2,188
				04/13/81	2,071
30	BR0203	-	-	06/27/80	2,324
				09/12/80	2,129
				09/12/80	2,129
				11/17/80	2,505
31	BR0202	114	129	08/16/55	1,550
				01/22/70	1,560
				03/05/70	1,540
				11/06/70	1,560
				05/04/72	1,550
				12/04/79	1,600
				09/11/80	1,609
				06/14/83	1,750
				11/06/86	1,570
				04/14/87	1,650
				04/22/87	1,600
				04/05/88	1,594
				10/27/88	1,490
				10/03/89	1,690

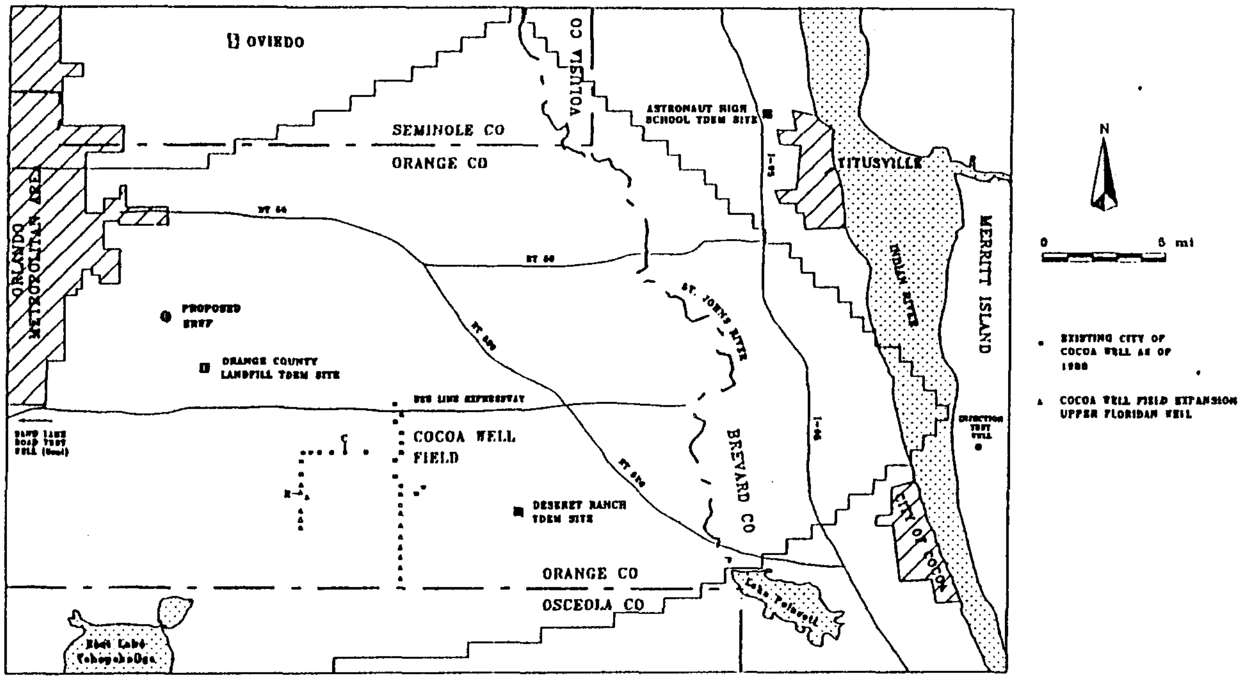
SJRWMD Map No.	Well ID	Casing Depth	Well Depth	Sample History Date	Cl- (mg/l)
36	BR0214	-	100	08/09/78	1,300
				09/16/80	990
41	BR0664	-	-	11/14/84	4,220

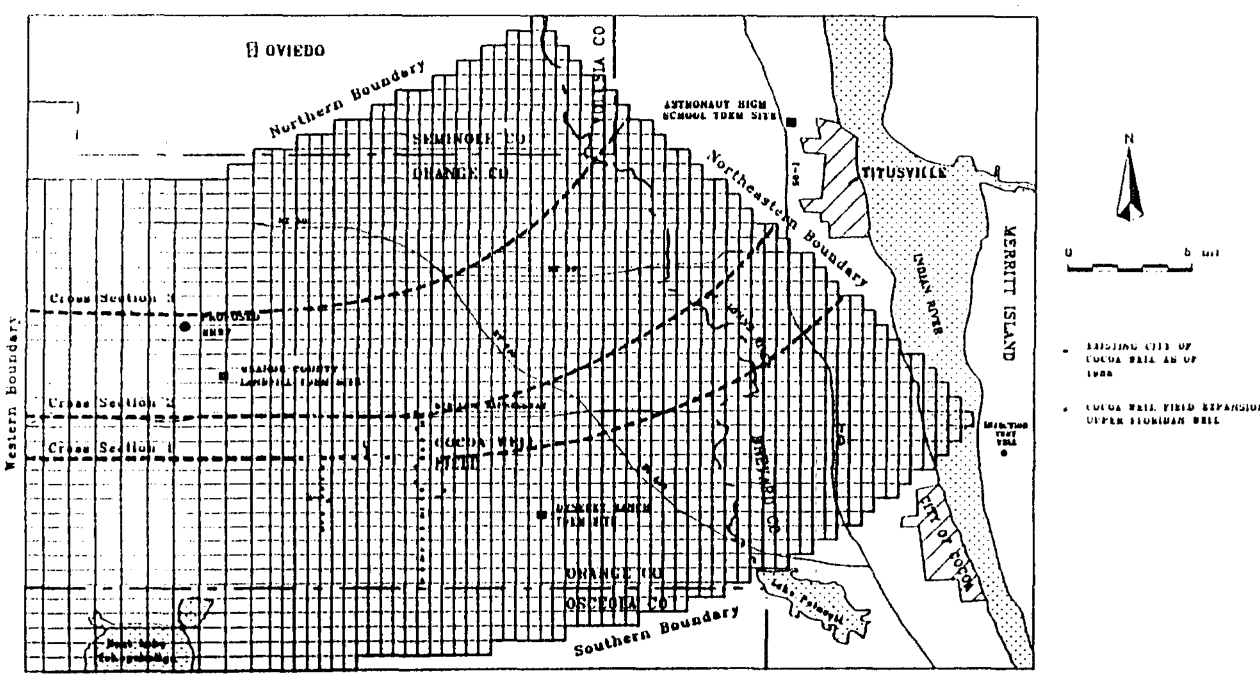
Note: There are no quality data available for the following wells listed on the base map (Brian McGurk, pers. comm., 5/16/91):

Map #	Well ID
18	BR0016
20	BR0237
39	BR1068

Appendix B


0 1 2 3 4 5 MILES
East Cocoa Well Field
West Cocoa Well Field
Econlockhatchee River
ERWF
17 16 15 14, C 13
7A
7
Route 520
St. Johns River
Bee Line Expressway
Interstate 95
-100
-100
Zone 4
Zone 3
Zone 1


OVIEDO
SEMINOLE CO
ORANGE CO
VOLUSIA CO
ORLANDO METROPOLITAN AREA
ASTRONAUT HIGH SCHOOL TDEM SITE
TITUSVILLE
MERRITT ISLAND
INDIAN RIVER
ST. JOHNS RIVER
PROPOSED
ORANGE COUNTY LANDFILL TDEM SITE
COCOA WELL FIELD
DESERET RANCH TDEM SITE
BREVARD CO
CITY OF COCOA
ORANGE CO
OSCEOLA CO
Lake Poinsett
East Lake Tohopekaliga
INJECTION TEST WELL
I-95
N
0 5 mi
EXISTING CITY OF COCOA WELL AS OF 1988
COCOA WELL FIELD EXPANSION UPPER FLORIDAN WELL


OVIEDO
Northern Boundary
Northeastern Boundary
Southern Boundary
Western Boundary
Cross Section 3
Cross Section 2
Cross Section 1
SEMINOLE CO
ORANGE CO
VOLUSIA CO
ASTRONAUT HIGH SCHOOL TDEM SITE
TITUSVILLE
MERRITT ISLAND
INDIAN RIVER
COCOA WELL FIELD
DESERET RANCH TDEM SITE
BREVARD CO
CITY OF COCOA
ORANGE CO
OSCEOLA CO
Lake Poinsett
N
I-95