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NUMERICAL MODELING OF GROUND-WATER FLOW AND SEAWATER INTRUSION, VOLUSIA COUNTY, FLORIDA

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Geraghty & Miller, Inc. appreciates the opportunity to work for St. Johns River Water Management District in Volusia County. If you have any questions or comments concerning this report, please contact one of the individuals listed below.

Respectfully submitted,

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EXECUTIVE SUMMARY

PROJECT SCOPE

In 1989, the Florida legislature directed water management districts of the State to undertake a water supply Needs and Sources Assessment. The framework for this program provides for a systematic evaluation of the projected water resource needs and the available resources for the next two decades. The Geraghty & Miller Modeling Group (GMM) has been retained to develop an updated tool that can be used for the analysis of impacts of current and projected water-supply needs and for more localized analyses of resource management questions within the Volusia Ground-Water Basin. To achieve this objective, a refined ground-water model is being developed to accurately simulate ground-water flow and chloride transport in the Volusia County ground-water basin. The model must incorporate appropriate data regarding existing and proposed wellfields, recharge and discharge areas, land use patterns, and the hydrologic configuration of the surficial aquifer.

The primary objective of this study is to develop an up-to-date ground-water flow and chloride transport model to be used for predictive purposes within the context of a Needs and Sources Assessment.

The specific objectives of this study are:

1. Incorporate new information regarding the location of recharge/discharge areas, land use patterns, wellfield locations, agricultural and other users, and the hydrology of the surficial aquifer into the ground-water model.

2. Determine the effects of existing and proposed withdrawals from public water supply wellfields on the flow regimes of the Floridan aquifer system.

3. Determine the potential for lateral migration of saline water (> 250 mg/L) from brackish areas within the Floridan aquifer under specified demand scenarios for the years 1990 and 2010.

4. Determine the potential for saltwater upconing within the Floridan aquifer under specified demand scenarios for the years 1990 and 2010.

The study is comprised of three primary tasks as follows:

1. Task I involves development of a cross-sectional flow and chloride transport model and preliminary conceptual design of the three-dimensional flow and brine transport model. The cross-sectional model extends from the St. Johns River east to the coastline at Daytona Beach. It is oriented along a southwest-to-northeast streamline, roughly parallel to the direction of flow. This model was used to perform sensitivity analyses for parameters, to interpret boundary conditions for the subsequent three-dimensional model, and to analyze the location and orientation of the saltwater interface based upon the ground-water flow and chloride transport simulations. Sensitivity analyses were performed to determine the density effects upon the flow field and the treatment of the surficial aquifer. A preliminary three-dimensional model grid was designed based on the results of the cross-sectional model analyses.

2. Task II involves development, calibration, and sensitivity analyses of the three-dimensional flow and chloride transport model. The model will incorporate all available information regarding land use, ground-water recharge and

withdrawals. The surficial aquifer will be discretized into an active free-surface layer.

3. Task III involves the use of the three-dimensional model to perform predictive assessments and make recommendations regarding potential pumping scenarios and wellfield placements from the time period of 1990 through 2010.

The Task I modeling study of ground-water flow and chloride transport consisted of the following four distinct phases:

(1) Conduct an intensive literature review and develop a conceptual model of the hydrogeologic system in Volusia County;

(2) Develop a two-dimensional cross-sectional ground-water flow and chloride transport model to establish regional and local ground-water flow conditions through the width of the county;

(3) Perform a sensitivity analysis of boundary conditions, treatment of the surficial aquifer, density effects, and mesh refinement; and

(4) Develop a three-dimensional conceptual model.

The Task II modeling study of ground-water flow and chloride transport consisted of the following four distinct phases:

1. Develop and calibrate a three-dimensional ground-water flow and chloride transport model for the Volusia County ground-water basin. Perform steady-state flow calibrations to represent predevelopment and 1988 flow conditions.

2. Perform a transient transport calibration to represent 1990 conditions.

3. Perform sensitivity analyses to compare the relative response of the ground-water flow system to changes in parameters and boundary conditions.

The Task III modeling study of ground-water flow and chloride transport consisted of the following two distinct phases:

1. Perform predictive simulations to assess current (1990) water use conditions, including assessments of:
   A. The effects of present pumping on the potentiometric surface and water quality of the Floridan aquifer system within the project area;
   B. The potential for lateral migration of saline water within the Floridan aquifer system; and
   C. The potential for vertical upconing of saline water within the Floridan aquifer system.

2) Perform predictive simulations to assess projected (2010) water-use conditions. Analyze two configurations for projected pumping, one with needs met by the existing wellfields and the second with needs met by existing and proposed wellfields. Include assessments of:
   A. The effects of the projected pumping on the potentiometric surface and water quality of the Floridan aquifer system within the project area;
   B. The potential for lateral migration of saline water within the Floridan aquifer system; and
   C. The potential for vertical upconing of saline water within the Floridan aquifer system.

These phases were conducted in a systematic fashion to meet the objectives of the study.

HYDROGEOLOGIC FRAMEWORK

The Floridan aquifer system is a sequence of carbonate rocks mostly ranging in age from Paleocene to early Miocene that are hydraulically connected in varying degrees, and whose permeability is generally several orders of magnitude greater than rocks that bound the system above and below. The Floridan aquifer consists of two active permeable zones (the Upper and Lower Floridan aquifers) separated by a zone of low permeability (a middle confining unit).

In the aquifer recharge areas, water leaks down from the surficial aquifer through the confining beds to the Upper Floridan. The process has produced a ground-water ridge near the middle of the County in the Upper Floridan. The water table in the surficial aquifer is thought to follow topography closely except in the highlands where it is more subdued. In the DeLand Ridge area, the gradients are strongly downward from the surficial aquifer to the Upper Floridan. Near the middle of the county, the Upper Floridan recharges the Lower Floridan.

The primary discharge areas are the St. Johns River Valley (including large lakes and springs) and the Atlantic Ocean. Diffuse flow into the St. Johns River is driven by strong upward vertical gradients.

There are two major factors affecting the natural quality of water in the Floridan aquifer. Ground-water moving downgradient through the aquifer system becomes highly mineralized by gradually dissolving rock materials. Ground water quality is also affected by mixing and chemically reacting with highly mineralized water that is in the aquifer at depth, along the Atlantic Coast, and along the St. Johns River Valley.

The lateral transition from freshwater to brackish water in the Upper Floridan in Volusia County occurs over distances of one half-mile to several tens of miles. The vertical transition from freshwater to brackish water occurs over intervals as small as a few tens of feet. The additional vertical transition of slightly brackish water to water with a chloride concentration of 10,000 mg/L occurs over distances of a few tens of feet to several hundred feet. The depth to water containing more than 10,000 mg/L chloride ranges from 500 to 1,000 ft below msl. These high concentrations are found in shallow ground water along the St. Johns River and Atlantic Coast. Near the middle of the County the high chlorides occur at the greatest depths.

CROSS-SECTIONAL MODEL

Current modeling analyses of the ground-water system in Volusia County began with the development of a cross-sectional ground-water flow and chloride transport model. The cross-sectional model simulates the distribution of hydraulic heads in the surficial and Floridan aquifers, the distribution of chlorides, and the rates and directions of ground-water flow. The cross-sectional model has been adjusted to steady-state predevelopment ground-water flow conditions. The cross-sectional model was not calibrated in the traditional meaning of the word. The model was adjusted, however, to match the conceptual model. Estimated predevelopment (1955) water levels and chloride concentrations were also used to guide model construction. After a suitable match of the flow model was achieved, sensitivity analyses were performed with the model.

Although the two-dimensional cross-sectional model is not calibrated, it is very important for setting accurate boundary conditions in the three-dimensional model and understanding regional patterns of ground-water flow and brackish water transport. The three-dimensional model accounts for horizontal and vertical movement of ground water and also permits more accurate definition of geologic heterogeneity in the aquifers.

SWIFT III (Sandia Waste Isolation, Flow and Transport Code) was selected for flow and chloride transport modeling. SWIFT III was chosen because:

- it is a public domain code
- it considers variable density
- it is well tested
- it is well-suited for seawater intrusion

The cross-sectional model was finely discretized to achieve a high degree of accuracy in the transport model. The ultimate discretization of the three-dimensional model will be based upon the results of the grid sensitivity analysis.

Model boundaries were chosen to correspond to natural hydrologic boundaries of the physical ground-water flow system. All available information on water levels near the boundaries were used to establish the constant head boundary conditions for the surface water bounding the model.

A sensitivity analysis was performed on the base case cross-sectional model to identify parameters that control the movement of the saltwater front. Sensitivity analyses were performed in which each model parameter in the base case cross-section was increased by ten percent. Sensitivity analyses were performed to determine the finite-difference mesh design in the three-dimensional model. The ability to use a coarse finite-difference mesh is desirable in order to reduce the development time of the three-dimensional model and costs required to use the model as a predictive tool. The base case cross-sectional model was highly refined to properly model chloride transport without introducing excessive numerical dispersion due to large grid spacings. Sensitivity analyses were performed to determine the maximum coarseness of the model while maintaining adequate accuracy.

THREE-DIMENSIONAL MODEL

The three-dimensional ground-water flow and seawater transport model of Volusia County was an extension of the cross-sectional model. The three-dimensional model consisted of five layers, which was determined in the cross-sectional analyses to be the minimum amount of vertical discretization needed to simulate upconing. The degree of horizontal discretization was based upon the location of major wellfields. Grid spacings of 0.25 miles were used around wellfields to more accurately characterize drawdown and the potential for upconing. The 0.25 mile grid spacing around wellfields was determined by the District.

The three-dimensional model was calibrated three different ways, including the following:

- Steady-state calibration of the flow model to predevelopment (1955) conditions
- Steady-state calibration of the flow model to 1988 conditions
- Transient calibration of the seawater intrusion model to 1990 conditions

The Volusia County ground-water model was developed by first constructing and calibrating a ground-water flow model separate from the seawater intrusion model. The ground-water flow model was calibrated to two different time periods representing predevelopment conditions and conditions in 1988. Both flow calibrations were assumed to be steady-state and utilized equivalent freshwater heads in all boundary conditions.

The modular finite-difference ground-water flow code, also known as MODFLOW, developed by the U. S. Geological Survey was selected for the ground-water flow model calibrations. MODFLOW is publicly available, widely used, and features extensive documentation.

After the two flow model calibrations were started using the MODFLOW code, the ground-water flow model was converted to another code (SWIFT III) that simulated ground-water flow and seawater intrusion simultaneously. The seawater (chloride) model was calibrated transiently to 1990 conditions. The seawater calibration and the two flow calibrations continued iteratively until satisfactory results were obtained in all three cases.

The iterative calibration approach was necessary because the chloride transport model was found to be sensitive to subtle changes in the ground-water flow model. In addition, a high priority was placed on using the same aquifer properties and boundary conditions for all three calibrations. Thus, any change to one model calibration affected the other two calibrations.

SWIFT III was chosen for the three-dimensional seawater intrusion model by the District. The SWIFT III code has the same basic capabilities as MODFLOW, but can solve the ground-water flow, solute transport, heat transport, and density-dependent flow and transport (seawater intrusion) equations. MODFLOW, on the other hand, can only solve the ground-water flow equation.

Computer programs such as MODFLOW and SWIFT III approximate the exact mathematical equation for ground-water flow by numerical discretization techniques. Both MODFLOW and SWIFT III use the method of finite differences to approximate the ground-water flow and solute transport equations. Spatial discretization consists of subdividing the entire model domain into a grid or mesh of smaller blocks or cells. In the discretized system, hydraulic heads and chloride concentrations are computed at the center of each grid block. In general, computational accuracy increases as the number of rows and columns in the grid increase. Minimizing the number of grid cells is extremely important to reducing computational effort and increasing model stability. Prior to construction of the three-dimensional model, additional sensitivity analyses were performed using the cross-sectional model to determine whether a coarser grid could produce results similar to the base case while maintaining the same degree of numerical stability. A major concern, however, was that coarsening of grid cells representing the Atlantic Ocean could result in numerical instability. Cell spacings were varied from 0.25 to 2.5 miles. These analyses indicated that grid cells could be coarsened up to a spacing of one mile with no obvious numerical instability.

The finite-difference grid developed after careful consideration of project goals and numerical stability consists of 86 columns, 91 rows, and 5 layers. The model covers an area of approximately 1,850 square miles to simulate regional ground-water flow and chloride transport in three dimensions. The model domain extends from the St. Johns River in the west to about seven miles off the Atlantic Coast in the east. Cell dimensions along the column direction range from 0.25 to 1.5 mi. Cell dimensions along the row direction range from 0.25 to 2.0 mi. Smaller grid cells are used along the Atlantic Coast and in the vicinity of municipal pumping centers to enhance the computational accuracy of the model in these critical areas.

The aquifer is defined by 5 layers of grid cells in the vertical dimension (Figure 3). Layer 1 represents the surficial aquifer. Layer 2 represents the Upper Floridan system. The middle semi-confining unit of the Floridan aquifer is discretized as Layer 3. The lower two layers (4 and 5) represent the Lower Floridan aquifer.

Pumping data for this modeling effort were gathered from the St. Johns River Water Management District (SJRWMD), the Volusia County Department of Environmental Management, and through the various individual municipal utility departments. Data were collected for the calendar year 1988, as this was determined, through consultation with District staff, to be a period which was representative of long-term average conditions indicative of a quasi-steady state system. Transient simulations to examine projected pumpage for the period 1990 to 2010 utilized municipal supply rates determined by SJRWMD.

The distribution of parameter zones was initially determined from previous modeling studies of Volusia County. The distribution and number of zones was subsequently modified during calibration in order to match observed heads and chloride concentrations. Parameter values and zones modified during calibration were checked against published data wherever possible to make sure that parameter values chosen for the model were reasonable.

The transient chloride calibration was performed in two steps. First, the predevelopment chloride transport model was run to provide initial hydraulic head and chloride conditions for the transient simulation. The transient simulation was then run from 1950 to 1990. The calibration was performed by comparing the results after 40 years of transport (1990 conditions) to chloride concentrations measured in monitoring wells in the late 1980s and 1990.

Before using the predevelopment chloride model results as initial conditions for the transient calibration, the predevelopment chloride model was qualitatively calibrated. Basic transport parameters were adjusted until the transport model computed chloride concentrations close to those observed or postulated for predevelopment conditions.

Comparing computed chloride concentration with observed values, indicates that the model matches the general pattern of chloride concentrations throughout Volusia County. Due to the regional nature of the current model, however, isolated high chlorides may not be matched closely. Model computed chloride concentrations represent average chloride concentrations for the entire Upper Floridan aquifer. Localized areas of high chloride concentrations near Port Orange are shallow features which may have formed through seasonal interaction of surface water and groundwater. This phenomena is not easily simulated in a regional seawater intrusion model.

The response of the calibrated flow model to changes in recharge, hydraulic conductivity, and boundary conditions was evaluated using a sensitivity analysis. One parameter at a time was varied over a specified range while all other parameters are held constant. Changes in parameters were implemented as increases or decreases by a multiplication factor throughout the entire model. The sensitivity of the model to variations in each parameter was evaluated based on the change in the residual sum of squares from the 1988 calibrated model.

The model was found to be most sensitive to changes in recharge. Small changes, increases or decreases, in overall recharge caused large changes in the residual sum of squares.

Hydraulic conductivities were the next most sensitive parameters tested, especially the hydraulic conductivity of the surficial aquifer. This parameter becomes more sensitive to large decreases.

Sensitivity analyses were performed on all vertical leakance zones. Vertical leakance in the DeLand area was the most sensitive vertical leakance zone, probably due to its importance in controlling recharge to the Upper Floridan aquifer from the surficial aquifer where vertical flow is significant.

Sensitivity of chloride concentrations to changes in transport parameters (dispersivity and porosity) was analyzed from a limited number of simulations that tested a reasonable range for these parameters. In the first sensitivity run, porosity was decreased to 10 percent from the value of 25 percent used in the calibration. Dispersivity was then increased from 600 ft to 1500 ft to illustrate the effects of increased dispersion. Finally, since the chloride calibration was transient, the effect of storage were examined by increasing storage by a factor of 5, from 0.001 to 0.005.

Results from the ground-water flow modeling indicate that ground water in Volusia County generally flows radially away from a potentiometric high in the center of the county. Primary discharge areas are the Atlantic Ocean on the east and the St. Johns River on the west. This pattern of flow is evident in both the surficial aquifer and the Floridan aquifer system.

Vertical gradients are strongly downward between the surficial and Upper Floridan aquifers, especially in the center of the county. Near Deland, the difference in head between the two aquifers is over 25 feet. Vertical gradients become less pronounced near the discharge areas, where an upward vertical gradient is established from the Upper Floridan into the surficial aquifer.

The strong vertical gradients in the center of Volusia County provide a significant source of fresh water to recharge the Upper Floridan aquifer. This is the driving force that keeps chloride concentrations low in the center of the county. Chloride concentrations increase near the coast due to a natural saltwater wedge. Chloride concentrations also increase beneath the St. Johns River, where ground water high in chlorides discharge from the Lower Floridan aquifer through the Upper Floridan aquifer and finally into the surficial system.

The primary discharge areas are the St. Johns River Valley (including large lakes and springs) and the Atlantic Ocean. Off the coast of Volusia County, the top of the Floridan aquifer is about 80 to 100 ft below sea level. Thus, the materials overlying the Upper Floridan are as thin as 20 ft. This allows for high rates of upward discharge to the Atlantic Ocean. Flow entering the east and west lateral boundaries of the Lower Floridan aquifer generally exits the model as upward flow into the St. Johns River Valley or the Atlantic Ocean. These lateral flow boundaries also act as chloride sources for the model.

There is a high degree of uncertainty in the Lower Floridan aquifer flow system. Data do not exist to accurately define hydraulic head or chloride concentration boundary conditions. Undoubtedly, more data is necessary to improve the model in this area. Overall, the model appears to simulate flow and chloride transport as described in the conceptual model of ground-water flow and chloride transport in Volusia County.

The steady-state flow calibration performed for 1988 conditions differed from the predevelopment simulation through the introduction of 1988 estimated ground-water withdrawals for water supply. About 75 million gallons per day (MGD) was pumped from the Upper Floridan aquifer in Volusia County in 1988. The overall effect of this pumping has been a decrease in head in the Upper Floridan of about 5 to 8 feet in the center of the county. The north-south trending ground-water divide has also shifted about 1.5 to 2 miles to the west in response to pumping along the Atlantic coast.

Overall, pumping in Volusia County has depressed the potentiometric surface in the surficial aquifer and the Upper Floridan (Figures 47 and 48). Pumping is highest near Ormond Beach, Daytona Beach and New Smyrna Beach. It should be noted that pumping in Volusia County does not exceed overall recharge into the model domain or the amount of ground-water flow in the Upper Floridan aquifer. Therefore, lateral saltwater intrusion should not become a severe problem in inland areas.

The greatest increases in chloride concentrations from predevelopment to 1990 occur beneath the Atlantic Ocean on the east and the St. Johns River on the west. The largest increases on the east are about 10 to 100 mg/L near the pumping centers of South Daytona Beach and New Smyrna Beach. Increases in this area are characterized by curved chloride difference contours, which are indicative of upconing effects. Upconing refers to a local rise of the interface in an aquifer. This generally occurs when an aquifer contains an underlying layer of saline water and is pumped by a well penetrating only the upper freshwater portion of the aquifer. Lateral intrusion is basically the landward migration of the interface usually in response to strong pumping in a confined aquifer. Ideally upconing processes are identified by closed (circular) chloride change contours.

Changes in chloride concentrations in Volusia County are very small. Chloride distributions and difference plots in the lower layers of the model do not indicate whether upconing or intrusion processes are predominant. The greater thicknesses of these layer may be averaging out minor changes in the interface. Concentration difference plots of the Upper Floridan aquifer reveal the most valuable information regarding the amount and location of chloride changes. The greatest impact appears to be from upconing of chloride from the Lower Floridan aquifer. The chloride difference plot reveals that upconing processes are occurring along the Atlantic Coast particularly near South Daytona and New

Smyrna Beach (Figure 56). All chloride increases are attributed to pumping withdrawals in Volusia County.

PREDICTIVE ANALYSES

The first predictive scenario distributed increased future water demand to existing wellfields. By the year 2010, the total pumping from existing wellfields increased by about 50 percent from 75 MGD to 112 MGD. The ground-water flow system is similar to that produced in 1988, but depressed due to greater pumping. The ground-water ridge in the center of the County has been lowered about 5 feet to an elevation of about 30 feet msl. The ground-water divide in the Upper Floridan aquifer has shifted about one mile to the west compared to 1988 conditions. The surficial aquifer also shows decreases 5 ft or more in the Daytona Beach area.

The Daytona Beach, Ormond Beach, New Smyrna, and Port Orange wellfields appear to have the greatest impact on the flow system, forming large cones of depression in the Upper Floridan aquifer. The cone of depression around the Daytona Beach wellfield extends to about 10 feet below sea level. This depression and the overall lowering of the potentiometric surface is also due to an overall increase in pumpage throughout Volusia County.

The chloride distributions simulated in 2010 with existing wells indicate that additional seawater intrusion is occurring due to increased pumping. Increases in chloride concentration along the Atlantic Coast are greatest near Ormond Beach and New Smyrna Beach. Chloride difference maps were generated by subtracting the 1990 chloride distribution from the 2010 chloride distribution in the Upper Floridan aquifer. The greatest chloride increases occur near Ormond Beach. Chloride concentrations increased from 10 mg/L to 250 mg/L near Ormond Beach, and about 10 mg/L to 50 mg/L in other areas along the coast. Increases in chloride concentrations are observed in the St. Johns River

Valley near high yield springs. Along the Atlantic Coast, especially near New Smyrna Beach, and in the St. Johns River Valley, upconing is responsible for chloride increases.

The second predictive scenario involved redistribution of future pumping between existing and proposed wellfields. The amount of pumping is the same as in the first scenario, with total withdrawals from the Upper Floridan aquifer at about 112 MGD.

Ground-water flow patterns were altered from 1988 conditions in the aquifer system due to pumping of the proposed wellfields. The ground-water ridge in the center of the County has been lowered five to ten feet due to pumping of proposed wellfields near the center of the County, northeast of DeLand.

Key wellfields causing the greatest impacts are Daytona Beach (existing and proposed), Ormond Beach, Port Orange, and New Smyrna Beach. A large depression in the Upper Floridan aquifer formed as result of pumping near Daytona Beach. Pumping in central Volusia County has also produced a cone of depression in the Upper Floridan potentiometric surface. The surficial aquifer is depressed by 5 to 10 ft due to proposed pumping.

The chloride distributions simulated in 2010 with existing and proposed wells are very similar to the first scenario. While the distribution of chloride increases is somewhat different due to redistribution of pumping, the overall pattern and magnitude of chloride increases are very similar. Increases in chloride concentration along the Atlantic Coast are greatest near Ormond Beach, Port Orange, and New Smyrna Beach. Chloride concentrations increased from 10 mg/L to 100 mg/L near Ormond Beach and about 10 mg/L to 50 mg/L in other areas along the coast. Chloride increases are significantly less in certain areas along the Atlantic Coast when compared to the use of existing wells for future pumpage. This is because the use of existing wellfields concentrate pumpage closer to the Coast. Along the Atlantic Coast, especially near Ormond Beach, New Smyrna

Beach, and in the St. Johns River Valley, upconing is responsible for chloride increases. In central Volusia County, there was virtually no change in chloride concentration.

SUMMARY AND CONCLUSIONS

In this study of the ground-water system in the Volusia County, a two-dimensional cross-sectional ground-water flow and chloride transport model was developed to simulate steady-state predevelopment conditions. A calibrated three-dimensional flow and chloride transport model was then developed to examine flow and chloride distributions under predevelopment, 1988, current, and future conditions. Both models simulate ground-water flow in the unconsolidated surficial aquifer and the Floridan aquifer system. The cross-sectional model is a practical learning tool to gain insight about boundary relationships and their impact on the distribution of chlorides in the Floridan aquifer. The three-dimensional model is an up-to-date ground-water flow and chloride transport model to be used for predictive purposes within the context of a Needs and Sources assessment for Volusia County.

The model documented in this report is an extension and enhancement of a previous modeling study. The primary enhancements include the following:

- The present model contains about 10 times more cells than the previous model. Cell spacings were refined down to 0.25 miles around major wellfields to enhance the accuracy of model calculations. Two layers were added to more accurately simulate upconing effects.

- A detailed review of water use in Volusia County resulted in the inclusion of over 14,000 pumping wells in the current model. The previous model contained only major wellfields.

- Recent characterization of the Floridan and surficial aquifer system, especially information from the USGS RASA study.

- Three levels of calibration were performed in the current model for predevelopment and 1988 flow conditions and a transient chloride calibration to 1990 conditions.

Model predictive simulations show the potential for seawater upconing under all pumping scenarios. The model determined that there was a potential for upconing of chlorides along the Atlantic Coast, although these increases are predominantly on the order of 50 to 100 mg/L. Large depressions in the Upper Floridan potentiometric surface enhance the potential for seawater intrusion. Model simulations indicated that seawater intrusion will occur at a slightly accelerated rate during the next 20 years. The amount of seawater intrusion occurring by the year 2010 is greater than the seawater migration over the past 50 years.

Assessing the reliability of a ground-water model is difficult; however, some general statements can be made regarding the reliability of the Volusia County model. In discussing reliability three concepts must be understood, as outlined below:

- Heads and chloride concentrations computed by the model represent average values for a rectangular prism constituting the model cell. The smallest such cells in the Volusia County model are 0.25 miles on each side and generally well over one hundred feet thick. In areas where the model grid is coarse, such as in the southern portion of Volusia County, model predictions are much less accurate due to the scale of the individual cells.

- The model is only as good as the database upon which model assumptions are based.

- Model parameters are representative of bulk regional properties and may not match individual aquifer or laboratory tests in wells.

Another key concept to remember when using or evaluating the Volusia County model is that the model is regional. Thus, the model should be used to solve County-wide problems or to assess flow system response over significant portions of the County. The concept is especially true for the chloride simulations, which are not as accurate as the ground-water flow simulations.

The present model has been shown, through calibration, to reliably simulate hydraulic heads under predevelopment (1955) and recent pumping (1988) conditions. Over the size of a model cell, the model computes heads during these time frames generally within ±3 ft. Considering the size of the model and the range in head across the aquifer system (from 0 ft to 60 ft msl), these are reliable simulations. The fact that the model can simulate flow in the Volusia County ground-water basin under both 1988 and 1955 conditions adds to credibility of the model.

Given that the flow model reliably simulates flow conditions in 1955 and 1988, it is reasonable to assume that the model predictions would also be reliable to ±3 ft in areas where observation wells currently exist. In areas with limited data, such as the south-central and north-eastern parts of the County, model predictions may not be as reliable due to uncertainty regarding aquifer characteristics.

Model predictions of water levels in the surficial aquifer are not as reliable as the Upper Floridan. The surficial aquifer is quite heterogeneous; however, it was treated as a homogeneous layer in the current model. This simplifying assumption was made due to (1) the lack of sufficient calibration targets in the surficial aquifer and (2) the difficulty in simulating a thin unconfined aquifer at a regional scale. In addition, the focus of this study was the Floridan aquifer system. The primary importance of the surficial aquifer is to serve as a source of recharge to the underlying Floridan.

The seawater intrusion or chloride transport model of Volusia County is generally less reliable than the flow model. The primary reasons for this are: (1) the problem of vertical chloride gradients that cannot be predicted when an aquifer such as the Upper Floridan is simulated with one layer, and (2) the problem of numerical dispersion caused by errors in approximating the governing transport equations in the numerical model.

The seawater intrusion model cannot reliably predict chloride concentrations in individual wells. However, the transport model can adequately simulate chloride concentrations and concentration changes at the scale of one or more model cells. The model is especially useful for evaluating the potential for lateral and vertical migration of saline water as outlined in the project scope of work. The model can also be used to reliably choose between pumping alternatives.

The model can predict upconing in regions of heavy municipal pumping. The scale at which the model produces upconing is on a wellfield scale. Individual wells in the model would not produce upconing effects, because drawdowns are averaged over at least a 0.25 mile grid cell. This results in less drawdown than would actually occur at the individual well.

Future data collection activities in Volusia County should focus on areas of greatest uncertainty in the present model. These areas include the following general data types:

- Chloride concentrations with depth within the Floridan aquifer system.
- Transmissivity measurements in areas of proposed wellfields.
- Porosity measurements in the Floridan aquifer system.
- Aquifer testing to determine the vertical hydraulic conductivity of the middle semi-confining unit.
- Metering of individual wells in major wellfields.

Of particular concern to the current model is the nature of the saltwater interface along the Atlantic Coast. The chloride front should be monitored using cluster wells within both the Upper and Lower Floridan aquifers. These wells should be placed along transects running perpendicular to the coast in the vicinity of major wellfields. Additional water level and chloride measurements should be made in the Lower Floridan along the western edge of the County to verify treatment of this model boundary.

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1.0 INTRODUCTION

1.1 BACKGROUND

Volusia County covers an area of about 1,200 square miles (mi^2) in east-central Florida (Figure 1). The county is bounded to the east by the Atlantic Ocean and to the west by the St. Johns River. Ground water from the Upper Floridan aquifer system is the sole source of public water supplies (Kimrey 1990). The thickest zone of fresh ground water is in the central part of the county, in the generally swampy area between DeLand Ridge and Rima Ridge. The Upper Floridan aquifer contains brackish ground water in the St. Johns River Valley, along the Atlantic coast, and to the north in Flagler County (Kimrey 1990).

Intensive ground-water development was first concentrated in the coastal areas where most of the population still resides in the cities of Daytona Beach, Ormond Beach, New Smyrna Beach, and adjacent areas (Kimrey 1990). By the 1950's, saltwater encroachment and growing water needs in the beach areas had resulted in the expansion of the original well fields to the west toward central Volusia County (Kimrey 1990). Additional wellfield sites have been proposed for Daytona Beach, Ormond Beach, and Port Orange.

In 1989, the Florida legislature directed water management districts of the State to undertake a water supply Needs and Sources Assessment. The framework for this program provides for a systematic evaluation of the projected water resource needs and the available resources for the next two decades. In an earlier investigation of the ground-water resources of Volusia County, a three-dimensional ground-water model was developed for regional flow and chloride transport in the county (Mercer 1984). The Geraghty & Miller Modeling Group (GMM) has been retained to develop an updated tool that can be used for the analysis of impacts of current and projected water-supply needs and for more localized analyses of resource management questions. To achieve this objective, a refined ground-water model is being developed to accurately simulate ground-water flow and chloride transport in the Volusia County ground-water basin. The model must incorporate appropriate data regarding existing and proposed wellfields, recharge and discharge areas, land use patterns, and the hydrologic configuration of the surficial aquifer.

1.2 STUDY OBJECTIVES

The primary objective of this study is to develop an up-to-date ground-water flow and chloride transport model to be used for predictive purposes within the context of a Needs and Sources Assessment. Sections 1.2, 1.3, and 1.4 are taken primarily from the contract Scope of Work (SJRWMD 1991a).

The specific objectives of this study are:

1. Incorporate new information regarding the location of recharge/discharge areas, land use patterns, wellfield locations, agricultural and other users, and the hydrology of the surficial aquifer into the ground-water model.

2. Determine the effects of existing and proposed withdrawals from public water supply wellfields on the flow regimes of the Floridan aquifer system.

3. Determine the potential for lateral migration of saline water (> 250 mg/L) from brackish areas within the Floridan aquifer under specified demand scenarios for the years 1990 and 2010.

4. Determine the potential for saltwater upconing within the Floridan aquifer under specified demand scenarios for the years 1990 and 2010.

1.3 TECHNICAL APPROACH

The study is comprised of three primary tasks as follows:

1. Task I involves development of a cross-sectional flow and chloride transport model and preliminary conceptual design of the three-dimensional flow and brine transport model. The cross-sectional model extends from the St. Johns River east to the coastline at Daytona Beach. It is oriented along a southwest-to-northeast streamline, roughly parallel to the direction of flow (Figure 2). This model was used to perform sensitivity analyses for parameters, to interpret boundary conditions for the subsequent three-dimensional model, and to analyze the location and orientation of the saltwater interface based upon the ground-water flow and chloride transport simulations. Sensitivity analyses were performed to determine the density effects upon the flow field and the treatment of the surficial aquifer. A preliminary three-dimensional model grid was designed based on the results of the cross-sectional model analyses.

2. Task II involves development, calibration, and sensitivity analyses of the three-dimensional flow and chloride transport model. The model roughly encompasses the entire Volusia County ground-water basin, and is based upon the earlier model developed by Mercer (1984). The model will incorporate all available information regarding land use, ground-water recharge and withdrawals. The surficial aquifer will be discretized into an active free-surface layer.

3. Task III involves the use of the three-dimensional model to perform predictive assessments and make recommendations regarding potential pumping scenarios and wellfield placements from the time period of 1990 through 2010.

1.4 METHOD OF INVESTIGATION

The Task I modeling study of ground-water flow and chloride transport consisted of the following four distinct phases:

(1) Conduct an intensive literature review and develop a conceptual model of the hydrogeologic system in Volusia County;

(2) Develop a two-dimensional cross-sectional ground-water flow and chloride transport model to establish regional and local ground-water flow conditions through the width of the county;

(3) Perform a sensitivity analysis of boundary conditions, treatment of the surficial aquifer, density effects, and mesh refinement; and

(4) Develop a three-dimensional conceptual model.

The Task II modeling study of ground-water flow and chloride transport consisted of the following four distinct phases:

1. Develop and calibrate a three-dimensional ground-water flow and chloride transport model for the Volusia County ground-water basin. Perform steady-state flow calibrations to represent predevelopment and 1988 flow conditions.

2. Perform a transient transport calibration to represent 1990 conditions.

3. Perform sensitivity analyses to compare the relative response of the ground-water flow system to changes in parameters and boundary conditions.

The Task III modeling study of ground-water flow and chloride transport consisted of the following two distinct phases:

1. Perform predictive simulations to assess current (1990) water use conditions, including assessments of:
   A. The effects of present pumping on the potentiometric surface and water quality of the Floridan aquifer system within the project area;
   B. The potential for lateral migration of saline water within the Floridan aquifer system; and
   C. The potential for vertical upconing of saline water within the Floridan aquifer system.

2) Perform predictive simulations to assess projected (2010) water-use conditions. Analyze two configurations for projected pumping, one with needs met by the existing wellfields and the second with needs met by existing and proposed wellfields. Include assessments of:
   A. The effects of the projected pumping on the potentiometric surface and water quality of the Floridan aquifer system within the project area;
   B. The potential for lateral migration of saline water within the Floridan aquifer system; and
   C. The potential for vertical upconing of saline water within the Floridan aquifer system.

These phases were conducted in a systematic fashion to meet the objectives of the study.

2.0 CONCEPTUAL MODEL

2.1 HYDROGEOLOGIC FRAMEWORK

In this report, the discussion of the geology and structure is limited to a brief discussion of the hydrogeologic framework of the Floridan aquifer and related geologic units. The geology has been described by many investigators including Miller (1986), Tibbals (1990), and Kimrey (1990). Figure 3 summarizes the geologic and hydrogeologic units in the study area and vicinity.

2.1.1 Surficial Aquifer

The uppermost water bearing formation is the surficial aquifer. Throughout the area the surficial aquifer generally consists of fine to medium quartz sands that contain varying amounts of silts, clay, and cemented shell (coquina) (Tibbals 1990). Ground water occurs in the surficial aquifer under unconfined conditions. In the lowlands and flatlands, the water-table is generally at or near land surface throughout most of the year; in the highlands, the water table is generally a subdued reflection of topography (Tibbals 1990).

The surficial aquifer is recharged mainly by rainfall, irrigation, and lakes. Leakage occurs between the Upper Floridan and the surficial aquifer. In areas where the potentiometric surface of the Upper Floridan aquifer is below the water table, there is downward leakage into the Upper Floridan. The opposite occurs when the potentiometric surface of the Upper Floridan aquifer is above the water table and upward leakage occurs from the Upper Floridan (Tibbals 1990). In some areas, the most important function of the surficial aquifer is to store water, some of which recharges the Upper Floridan aquifer (Tibbals 1990).

In Volusia County the surficial aquifer is most suitable as a source of recharge if (1) the depth to the water table is great, (2) the aquifer has a high specific yield, and (3) the thickness of the aquifer is large (Rutledge 1982). The depth to the water table is important because a greater depth will reduce the loss of surficial aquifer water to evapotranspiration. A high specific yield will mean greater storage of water for recharge and less loss of infiltrating water to unsaturated retention. A large surficial aquifer thickness will provide a more consistent source of recharge during periods of drought.

Underlying the surficial aquifer in most of Volusia County is an intermediate confining unit of clay or silty sand of Miocene to Pleistocene age. The confining unit is leaky, but serves to confine water in the underlying Floridan aquifer system under artesian pressure (Phelps 1990). The confining unit is thicker and more aerially continuous in the eastern part of the county than in the west, where in some localities it may be absent (Phelps 1990). In the central and western parts of the county, where the intermediate confining unit is apparently not continuous and mappable, the overlying sediments contain sufficient clay or silt to confine the Upper Floridan in all but a few areas of DeLand Ridge (Phelps 1990). According to Rutledge (1982), in areas such as DeLand Ridge and DeLeon Springs the confining unit may be breached by sinkholes. Cross-sections through Volusia County (Phelps 1990) depict the contact between the surficial and the Upper Floridan to range from 50 to 100 ft below mean sea level (msl).

2.1.2 Floridan Aquifer

The Floridan aquifer system is a sequence of carbonate rocks mostly ranging in age from Paleocene to early Miocene that are hydraulically connected in varying degrees, and whose permeability is generally several orders of magnitude greater than rocks that bound the system above and below (Johnston and Bush 1988). The Floridan aquifer consists of two active permeable zones (the Upper and Lower Floridan aquifers) separated by a zone of low permeability (a middle confining unit) (Miller 1986).

The geologic formations that make up the Floridan aquifer system in Volusia County are, from top to bottom, Eocene rocks comprising the Ocala Limestone, the Avon Park

Formation, and the Oldsmar Formation. Paleocene Rocks of the Cedar Keys Formation generally form the base of the aquifer system. According to Tibbals (1990) the basal parts of the Oldsmar Formation may be of low permeability.

In Volusia County, the Ocala Limestone (late Eocene) is the top of the Floridan aquifer system. Because of extensive erosion after deposition, the formation is very thin in most of Volusia County (Rutledge 1982). The formation is the main source of water for domestic use, but its importance for irrigation is secondary to the Avon Park limestone (Rutledge 1982). The thickness of the Ocala averages about 50 ft, but could be as much as 120 ft in some parts of the county (Wyrick 1960).

The Avon Park limestone (middle Eocene age), next in sequence, is an extensively dolomitized unit (Rutledge 1982). The Avon Park is the principal source of artesian water in the western part of the county, where the Ocala is thin (Wyrick 1960). Wyrick (1960) states that during drilling of the Avon Park, relatively dense impermeable zones were encountered. Wherever these layers are continuous for a considerable distance, they greatly retard upward or downward movement of water between the different permeable zones of the Upper Floridan (Wyrick 1960).

The thickness of the Avon Park limestone ranges from approximately 1,500 ft to 1,800 ft in Volusia County. The middle semi-confining unit ranges in thickness from 200 ft to 400 ft. The top of the semi-confining unit occurs at 350 to 450 ft below msl. The middle semi-confining unit is within the Avon Park limestone.

The Oldsmar Formation (lower Eocene age) underlies the Avon Park in Volusia County. While few wells have been drilled into the Oldsmar, it is thought to contain mostly saline water and is hydrogeologically similar to the Avon Park Formation (Johnston and Bush 1988). The Oldsmar is approximately 500 ft thick in Volusia County. The entire thickness of the Floridan aquifer system ranges from approximately 1,800 ft to 2,300 ft in

Volusia County. The lower parts of the Avon Park and Oldsmar Formations comprise the Lower Floridan.

2.2 HYDRAULIC CHARACTERISTICS

2.2.1 Surficial Aquifer

Phelps (1990) provides laboratory estimated vertical hydraulic conductivities for the surficial aquifer which range from 7.6×10^{-5} to 3.4×10^{-1} feet per day (ft/d) with a median of 1×10^{-2} ft/d. Hydraulic conductivities determined from slug tests ranged from 3×10^{-2} to 12.8 ft/d with a median of 2.9×10^{-1} ft/d (Phelps 1990). Hydraulic conductivities determined from aquifer tests yield values ranging from 28 to 49 ft/d (Phelps 1990). Large ranges in values attained from aquifer tests may be due to variations in saturated thickness and permeability of the surficial aquifer (Phelps 1990). For the purposes of modeling the hydraulic conductivity values determined from aquifer tests are considered to be more reliable. Aquifer test generally provide sufficient stress to the aquifer yielding better estimates of the aquifer permeability. Slug tests generally work best in very low permeability aquifers.

The specific yield can be determined from a method using well hydrograph data to compute recharge entering the system (Phelps 1990). Specific yield ranges between 0.1 and 0.5 (Phelps 1990).

A leakance coefficient, sometimes referred to as vertical leakance, is often used in modeling studies to represent the thickness and vertical hydraulic conductivity of aquitard units. The leakance coefficient is approximated by dividing the vertical hydraulic conductivity by the thickness of the aquitard unit. Tibbals (1990) estimated that leakage coefficient values for the confining unit at the base of the surficial aquifer range from about 1×10^{-6} to 6×10^{-4} inverse days (d^{-1}). Higher values occur where recharge and discharge is greatest and where the confining unit is known to be thin. The confining unit is thin in central and western Volusia County.

2.2.2 Floridan Aquifer

Tibbals (1990) presents model derived transmissivities and aquifer test data for the Upper Floridan aquifer. The average model-derived transmissivity value for the Upper Floridan is about 120,000 ft^2/d; the range is from about 10,000 to about 400,000 ft^2/d in Volusia County (Tibbals 1990). Values derived from aquifer tests in the Upper Floridan range from about 11,000 to 42,000 ft^2/d. Tibbals (1990) suggests that higher transmissivities generally occur near springs. He also explains that model derived transmissivities do not always agree with aquifer test analyses. Model derived transmissivities are generally higher because the wells used in the aquifer tests usually tap less than the full thickness of the Upper Floridan (Tibbals 1990). Transmissivity ranges obtained from a model calibration are considered to have more regional significance than individual test values (Tibbals 1990).

Upper Floridan aquifer tests performed near State Road 44 (Samsula & Glencoe well fields) resulted in transmissivity estimates ranging from 6,870 ft^2/d to 18,847 ft^2/d (Dyer, Riddle, Mills & Precourt, Inc. 1990). A pumping test conducted in the Ormond Beach western wellfield yielded a transmissivity estimate of 10,505 ft^2/d (Jammal & Assoc. 1989). Aquifer tests performed in northeastern Volusia County near National Gardens Trust yielded low transmissivities of about 2,165 ft^2/d (Gomberg 1980).

Only one aquifer test is known to have been conducted in the Lower Floridan. Lichtler (1968) conducted an aquifer test in Orange County and estimated a transmissivity value of 570,000 ft^2/d. Tibbals (1990) estimated a transmissivity range from 30,000 to 60,000 ft^2/d in Volusia County for the Lower Floridan aquifer using a numerical model.

The determination of values for storage coefficients from aquifer tests poses problems similar to those for obtaining transmissivity estimates (Tibbals 1990). Storage values typically range from $5x10^{-4}$ to $1x10^{-3}$ for the Upper Floridan (Tibbals 1990).

Tibbals (1990) estimated the leakage coefficient of the middle semi-confining unit. Calibration of his steady-state predevelopment model led to an estimated a value of $5x10^{-5}$ d^{-1}. Tibbals used a uniform leakage coefficient for the middle semi-confining unit except in the Blue Spring area where a fault through the semi-confining unit is thought to exist. In these nodes, the leakance coefficient was set very high to hydraulically simulate a geologic fault that provides very good hydraulic connection between the Upper and Lower Floridan (Tibbals 1981).

2.3 RECHARGE AND EVAPOTRANSPIRATION

The average annual rainfall (for the period of 1951 to 1980) is about 52 inches in the study area (Tibbals 1990). Typically rainfall is unevenly distributed throughout the area and during the year, the highest amounts typically occurring from June to September.

The potential evaporation ranges from a maximum range of about 46 to 50 in/yr in lowland areas to a minimum range of 25 to 35 in/yr in the highland areas (western Volusia County). Tibbals (1990) explains an estimated function to describe the relationship between depth to ground-water and rate of evapotranspiration. The minimum potential evaporation occurs when the water table depth is 15 ft or greater.

Topography across the Volusia County ground-water basin ranges from 0 to 150 ft, the highest elevations occurring in the DeLand Ridge areas. Here recharge to the aquifer system is high because the water table is approximately 15 to 60 ft below land surface. Recharge in these ridge areas occurs within a range of 10 to 18 in/yr, whereas in terrace areas not in areas of artesian-flow in the Upper Floridan the rate was about 4 in/yr (Phelps 1990). Qualitative mapping of recharge to the surficial aquifer was performed by Vecchioli (1990). This analysis was used as a basis for delineating recharge areas in this modeling study.

2.4 POTENTIOMETRIC SURFACE

The predevelopment (1955) potentiometric surface of the Upper Floridan is depicted in Figure 4 (Rutledge 1985). In the aquifer recharge areas, water leaks down from the surficial aquifer through the confining beds to the Upper Floridan. The process has produced a ground-water ridge near the middle of the County in the Upper Floridan. The water table in the surficial aquifer is thought to follow topography closely except in the highlands where it is more subdued. In the DeLand Ridge area, the gradients are strongly downward from the surficial aquifer to the Upper Floridan. Near the middle of the county, the Upper Floridan recharges the Lower Floridan.

The primary discharge areas are the St. Johns River Valley (including large lakes and springs) and the Atlantic Ocean. Diffuse flow into the St. Johns River is driven by strong upward vertical gradients. Faults are believed to exist all along the St. Johns River valley, most of which have been delineated with sparse well data. The presence of faults could preferentially induce upconing into the St. Johns River. A fault perpendicular to the St. Johns River has been postulated in the area near Lake Woodruff (Johnson 1981). Miller (1986) has determined that at least one large fault zone is present in the St. Johns River Valley in southwestern Volusia County. Miller states, however, that these faults do not appear to effect ground-water flow in the Floridan aquifer system.

Off the coast of Volusia County, the top of the Floridan aquifer is about 80 to 100 ft below sea level and the sea bottom is approximately 60 ft deep. Thus, the materials overlying the Upper Floridan are as thin as 20 ft, allowing for high rates of upward diffuse discharge to the Atlantic Ocean (Tibbals 1990).

2.5 WATER QUALITY

There are two major factors affecting the natural quality of water in the Floridan aquifer. Ground-water moving downgradient through the aquifer system becomes highly mineralized by gradually dissolving rock materials (Tibbals 1990). Ground water quality is also affected by mixing and chemically reacting with highly mineralized water that is in the aquifer at depth, along the Atlantic Coast, and along the St. Johns River Valley (Tibbals 1990).

Most of the highly mineralized water in the Upper Floridan is probably a mixture of freshwater and relict seawater that entered the aquifer during a higher stand of the sea in past geologic time (Tibbals 1990). Brackish water found currently is due to incomplete flushing of ancient seawater. For the purpose of this report, water having a chloride concentration less than 50 mg/L is considered freshwater. Water having a chloride concentration close to 19,000 mg/L is considered seawater and chloride concentrations intermediate between these two extremes is considered brackish.

Chloride concentrations are lowest in areas of greatest recharge to the aquifer system Wyrick (1960) determined the distribution of chlorides in the upper portion of the Upper Floridan during predevelopment conditions (Figure 5). Tibbals (1990) provides contour plots of average chloride concentrations in the Upper Floridan. Concentrations are generally more than 1000 mg/L along the St. Johns River and the Atlantic Coast. Several occurrences of high chloride concentrations in the Upper Floridan ranging from 9,000 to 12,000 mg/L in Volusia County were measured near the St. Johns River and the Atlantic Coast (Tibbals 1990)(Figure 6).

The lateral transition from freshwater to brackish water in the Upper Floridan in Volusia County occurs over distances of one half-mile to several tens of miles (Tibbals 1990). The vertical transition from freshwater to brackish water occurs over intervals as small as a few tens of feet. The additional vertical transition of slightly brackish water to water with a chloride concentration of 10,000 mg/L occurs over distances of a few tens of feet to several hundred feet (Tibbals 1990). Tibbals (1990) depicts the depth to water containing more than 10,000 mg/L chloride ranging from 500 to 1,000 ft below msl (Figure 6). These high concentrations are found in shallow ground water along the St. Johns River and Atlantic Coast. Near the middle of the County the high chlorides occur at the greatest depths.

As described earlier, faults along the St. Johns River were proposed to explain the occurrence of high chloride concentrations in shallow ground water by providing an avenue for upward chloride transport. Tibbals (1990) also states that even if faults do not exist, upward gradients are strong enough to replenish brackish water discharged to the St. Johns River with brackish water at depth (Lower Floridan).

3.0 PREVIOUS MODELING EFFORTS

Numerous modeling studies have been conducted in Volusia County. A brief description of relevant modeling studies is described below.

Bush (1978) calibrated a three-dimensional flow model to the Volusia County ground-water basin. The model consists of 48 columns, 59 rows, and 2 layers. The model extends from the Atlantic Ocean on the east to St. Johns River on the west, and the Volusia County boundaries on the north and south. The upper model layer represents the water-table aquifer and the second model layer represents the Floridan aquifer system. The confining unit above the Floridan aquifer was simulated with a vertical leakance in the model. The model was calibrated to steady-state predevelopment conditions (1955).

Mercer (1984) developed a county-wide flow and chloride transport model for St. Johns River Water Management District (SJRWMD). The model consists of 27 columns, 41 rows, and 3 layers. The model extends from the Atlantic Ocean in the east to St. Johns River in the west, and the Volusia County boundaries in the north and south. Grid cell spacings vary from .5 miles to 3.5 miles. The uppermost model layer represents the surficial aquifer. The Upper and Lower Floridan aquifer is represented by model layers 2 and 3, respectively. A uniform hydraulic conductivity of 0.1 ft/d was used to represent the surficial aquifer. Model layer 2 (Upper Floridan) contains six hydraulic conductivity zones ranging from 68.5 ft/d to 400 ft/d. Model layer 3 (Lower Floridan) contains 2 hydraulic conductivity zones ranging from 75 ft/d to 150 ft/d.

Model boundaries consist of no-flow boundaries surrounding model layers 1 and 3. In the model by Mercer (1984), layer 2 is bounded by constant heads in the east and west, to represent the Atlantic Ocean and St. Johns River, respectively. Both northern and southern edges of the model are no-flow boundaries. Constant chloride boundaries were defined in layer 2 and corresponding to the constant heads. The Atlantic Ocean was defined as a constant chloride source of 1,000 mg/L and the St. Johns River was defined as a 770 mg/L concentration. The bottom of model layer 3 was defined as a constant chloride concentration of 1,000 mg/L.

Mercer (1984), during model calibration to predevelopment conditions determined that the chloride boundary condition beneath the Lower Floridan (layer 3) was a sensitive parameter and that the concentration of 1,000 mg/l was assumed to be a representative value. Constant concentration boundaries in model layer 2 were not sensitive due to the scale of the model and dilution effects (Mercer 1984). The model is not able to accurately predict upconing because density dependent flow was not simulated and the constant concentration boundaries specified at the bottom of the model are not accurately defined. The model simulated a maximum Floridan aquifer thickness of about 1,000 ft. A special boundary condition was developed to simulate brackish water found beneath the middle semi-confining unit of the Floridan aquifer. This boundary behaves like a constant source of chloride, but is a no-flow boundary for ground water. This condition was probably necessary since the full thickness of the Floridan aquifer was not modeled and density dependent flow was not simulated.

In an effort to minimize computational time and memory usage, the confining unit at the base of the surficial aquifer and middle semi-confining unit in the Floridan aquifer were not discretized. Instead, vertical hydraulic conductivities were defined in the surficial and Floridan aquifers to restrict vertical flow in the model. This approach, where confining units are not explicitly discretized, is know as quasi-three-dimensional modeling. The confining unit is represented by a low vertical conductance term between adjacent model layers.

Mercer (1984) performed simulations to examine the effects of future pumping stresses in Volusia County. Mercer (1984) concluded that the surficial aquifer thickness was important, especially regarding its impact on the thickness of the freshwater lens near the DeLand Ridge area. Ground-water leakage from the surficial aquifer is a function of the saturated thickness of the surficial aquifer (Mercer 1984). Mercer (1984) states that the surficial aquifer should be an active free-water surface in any modeling effort. Mercer's (1984) predictive simulations indicate that increased future pumping of existing wells along the Atlantic Coast could lead to water quality degradation.

Tibbals (1990) constructed a regional three-dimensional ground-water flow model in east-central Florida as part of the Regional Aquifer Systems Analysis (RASA) study. The model area is structured to simulate a three-layered system separated by confining units (Figure 3). Vertical resistance to flow between layers is simulated by aerially variable leakage coefficients that characterize the vertical hydraulic conductivity and thickness of the confining units (Tibbals 1990).

Tibbals (1990) describes the model as follows. The model area is subdivided into a finite-difference grid of 24 rows and 50 columns, each of the 1,200 grid blocks is 4 mi on a side and 16 mi^2 in area. The Lower Floridan is modeled with no-flow boundaries around its sides and an impermeable base. All flow into or out of the Lower Floridan (except for pumping) must ultimately flow through the Upper Floridan. Though three aquifer layers are simulated (surficial aquifer, and Upper and Lower Floridan aquifers), only the Upper Floridan is considered calibrated. The overlying surficial aquifer is treated as a constant head (though aerially variable) source-sink layer for leakage to and from the Upper Floridan. The Lower Floridan aquifer system is not considered to be calibrated because of the lack of hydraulic head data for the Lower Floridan. The Lower Floridan aquifer and the middle semi-confining unit act as a leaky basal boundary condition for the Upper Floridan.

4.0 TWO-DIMENSIONAL CROSS-SECTIONAL MODEL

4.1 INTRODUCTION

Current modeling analyses of the ground-water system in Volusia County began with the development of a cross-sectional ground-water flow and chloride transport model. The cross-sectional model simulates the distribution of hydraulic heads in the surficial and Floridan aquifers, the distribution of chlorides, and the rates and directions of ground-water flow. The cross-sectional model has been adjusted to steady-state predevelopment ground-water flow conditions. The cross-sectional model was not calibrated in the traditional meaning of the word. The model was adjusted, however, to match the conceptual model presented in chapter 2. Estimated predevelopment (1955) water levels and chloride concentrations were also used to guide model construction. After a suitable match of the flow model was achieved, sensitivity analyses were performed with the model.

Although the two-dimensional cross-sectional model is not calibrated, it is very important for setting accurate boundary conditions in the three-dimensional model and understanding regional patterns of ground-water flow and brackish water transport. The three-dimensional model accounts for horizontal and vertical movement of ground water and also permits more accurate definition of geologic heterogeneity in the aquifers.

4.2 CODE SELECTION

SWIFT III (Sandia Waste Isolation, Flow and Transport Code)(Reeves 1985) was selected for flow and chloride transport modeling. SWIFT III was not only chosen in order to be consistent with work by Mercer (1984), but more importantly, because:

- it is a public domain code
- it considers variable density
- it is well tested
- it is well-suited for seawater intrusion

SWIFT III (Reeves 1985) is a fully transient, three-dimensional code that solves the coupled equations for transport in geologic media. The processes considered are:

- fluid flow
- heat transport
- density-dependent miscible transport
- solute (trace species) transport

The first three processes are coupled via fluid density and viscosity. Together they provide the velocity field required in the third and fourth processes.

The SWIFT III code is designed to simulate flow and transport processes in both fractured and porous media. The fractured regions are designated as regions where a dual-porosity approach will be implemented. In the fractured regions, two sets of equations are solved, one for the fractures and the other for processes in the matrix. The fracture-porosity equations describing flow and transport for the fractured regions are identical to the equations for the porous zone, except for sink/source terms representing exchange processes with the matrix. Consequently, one general set of equations that applies to both zones is presented. The matrix-porosity equations for the fractured zone differ somewhat from their global counterparts. Therefore, a separate set of equations is developed that are called the "local" set of equations. A variable-density formulation is used throughout the code, so that processes such as seawater intrusion may be simulated with SWIFT. Density, viscosity, porosity, and enthalpy are treated as functions of pressure, temperature, and brine concentration, but not solute (trace) constituent concentrations. For this reason, the flow, heat, and brine (density-dependent transport) equations are termed the primary equations.

In cases where SWIFT III is used to model ground-water flow and solute transport where the solute does not effect the water density, the temperature and brine equations are not included in the formulation. The steady-state solution options allow the simulation of steady-state pressure and brine distributions in one step, thus, avoiding long transient simulations to reach steady-state conditions.

SWIFT III evolved from an earlier code called SWIFT II. SWIFT II was modified to include fractured media and was rewritten in more standard FORTRAN-77. SWIFT evolved from a code developed by the USGS in the mid-1970's called SWIPR. The SWIFT family is one of the most thoroughly documented and tested models available in the public domain.

4.3 MODEL CONSTRUCTION

To simulate regional ground-water flow and chloride transport along the cross-section (Figure 2), GMM developed a finite-difference grid consisting of 200 columns, 1 row, and 10 layers extending nearly 40 miles (Figure 2). The domain of the model extends from the St. Johns River in the southwest to about 12 miles off the Atlantic Coast (near Daytona Beach) in the northeast. In the model grid, cell dimensions along the columns range from 0.125 to 0.5 mi (Figure 7). Smaller grid cells were used around the highest concentrations of brackish water to enhance the computational accuracy of the model.

In the vertical dimension, the aquifer is defined by 10 layers of grid cells (Figure 7). Model layer 1 incorporates the entire saturated thickness of the surficial aquifer. The base of the surficial aquifer is 50 ft below msl (Tibbals 1990). The saturated thickness is computed by the model and is simulated as a free-water surface layer (unconfined). The confining unit directly beneath the surficial aquifer is simulated with a leakage coefficient in a manner similar to Tibbals (1990). Model layers 2 and 3 simulate the Upper Floridan aquifer. A uniform thickness of 350 ft is defined for the Upper Floridan. The base of the Upper Floridan is 400 ft below msl. Model layer 4 simulates the middle semi-confining unit of the Floridan aquifer. The semi-confining unit is set to a uniform thickness of 200 ft. Model layers 5 through 10 simulate the Lower Floridan aquifer. Layer thicknesses range from 200 ft to 300 ft. The base of the model is assumed to be a no-flow boundary 2,000 ft below msl.

The cross-sectional model was finely discretized to achieve a high degree of accuracy in the transport model. The ultimate discretization of the three-dimensional model will be based upon the results of the grid sensitivity analysis.

Model boundaries were chosen to correspond to natural hydrologic boundaries of the physical ground-water flow system. All available information on water levels near the boundaries were used to establish the constant head boundary conditions for the surface water bounding the model. The Atlantic Ocean and the Halifax River were defined as constant heads at an elevation of 0 ft msl and a chloride concentration of seawater (19,000 mg/L)(Figure 8). The swampy areas in the St. Johns River Valley were defined as a constant head at an elevation of 2 ft msl (Figure 8). Constant heads were defined at the edge cells of the model in all deeper layers (first and last columns). Elevations of the Upper Floridan constant heads were estimated using potentiometric surface maps (Wyrick 1960; Johnston and Bush 1988; Bush 1978; and Mercer 1984).

The Lower Floridan constant heads were estimated through model development. Along the Atlantic Coast, the constant heads were defined as 0 ft msl with chloride concentration of seawater (Figure 8). The boundary cells beneath the St. Johns River simulate a small component of regional flow from Lake County entering the St. Johns River Valley. These cells are also sources of chloride at depth. The source concentrations along this boundary range from 1,900 to 12,350 mg/L chloride. Previous investigators simulated the western boundary in the Lower Floridan as a no-flow boundary; however, the analyses performed with the cross-sectional model indicated that a chloride source probably exists along this boundary. A small amount of flow from more inland areas carries brackish water at depth to discharge in the St. Johns River. This approach is also consistent with the conceptual model of Tibbals (1990) as illustrated in Figure 6.

4.4 PARAMETER ESTIMATION

Simulation of steady-state ground-water flow in a SWIFT III model requires the definition of hydraulic conductivity in all layers. Hydraulic parameters were adjusted until a suitable match was achieved with the conceptual model. The surficial aquifer (model layer 1) was set to a uniform horizontal hydraulic conductivity value of 5 ft/d. Table 1 lists the hydraulic parameter used in the cross-sectional model. A uniform vertical hydraulic conductivity was estimated at 0.01 ft/d to be consistent with Mercer (1984). These values fit within the range suggested by Phelps (1990). The Upper Floridan aquifer (model layers 2 & 3) was set to a uniform horizontal and vertical hydraulic conductivity of 225 ft/d and 0.01 ft/d, respectively. This value is within the range of horizontal hydraulic conductivities estimated by Tibbals (1990). Since the cross-sectional model was not calibrated in detail, variable zonation of Upper Floridan was deemed unnecessary.

The middle semi-confining unit (model layer 4) was divided into zones of hydraulic conductivity along the cross section. Horizontal and vertical hydraulic conductivity values of 0.5 and 0.002 ft/d, respectively, were estimated throughout much of the county (Zone 1)(Figure 9). In the area beneath the St. Johns River, the vertical hydraulic conductivity was increased to 0.01 ft/d to account for a probable fault breaching the semi-confining unit (Zone 2)(Figure 9). The same vertical hydraulic conductivity increase was applied to the semi-confining unit extending from the Atlantic coast to the eastern edge of the model under the ocean (Figure 9). This increase helped to induce a slight upward flow from the Lower Floridan through the Upper Floridan to discharge into the Atlantic Ocean. The leakance coefficients computed from the vertical hydraulic conductivity is within the range estimated by Tibbals (1990).

The Lower Floridan aquifer was simulated with a uniform values of 70 and 0.01 ft/d for horizontal and vertical hydraulic conductivity, respectively. The estimate of horizontal hydraulic conductivity correlates well with results from Tibbals (1990) and Mercer (1984).

The upper confining unit above the Upper Floridan is not discretized; rather, the model simulates vertical leakage between the two aquifers with leakance coefficients that account for the vertical hydraulic conductivity and thickness of the aquitard. This type of model discretization, in which aquitards are represented mathematically by leakance coefficients, is known as quasi-three-dimensional. The quasi-three-dimensional approach was only applied to the interface between the surficial and Upper Floridan aquifers. The middle confining unit between the Upper and Lower Floridan aquifers was explicitly discretized.

Three vertical leakance zones were simulated along the cross-section, leakance zone 1 has a value of $8x10^{-5}$ d^{-1} and simulates a majority of the confining unit (Figure 10). The value for leakance coefficient zone 2 is $1x10^{-4}$ d^{-1}, which represents karstic areas where it is suspected that the confining unit is thin to non-existent. This zone is also used to represent the confining unit which may be present off the Atlantic Coast. The third zone represents the area of discharge beneath the St. Johns River. Zone 3 has a value of $3x10^{-3}$ d^{-1}.

Precipitation recharge infiltrating through the vadose zone to the water table (surficial aquifer) is variable across the cross section. Recharge ranges from 0 to 12 inches per year (in/yr). The recharge distribution grades from 0 in/yr in the St. Johns River Valley and the Atlantic Coast to 12 in/yr in the DeLand Ridge area (Figure 11). This recharge zonation was estimated during model construction and agrees with other reported recharge values presented in section 2.3.

Simulation of chloride migration requires the specification of various transport parameters that control the rate of movement and mixing of a contaminant in the subsurface. Advection defines the process of contaminant migration due to the movement of ground water. Dispersion describes the mixing of a contaminant in subsurface due to tortuous, non-ideal flow paths in the aquifer medium.

Simulation of advective transport requires the definition of porosity to compute interstitial ground-water velocities. A uniform value of 25% was specified in the solute transport simulations. This value was estimated by Mercer (1984).

Simulation of Floridan aquifer system concentration fronts from freshwater to brackish water require relatively low longitudinal and transverse dispersivity values. Transverse dispersion (direction normal to flow) is typically less than longitudinal dispersion (direction of flow) by an order of magnitude. Values of longitudinal and transverse dispersivity used in all of the simulations were 25 ft and 2.5 ft, respectively. These are the estimated values from Mercer (1984).

The molecular diffusion coefficient of chloride in the pore fluid is 1.76×10^{-3} ft^2/d (Cussler 1984). Aquifer material tortuosity effects are not included in the diffusion coefficient calculation in order to provide more conservative results.

4.5 RESULTS

The steady-state predevelopment hydraulic head and chloride distribution simulated by the cross-sectional model is shown in Figure 12. The simulated and observed potentiometric surfaces of the Upper Floridan (Figures 4 and 12) are similar in terms of general flow directions and potentiometric levels. Even though this was not a strict calibration, the match is close enough that the model can be used to understand the regional behavior of ground-water flow and brackish water transport. The cross-sectional model can also be used to test boundary conditions to be used in the three-dimensional model.

The steady-state predevelopment chloride distribution simulated by the cross-sectional model is similar to the chloride distribution presented by Wyrick (1960) (Figure 5). The model also agrees in general with Tibbals' (1990) chloride distribution in the Lower Floridan aquifer (Figure 6).

Overall, the cross-sectional model appears to simulate flow and chloride transport as described in the conceptual model of ground-water flow and brackish water transport in Volusia County.

5.0 CROSS-SECTIONAL SENSITIVITY ANALYSES

A sensitivity analysis was performed on the base case cross-sectional model to identify parameters that control the movement of the saltwater front. Sensitivity analyses were performed in which each model parameter in the base case cross-section was increased by ten percent. The results were analyzed by subtracting the base case hydraulic heads and relative chloride concentration in each model cell from the sensitivity simulations. The relative hydraulic heads and chloride differences are summarized by presenting the highest positive difference, highest negative difference, and standard deviation of the differences. A positive difference indicates that the parameter change resulted in a higher relative hydraulic head or chloride concentration. Other sensitivity analyses on the model framework (boundaries, surficial aquifer, discretization, and density effects) are discussed in more qualitative terms.

5.1 HYDROGEOLOGIC PARAMETERS

Table 2 lists a summary of parameter sensitivity trials performed on the cross-sectional model. Hydraulic conductivities were adjusted by aquifer to help identify the most sensitive zones. The analysis determined that the leakance coefficient of the confining unit above the Upper Floridan is the most sensitive model parameter, followed by the hydraulic conductivity of the Upper Floridan. However, the latter parameter is the third most sensitive parameter in terms of the chloride distribution. Changes in the Lower Floridan have a larger impact on the distribution of chlorides.

A ten percent increase in the hydraulic conductivity of the surficial aquifer resulted in small impacts on the hydraulic head and chloride distribution. A ten percent increase in the hydraulic conductivity of the middle semi-confining unit showed little impact on the hydraulic head distribution, but did cause considerable changes in the chloride distribution. Increasing hydrodynamic dispersivity (both longitudinal and lateral) produced almost no change in hydraulic heads, but caused considerable changes in the chloride distribution.

5.2 BOUNDARY CONDITIONS

Model boundary sensitivities were performed to assess the importance of the chloride source defined in the Lower Floridan beneath the St. Johns River, and the extent to which the model should be extended into the Atlantic Ocean. Figure 13 represents the hydraulic head and chloride distribution with a 25% decrease in chloride source concentration along the western model boundary. The simulated concentrations in the Lower Floridan near the western boundary drop to less than 10,000 mg/L. This does not fit well with Tibbals' (1990) conceptual model which depicts higher concentrations of chlorides at depth (Figure 6). Alternatively, a 25% increase in the chloride source concentration may overestimate the chloride concentrations in the Lower Floridan (Figure 14). Thus, chloride concentrations along this boundary are a sensitive model parameter.

During the cross-sectional model development, it was determined that the eastern boundary must be extended far enough for the ocean to properly behave as a sink for the Floridan aquifer. To test the sensitivity of the eastern boundary (Atlantic Coast), the extent of the Atlantic Ocean boundary was reduced approximately 6 miles. Figure 15 depicts the hydraulic head and chloride distribution with the adjusted Atlantic boundary. The boundary change did not significantly change the results from the base case. This sensitivity analysis suggests that the memory requirements can be minimized for the three-dimensional modeling effort by setting this boundary closer to the coast.

5.3 DENSITY EFFECTS

A sensitivity run was performed in which there was no density contrast between seawater and freshwater to determine if density-dependent flow for chloride transport should be simulated. In the base case simulation, the density of freshwater is assumed to be 62.4 pounds per cubic foot (lb/ft^3) and the density of seawater is 63.96 lb/ft^3. Figure 16 depicts the computed hydraulic heads and chloride distribution and clearly illustrates that the freshwater/saltwater interface along the Atlantic boundary is no longer present. Without the density contrast freshwater from inland areas restricts seawater from migrating inland, which is unrealistic. Thus, density effects are necessary to adequately match the conceptual model of chloride transport in Volusia County.

Mercer (1984) concluded that density effects were negligible in previous chloride modeling in Volusia County. It is suspected that their preliminary flow calibration did not incorporate density effects of brackish water, which could explain the insensitivity of density effects in the model by Mercer (1984). In addition, the boundary conditions along the Atlantic Ocean assumed a chloride concentration of only 1,000 mg/L, which is an order of magnitude less than the present study. In contrast to this approach, the preliminary cross-sectional model developed in the GMM study simultaneously simulated ground water flow and chloride transport. Thus, the estimated boundaries properly account for the density contrasts. Laboratory experiments by Schincariol and Schwartz (1990) have determined that chloride concentrations of 1,000 mg/L or greater cause gravitational instabilities at ground-water velocities. Lower Floridan chloride concentrations in Volusia County exceed 1,000 mg/L, therefore, it is expected that density contrasts should be an important factor.

5.4 DISCRETIZATION

The ability to use a coarse finite-difference mesh is desirable in order to reduce the development time of the three-dimensional model and costs required to use the model as a predictive tool. The base case cross-sectional model was highly refined to properly model chloride transport without introducing excessive numerical dispersion due to large grid spacings. Sensitivity analyses presented in this section were designed to determine the maximum coarseness of the model while maintaining adequate accuracy.

Grid coarsening was first attempted in the vertical direction by removing or consolidating layers. The Upper Floridan aquifer was reduced to one model layer and the Lower Floridan was reduced to three model layers yielding a six layer model (Figure 17). The six-layer model was not recalibrated (adjusted) to yield the best possible result. These simulations should be used to gain a general understanding of the effects of a coarser mesh. Results of the 6 layer model are shown in Figure 18. The results are favorable in that coarsening did not drastically effect the chloride resolution of the model.

The model was reduced to a five-layer representation in which the Lower Floridan was simulated with two layers (Figure 19). The hydraulic head and chloride distribution are shown in Figure 20. Some loss of chloride resolution is noticeable but is still reasonable considering the availability of data especially in the Lower Floridan aquifer.

A four layer model was also attempted in which the Lower Floridan was discretized as a single layer (Figure 21). The simulated chloride distribution in the surficial and Upper Floridan aquifers is adversely affected by the coarse Lower Floridan layer (Figure 22). Although no recalibration was attempted, this coarse discretization may prove to be too inaccurate for three-dimensional modeling in Volusia County.

Two simulations were performed to determine the effects of grid spacing in the column direction. The first attempt reduced the number of columns from 200 to 118 by increasing the minimum spacing to 0.25 mi and increasing the grid blocks in the middle of the county to 1 mi spacings (Figure 23). Voss and Souza (1987) state that if longitudinal concentration gradients are low the Peclet number criterion may be violated by more than an order of magnitude. Violation of the Peclet number criterion without introducing significant oscillatory behavior has also been documented by Huyakorn (1983). The Peclet number is defined as

$$P_e = \frac{\Delta X}{\alpha}$$

where Δx is length of the grid cell [L] and α is dispersivity [L]. Normally, the Peclet number should be less than 2.0. The Peclet number is a measure of the amount of local advective transport relative to the local amount of diffusive and dispersive transport. As the Peclet increases finite-difference equations can give values of concentration that oscillate in space. The numerical dispersion computed by SWIFT III is defined as

$$\frac{v\,\Delta x}{2} + \frac{v^2\,\Delta t}{2}$$

where v is the Darcy velocity, Δx is length of the grid cell [L] and Δt is the time step. More detailed discussion of model stability and dispersivity effects are included in the three-dimensional model analyses.

The results of this simulation (118 columns) are depicted in Figure 24. The results are not significantly different from the base case. This suggests that chloride concentration gradients are not that severe to limit the grid cell spacing.

The model was reduced to 107 columns by limiting the use of 0.25 mi grid blocks (Figure 25). Coarsening the model in areas of steeper concentration gradients (St. Johns River and the Atlantic Coast) introduced numerical oscillations. The 107 column SWIFT III model would not converge with a longitudinal dispersivity of 25 ft. Therefore, the longitudinal dispersivity was increased from 25 ft to 50 ft to reduce the Peclet number and regain stability. The larger effective dispersivity appears to have slightly affected the chloride distribution in the Lower Floridan (Figure 26).

Grid sensitivity results provide valuable information to aid in the preliminary design of the three-dimensional model. A combination of these mesh coarsening scenarios will be used in the preliminary three-dimensional model design to further refine the size of the model. Based upon a preliminary estimate, the three-dimensional mesh will probably consist of 5 layers with approximately 100 to 120 columns.

5.5 UPCONING TESTS

The cross-sectional model was tested to determine its potential to simulate lateral saltwater intrusion and upconing of brackish water. Figure 27 shows the location of a hypothetical well field. The well field was implemented in the model as constant head in the Upper Floridan and set to an elevation of 10 ft msl. This produced a hypothetical drawdown in the potentiometric surface of the Upper Floridan aquifer. The steady-state distribution of hydraulic heads and chlorides is shown in Figure 28. The model clearly shows increases in chloride concentrations at depth beneath the well and to the east toward the Atlantic Coast. Thus, the model demonstrates the effect of upconing and lateral migration of brackish water.

The same well was placed in the 5 layer and the 107 column models to ensure upconing and lateral migration of brackish water can be simulated with a coarser grid. The results of these simulations are shown in Figures 29 and 30 and indicate that the coarser models can also simulate upconing and brackish water transport.

5.6 SURFICIAL AQUIFER

In previous studies, the surficial aquifer has been treated either as an active free-water surface (Mercer 1984) or has been fixed as a constant head (Tibbals 1990). A test was designed for the cross-sectional model to determine how the model responds to the two different treatments of the surficial aquifer. The base case cross-sectional model was adjusted so that the final computed hydraulic head distribution in the surficial aquifer was defined as constant heads. The model was then stressed with the hypothetical well described in the previous section. The results of this analysis are shown in Figure 31. The distribution of chlorides is almost identical to the stressed base case model. There are considerable differences in the predicted hydraulic heads in the surficial aquifer. However, if the surficial is simulated as an active layer, the saturated thickness of the layer is reduced due to pumping in the Upper Floridan. The saturated thickness of the surficial has proven to be an important factor in modeling studies by Mercer (1984).

Although the distribution of chlorides seems unaffected by the fixed surficial aquifer, treating the surficial aquifer as an active free water surface enables a more realistic simulation of conditions during pumping periods. Also, the surficial aquifer can be calibrated conceptually to yield confidence in estimated parameters. Fixing the surficial aquifer to a predevelopment head distribution could lead to unrealistic flow between the surficial and Upper Floridan aquifers.

Simulation of direct recharge to the Upper Floridan was not attempted. Previous researchers who have attempted this were required to perform simulations with the surficial aquifer discretized as a layer to estimate flux to the Upper Floridan. Since this is necessary, it seems unreasonable to disregard the surficial aquifer. This technique is also plagued by possible inaccuracies during pumping stresses. Based on this information the surficial aquifer will be treated as originally proposed in the base case model.

6.0 THREE-DIMENSIONAL MODEL

6.1 INTRODUCTION

The three-dimensional ground-water flow and seawater transport model of Volusia County was an extension of the cross-sectional model presented in the previous section. The three-dimensional model consisted of five layers, which was determined in the cross-sectional analyses to be the minimum amount of vertical discretization needed to simulate upconing. The degree of horizontal discretization was based upon the location of major wellfields. Grid spacings of 0.25 miles were used around wellfields to more accurately characterize drawdown and the potential for upconing. The 0.25 mile grid spacing around wellfields was determined by the District (SJRWMD, 1991a).

The three-dimensional model was calibrated three different ways, including the following:

- Steady-state calibration of the flow model to predevelopment (1955) conditions
- Steady-state calibration of the flow model to 1988 conditions
- Transient calibration of the seawater intrusion model to 1990 conditions

The Volusia County ground-water model was developed by first constructing and calibrating a ground-water flow model separate from the seawater intrusion model. The ground-water flow model was calibrated to two different time periods representing predevelopment conditions and conditions in 1988. Both flow calibrations were assumed to be steady-state and utilized equivalent freshwater heads in all boundary conditions (Senger 1990). The MODFLOW code is described below and was used in both flow model calibrations.

After the two flow model calibrations were started, the ground-water flow model was converted to another code (SWIFT III) that simulated ground-water flow and seawater intrusion simultaneously. The seawater (chloride) model was calibrated transiently to 1990 conditions. The seawater calibration and the two flow calibrations continued iteratively until satisfactory results were obtained in all three cases. The iterative calibration approach was necessary because the chloride transport model was found to be sensitive to subtle changes in the ground-water flow model. In addition, a high priority was placed on using the same aquifer properties and boundary conditions for all three calibrations. Thus, any change to one model calibration effected the other two calibrations.

6.2 CODE SELECTION

The modular finite-difference ground-water flow code, also known as MODFLOW, developed by the U. S. Geological Survey (McDonald and Harbaugh 1988) was selected for the ground-water flow model calibrations. MODFLOW is publicly available, widely used, and features extensive documentation. The program is capable of simulating transient or steady-state flow in two or three dimensions for many different types of boundary conditions including specified head, specified flux, and head-dependent flux. MODFLOW simulates ground-water flow using a block-centered, finite-difference formulation. Layers can be simulated as confined, unconfined, or a combination of both. MODFLOW can simulate various external stresses such as extraction or injection wells, areal recharge, evapotranspiration, drains, and streams or rivers. In the program, the finite-difference equations are solved using the strongly implicit procedure, slice-successive overrelaxation, or the preconditioned conjugate gradient method.

All of these features make MODFLOW well-suited for modeling the ground-water flow system in the Volusia County ground-water basin. The multiaquifer system at the site required a code capable of simulating flow in three dimensions. The unconfined surficial aquifer necessitates a code option for simulating a free-water surface. Simulation of boundary conditions required the following options contained in MODFLOW: constant head, head-dependent flux (drain and general head boundaries), and constant flux (recharge and wells) boundary conditions.

SWIFT III (Reeves 1985) was chosen for the seawater intrusion model by the District (SJRWMD 1991a). SWIFT III was the same model used in the previous seawater intrusion model of Volusia County (Mercer 1984). The SWIFT III code has the same basic capabilities as MODFLOW, but can solve the ground-water flow, solute transport, heat transport, and density-dependent flow and transport (seawater intrusion) equations. MODFLOW, on the other hand, can only solve the ground-water flow equation. A description of the SWIFT III code is provided in the cross-sectional model section of this report.

The MODFLOW code was selected for calibration of the Volusia County flow model because it is easier and faster to use than the SWIFT III model. While the SWIFT III model does simulate the ground-water flow system, these simulations require a significant amount of computer time to run and the data input file is cumbersome to work with. It is recommended that the MODFLOW model be used when ground-water flow simulations are required. The SWIFT III model should be used when chloride concentrations must be predicted. A description of the SWIFT III code is supplied in the cross-sectional model analysis section.

6.3 MODEL CONSTRUCTION

6.3.1 Three-Dimensional Grid Design

Computer programs such as MODFLOW and SWIFT III approximate the exact mathematical equation for ground-water flow by numerical discretization techniques. Both MODFLOW and SWIFT III use the method of finite differences to approximate the ground-water flow and solute transport equations. Spatial discretization consists of subdividing the entire model domain into a grid or mesh of smaller blocks or cells. In the discretized system, hydraulic heads and chloride concentrations are computed at the center of each grid block. In general, computational accuracy increases as the number of rows and columns in the grid increase.

In general, the need for computational accuracy in a computer model is greatest in the vicinity of pumping wells, such as the municipal supply wells along the Atlantic coast and central areas within Volusia County. Therefore, a finite-difference mesh normally is designed with smaller grid blocks in areas of interest, grading to larger grid blocks near the edges of the model.

The size of cells and the number of layers used in the three dimensional model were based on the cross-sectional model and grid sensitivity analyses. The cross-sectional model results indicated that the model should be discretized into at least 5 layers to enhance the model's ability to predict the vertical distribution of chlorides and upconing. Greater flexibility is available in the column and row directions. Finer discretization is usually needed in the direction of the steepest concentration gradients (column direction). Since the model is oriented along the Atlantic Coast, the row direction is approximately perpendicular to ground-water flow and chloride transport, allowing for coarser discretization in the row direction.

Minimizing the number of grid cells is extremely important to reducing computational effort and increasing model stability. Prior to construction of the three-dimensional model, additional sensitivity analyses were performed using the cross-sectional model to determine whether a coarser grid could produce results similar to the base case while maintaining the same degree of numerical stability. A major concern, however, was that coarsening of grid cells representing the Atlantic Ocean could result in numerical instability. Cell spacings were varied from 0.25 to 2.5 miles. These analyses indicated that grid cells could be coarsened up to a spacing of one mile with no obvious numerical instability.

The finite-difference grid developed after careful consideration of project goals and numerical stability consists of 86 columns, 91 rows, and 5 layers. The model covers an area approximately 1,850 square miles to simulate regional ground-water flow and chloride transport in three dimensions (Figure 32). The model domain extends from the St. Johns River in the west to about seven miles off the Atlantic Coast in the east. Cell dimensions along the column direction range from 0.25 to 1.5 mi (Figure 32). Cell dimensions along the row direction range from 0.25 to 2.0 mi. Smaller grid cells are used along the Atlantic Coast and in the vicinity of municipal pumping centers to enhance the computational accuracy of the model in these critical areas.

The aquifer is defined by 5 layers of grid cells in the vertical dimension (Figure 3). Layer 1 represents the surficial aquifer. Layer 2 represents the Upper Floridan system. The middle semi-confining unit of the Floridan aquifer is discretized as Layer 3. The lower two layers (4 and 5) represent the Lower Floridan aquifer.

Model layer 1 incorporates the entire saturated thickness of the surficial aquifer. The base of the surficial aquifer is variable, but has an approximate mean elevation of 50 to 60 ft below msl (Tibbals 1990). The base elevations of the surficial aquifer were determined from structural contours shown by Phelps (1990). The base of the surficial aquifer ranges in elevation from 50 to 100 ft below mean sea level (msl), generally shallower in central Volusia County and deeper towards the Atlantic Coast and St. Johns River. Layer 1 is simulated as an unconfined active layer. This approach was also taken by Mercer (1984) in a previous seawater intrusion model of Volusia County. In the Mercer study however, the surficial aquifer was simulated using a very low hydraulic conductivity so that ground-water flow was primarily vertical. In this approach, the surficial aquifer served as a reservoir for recharge to the underlying Floridan. A similar approach was used in the current study, although horizontal flow in the surficial aquifer was also simulated. The saturated thickness of the surficial aquifer ranges from 125 ft near DeLand Ridge to about 60 ft along the Atlantic Coast. The confining unit directly beneath the surficial aquifer is simulated with a leakage coefficient in a manner similar to Tibbals (1990).

Model layer 2 simulates the Upper Floridan aquifer. Unlike the cross-sectional model, the thickness of this layer is variable. The base elevations of the Upper Floridan aquifer were determined from structural contours shown by Tibbals (1990). The base of the Upper Floridan ranges in elevation from 350 to 500 ft below sea level, generally shallower in the northwest, and deeper to the northeast and the southeast. The thickness of the Upper Floridan ranges from 300 ft to 450 ft.

Model layer 3 simulates the middle semi-confining unit of the Floridan aquifer. Tibbals' (1990) analysis was used to delineate the top elevation and thickness of the middle semi-confining unit. Thickness of the middle semi-confining unit ranges from approximately 300 ft to 400 ft.

Model layers 4 and 5 simulate the Lower Floridan aquifer. Tibbals (1990) shows contours of the base of the Lower Floridan which were used to define the base of layer 5. Elevations range from 1,900 to 2,350 ft below msl. The bottom of layer 4 closely mimics the elevation contours of layer 5, but defined at higher elevations. Layer 4 base elevations range from 1,350 ft to 1,700 ft below msl.

6.3.2 Boundary Conditions

6.3.2.1 General Discussion

A variety of boundary conditions were used in the construction of the Volusia County three-dimensional flow model. In general, these boundary conditions include: constant head, constant flux, and head-dependent flux. In a constant head boundary condition, the head remains fixed at a given value throughout all model simulations. Constant head cells were placed in areas where impacts from pumping were assumed to be minimal, such as the eastern edge of the model, located in the Atlantic Ocean. In a constant flux boundary condition, the ground-water flow rate into or out of the model cell is assumed to be constant. Constant flux cells represent wells and recharge in the Volusia

County model. Head-dependent flux boundary conditions, often called mixed-type boundary conditions, are a hybrid between constant head and constant flux. The ground-water flow into or out of a head-dependent flux boundary cell is computed based upon three factors: (1) the head in the cell, (2) the head representing the boundary condition, and (3) a conductance term. Head-dependent flux boundary conditions are used when ground-water must enter or exit the boundary, but the rate is unknown and the head may change with time. Examples of head-dependent flux cells in this model include the western edge of the model and major springs. Table 3 contains generalized boundary condition information.

Heads and chloride concentrations must be specified in both constant heads and head-dependent flux boundary cells. Chloride concentrations are required because this is a seawater intrusion model and density effects are significant. Specification of heads and chloride concentrations in the SWIFT III model is straight forward because density effects are computed by the code. Alternatively, MODFLOW does not consider the impact of fluid density on hydraulic head. Thus, MODFLOW boundary heads are converted to equivalent freshwater heads before specification of the boundary conditions. The following equation is used to compute the equivalent freshwater head for MODFLOW:

$$h_f = h_e + \frac{\rho_s}{\rho_f}(h - h_e)\,C_r$$

Where: h_f = equivalent freshwater head, h = total head, h_e = elevation head at center of the grid block, ρ_s = density of seawater, ρ_f = density of fresh water, and C_r = relative chloride concentration. The relative chloride concentration (C_r) is computed by dividing the actual chloride concentration (mg/L) by the chloride concentration of seawater (19,000 mg/L). This equation is similar to the approach of Senger (1990).

Heads discussed in this section are described as an elevation and associated chloride concentration. The concentration is specified to inform the reader that equivalent heads based on these two parameters were actually used in the MODFLOW flow model and the actual head and concentrations were used in the SWIFT III model. A detailed listing of all boundary conditions, including heads and chloride concentrations are contained in Volume II of this report.

The same boundary conditions were used in all three model calibrations, except for well discharge rates which were variable throughout time. Boundary conditions were chosen, therefore, so that model boundaries would not be sensitive to changes in pumping in the interior of the model.

The model grid and boundary conditions for the MODFLOW ground-water flow model and SWIFT III transport model are identical. Minor differences between the models occur in the implementation of the boundary conditions, however. SWIFT III does not have a true constant head boundary condition; rather, SWIFT III uses an aquifer influence function (AIF) or, in some cases, a pressure limiting well (Reeves 1985). Kipp (1986) provides a detailed discussion of the numerical implementation of the aquifer-influence function boundary type. AIFs and pressure limiting wells can give the same result as constant heads or general heads in MODFLOW.

General head boundary conditions (a type of head-dependent flux boundary described below) and constant heads used in the MODFLOW model were translated as AIFs or rate limiting wells in the SWIFT III model.

6.3.2.2 Constant Head Boundaries

The Atlantic Ocean and the Halifax River were defined as constant heads at an elevation of 0 ft msl in Layer 1. The locations of these constant head cells in Layer 1 are shown in Figure 32. The Atlantic Ocean was specified with a chloride concentration of 19,000 mg/L, which is the average chloride concentration in seawater. The Halifax River was specified with half the concentration of seawater (9500 mg/L). This was based upon discussions with District staff and data collected by the city of Daytona Beach. The St. Johns River was defined by constant heads in the surficial aquifer of the model at an elevation of 1 ft msl (Figure 32).

In the Floridan aquifer system (layers 2 through 5), the eastern boundaries beneath the Atlantic Ocean (edge cells only) were defined as constant heads at elevation 0 ft msl and chloride concentrations range from 9500 to 16,150 mg/L. The finite-difference grid and boundary conditions for Layer 2 are shown in Figure 33. Boundary conditions for Layers 3 through 5 are identical and are shown in Figure 34. Unlike previous modeling studies which used no-flow boundaries (Mercer 1984 and Tibbals 1990), constant heads and general heads were used at the lateral edges of the model in the Lower Floridan to provide a source of ground water and chloride.

The surficial aquifer (Layer 1) contains constant head cells along the edge of the model and in the interior (Figure 32). Miscellaneous lakes within Volusia County in the surficial aquifer were defined with interior constant heads. Elevations for these lakes were determined from USGS topographic maps. Constant heads were also used along the edge of the model in the surficial aquifer to provide inflow into the model from Lake County in the vicinity of Blue Spring. The elevations of these boundaries were determined from topographic maps and surficial hydraulic head estimates from SJRWMD.

Most of the ground-water for Blue Spring is derived from the Floridan aquifer system; therefore, the model was extended to the southwest to enable accurate modeling of spring flow rates discharging from the Floridan aquifer. Extending the model grid to the southwest in the Floridan required that the surficial aquifer also be extended westward. Because the surficial is relatively unaffected by stresses in this area, constant heads were used. The constant heads in the surficial aquifer along the western boundary range from 1 ft msl to about 45 ft msl in the vicinity of Blue Spring (Figure 32).

6.3.2.3 Head-dependent Flux Boundaries

Small creeks were simulated with head-dependent flux (drain) cells in the surficial aquifer (Figure 32). Elevations of these creeks were also estimated from topographic maps.

Three springs were simulated in the model, Ponce De Leon Springs, Blue Spring, and Gemini Springs. Springs were simulated as head-dependent flux boundaries with a specified head of 1 ft msl (Figure 33). The water level elevation of the springs was estimated from topographic maps and from descriptions from Tibbals (1990). The conductance of the head-dependent flux boundary was adjusted during calibration to match spring discharge rates measured in the field.

The western and northern boundaries of the Floridan aquifer system were defined with general head boundaries. A general head boundary is a type of head-dependent flux boundary condition that provides sufficient inflow to the large springs along this boundary while minimizing boundary effects when pumping rates change (McDonald 1988). In the northwest, the general head boundaries provide flow of ground-water from Lake County into the St. Johns River. Simulating this boundary with no-flow conditions could result in detrimental boundary effects which would increase the contribution of ground water from the Volusia County ground-water basin to the St. Johns River in the Floridan aquifer system. This is a potential problem near Blue Spring, where ground water from Lake County contributes to the spring. Simulating the boundary near Blue Spring as a no-flow condition would require that all of the ground water entering Blue Spring comes from the Volusia County ground-water basin. This could lead to prediction of unreasonable ground-water flow in the western region of the model.

Elevations of the Upper Floridan general heads were estimated using potentiometric surface maps (SJRWMD 1991b; Wyrick 1960; Johnston 1988; Bush 1978; and Mercer 1984). In the Upper Floridan aquifer (layer 2), heads along the western boundary range in elevation from 10 ft msl to 31 ft msl. Along the northern boundary general heads range from 2 ft msl to about 30 ft msl. Chloride concentrations along the western boundary range from 0 mg/L to 1,140 mg/L. Chloride concentrations were also defined along the northern boundary to simulate high chlorides as depicted by Tibbals (1990) just north of Lake Disston. Chloride concentrations along this boundary range from 0 mg/L to 2850 mg/L.

As described in the cross-sectional model discussion and by Tibbals (1990), flow from inland areas west of Volusia County carries brackish water at depth to discharge into the St. Johns River and major springs. The general head boundaries make a convenient chloride source boundary to simulate the upconing of chloride into the St. Johns River Valley. This approach was shown to work well in the cross-sectional model analyses.

The general heads found in the middle semi-confining unit and the Lower Floridan aquifer (layers 3,4, and 5) were set by adding 2 ft per layer to Upper Floridan general heads in discharge areas. In recharge areas along the norther and western boundaries, where the model domain includes some of Flagler, Lake, and Seminole Counties no vertical gradient was simulated. Insufficient data exist to estimate the heads along this boundary. The value of 2 ft per layer that was added to some of the Floridan heads at the western boundary was determined during calibration. It was found that lower heads along this boundary did not allow for sufficient influx of chloride to simulate the upconing observed along the St. Johns River.

Chloride concentrations are also specified with depth. The middle semi-confining unit (layer 4) chloride concentrations range from 0 mg/L to 1140 mg/L along the western boundary. Along the northern boundary, the concentration ranges from 0 mg/L to 2850 mg/L. Chlorides defined in the Lower Floridan along the western boundary range from 0 mg/L in layer 4 to 6650 mg/L in layer 5. Concentrations range from 0 mg/L to 2850 mg/L along the northern boundary. These concentrations were determined from the cross-sectional model analyses and calibration of the three-dimensional model.

6.3.2.4 Constant Flux Boundaries

6.3.2.4.1 Well Pumping Data for 1988

Wells were implemented in the model as constant flux boundary conditions. The flow rates for each constant flux cell were computed by adding the pumping rates from all wells located in that cell for a given layer. Pumping rates for wells in Volusia County were determined through a detailed data gathering phase of the project, as described below. The data for pumping rates in Volusia County are contained in Volume II of this report.

Pumping data for this modeling effort were gathered from the St. Johns River Water Management District (SJRWMD), the Volusia County Department of Environmental Management, and through the various individual municipal utility departments. Data were collected for the calendar year 1988, as this was determined, through consultation with District staff, to be a period which was representative of long-term average conditions indicative of a quasi-steady state system.

The majority of the data was obtained from the SJRWMD consumptive use permit (CUP) files. These files are kept for all facilities using wells six inches in diameter or greater, that pump an average of 100,000 gallons per day or more, or have the capacity to pump one million gallons per day. These files include a description of the water use, acreage (for agricultural wells) or population served (for municipal wells), the number of wells, the locations of wells by latitude and longitude, and the permitted withdrawal rate. Actual pumping rates are not recorded, however.

To determine the monthly volumes withdrawn by the various municipal utilities, data were obtained from the monthly operating reports that are filed with the Florida Department of Environmental Regulation. This data is compiled by the SJRWMD for use in their annual water use survey. These reported withdrawal volumes were divided by the number of wells recorded in the CUP files to determine the withdrawal volume for each well. The pumping location for each of the these wells was taken to be the location listed in the CUP files.

For utilities which were not listed in the MORS, an estimate of the per capita usage rate was made by taking the average per capita usage rate over all of the utilities that were listed in the MOR. This average rate was calculated by taking the average of withdrawal rate divided by population served (as listed in the MOR). This usage rate was then used along with the population served listed in the CUP file to make an estimate of the pumping rate. Some discrepancies were found to exist between locations reported in the CUP files and those reported by the utilities. In these cases, corrections were made by the SJRWMD. Table 4 contains a list of all municipal wells used in the model for the 1988 calibration.

For agricultural wells, a crop usage rate was determined by dividing the county wide withdrawal volume per crop by the number of acres devoted to that crop within the county. These crop specific withdrawal volumes were estimated by the SJRWMD with the use of the Blainey-Criddle model. This information was obtained from the 1988 Water Use Survey (Florence 1990). This crop-specific usage rate was then multiplied by the acreage listed in the CUP file to estimate the monthly withdrawal volume. This volume was then divided by the number of existing wells listed in the CUP file, and this pumping rate was associated with the latitude and longitude for each well. In addition to vegetable and fruit crops, this method was also used to make estimates for turfgrass and golf courses.

To confirm these crop usage rates, calculated values were compared to actual measured crop usage rates that were collected during the Benchmark Farms investigation conducted by the SJRWMD (Singleton 1988). Spot checking revealed that the range of agreement between measured and estimated crop specific usage rates was from 98 percent to 44 percent. This wide range indicates the variation in crop usage rates between farms.

The majority of agricultural wells in Volusia county are used for fern irrigation (approximately 70 percent based on the CUP files). In 1990 a fernery acreage inventory was performed by the SJRWMD. Wherever updated data were available, this was the acreage used in the water use estimate. It was the consensus of the SJRWMD that this would be the best estimate of actual acreage.

If no description of water use was available, the permitted yearly withdrawal volume was divided by 12 to estimate the monthly withdrawal volume. This value was then divided by the number of existing wells listed in the CUP file, and this rate was associated with each latitude and longitude. If no yearly withdrawal volume was specified in the CUP file, the permitted daily withdrawal was multiplied by the average number of days in a month (365/12=30.42) to determine a monthly withdrawal volume. Again this volume was divided by the number of existing wells listed in the CUP file, and this was the pumping rate associated with each latitude and longitude.

Where the permit specified the combined use of ground water and surface water, it was considered that 17 percent of the estimated total would be supplied by the surface water source. This is the county wide average of total water use supplied by surface water as listed in the 1988 Water Use Survey (Florence 1990).

If two crops were listed in the CUP file, it was considered that half of the reported acreage was devoted to each crop.

To address wells that were less than six inches in diameter, a copy of the VOLDAT data base was acquired from the Volusia County Department of Environmental Management. This data base was assembled by the United States Geological Survey (USGS), and includes all wells that are less than six inches in diameter. The wells are listed along with location in latitude and longitude, type of use, diameter, casing depth, and total depth. Uses that were considered include public supply, domestic home supply, industrial, and irrigation. Of these various uses, domestic home supply and irrigation accounted for approximately 95 percent of the wells in this database.

Pumping estimates could not be made for the public supply wells since no estimate of population served was included. However, very few of these wells (1.6%) were public supply wells. Pumping estimates also could not be made for the industrial wells due to a lack of description.

Injection wells were assumed to be lawn irrigation wells. An estimate of the pumping rate was made assuming a pump flow rate of 20 gallons per minute, and an average of three one hour watering events per week. This would apply approximately 0.75 inches per week to a lawn 75 ft by 100 ft (7,500 square ft). This value compares well with the irrigation rate for turf grass of 0.6 inches per week as listed in the 1988 Water Use Survey (Florence 1990). Fifty eight percent of these irrigation wells are pumping from the surficial aquifer, thirty nine percent are pumping from the Floridan aquifer, and three percent are pumping from the deep aquifer.

Estimates were made for the domestic home supply wells by assuming that each well served one household, and multiplying the county wide per capita usage rate (120.23 gpd/capita) by the average number of persons per household (2.416). Information on the average number of persons per household for Volusia County was obtained from the United States Bureau of Census in Atlanta, Georgia. Domestic home supply wells were found to be withdrawing from both the surficial and Floridan aquifers.

The above data was tabulated and imported into the numerical model. A complete listing of this data is included in Volume II of this report.

6.3.2.4.2 Well Pumping from 1955 to 1988

Seawater intrusion is a very slow transient process that seldom reaches steady-state conditions. This is especially true of an area such as Volusia County where ground-water pumping increases steadily with time. It was determined, therefore, that the seawater calibration must be a transient calibration starting from predevelopment conditions (which were at steady state) through present conditions (1990). To calibrate the transient chloride transport model, it was necessary to recreate the pumping history from 1955 (predevelopment conditions) to 1990.

Unfortunately, historical pumping data were difficult to obtain. Individual utilities were contacted and total yearly withdrawal volumes were requested along with well locations for wells pumped during each individual year since 1955. For most of the utilities, however, data were available only back to the mid 1970's. Some utilities had data no older than two or three years. Three municipal wellfields (Daytona Beach, Ormond Beach and Port Orange) presented data from the late 1950's or early 1960's. At least on major wellfield (Daytona Beach) was in operation in the mid 1940's.

Smaller wellfields for which historical data was not available, were simulated through time by assuming that pumping followed a straight line from zero in 1940 to published rates in 1988. The assumption that all pumping began in 1940 is based on the fact that municipal withdrawals from the Upper Floridan began sometime in the mid 1940's. Most pumping other than municipal supply was handled in this manner for the transient calibration. Total agricultural pumpage data existed for Volusia County in 1970. This data was used to fit two straight lines, one from 1940 to 1970, and from 1970 to 1988.

The transient chloride calibration was simulated from 1950 to 1990. Starting pumping rates were estimated in 1955 using the approach described above. The pumping rates were updated at ten year intervals (1955,1965,1975,1985) during the simulation.

6.3.2.4.3 Well Pumping from 1990 to 2010

Transient simulations to examine projected pumpage for the period 1990 to 2010 utilized municipal supply rates determined by SJRWMD. The methodology for public supply projections was as follows. For a given municipality, a ratio of the total pumpage for 1989 (from the MOR) and reported population for that municipality in 1989 was calculated.

This ratio was then assumed to remain constant over time and used to calculate an expected MOR in 2010 based upon the 2010 population projection. For smaller municipalities and unincorporated areas, the same procedure was used except the calculated ratio was based upon an unincorporated aggregated population growth estimate for these areas. Tables 5 through 7 list all municipal wells used in the model for 1990 and 2010 simulations.

Review of water use projections by the Institute of Food and Agricultural Sciences revealed that the change in agricultural water use predicted for the period 1950 through 2010 was virtually negligible as compared to 1988 usage. Therefore, agricultural pumpage is assumed to remain constant through 2010.

6.3.3 Parameter Zonation

Hydraulic parameter values are described in this section for the final calibrated model. Many of the parameter values used in the model were estimated through model calibration, which is described in Section 6.4.

Simulation of ground-water flow and chloride transport requires the definition of hydraulic and transport parameters in each model cell. Ground-water flow parameters include horizontal and vertical hydraulic conductivity, vertical leakance, and storage. Chloride transport parameters include porosity, dispersivity, and the diffusion coefficient.

In the modeling approach used in this study, all parameters are defined by zones of equal value. Zones are identified with both an integer number and a parameter value and each cell in the model is assigned a zone number for each parameter. For example, hydraulic conductivity zone 1 is a assigned a value of 20 ft/d in all cells in Layer 1.

The distribution of parameter zones was initially determined from previous modeling studies of Volusia County, primarily those of Tibbals (1990) and Mercer (1984). The distribution and number of zones was subsequently modified during calibration in order to match observed heads and chloride concentrations. Parameter values and zones modified during calibration were checked against published data wherever possible to make sure that parameter values chosen for the model were reasonable.

The following sections discuss the parameters used in the Volusia County model. The first three sections are hydraulic properties (hydraulic conductivity, vertical leakance, and recharge) that are common to both the flow model (MODFLOW) and the chloride transport model (SWIFT III). The last three sections (dispersivity, porosity, and the diffusion coefficient) are transport parameters that are only used in the chloride transport (SWIFT III) model.

6.3.3.1 Hydraulic Conductivity

Active cells in the surficial aquifer (model layer 1) were assigned a uniform horizontal hydraulic conductivity value of 20 ft/d (zone 1). A uniform vertical hydraulic conductivity was set to 0.2 ft/d (zone 1). These values fit within the range suggested by Phelps (1990). It is slightly lower than the range determined through pumping test analyses, but is higher than those estimated from slug tests. While the hydraulic conductivity of the surficial aquifer is variable, as described by Phelps (1990), a uniform value was adequate for the Volusia County model because the surficial was only important as a source of water for the Upper Floridan aquifer. A similar approach was used by Mercer (1984) in the previous seawater model of Volusia County, although only vertical movement of water was simulated in the surficial aquifer in that study.

The Upper Floridan aquifer (model layer 2) was divided into several zones of hydraulic conductivity. The placement of zones was initially based on hydraulic conductivity distributions used in the Tibbals (1990) model and the Mercer (1984) model. These zones were further refined during calibration to achieve a match between observed and calculated water levels. Wherever possible, hydraulic testing information was used to justify the changes in parameter zonation. The areal distribution of hydraulic conductivity zones is depicted in Figure 35 and parameter values are listed in Table 8. Generally, hydraulic conductivity is lower in the central part of the county, and increases towards the Atlantic Coast and near Blue Spring in the St. Johns River Valley.

The distribution and magnitude of the hydraulic conductivity zones are similar to the transmissivity zonation shown by Tibbals (1990). Tibbals (1990) states that the highest transmissivities are usually found near springs. Tibbals also concluded that the transmissivity was low in the center of the county.

Tibbals defined the transmissive properties of the Upper Floridan aquifer in terms of transmissivity, which is the product of the aquifer thickness and hydraulic conductivity. The Volusia County modeling study defined the transmissive properties of the Upper Floridan by explicitly defining the hydraulic conductivity, top elevations, and bottom elevations for each grid cell. This technique was used because the SWIFT III model requires that layer elevations and hydraulic conductivity be defined for each cell rather than transmissivity as in the Tibbals (1990) model. Using this approach, the computed transmissivity can be variable within a single hydraulic conductivity zone.

Hydraulic conductivities in the Upper Floridan range from 5 ft/d to 1500 ft/d for the current study. Transmissivity computed from hydraulic conductivity and layer thickness ranges from about 2500 ft^2/d to 350,000 ft^2/d. In nodes which contain springs, hydraulic conductivities of 3600 ft/d (zone 13, transmissivity of about 900,000 ft^2/d) were specified. Tibbals (1981) estimated a similar transmissivity of 800,000 ft^2/d in large spring nodes.

The magnitude and distribution of hydraulic conductivity zones were determined during model calibration. Aquifer test data were used where available to select appropriate values (Table 9). Hydraulic conductivity zone 12 (5 ft/d) was needed to form the steep hydraulic gradients observed near DeLand. Hydraulic conductivity zones 2 and 6 (30 ft/d and 25 ft/d, respectively) were required to form the broad ground-water high in central Volusia County. Zone 5 (40 ft/d) was used in the northwest corner of the county. Zones

14 and 15 (235 ft/d and 100 ft/d, respectively) were used mainly to reduce the amount of computed drawdown under 1988 pumping conditions near Daytona Beach. Zone 16 (18 ft/d) is a slightly lower permeability zone used form observed drawdowns under 1988 pumping along the Atlantic Coast near Ormond and Daytona Beach. Zone 8 (86 ft/d) represents a transition zone to higher permeability zones and helped to form a natural depression observed in southern Flagler County (Figure 35). Zone 9 (200 ft/d) represents more transmissive areas along the Atlantic Coast and along parts of the St. Johns River Valley. All hydraulic conductivity estimates in the Upper and Lower Floridan aquifers except for spring nodes maintained a 100 to 1 ratio of horizontal to vertical hydraulic conductivity. This vertical anisotropy ratio was determined during model calibration and is consistent with the previous seawater intrusion model of Volusia County (Mercer 1984). In general the permeability zonation agrees with Tibbals (1990); however, in some areas the estimated permeabilities are slightly lower than those estimated by Tibbals. It is not unreasonable that the estimated parameter zonation differs from Tibbals (1990), since there are considerable differences in the model framework (handling of the surficial aquifer and treatment of lateral boundaries) and the finer grid discretization enabled simulation of steep hydraulic gradients in some areas of the model.

The middle semi-confining unit (model layer 3) was divided into 5 zones of hydraulic conductivity (Figure 36, Table 3). Horizontal and vertical hydraulic conductivity values of 0.4 ft/d and 0.04 ft/d (zone 3), respectively, was estimated throughout much of the county (Figure 36). In some areas beneath the St. Johns River, the horizontal and vertical hydraulic conductivity was increased to 0.5 ft/d and 0.05 ft/d, respectively, to account for a probable fault (Miller 1986) breaching the semi-confining unit (Zone 7) (Figure 36). In areas beneath major springs, a higher permeability was used to represent a conduit of flow from the Lower Floridan aquifer to the spring node (zone 11, hydraulic conductivity of 5000 ft/d, 1:1 horizontal to vertical anisotropy). Zones 17 and 18 (0.63 ft/d and 0.01 ft/d, respectively, 10:1 horizontal to vertical anisotropy) were used to regulate discharge of ground water from the Lower Floridan aquifer. Zones 17 and 18 were estimated during the calibration procedure. In order to match hydraulic heads in the Upper Floridan in the vicinity of these two zones, the interaction between the Upper Floridan and the Lower Floridan aquifers needed to be adjusted. Interaction between these aquifers was increased in zone 17 and decreased in zone 18. It was decided to regulate flow through the middle semi-confining unit after all attempts were made to match hydraulic heads using reasonable parameters for the surficial aquifer and Upper and Lower Floridan aquifer permeabilities.

The vertical hydraulic conductivity values for the middle semi-confining unit were estimated during the calibration process. The higher values of vertical hydraulic conductivity were required to achieve a good match between observed and computed spring discharges. The higher values in the probable fault zone were required to allow upconing of chloride beneath the St. Johns River.

Tibbals (1990) simulated the middle semi-confining unit using a leakance coefficient, while the current model explicitly discretized this aquitard. An effective leakance coefficient between the Upper Floridan and Lower Floridan aquifers can be computed for the present model using the layer thicknesses and vertical hydraulic conductivity values. The effective leakance coefficient for zone 3 in the current model is about $8.0x10^{-5}$ d^{-1}. In the vicinity of springs the effective leakance coefficient is about $1.2x10^{-3}$ d^{-1}. These vertical leakance coefficients are similar to those estimated by Tibbals (1990) (Table 9).

The Lower Floridan aquifer was simulated with three values of hydraulic conductivity, 20 ft/d, 55 ft/d, and 40 ft/d (zones 4, 19, and 20 respectively) as shown in Figure 37. The estimate of horizontal hydraulic conductivity correlates well with results from Tibbals (1990) and Mercer (1984) (Table 9). Layers 4 and 5 are identical in terms of hydraulic conductivity zonation.

6.3.3.2 Vertical Leakance

The upper confining unit between the Upper Floridan and the surficial aquifer was not discretized in this model. Rather, the model simulates vertical leakage between the two aquifers with leakance coefficients that account for the vertical hydraulic conductivity and thickness of the confining bed. This type of model discretization, in which aquitards are represented mathematically by leakance coefficients, is known as quasi-three-dimensional modeling. The quasi-three-dimensional approach was only applied to the interface between the surficial and Upper Floridan aquifers.

Twelve leakance coefficient zones were simulated in the upper model layer. Zone 1 has an estimated leakance coefficient of $2.8x10^{-4}$ d^{-1} and simulates a majority of the confining unit where the Hawthorn group is very thin to non-existent (McGurk et al. 1989) (Figure 38, Table 8). The estimated leakance coefficient zone 2 is $6x10^{-5}$ d^{-1}, which represents karstic areas where precipitation recharge is greatest and it is suspected that the confining unit is thin to non-existent. Zone 3 represents river bed conductance for the St. Johns River. The estimated value of zone 3 is $1x10^{-3}$ d^{-1}. Zone 4 is estimated to be $1.9x10^{-3}$ d^{-1}. Zone 6 (0.6 d^{-1}) was used to represent the leakance between the Upper Floridan and the Atlantic Ocean. This leakance coefficient is considerably higher than those used in other areas of Volusia County. During the calibration procedure it was determined that a high value was needed to allow diffuse leakage of groundwater from the Upper Floridan to the Atlantic Ocean. Tibbals (1990) cites some evidence to account for this high leakance coefficient:

> "Off the coast of Volusia County and in the north Merrit Island area, the top of the Floridan aquifer is about 80 to 100 ft below sea level and the sea bottom is at a depth of about 60 ft. Therefore, the materials that overlie the Floridan are as thin as 20 ft. There, conditions are favorable for spring formation or, if the overlying materials are sufficiently permeable, for high rates of diffuse upward leakage. Stringfield (1936) mentioned that a large spring was reported about 16

miles east of the south Volusia County-north Brevard County area. The existence of this spring is not confirmed.

Several investigators have confirmed a submarine spring about 2.5 miles east of Crescent Beach, Flagler County (Stringfield and Cooper 1951, Brooks 1961). Brooks described the spring and took water samples."

Diffuse discharge from the Upper Floridan to the Atlantic Ocean estimated from Tibbals (1990) can not be directly compared with those determined in this study. This is due to differences in the model boundaries (along the Atlantic Coast), such as handling of the freshwater/saltwater interface in the flow model.

Zone 8 has a value of $1.16x10^{-2}$ d^{-1} and is used to allow for diffuse upward leakage. This is the probable cause for the depression near Flagler County. Leakance coefficient zones 5, 10, and 12 occur along the Atlantic Coast and range from $2.8x10^{-5}$ d^{-1} to $1.8x10^{-6}$ d^{-1}. This agrees closely with Tibbals (1990) who estimated leakance coefficients that range from $1x10^{-5}$ d^{-1} to $5x10^{-5}$ d^{-1} near Daytona Beach (Table 9).

6.3.3.3 Recharge

Recharge is technically a constant flux boundary condition. Each cell in the upper model layer (surficial aquifer) receives a constant influx of ground water computed by multiplying the area of the grid cell by the recharge rate. Recharge is discussed under parameter zonation because recharge was defined in the Volusia County model in zones of equal value.

Recharge from precipitation infiltrating through the vadose zone to the water table (surficial aquifer) is variable throughout Volusia County. Recharge is estimated to range from 0 to 14 in/yr (Phelps 1990) (Figure 39). The recharge distribution is generally 0 in/yr to 5 in/yr in lowland areas and 3 to 7 in/yr in eastern highland areas, such as Rima Ridge.

Swampy areas in central Volusia County and near Flagler County were estimated to receive less recharge. In the DeLand Ridge area recharge ranges from 5 to 16 in/yr. These values correlate well with estimated values reported by Phelps (1990) and Vecchioli (1991).

6.3.3.4 Dispersivity

Two primary processes are simulated in the seawater transport model: advection and dispersion. Advection defines the process of contaminant migration due to the movement of ground water. The advective transport term is computed using velocities determined by the flow model. Dispersion describes the mixing of a contaminant in subsurface due to tortuous, non-ideal flow paths in the aquifer medium. Dispersion is simulated using a coefficient known as dispersivity.

The cross-sectional analyses showed that dispersivities between 25 and 50 ft resulted in a good representation of the chloride front. The cross-sectional model had a considerably finer grid spacing than exists in the three-dimensional model, allowing for simulation of low dispersivity values. Higher dispersivity values were used in the three-dimensional model because Peclet numbers were too high using dispersivities from the cross-sectional model.

As mentioned previously, the Peclet number is a measure of the amount of local advective transport relative to the local amount of diffusive and dispersive transport (Voss 1987). When the Peclet number is high (greater than 2 to 10), models can give values of concentration which oscillate in space. In order to avoid oscillatory effects, the dispersivity values are generally increased. A longitudinal dispersivity of 600 ft and a transverse dispersivity of 60 ft provided the best results in the three-dimensional transport model with no numerical instability. Peclet numbers range from 2.2 to 8.8 in the column direction and 2.2 to 17.6 in the row direction of the three-dimensional model.

Another reason for the difference in dispersivity between the cross-section and three-dimensional models is the solution method used in the SWIFT III model. The cross-sectional model contained only 2,000 nodes, which allowed the use of the direct-solver (Reeves 1985). This solver uses significantly more computer memory than an iterative solver, but is generally more stable at higher Peclet numbers. The three-dimensional model contains approximately 40,000 active nodes and the direct-solver became impractical. Simulations required the use of the L2SOR directional solver to conserve memory usage. A disadvantage of the L2SOR solver is instability as the Peclet criterion is violated. A longitudinal dispersivity of approximately 300 ft was found to be the minimum value possible before numerical instability caused non-convergence in the solution. Experimental simulations revealed that a longitudinal dispersivity of 600 ft and a transverse dispersivity of 60 ft provided the best results with no numerical instability.

6.3.3.5 Porosity

Simulation of advective transport requires the definition of porosity to compute interstitial ground-water velocities. A value of 25% was determined to be the base case porosity, and a value 10% was examined to provide a sensitivity analysis of porosity. A porosity of 25% is reasonable for the Floridan aquifer system. Floridan aquifer studies (Navoy 1984, Toth 1985) cite a wide range in porosities averaging to about 23%. Porosity was determined to be the most sensitive transport parameter in the transient analyses.

6.3.3.6 Diffusion Coefficient

The molecular diffusion coefficient of chloride in the pore fluid is 1.76×10^{-3} ft^2/d (Cussler 1984). Aquifer material tortuosity effects are not included in the diffusion coefficient calculation. This allows for maximum chloride spreading due to molecular diffusion to provide more conservative results.

6.4 MODEL CALIBRATION

6.4.1 General Calibration Procedure

Calibration of a numerical ground-water flow model refers to the process of obtaining a reasonable match between observed and simulated water levels. The calibration procedure is generally carried out by varying estimates of hydraulic properties from a set of initial values until the best fit of calculated results to observed water-level calibration targets is achieved. Examples of hydraulic properties that may be varied from a set of initial estimates include hydraulic conductivities, leakance coefficients, and precipitation recharge. Calibration targets are used to evaluate the results generated by the model for a given set of input parameters. Observed hydraulic head data, spring flow measurements, and chloride concentrations are examples of calibration targets used in the Volusia County model.

Calibration of the Volusia County ground-water flow and chloride transport model proceeded iteratively between the three types of calibrations including: (1) steady-state predevelopment (1955) ground-water flow; (2) steady-state ground-water flow representing conditions in 1988; and (3) transient chloride simulations from predevelopment conditions through 1990. Statistical analyses of model residuals were applied to both steady-state flow models. The transient chloride concentration simulations were compared qualitatively to median chloride concentrations measured in the late 1980's and 1990.

A statistical or inverse procedure for hydraulic parameter estimation was used. Inverse algorithms systematically calculate improved parameter estimates that minimize the difference between calculated results and calibration targets. This routine can greatly reduce the time required for model calibration. The fit of the model is checked by calculating a residual head (observed head minus calculated head) at each calibration target. The inverse algorithm attempts to minimize the sum of squares of the residual heads at the calibration targets, and thereby achieves a least-squares fit to the observed data.

The inverse method used to facilitate the predevelopment and 1988 flow model calibration simply provided estimates of parameter values to achieve the best statistical match between observed and calculated water levels with a given model configuration. After each inverse simulation, the model was re-evaluated to determine if the parameter values were reasonable or if there was bias in the computed potentiometric surfaces. Changes were then made to parameter zones and boundary conditions and another iteration of the inverse method was performed.

Whenever changes were made to the flow model, the transient chloride calibration was also re-evaluated to determine the impact of the change on the calibration. While no inverse technique was applied to the chloride calibrations, a visual inspection of the 1990 chloride concentrations was made. The three calibrations continued iteratively until the best possible model of the physical system was achieved.

6.4.2 Predevelopment (1955) Flow Model Calibration

The water-level data used for the calibration of the three-dimensional model were the median water levels measured in monitoring wells during 1955 (provided by SJRWMD and Rutledge 1985). Table 10 lists the water level data used for calibration targets. In the three-dimensional model, calibration targets were assigned to an appropriate layer based on the depth interval of the monitoring well screen.

Three statistics were computed during calibration of the 1955 flow model, including: (1) the sum of squared residuals, (2) the mean residual, and (3) the residual standard deviation. A residual is the difference between observed and calculated head. The inverse calibration technique seeks to minimize the sum of squared residuals and the other two statistics provide a measure of the quality of the calibration. Through experience with numerous modeling studies, Geraghty & Miller has found that a satisfactory goal is to have the residual mean close to zero with a residual standard deviation less than ten percent of the total head change across the model domain.

Figures 40 and 41 depict the model-predicted predevelopment surficial aquifer and Upper Floridan aquifer potentiometric surfaces, respectively. Figure 42 shows the locations of target residuals used to ensure that the predevelopment calibration is acceptable with respect to observed water levels. From a visual perspective, the head distribution in the Upper Floridan agrees with that shown by Rutledge (1985). The ground water ridge in the Upper Floridan potentiometric surface is approximately 40 ft msl in north-central Volusia County as shown by Rutledge (1985). The model predicts a slightly higher and more diffuse ground water ridge (Figure 41). In other areas of the model, especially in the northwest and southern region, the agreement is quite good. The simulated predevelopment surficial aquifer (Figure 40) generally agrees well with the estimated predevelopment surficial aquifer provided by SJRWMD (Figure 43).

Calibration statistics for the predevelopment calibration are well within acceptable limits. The residual mean is close to zero (-0.2 ft) and the residual standard deviation is 7 percent of the total head change across the system (60 ft, including the surficial aquifer). A comparison of 1955 simulated and observed water levels at the calibration targets is shown in Table 11. The predicted water levels are within ±2.5 ft of observed heads at 10 of 18 target locations. The mean residual is 0.2 ft, the standard deviation of the residuals is 4.4 ft, and the residual sum of squares is 346.4 ft^2. Some residuals are quite high, approximately 7 to 9 ft, and may be due to errors in accurately locating the targets within the model domain. Many of the observed water levels were taken from Wyrick (1960), and accurate locations, screened intervals, and median observed water levels (typically used in steady-state calibrations) were not reported. Errors in location, and depth could explain some of the larger residuals, especially in areas of strong horizontal and vertical gradients within the Upper Floridan aquifer. More precise data was used in the 1988 calibration.

Figure 44 is contour plot of model computed recharge and discharge through the top of the Upper Floridan aquifer in inches per year. Positive values indicate recharge to the Upper Floridan aquifer from the surficial aquifer and negative values indicate Upper

Floridan discharge to the surficial. This recharge distribution is generally consistent with estimates by Tibbals (1990) and Vecchioli (1990).

Spring rates computed during predevelopment conditions were compared against observed values reported by Tibbals (1990) as a calibration target. Table 12 provides a summary of observed versus model computed spring rates. Generally the rates compare within 3.8% of observed rates during predevelopment conditions. Simulated predevelopment rates for the following springs are; Blue Spring at 99.1 mgd, Ponce De Leon Springs at 20.1 mgd, and Gemini Springs at 5.4 mgd.

6.4.3 1988 Flow Model Calibration

Calibration statistics for the 1988 calibration are well within acceptable limits. The residual mean is close to zero (0.2 ft) and the residual standard deviation is 5 percent of the total head change across the system (60 ft including the surficial aquifer). A comparison of 1988 simulated and observed water levels at the calibration targets is shown in Table 13. Figures 45 and 46 show residual heads at the target locations for layers 1 and 2 (surficial and Upper Floridan aquifer), respectively. Hydraulic heads in each of the model layers are shown in Figures 47 and 48. Figure 49 is contour plot of model computed recharge and discharge through the top of the Upper Floridan aquifer in inches per year. The predicted water levels are within ±3.5 ft of observed heads at 67 of 88 target locations. The mean residual is 0.2 ft, the standard deviation of the residuals is 3.1 ft, and the residual sum of squares is 862.1 ft^2.

Spring rates computed by the model during 1988 conditions are generally less than predevelopment conditions (Blue Spring at 90.9 mgd, Ponce De Leon Springs at 16.2 mgd, and Gemini Springs at 4.95 mgd) and match observed rates within 1% (Table 12). Lower spring discharge rates are probably caused by increased pumping from the Upper Floridan aquifer.

6.4.4 Transient Chloride Calibration

The transient chloride calibration was performed in two steps. First, the predevelopment chloride transport model was run to provide initial hydraulic head and chloride conditions for the transient simulation. The transient simulation was then run from 1950 to 1990. The calibration was performed by comparing the results after 40 years of transport (1990 conditions) to chloride concentrations measured in monitoring wells in the late 1980s and 1990.

Before using the predevelopment chloride model results as initial conditions for the transient calibration, the predevelopment chloride model was qualitatively calibrated. Basic transport parameters were adjusted until the transport model computed chloride concentrations close to those observed or postulated for predevelopment conditions. Predevelopment chloride measurements were limited; hence, it was determined that a qualitative match to the predevelopment chloride distribution presented by Wyrick (1960) would serve as a calibration guide. The predevelopment chloride distributions in the surficial aquifer and Upper Floridan aquifer are shown in Figures 50 and 51. The chloride distribution in the Upper Floridan aquifer matches the general chloride distribution of Wyrick (1960) (Figures 5 and 51). Chlorides are below 50 mg/L in the center of the County, with chloride increasing to greater than 500 mg/L along the Atlantic Coast and about 2500 mg/L in the Ponce De Leon and Blue Spring areas of the St. Johns River Valley.

The monitoring well data used for the transient calibration of the three-dimensional chloride model were the median chloride concentrations measured in monitoring wells during 1990 and the late 1980's (provided by SJRWMD). Table 14 lists the chloride concentration data used for calibration targets. Because of the high degree of variability associated with water quality analyses through time and due to variability with depth, residual statistics were not used to describe the transient chloride calibration. Rather, a qualitative calibration was performed. Observed chloride concentrations are posted on the model computed chloride concentration distributions, to allow for quick determination of the quality of the fit between observed and computed values.

Figures 52 through 55 depict the 1990 simulated equivalent hydraulic head and chloride distributions in the surficial aquifer and the Upper Floridan aquifer. The chloride distribution is very similar to predevelopment conditions with the exception of some increases in chlorides along the Atlantic Coast and in southwest Volusia County. Figure 56 is a plot of chloride concentration increases relative to predevelopment conditions in the Upper Floridan aquifer for the 1990 calibration. Comparing computed chloride concentration with observed values, indicates that the model matches the general pattern of chloride concentrations throughout Volusia County. Due to the regional nature of the current model, however, isolated high chlorides may not be matched closely. In the southeast portion of the model domain and in the area near Port Orange, there is some disagreement between Wyrick's proposed chloride distribution and model simulated results. Wyrick's chloride distribution represents the uppermost part of the Upper Floridan aquifer, whereas, chloride concentrations computed by the Volusia County model represent average concentrations over the depth interval for a given layer. Thus, chloride concentrations computed in layer 2 represent average chloride concentrations for the entire Upper Floridan aquifer. Localized areas of high chloride concentrations near Port Orange are shallow features which may have formed through seasonal interaction of surface water and groundwater. This phenomena is not easily simulated in a regional seawater intrusion model.

Tibbals (1990) shows chloride concentration maps for both the upper 100 ft of the Upper Floridan and for the entire Upper Floridan. While these two maps are similar, the chloride map for the upper 100 ft of the Upper Floridan exhibits greater variability in chloride concentration. The map of average chlorides, on the other hand, displays contours that roughly parallel the coast in the east and the St. Johns River in the west.

The pattern of chloride concentrations computed by the model is similar to the average chloride map described Tibbals (1990). The chloride target values posted on the 1990 chloride calibration map (Figure 55) represent chloride concentrations from various depth intervals within the Upper Floridan, however. Thus, differences between model-computed and observed chloride concentrations may be related more to depth of sampling than to errors in model construction.

6.5 SENSITIVITY ANALYSES

6.5.1 Flow Model Parameter Sensitivity

The response of the calibrated flow model to changes in recharge, hydraulic conductivity, and boundary conditions was evaluated using a sensitivity analysis. One parameter at a time was varied over a specified range while all other parameters are held constant. Changes in parameters were implemented as increases or decreases by a multiplication factor throughout the entire model. The sensitivity of the model to variations in each parameter was evaluated based on the change in the residual sum of squares from the 1988 calibrated model. Sensitivity graphs were made by plotting the percent change in the parameter versus the percent change in the residual sum of squares (RSS). The validity of the model can be explained by the sensitivity analysis since it indicates which parameters or factors are very important (sensitive). Evaluating the importance of each factor helps determine which data must be defined most accurately and which data are already adequate or require minimal definition (Konikow 1978). Formal sensitivity analyses were performed on all parameter zones, but are only discussed in detail if the change in residual sum of squares exceeded 10%.

The model was found to be most sensitive to changes in recharge. Small changes, increases or decreases, in overall recharge caused large changes in the residual sum of squares (Figure 57).

Hydraulic conductivities were the next most sensitive parameters tested. The hydraulic conductivity zone 1 (surficial aquifer) was determined to be very sensitive (Figure 58). The asymmetry of the curve reveals that the model becomes more sensitive as the parameter is decreased. Hydraulic conductivity zones 2, 5, and 8 moderately sensitive as shown by Figure 58. Hydraulic conductivity zones 9, 14, 16, 17 were the least sensitive to 50% and 100% changes (Figure 59). Vertical hydraulic conductivity of zone 3 in the middle semi-confining unit was moderately sensitive to small changes in the parameter and large increases (Figure 58). This parameter becomes more sensitive to large decreases. Parameter changes to individual zones do not cause very large changes in the residual sum of squares. Individual zone changes only effect the computed heads in the vicinity of the zone and may contain only a few targets.

Sensitivity analyses were performed on all vertical leakance zones; however, zones 1, 2, 4, and 10 were determined to be the most sensitive (Figure 60). Vertical leakance zone 2 was the most sensitive vertical leakance zone, probably due to importance in controlling recharge to the Upper Floridan aquifer from the DeLand Ridge area where vertical flow is significant. Vertical leakance zones 1, 4, and 10 were moderately sensitive to change, but both were more sensitive to decreases in the parameter.

Sensitivity analyses were performed on the general head boundary hydraulic head elevations. In each case, the hydraulic heads were increased and decreased by 5 ft. Within the ranges examined the boundary is relatively insensitive. The residual sum of squares changed by less than 10% during these sensitivity runs.

6.5.2 Transport Parameter Sensitivity

Sensitivity of chloride concentrations to changes in transport parameters (dispersivity and porosity) was analyzed from a limited number of simulations that tested a reasonable range for these parameters. In the first sensitivity run, porosity was decreased to 10 percent from the value of 25 percent used in the calibration. Dispersivity was then increased from

600 ft to 1500 ft to illustrate the effects of increased dispersion. Finally, since the chloride calibration was transient, the effect of storage were examined by increasing storage by a factor of 5, from 0.001 to 0.005.

A porosity of 10% was used to examine the effects of higher transport velocities. Higher velocities yield a higher degree of seawater intrusion. To properly test the effects of porosity, the chloride transport model was run from predevelopment through 1990 conditions. The 1990 chloride distributions in the surficial aquifer and Upper Floridan aquifer for 10% porosity are shown in Figures 61 and 62, respectively. Figure 63 is a plot of chloride concentration increases relative to predevelopment conditions in the Upper Floridan aquifer. Comparing this chloride difference map of 1990 conditions with the 25% porosity difference map (Figures 63 and 56), it is evident that the lower porosity results in somewhat greater amounts of chloride intrusion and upconing effects along the Atlantic Coast. The magnitude of the chloride changes from predevelopment to 1990 are similar for both the 10% and 25% cases, however, the effects extend about one mile further inland in the 10% case.

Dispersivity was varied to show its impact on the computed chloride distribution. Only an increase in the parameter was examined, because large decreases (approximately 50% or less) in dispersivity resulted in instability in the transport model due to an extreme violation of the Peclet number criterion. Thus, a longitudinal dispersivity of 1500 ft and a transverse dispersivity of 150 ft were used in this sensitivity run. Figures 64 and 65 depict the chloride distributions in the surficial aquifer and Upper Floridan aquifer, respectively. Figure 66 is a chloride concentration difference plot in the Upper Floridan aquifer between the large and base case dispersivities in the predevelopment transport model. Comparing these results with base case predevelopment chloride calibration, the higher dispersivities result in increased chloride concentrations on the coastline and reduced chloride concentrations in norther and southern extremes of the model.

The chloride difference maps of the Upper Floridan aquifer show chloride concentrations up to 250 mg/L higher than the base case model along the Atlantic Coast. This phenomenon is caused in part by the interaction of dispersivity and the density effects of seawater. If only pure advective flow existed (no dispersion), chlorides would tend to be highest in lower layers of the model. Convective currents formed by the density contrast between freshwater and saltwater form the S-shaped freshwater/saltwater interface. Increasing the dispersivity, tends to decrease the effects of the density contrast between the two fluids. More chlorides are retained in the upper layers of the model and chlorides do not migrate inland in the lowermost layers. Thus, the density effects become less significant and the saltwater interface becomes more vertical.

Storage, while not a transport parameter, was tested in the transient chloride transport analysis. This analysis was performed to identify the effects of storage on long term transport simulations. The base case value of storage used in the transient 1990 chloride calibration was $1x10^{-3}$. This value was increased to $5x10^{-3}$, and the model rerun from predevelopment through 1990 conditions (30% porosity). The maximum change in chloride due to the increase in storage was only about 5 mg/L. Thus, storage is not a sensitive parameter in long-term transient simulations.

6.6 SURFICIAL AQUIFER

The surficial aquifer (Layer 1) is simulated in this study as an active free-water surface. In earlier modeling studies, the surficial aquifer has been treated either as an active free-water surface (Mercer 1984) or has been fixed as a constant head (Tibbals 1990). Franke (1984) states that the water table is usually conceptualized as a free-surface recharge boundary; however, the water table may also be treated as a specified-head boundary in unstressed steady-state models. In the latter case, the position of the water table is fixed as part of the problem definition (Franke 1984).

There are several problems with treating the surficial aquifer as a constant head layer. The primary problem is that the fixed water table becomes an infinite source of water to the model. Ground-water is recharged into the model at whatever rate is necessary to maintain the specified head in all surficial aquifer cells. The model is then calibrated by adjusting the leakance coefficient between the surficial aquifer and the Upper Floridan (Layer 2) until heads in the Floridan water levels match observed heads. This could result, however, in an unrealistic amount of water recharging the surficial aquifer. An added problem during transient simulations is that the heads in the surficial aquifer will never fluctuate due to changes in pumping or recharge, which is also unrealistic.

There are also problems with treating the surficial aquifer as an active layer. Little is known about the surficial flow system, both in terms of flow system continuity and aquifer properties. By treating the surficial aquifer as a constant-head layer, no calibration is required to obtain a match between observed and calculated heads. In essence, the calculated heads are the observed heads.

In summary, neither method of treating the surficial aquifer in the numerical model is perfect; each method has known problems. The active free-water surface method was used in the current model primarily so that realistic recharge estimates could be input directly into the model and so that water levels in the surficial aquifer could fluctuate in response to pumping during the transient simulations.

A simulation was performed to examine the effects of fixing the surficial aquifer in the 1988 calibrated model. This provides a test to examine the impacts on the Upper Floridan aquifer with an unlimited source of water in the surficial aquifer. Figure 67 shows the 1988 simulated conditions in the Upper Floridan (layer 2) with the fixed surficial aquifer. Figure 48 presents the results of the 1988 calibration in the Upper Floridan using a free-water surface in the surficial aquifer. In an overall sense, the two simulations yield similar results. The greatest difference between the two simulations is observed in south central Volusia County, where the potentiometric high is somewhat greater due to greater amounts of ground-water recharge from the surficial aquifer. A slight decrease in the computed drawdown near Ormond and Daytona Beach occurs as a result of fixing the surficial aquifer.

A second simulation was performed in which the surficial aquifer was removed from the model framework and the computed predevelopment (1955) recharge discharge distribution (Figure 44) was applied as direct recharge and discharge to the Upper Floridan aquifer in the 1988 flow model. Figure 68 depicts the simulated 1988 potentiometric surface in the Upper Floridan aquifer. It is clearly shown from these results that the surficial aquifer acts as a dynamic source/sink for the Upper Floridan aquifer. Increased pumping in 1988 results in increased downward leakage from the surficial aquifer. Fixing the recharge from the surficial during 1955 conditions results in a severely depressed potentiometric surface in the Upper Floridan aquifer.

Since reasonable recharge rates and conductivities are used in the surficial and Upper Floridan aquifers, the model described herein is well constrained with regard to hydraulic parameters and boundary conditions. By fixing the surficial aquifer heads at constant elevations, unreasonable vertical leakage to the Upper Floridan aquifer was observed in certain areas of the model. It was determined, therefore, that the active free-water surface was a better approach than the constant-head approach.

It is evident that more data is needed in this area of the model to better determine the interaction between the surficial aquifer and Upper Floridan aquifer. Researchers should especially study the separation of regional and local flow systems in the surficial aquifer.

7.0 ANALYSIS OF MODEL RESULTS

7.1 PREDEVELOPMENT CONDITIONS

Ground water in Volusia County generally flows radially away from a potentiometric high in the center of the county. Primary discharge areas are the Atlantic Ocean on the east and the St. Johns River on the west. This pattern of flow is evident in both the surficial aquifer and the Floridan aquifer system (see Figures 40 and 41).

Vertical gradients are strongly downward between the surficial and Upper Floridan aquifers, especially in the center of the county. Near Deland, the difference in head between the two aquifers is over 25 feet. Vertical gradients become less pronounced near the discharge areas, where an upward vertical gradient is established from the Upper Floridan into the surficial aquifer.

The strong vertical gradients in the center of Volusia County provide a significant source of fresh water to recharge the Upper Floridan aquifer. This is the driving force that keeps chloride concentrations low in the center of the county. Chloride concentrations increase near the coast due to a natural saltwater wedge (see Figures 50 and 51). Chloride concentrations also increase beneath the St. Johns River, where ground water high in chlorides discharge from the Lower Floridan aquifer through the Upper Floridan aquifer and finally into the surficial system.

To better describe simulated flow conditions in the model a mass balance analysis was performed and is summarized in Figure 69. In general, most of the water in the surficial aquifer is derived from recharge. A considerable amount of the ground-water flow discharges from the Upper Floridan to the surficial aquifer (46 million ft^3/d (mft^3/d)); however, a large percentage of this ground water discharges directly to the Atlantic Ocean and St. Johns River Valley. Much of the ground-water flow in the surficial aquifer leaks down to the Upper Floridan aquifer. The Upper Floridan aquifer recharges the Lower

Floridan to some extent, but there is less communication between the Upper and Lower Floridan aquifers than between the surficial aquifer and Upper Floridan aquifer. This process has produced a ground-water ridge near the middle of the County in the Upper Floridan aquifer (Figure 41).

The primary discharge areas are the St. Johns River Valley (including large lakes and springs) and the Atlantic Ocean. Off the coast of Volusia County, the top of the Floridan aquifer is about 80 to 100 ft below sea level. Thus, the materials overlying the Upper Floridan are as thin as 20 ft (Tibbals 1990). This allows for high rates of upward discharge to the Atlantic Ocean. Flow entering the east and west lateral boundaries of the Lower Floridan aquifer generally exits the model as upward flow into the St. Johns River Valley or the Atlantic Ocean. These lateral flow boundaries also act as chloride sources for the model.

The steady-state predevelopment chloride distribution simulated by the three-dimensional model agrees in general with the chloride distribution presented by Wyrick (1960) (Figures 5, 50, and 51). Chloride concentrations are lowest in areas of greatest recharge to the aquifer system. Chloride concentrations increase to more than 1,000 mg/L along the St. Johns River Valley and increase from 500 mg/L to 1000 mg/L in some areas along the Atlantic Coast.

There is a high degree of uncertainty in the Lower Floridan aquifer flow system. Data do not exist to accurately define hydraulic head or chloride concentration boundary conditions. Undoubtedly, more data is necessary to improve the model in this area. Overall, the model appears to simulate flow and chloride transport as described in the conceptual model of ground-water flow and chloride transport in Volusia County.

7.2 1988 CONDITIONS

The steady-state flow calibration performed for 1988 conditions differed from the predevelopment simulation through the introduction of 1988 estimated ground-water withdrawals for water supply. About 75 million gallons per day (MGD) was pumped from the Upper Floridan aquifer in Volusia County in 1988. The overall effect of this pumping has been a decrease in head in the Upper Floridan of about 5 to 8 feet in the center of the county. The north-south trending ground-water divide has also shifted about 1.5 to 2 miles to the west in response to pumping along the Atlantic coast.

A flow balance analysis, shown in Figure 70, illustrates that the overall flow system behaves similarly to predevelopment flow conditions. The 10 million ft^3/d (mcfd) of pumping from the Upper Floridan is offset by a net increase of about 1 mcfd in upward leakage from the Lower Floridan. About half of the Upper Floridan withdrawals (5 mcfd) are offset by a net increase in downward leakage from the surficial aquifer. The latter also includes a decrease of 2 mcfd in discharges to the St. Johns River and Atlantic Ocean. Lateral inflow from the Atlantic Ocean increased by only 0.4 mcfd, or about 4 percent of total ground-water withdrawals.

Overall, pumping in Volusia County has depressed the potentiometric surface in the surficial aquifer and the Upper Floridan (Figures 47 and 48). Pumping is highest near Ormond Beach, Daytona Beach and New Smyrna Beach. It should be noted that pumping in Volusia County does not exceed overall recharge into the model domain or the amount of ground-water flow in the Upper Floridan aquifer. Therefore, lateral saltwater intrusion should not become a severe problem in inland areas.

7.3 1990 CONDITIONS

Ground-water flow patterns and chloride concentrations did not change significantly in the aquifer system between 1988 and 1990. The hydraulic head distributions during 1990 conditions are shown in Figures 52 and 53. The only noticeable changes in the potentiometric surface is in the direct vicinity of the Daytona Beach wellfield where drawdowns are increased slightly. Minor decreases in the surficial aquifer are also seen in this area.

The distribution of chloride in the Upper Floridan changed only subtly from predevelopment conditions through 1990, as shown by comparing Figures 51 (predevelopment) and 55 (1990). In fact, the changes were so slight that direct comparison of the chloride contours for both simulations is difficult. Thus, chloride difference maps have been prepared to make the comparison of chloride changes more straightforward. A chloride difference map for the Upper Floridan between predevelopment and 1990 conditions is shown in Figure 56.

The greatest increases in chloride concentrations from predevelopment to 1990 occur beneath the Atlantic Ocean on the east and the St. Johns River on the west. The largest increases on the east are about 10 to 100 mg/L near the pumping centers of South Daytona Beach and New Smyrna Beach. Increases in this area are characterized by curved chloride difference contours, which are indicative of upconing effects. Upconing refers to a local rise of the interface in an aquifer. This generally occurs when an aquifer contains an underlying layer of saline water and is pumped by a well penetrating only the upper freshwater portion of the aquifer (Todd 1980). Lateral intrusion is basically the landward migration of the interface usually in response to strong pumping in a confined aquifer. Ideally upconing processes are identified by closed (circular) chloride difference contours. Changes in chloride concentrations in Volusia County are very small. Chloride distributions and difference plots in the lower layers of the model do not indicate whether upconing or intrusion processes are predominant. The greater thicknesses of these layer may be averaging out minor changes in the interface. Concentration difference plots of the Upper Floridan aquifer reveal the most valuable information regarding the amount and location of chloride increases. The greatest impact appears to be from upconing of chloride from the Lower Floridan aquifer. The chloride difference plot reveals that upconing processes are occurring along the Atlantic Coast particularly near South Daytona and New Smyrna Beach (Figure 56).

Rutledge (1985) used chloride change ratios to determine whether current chloride concentrations in the Upper Floridan were due to seasonal variations or seawater intrusion. Chloride change ratios are defined as follows:

$$\text{Chloride concentration change ratio} = \frac{F(C_n - C_t)}{\frac{C_n + C_t}{2}}$$

Where: C_n = chloride concentration now (current conditions), in mg/L, C_t = chloride concentration then (predevelopment), in mg/L, and $F(C_n-C_t) = C_n-C_t-10$, if C_n-C_t is greater than +10; $F(C_n-C_t) = C_n-C_t+10$, if C_n-C_t is less than -10; $F(C_n-C_t)$ = zero, if C_n-C_t falls in the -10 to +10 range. Chloride change ratios (defined by Rutledge 1985) range from about 0.02 to 0.2. Rutledge (1985) determined that chloride change ratios typically range from -0.5 to 0.5 along the Atlantic Coast in Volusia County. Increases in chloride concentrations are observed in the St. Johns River Valley near major springs (Figure 56). In central Volusia County, there was virtually no change in the chloride distribution from predevelopment through 1990 conditions. All chloride increases are attributed to pumping withdrawals in Volusia County.

7.4 PREDICTIVE SIMULATIONS

7.4.1 Existing Wellfields

The first predictive scenario distributed increased future water demand to existing wellfields. By the year 2010, the total pumping from existing wellfields increased by about 50 percent from 75 MGD to 112 MGD. The hydraulic head distributions during 2010 conditions are shown in Figures 71 and 72. The ground-water flow system is similar to that produced in 1988, but depressed due to greater pumping. The ground-water ridge in the center of the County has been lowered about 5 feet to an elevation of about 30 feet msl. The ground-water divide in the Upper Floridan aquifer has shifted about one mile to the west compared to 1988 conditions. The surficial aquifer also shows decreases 5 ft or more in the Daytona Beach area.

The Daytona Beach, Ormond Beach, New Smyrna, and Port Orange wellfields appear to have the greatest impact on the flow system, forming large cones of depression in the Upper Floridan aquifer. The cone of depression around the Daytona Beach wellfield extends to about 10 feet below sea level. This depression and the overall lowering of the potentiometric surface is also due to an overall increase in pumpage throughout Volusia County.

The chloride distributions simulated in 2010 with existing wells indicate that additional chloride increases are occurring due to increased pumping (Figures 73 and 74). Chloride changes along the Atlantic Coast are greatest near Ormond Beach and New Smyrna Beach. Chloride difference maps were generated by subtracting the 1990 chloride distribution from the 2010 chloride distribution in the Upper Floridan aquifer (Figure 75). The greatest chloride increases occur near Ormond Beach (Figure 75). Chloride concentrations increased from 10 mg/L to 250 mg/L near Ormond Beach, and about 10 mg/L to 50 mg/L in other areas along the coast. Increases in chloride concentrations are observed in the St. Johns River Valley near high yield springs (Figure 75). Along the

Atlantic Coast, especially near New Smyrna Beach, and in the St. Johns River Valley, upconing is responsible for chloride increases.

The mass balance analysis shows similar flow trends as seen in the 1988 analysis (Figure 76). Large increases in pumpage (approximately 5 mcfd) in the Upper Floridan have enhanced downward leakage from the surficial aquifer and decreased downward leakage from the Upper Floridan aquifer. There is no difference in the lateral inflow from the Atlantic Ocean into the Upper Floridan aquifer between 1988 and 2010. Thus, the increased pumping in the Upper Floridan is countered by enhanced vertical flow. Therefore, most of the changes in chloride concentrations between 1988 and 2010 are probably due to upconing from the Lower Floridan aquifer.

7.4.2 Proposed and Existing Wellfields

The second predictive scenario involved redistribution of future pumping between existing and proposed wellfields. The amount of pumping is the same as in the first scenario, with total withdrawals from the Upper Floridan aquifer at about 112 MGD.

Ground-water flow patterns were altered from 1988 conditions in the aquifer system due to pumping of the proposed wellfields. The hydraulic head distributions during 2010 conditions are shown in Figures 77 and 78. The ground-water ridge in the center of the County has been lowered five to ten feet due to pumping of proposed wellfields near the center of the County, northeast of DeLand.

Key wellfields causing the greatest impacts are Daytona Beach (existing and proposed), Ormond Beach, Port Orange, and New Smyrna Beach. A large depression in the Upper Floridan aquifer formed as result of pumping near Daytona Beach (Figures 77 and 78). The Daytona Beach cone of depression is similar in magnitude to the depression produced in the first scenario (about 10 ft below sea level); however, the size of the cone of depression is smaller due to redistribution of pumping. Pumping in central Volusia

County has also produced a cone of depression in the Upper Floridan potentiometric surface. The surficial aquifer is depressed by 5 to 10 ft due to proposed pumping.

The chloride distributions simulated in 2010 with existing and proposed wells are very similar to the first scenario (Figures 80 and 81). While the distribution of chloride increases is somewhat different due to redistribution of pumping, the overall pattern and magnitude of chloride increases are very similar (Figure 82). Chloride increases along the Atlantic Coast are greatest near Ormond Beach, Port Orange, and New Smyrna Beach. Chloride concentrations increased from 10 mg/L to 100 mg/L near Ormond Beach and about 10 mg/L to 50 mg/L in other areas along the coast. There is significantly less change in chloride concentration in certain areas along the Atlantic Coast when compared to the use of existing wells for future pumpage. This is because the use of existing wellfields concentrate pumpage closer to the Coast. Along the Atlantic Coast, especially near Ormond Beach, New Smyrna Beach, and in the St. Johns River Valley, upconing is responsible for chloride increases. This conclusion is supported by the increase in vertical flow between the Upper and Lower Floridan, as previously discussed. In central Volusia County, there was virtually no change in chloride concentration.

Examination of the mass balance analysis shows similar flow trends as seen in the first 2010 scenario using only existing wells (Figure 82). Since overall pumpage is similar, there is no significant change in model fluxes between aquifers from the previous discussion.

8.0 SUMMARY

8.1 GENERAL SUMMARY

In this study of the ground-water system in the Volusia County, a two-dimensional cross-sectional ground-water flow and chloride transport model was developed to simulate steady-state predevelopment conditions. A calibrated three-dimensional flow and chloride transport model was then developed to examine flow and chloride distributions under predevelopment, 1988, current, and future conditions. Both models simulate ground-water flow in the unconsolidated surficial aquifer and the Floridan aquifer system. The cross-sectional model is a practical learning tool to gain insight about boundary relationships and their impact on the distribution of chlorides in the Floridan aquifer. The three-dimensional model is an up-to-date ground-water flow and chloride transport model to be used for predictive purposes within the context of a Needs and Sources assessment for Volusia County.

The model documented in this report is an extension and enhancement of a previous modeling study by Mercer (1984 and 1987). The primary enhancements include the following:

- The present model contains about 10 times more cells than the previous model. Cell spacings were refined down to 0.25 miles around major wellfields to enhance the accuracy of model calculations. Two layers were added to more accurately simulate upconing effects.

- A detailed review of water use in Volusia County resulted in the inclusion of over 14,000 pumping wells in the current model. The previous model contained only major wellfields.

- Recent characterization of the Floridan and surficial aquifer system, especially information from the USGS RASA study (Tibbals 1990) and from Phelps (1990), was included in the present model.

- Three levels of calibration were performed in the current model for predevelopment and 1988 flow conditions and a transient chloride calibration to 1990 conditions.

Model predictive simulations show the potential for seawater upconing under all pumping scenarios. The model determined that there was a potential for upconing of chlorides along the Atlantic Coast, although these increases are predominantly on the order of 50 to 100 mg/L. Large depressions in the Upper Floridan potentiometric surface enhance the potential for chloride increases. Model simulations indicated that seawater intrusion will occur at a slightly accelerated rate during the next 20 years. The amount of seawater intrusion occurring by the year 2010 is greater than the seawater migration over the past 50 years.

8.2 MODEL RELIABILITY

Assessing the reliability of a ground-water model is difficult; however, some general statements can be made regarding the reliability of the Volusia County model. In discussing reliability three concepts must be understood, as outlined below:

- Heads and chloride concentrations computed by the model represent average values for a rectangular prism constituting the model cell. The smallest such cells in the Volusia County model are 0.25 miles on each side and generally well over one hundred feet thick. In areas where the model grid is coarse, such as in the southern portion of Volusia County, model predictions are much less accurate due to the scale of the individual cells.

- The model is only as good as the database upon which model assumptions are based.

- Model parameters are representative of bulk regional properties and may not match individual aquifer or laboratory tests in wells.

Another key concept to remember when using or evaluating the Volusia County model is that the model is regional. Thus, the model should be used to solve County-wide problems or to assess flow system response over significant portions of the County. The concept is especially true for the chloride simulations, which are not as accurate as the ground-water flow simulations.

The present model has been shown, through calibration, to reliably simulate hydraulic heads under predevelopment (1955) and recent pumping (1988) conditions. Over the size of a model cell, the model computes heads during these time frames generally within ±3 ft. Considering the size of the model and the range in head across the aquifer system (from 0 ft to 60 ft msl), these are reliable simulations. The fact that the model can simulate flow in the Volusia County ground-water basin under both 1988 and 1955 conditions adds to credibility of the model.

Given that the flow model reliably simulates flow conditions in 1955 and 1988, it is reasonable to assume that the model predictions would also be reliable to ±3 ft in areas where observation wells currently exist. In areas with limited data, such as the south-central and north-eastern parts of the County, model predictions may not be as reliable due to uncertainty regarding aquifer characteristics.

Model predictions of water levels in the surficial aquifer are not as reliable as the Upper Floridan. The surficial aquifer is quite heterogeneous, as reported by Phelps (1990); however, it was treated as a homogeneous layer in the current model. This simplifying assumption was made due to (1) the lack of sufficient calibration targets in the surficial aquifer and (2) the difficulty in simulating a thin unconfined aquifer at a regional scale. In addition, the focus of this study was the Floridan aquifer system. The primary importance of the surficial aquifer is to serve as a source of recharge to the underlying Floridan.

The seawater intrusion or chloride transport model of Volusia County is generally less reliable than the flow model. The primary reasons for this are: (1) the problem of vertical chloride gradients that cannot be predicted when an aquifer such as the Upper Floridan is simulated with one layer, and (2) the problem of numerical dispersion caused by errors in approximating the governing transport equations in the numerical model.

The seawater intrusion model cannot reliably predict chloride concentrations in individual wells. However, the transport model can adequately simulate chloride concentrations and concentration changes at the scale of one or more model cells. The model is especially useful for evaluating the potential for lateral and vertical migration of saline water as outlined in the project scope of work (SJRWMD 1991a). The model can also be used to reliably choose between pumping alternatives.

The model can predict upconing in regions of heavy municipal pumping. The scale at which the model produces upconing is on a wellfield scale. Individual wells in the model would not produce upconing effects, because drawdowns are averaged over at least a 0.25 mile grid cell. This results in less drawdown than would actually occur at the individual well.

8.3 FUTURE DATA COLLECTION

Future data collection activities in Volusia County should focus on areas of greatest uncertainty in the present model. These areas include the following general data types:

- Chloride concentrations with depth within the Floridan aquifer system.
- Transmissivity measurements in areas of proposed wellfields.

- Porosity measurements in the Floridan aquifer system.
- Aquifer testing to determine the vertical hydraulic conductivity of the middle semi-confining unit.
- Metering of individual wells in major wellfields.

Of particular concern to the current model is the nature of the saltwater interface along the Atlantic Coast. The chloride front should be monitored using cluster wells within both the Upper and Lower Floridan aquifers. These wells should be placed along transects running perpendicular to the coast in the vicinity of major wellfields. Additional water level and chloride measurements should be made in the Lower Floridan along the western edge of the County to verify treatment of this model boundary.

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Table 1. Summary of the cross-sectional model parameter zonation.

Parameter Type	Zone Number	Value
Hydraulic Conductivity	Surficial aquifer	5 ft/d
Hydraulic Conductivity	Upper Floridan aquifer	225 ft/d
Hydraulic Conductivity	Middle Semi-confining	0.5 ft/d
Hydraulic Conductivity	Lower Floridan aquifer	70 ft/d
Vertical K	Surficial aquifer	0.01 ft/d
Vertical K	Upper Floridan aquifer	0.01 ft/d
Vertical K	Middle Semi-confining(1)	0.002 ft/d
Vertical K	Middle Semi-confining(2)	0.01 ft/d
Vertical K	Lower Floridan aquifer	0.01 ft/d

Table 2. Summary of the cross-sectional model parameter sensitivity analyses.

Aquifer	*Minimum Residual*	*Maximum Residual*	*Standard Deviation*
Hydraulic Heads			
Hydraulic Conductivity			
Surficial	-0.93	0.18	0.06
Upper Floridan	-1.71	0.43	0.37
Lower Floridan	-0.17	1.13	0.20
Vertical Leakance			
Upper Confining Unit	-18.89	3.27	2.18
Semi-Confining Unit	-0.31	0.11	0.06
Dispersivity			
Model Domain	-0.16	0.31	0.08
Chloride Concentrations			
Hydraulic Conductivity			
Surficial	-27.41	74.40	9.68
Upper Floridan	-363.70	1039.09	206.16
Lower Floridan	-2248.70	150.10	243.06
Vertical Leakance			
Upper Confining Unit	-1238.56	5077.40	869.57
Semi-Confining Unit	-152.38	575.50	57.42
Dispersivity			
Model Domain	-408.40	885.60	132.84

Residual = Sensitivity - Base Case

Table 3. Boundary condition summary.

Surficial aquifer

Location	Boundary Type	Head	Chloride
West	Constant Head	1 to 45 ft	0 mg/L

Upper Floridan aquifer

Location	Boundary Type	Head	Chloride
West	General Head	10 to 31 ft	0 to 1140 mg/L
East	Constant Head	0 ft	9500 to 16150 mg/L
North	General Head	2 to 30 ft	0 to 2850 mg/L

Middle Semi-Confining unit

Location	Boundary Type	Head	Chloride
West	General Head	12 to 31 ft	0 to 1140 mg/L
East	Constant Head	0 ft	9500 to 16150 mg/L
North	General Head	4 to 32 ft	0 to 2850 mg/L

Lower *Floridan aquifer*

Location	Boundary Type	Head	Chloride
West	General Head	14 to 32 ft	0 to 6650 mg/L
East	Constant Head	0 ft	9500 to 16150 mg/L
North	General Head	7 to 33 ft	0 to 2850 mg/L

Table 4. 1988 municipal pumpage used in the calibrated three-dimensional model (all rates in cubic feet per day).

Municipality	Number	State Planar Coordinates X Coord	Y Coord	Rate
DELAND	2-127-001	404038.2	1707249.0	72343.60
WATER UTILITY	2-127-001	401994.1	1706345.0	72343.60
	2-127-001	401021.6	1707863.0	72343.60
	2-127-001	401110.3	1707863.0	72343.60
	2-127-001	397832.1	1710195.0	72343.60
	2-127-001	407504.8	1709059.0	72343.60
	2-127-001	402196.0	1715738.0	72343.60
	2-127-001	396406.1	1708077.0	72343.60
HOLLY HILL	2-127-002	484939.9	1784396.0	2274.80
EASTERN WF	2-127-002	485117.0	1784093.0	2274.80
	2-127-002	485294.0	1783689.0	2274.80
	2-127-002	485471.6	1784800.0	2274.80
	2-127-002	484408.5	1784700.0	2274.80
	2-127-002	482990.8	1784094.0	2274.80
WESTERN WF	2-127-002	461629.5	1773101.0	19498.31
	2-127-002	461895.8	1773606.0	19498.31
	2-127-002	462250.7	1774009.0	19498.31
	2-127-002	462694.0	1774211.0	19498.31
	2-127-002	461631.9	1775424.0	19498.31
	2-127-002	462163.0	1774918.0	19498.31
	2-127-002	463402.4	1773705.0	19498.31
OR. CITY CTRY VILLAGE	2-127-004	415950.8	1675002.0	17947.40
SO ST UTIL:	2-127-008	506124.5	1711168.0	3214.05
SUGAR MILL EST	2-127-008	506124.6	1710865.0	3214.05
	2-127-008	506302.1	1710966.0	3214.05
	2-127-008	506479.6	1710966.0	3214.05
V CTY - IND HBR	2-127-009	544886.4	1659078.0	3516.23
PORT ORANGE	2-127-009	457955.5	1736744.0	0.00
WESTERN WF	2-127-009	457862.4	1732805.0	35475.29
	2-127-009	457593.9	1730684.0	35475.29
	2-127-009	457504.8	1730381.0	35475.29
	2-127-009	457592.1	1729068.0	35475.29
	2-127-009	457946.5	1728664.0	35475.29
	2-127-009	456001.0	1734120.0	35475.29
	2-127-009	455911.0	1733009.0	35475.29
	2-127-009	455998.5	1731999.0	35475.29
	2-127-009	456174.7	1730888.0	35475.29
	2-127-009	453960.6	1734022.0	35475.29
	2-127-009	454491.3	1732708.0	35475.29
	2-127-009	454046.4	1731597.0	35475.29
	2-127-009	457947.6	1729674.0	35475.29
	2-127-009	454222.4	1730486.0	35475.29
EASTERN WF	2-127-009	491132.0	1745711.0	4093.25
	2-127-009	491132.1	1746216.0	4093.25
	2-127-009	491132.2	1746721.0	4093.25
	2-127-009	491132.1	1746014.0	4093.25
	2-127-009	490599.9	1745610.0	4093.25

	2-127-009	491132.6	1748236.0	4093.25
	2-127-009	491132.7	1748741.0	4093.25
	2-127-009	491132.8	1749246.0	4093.25
	2-127-009	490689.5	1749448.0	4093.25
	2-127-009	490334.8	1749448.0	4093.25
	2-127-009	489891.5	1749448.0	4093.25
	2-127-009	489093.4	1749448.0	4093.25
	2-127-009	488916.1	1749448.0	4093.25
DELTONA	2-127-009	417788.1	1661868.0	64893.90
	2-127-009	413161.8	1659858.0	64893.90
	2-127-009	422067.5	1668323.0	64893.90
	2-127-009	428260.6	1653868.0	64893.90
	2-127-009	417606.8	1660252.0	64893.90
	2-127-009	417784.8	1660353.0	64893.90
	2-127-009	424447.7	1658723.0	64893.90
	2-127-009	424713.2	1658116.0	64893.90
	2-127-009	424270.7	1659127.0	64893.90
	2-127-009	441983.3	1675155.0	64893.90
	2-127-009	424447.7	1658723.0	64893.90
	2-127-009	441983.6	1675357.0	64893.90
	2-127-009	442161.2	1675256.0	64893.90
	2-127-009	418695.9	1670754.0	64893.90
	2-127-009	441438.5	1667581.0	64893.90
SPRUCE CREEK	2-127-014	483673.8	1724907.0	21646.77
	2-127-014	484295.2	1725513.0	21646.77
NEW SMYRNA	2-127-021	513319.8	1695414.0	39712.47
GLENCOE WF	2-127-021	512520.6	1695413.0	39712.47
	2-127-021	511721.4	1695413.0	39712.47
	2-127-021	513320.1	1694606.0	39712.47
	2-127-021	512520.9	1694605.0	39712.47
	2-127-021	511721.7	1694605.0	39712.47
	2-127-021	512521.1	1693797.0	39712.47
SAMSULA WF	2-127-021	475583.2	1699863.0	39712.47
	2-127-021	474162.6	1699864.0	39712.47
	2-127-021	473186.2	1700269.0	39712.47
	2-127-021	472565.0	1700572.0	39712.47
	2-127-021	471322.3	1701078.0	39712.47
	2-127-021	470701.1	1701483.0	39712.47
HALIFAX PLANTATION	2-127-027	453475.1	1842702.0	2637.17
	2-127-027	452060.1	1842906.0	2637.17
DAYTONA BCH	2-127-032	478107.8	1765916.0	0.00
EASTERN WF	2-127-032	477221.2	1765513.0	0.00
MARION ST WP	2-127-032	476511.9	1765109.0	0.00
7 WELLS INACTIV	2-127-032	475182.4	1765110.0	0.00
	2-127-032	474473.0	1764606.0	0.00
	2-127-032	473852.3	1764303.0	0.00
	2-127-032	472522.4	1763799.0	0.00
	2-127-032	471990.3	1763496.0	78521.69
	2-127-032	471192.3	1763093.0	78521.69
	2-127-032	469862.3	1762589.0	78521.69
	2-127-032	464897.4	1761482.0	78521.69
	2-127-032	464187.8	1760978.0	78521.69
WESTERN WF	2-127-032	462768.7	1760272.0	124802.7
BRENNAN WP	2-127-032	461794.5	1761081.0	124802.7

11 WELLS	2-127-032	458588.6	1747752.0	124802.7
	2-127-032	458145.0	1747551.0	124802.7
	2-127-032	457169.1	1747148.0	124802.7
	2-127-032	456370.6	1746846.0	124802.7
	2-127-032	455305.9	1746342.0	124802.7
	2-127-032	454507.4	1746040.0	124802.7
	2-127-032	454242.4	1746848.0	124802.7
	2-127-032	453800.3	1747960.0	124802.7
	2-127-032	453269.3	1748769.0	124802.7
Western wf	2-127-032	451854.4	1751800.0	0.00
1988 constr.	2-127-032	451145.9	1752407.0	0.00
	2-127-032	450969.5	1753115.0	0.00
	2-127-032	451147.8	1753922.0	0.00
	2-127-032	450971.8	1754933.0	0.00
	2-127-032	451061.9	1756044.0	0.00
	2-127-032	449910.0	1756449.0	0.00
	2-127-032	453265.4	1745638.0	0.00
	2-127-032	452916.9	1750587.0	0.00
	2-127-032	452296.8	1751093.0	0.00
ORMOND BCH	2-127-034	479276.3	1795409.0	30162.62
DIVISION AVE	2-127-034	479364.9	1795308.0	30162.62
	2-127-034	478832.6	1793692.0	30162.62
	2-127-034	478478.6	1794197.0	30162.62
	2-127-034	478301.6	1794399.0	30162.62
	2-127-034	478124.3	1794096.0	30162.62
	2-127-034	476175.6	1793794.0	30162.62
	2-127-034	475643.9	1793290.0	30162.62
	2-127-034	475023.8	1793088.0	30162.62
	2-127-034	478479.7	1796116.0	30162.62
	2-127-034	478125.3	1795914.0	30162.62
	2-127-034	475821.9	1794704.0	30162.62
SR 40 WF	2-127-034	467318.6	1793397.0	84902.20
	2-127-034	464038.3	1789966.0	84902.20
	2-127-034	467939.9	1794912.0	0.00
	2-127-034	468293.6	1794305.0	0.00
	2-127-034	462089.2	1789564.0	84902.20
HUDSON WF	2-127-034	450487.7	1791092.0	0.00
	2-127-034	450488.9	1792002.0	0.00
	2-127-034	450490.1	1792911.0	0.00
	2-127-034	450491.2	1793719.0	0.00
	2-127-034	450492.4	1794628.0	0.00
	2-127-034	450493.6	1795537.0	0.00
	2-127-034	450494.8	1796446.0	0.00
	2-127-034	451552.9	1792909.0	0.00
	2-127-034	451997.0	1793818.0	0.00
	2-127-034	451998.1	1794727.0	0.00
	2-127-034	452001.2	1797151.0	0.00
	2-127-034	449515.9	1792912.0	0.00
	2-127-034	448718.7	1792913.0	0.00
JOHN KNOX VILL.	2-127-038	407780.8	1676637.0	2112.18
	2-127-038	407869.6	1676636.0	2112.18
	2-127-038	408491.8	1676736.0	2112.18
V CTY - OR CITY IND	2-127-042	405548.3	1672097.0	4724.93
V CTY - FOUR TOWNS	2-127-042	404205.6	1668162.0	26499.89

V CTY - FOUR TOWNS	2-127-042	404478.5	1670686.0	26499.89
V CTY - LAKE MARIE	2-127-042	400182.2	1658880.0	9358.29
V CTY - LAKE MARIE	2-127-042	400093.1	1658779.0	9358.29
V CTY - BREEZEWOOD	2-127-042	406249.4	1668156.0	19046.22
V CTY - TERRA ALTA	2-127-042	402507.8	1664530.0	4834.81
V CTY -SWALLOWS	2-127-042	406854.8	1661388.0	0.00
V CTY - ?	2-127-042	398902.9	1679083.0	0.00
V CTY - HLND CTRY EST	2-127-042	401440.8	1664331.0	3607.79
V CTY - HLND CTRY EST	2-127-042	401618.6	1664330.0	3607.79
V CTY - W ORANGE CITY	2-127-042	395515.3	1674851.0	695.92
V CTY - SWALLOWS	2-127-042	406499.6	1661490.0	0.00
V CTY - SWALLOWS	2-127-042	401166.6	1661402.0	0.00
V CTY - SWALLOWS	2-127-042	406855.1	1661489.0	0.00
V CTY - CASSADAGA	2-127-042	424500.5	1685185.0	3442.97
DELAND-BRANDYWINE	2-127-042	398315.2	1724738.0	61607.21
DELAND-SPRING GARDEN	2-127-042	396359.2	1723329.0	1721.49
DELAND-SPRING GARDEN	2-127-042	396536.7	1723328.0	1721.49
DELAND-LONGLEAF PLANT.	2-127-042	409956.3	1694811.0	16042.78
DELAND-TOMOKA WOODS	2-127-042	412752.1	1751669.0	1574.98
DELAND-WOODLAND MANR	2-127-042	397529.0	1729285.0	7801.63
DELAND-GLENWOOD EST	2-127-042	393519.5	1723236.0	2087.76
DELAND-HOLIDAY HILLS	2-127-042	398684.3	1696961.0	3259.83
DELAND-HOLIDAY HILLS	2-127-042	398594.7	1696658.0	3259.83
ELLWOOD TITCOMB	2-127-043	430372.7	1690526.0	6103.25
CITY OF EDGEWATER	2-127-051	520604.4	1689660.0	18713.25
	2-127-051	519982.9	1689357.0	18713.25
	2-127-051	519450.1	1689154.0	18713.25
	2-127-051	518828.5	1689053.0	18713.25
	2-127-051	518384.5	1688952.0	18713.25
	2-127-051	513414.7	1678143.0	18713.25
	2-127-051	512792.8	1678142.0	18713.25
	2-127-051	512437.5	1678041.0	18713.25
	2-127-051	511993.3	1678041.0	18713.25
	2-127-051	517145.9	1678346.0	18713.25
	2-127-051	516790.1	1679255.0	18713.25
FALCON DEVEL-PINE RUN	2-127-O51	462824.0	1815824.0	0.00
HOWARD S. DORR	2-127-054	454558.5	1640899.0	1204.59
	2-127-054	454380.4	1640697.0	1204.59
TYMBER CREEK UTIL.	2-127-056	459435.6	1792900.0	12233.54
DELTONA WOODS	2-127-056	423686.6	1678015.0	0.00
THE TRAILS INC.	2-127-061	453144.6	1790887.0	42722.78
LAKE HELEN	2-127-064	425660.5	1687909.0	14870.71
	2-127-064	425315.6	1693162.0	14870.71
HACIENDA DEL RIO	2-127-066	537765.3	1669473.0	7508.61
NATIONAL GARDENS	2-127-066	466370.6	1822487.0	1428.78
	2-127-066	465838.9	1821680.0	1428.78
	2-127-066	466103.8	1821073.0	1428.78
	2-127-066	467166.2	1821476.0	1428.78
	2-127-066	466457.2	1820366.0	1428.78
	2-127-066	467431.1	1820769.0	1428.78
	2-127-066	467429.8	1819254.0	1428.78
	2-127-066	467429.4	1818850.0	1428.78
	2-127-066	465747.1	1818145.0	1428.78
	2-127-066	466366.7	1818144.0	1428.78

	2-127-066	465923.7	1817639.0	1428.78
	2-127-066	466011.3	1816629.0	1428.78
	2-127-066	466719.7	1817033.0	1428.78
	2-127-066	466188.1	1816427.0	1428.78
	2-127-066	466541.8	1816023.0	1428.78
	2-127-066	467250.3	1816426.0	1428.78
	2-127-066	466895.4	1815517.0	1428.78
	2-127-066	466983.7	1815214.0	1428.78
	2-127-066	467160.4	1814911.0	1428.78
	2-127-066	467957.5	1815415.0	1428.78
	2-127-066	468046.4	1815920.0	1428.78
	2-127-066	469288.1	1818949.0	1428.78
	2-127-066	469110.6	1818344.0	1428.78
	2-127-066	468844.8	1817940.0	1428.78
ORANGE CITY	2-127-067	404581.6	1676342.0	22660.12
	2-127-067	404581.1	1676140.0	22660.12
	2-127-067	404491.3	1675736.0	22660.12
SUNSHINE HOLIDAY PK	2-127-068	455838.1	1821488.0	9315.49
KOVE ASSOCIATION	2-127-077	445038.4	1637478.0	2142.70
	2-127-077	445038.1	1637276.0	2142.70
LEMON BLUFF	2-127-079	455879.5	1629788.0	1887.19
	2-127-079	455968.5	1629788.0	1887.19
VOLUSIA COUNTY -	2-127-079	546671.1	1653424.0	5653.54
GOLDEN BAY COLONY	2-127-079	546759.8	1653526.0	5653.54
HOLIDAY TRAILER PK	2-035-006	448966.2	1844223.0	1355.21
PLANTATION BAY	2-035-002	439763.8	1841813.0	2515.08
	2-035-002	439762.3	1840904.0	2515.08
	2-035-002	439495.6	1840096.0	2515.08
KINGSTON SHORES	--	472576.7	1837633.0	3369.72
L BERESFORD WATER ASSN	--	389456.6	1699411.0	21427.00

Table 5. 1990 municipal pumpage used in the three-dimensional model (all rates in cubic feet per day).

Municipality	Number	State Planar Coordinates X Coord	Y Coord	Rate
DELAND	2-127-001	404038.2	1707249.0	44751.97
WATER UTILITY	2-127-001	401994.1	1706345.0	44751.97
	2-127-001	401021.6	1707863.0	44751.97
	2-127-001	401110.3	1707863.0	44751.97
	2-127-001	397832.1	1710195.0	44751.97
	2-127-001	407504.8	1709059.0	44751.97
	2-127-001	402196.0	1715738.0	44751.97
	2-127-001	396406.1	1708077.0	44751.97
1990 constr.	2-127-001	398793.1	1704435.0	44751.97
	2-127-001	404207.3	1703916.0	44751.97
	2-127-001	404206.8	1703714.0	44751.97
HOLLY HILL	2-127-002	484939.9	1784396.0	2176.27
EASTERN WF	2-127-002	485117.0	1784093.0	2176.27
	2-127-002	485294.0	1783689.0	2176.27
	2-127-002	485471.6	1784800.0	2176.27
	2-127-002	484408.5	1784700.0	2176.27
	2-127-002	482990.8	1784094.0	2176.27
WESTERN WF	2-127-002	461629.5	1773101.0	18651.43
	2-127-002	461895.8	1773606.0	18651.43
	2-127-002	462250.7	1774009.0	18651.43
	2-127-002	462694.0	1774211.0	18651.43
	2-127-002	461631.9	1775424.0	18651.43
	2-127-002	462163.0	1774918.0	18651.43
	2-127-002	463402.4	1773705.0	18651.43
HH - Proposed	2-127-002	462783.4	1775019.0	0.00
OR. CITY CTRY VILLAGE	2-127-004	415950.8	1675002.0	26518.20
SO ST UTIL:	2-127-008	506124.5	1711168.0	2074.02
SUGAR MILL EST	2-127-008	506124.6	1710865.0	2074.02
	2-127-008	506302.1	1710966.0	2074.02
	2-127-008	506479.6	1710966.0	2074.02
"" 1990 CONSTR.	2-127-008	506302.2	1710461.0	2074.02
	2-127-008	506479.7	1710562.0	2074.02
	2-127-008	505591.9	1711976.0	2074.02
	2-127-008	505680.7	1711673.0	2074.02
V CTY - IND HBR	2-127-009	544886.4	1659078.0	3552.85
PORT ORANGE	2-127-009	457955.5	1736744.0	38953.68
WESTERN WF	2-127-009	457862.4	1732805.0	38953.68
	2-127-009	457593.9	1730684.0	38953.68
	2-127-009	457504.8	1730381.0	38953.68
	2-127-009	457592.1	1729068.0	38953.68
	2-127-009	457946.5	1728664.0	38953.68
	2-127-009	456001.0	1734120.0	38953.68
	2-127-009	455911.0	1733009.0	38953.68
	2-127-009	455998.5	1731999.0	38953.68
	2-127-009	456174.7	1730888.0	38953.68
	2-127-009	453960.6	1734022.0	38953.68
	2-127-009	454491.3	1732708.0	38953.68

	2-127-009	454046.4	1731597.0	38953.68
	2-127-009	457947.6	1729674.0	38953.68
	2-127-009	454222.4	1730486.0	38953.68
EASTERN WF	2-127-009	491132.0	1745711.0	4494.65
	2-127-009	491132.1	1746216.0	4494.65
	2-127-009	491132.2	1746721.0	4494.65
	2-127-009	491132.1	1746014.0	4494.65
	2-127-009	490599.9	1745610.0	4494.65
	2-127-009	491132.6	1748236.0	4494.65
	2-127-009	491132.7	1748741.0	4494.65
	2-127-009	491132.8	1749246.0	4494.65
	2-127-009	490689.5	1749448.0	4494.65
	2-127-009	490334.8	1749448.0	4494.65
	2-127-009	489891.5	1749448.0	4494.65
	2-127-009	489093.4	1749448.0	4494.65
	2-127-009	488916.1	1749448.0	4494.65
DELTONA	2-127-009	417788.1	1661868.0	79771.93
	2-127-009	413161.8	1659858.0	79771.93
	2-127-009	422067.5	1668323.0	79771.93
	2-127-009	428260.6	1653868.0	79771.93
	2-127-009	417606.8	1660252.0	79771.93
	2-127-009	417784.8	1660353.0	79771.93
	2-127-009	424447.7	1658723.0	79771.93
	2-127-009	424713.2	1658116.0	79771.93
	2-127-009	424270.7	1659127.0	79771.93
	2-127-009	441983.3	1675155.0	79771.93
	2-127-009	424447.7	1658723.0	79771.93
	2-127-009	441983.6	1675357.0	79771.93
	2-127-009	442161.2	1675256.0	79771.93
	2-127-009	418695.9	1670754.0	79771.93
	2-127-009	441438.5	1667581.0	79771.93
SPRUCE CREEK	2-127-014	483673.8	1724907.0	16225.92
	2-127-014	484295.2	1725513.0	16225.92
NEW SMYRNA	2-127-021	513319.8	1695414.0	42417.29
GLENCOE WF	2-127-021	512520.6	1695413.0	42417.29
	2-127-021	511721.4	1695413.0	42417.29
	2-127-021	513320.1	1694606.0	42417.29
	2-127-021	512520.9	1694605.0	42417.29
	2-127-021	511721.7	1694605.0	42417.29
	2-127-021	512521.1	1693797.0	42417.29
SAMSULA WF	2-127-021	475583.2	1699863.0	42417.29
	2-127-021	474162.6	1699864.0	42417.29
	2-127-021	473186.2	1700269.0	42417.29
	2-127-021	472565.0	1700572.0	42417.29
	2-127-021	471322.3	1701078.0	42417.29
	2-127-021	470701.1	1701483.0	42417.29
HALIFAX PLANTATION	2-127-027	453475.1	1842702.0	3003.44
	2-127-027	452060.1	1842906.0	3003.44
DAYTONA BCH	2-127-032	478107.8	1765916.0	0.00
EASTERN WF	2-127-032	477221.2	1765513.0	0.00
MARION ST WP	2-127-032	476511.9	1765109.0	0.00
7 WELLS INACTIV	2-127-032	475182.4	1765110.0	0.00
	2-127-032	474473.0	1764606.0	0.00
	2-127-032	473852.3	1764303.0	0.00

	2-127-032	472522.4	1763799.0	0.00
	2-127-032	471990.3	1763496.0	83602.48
	2-127-032	471192.3	1763093.0	83602.48
	2-127-032	469862.3	1762589.0	83602.48
	2-127-032	464897.4	1761482.0	83602.48
	2-127-032	464187.8	1760978.0	83602.48
WESTERN WF	2-127-032	462768.7	1760272.0	68789.66
BRENNAN WP	2-127-032	461794.5	1761081.0	68789.66
11 WELLS	2-127-032	458588.6	1747752.0	68789.66
	2-127-032	458145.0	1747551.0	68789.66
	2-127-032	457169.1	1747148.0	68789.66
	2-127-032	456370.6	1746846.0	68789.66
	2-127-032	455305.9	1746342.0	68789.66
	2-127-032	454507.4	1746040.0	68789.66
	2-127-032	454242.4	1746848.0	68789.66
	2-127-032	453800.3	1747960.0	68789.66
	2-127-032	453269.3	1748769.0	68789.66
Western wf	2-127-032	451854.4	1751800.0	68789.66
1988 constr.	2-127-032	451145.9	1752407.0	68789.66
	2-127-032	450969.5	1753115.0	68789.66
	2-127-032	451147.8	1753922.0	68789.66
	2-127-032	450971.8	1754933.0	68789.66
	2-127-032	451061.9	1756044.0	68789.66
	2-127-032	449910.0	1756449.0	68789.66
	2-127-032	453265.4	1745638.0	68789.66
	2-127-032	452916.9	1750587.0	68789.66
	2-127-032	452296.8	1751093.0	68789.66
ORMOND BCH	2-127-034	479276.3	1795409.0	21214.56
DIVISION AVE	2-127-034	479364.9	1795308.0	21214.56
	2-127-034	478832.6	1793692.0	21214.56
	2-127-034	478478.6	1794197.0	21214.56
	2-127-034	478301.6	1794399.0	21214.56
	2-127-034	478124.3	1794096.0	21214.56
	2-127-034	476175.6	1793794.0	21214.56
	2-127-034	475643.9	1793290.0	21214.56
	2-127-034	475023.8	1793088.0	21214.56
	2-127-034	478479.7	1796116.0	21214.56
	2-127-034	478125.3	1795914.0	21214.56
	2-127-034	475821.9	1794704.0	21214.56
SR 40 WF	2-127-034	467318.6	1793397.0	21214.56
	2-127-034	464038.3	1789966.0	21214.56
	2-127-034	467939.9	1794912.0	21214.56
	2-127-034	468293.6	1794305.0	21214.56
	2-127-034	462089.2	1789564.0	21214.56
HUDSON WF	2-127-034	450487.7	1791092.0	21214.56
	2-127-034	450488.9	1792002.0	21214.56
	2-127-034	450490.1	1792911.0	21214.56
	2-127-034	450491.2	1793719.0	21214.56
	2-127-034	450492.4	1794628.0	21214.56
	2-127-034	450493.6	1795537.0	21214.56
	2-127-034	450494.8	1796446.0	21214.56
	2-127-034	451552.9	1792909.0	21214.56
	2-127-034	451997.0	1793818.0	21214.56
	2-127-034	451998.1	1794727.0	21214.56

	2-127-034	452001.2	1797151.0	21214.56
	2-127-034	449515.9	1792912.0	21214.56
	2-127-034	448718.7	1792913.0	21214.56
JOHN KNOX VILL.	2-127-038	407780.8	1676637.0	3211.00
	2-127-038	407869.6	1676636.0	3211.00
	2-127-038	408491.8	1676736.0	3211.00
V CTY - OR CITY IND	2-127-042	405548.3	1672097.0	4724.93
V CTY - FOUR TOWNS	2-127-042	404205.6	1668162.0	21372.06
V CTY - FOUR TOWNS	2-127-042	404478.5	1670686.0	21372.06
V CTY - LAKE MARIE	2-127-042	400182.2	1658880.0	8973.70
V CTY - LAKE MARIE	2-127-042	400093.1	1658779.0	8973.70
V CTY - BREEZEWOOD	2-127-042	406249.4	1668156.0	24393.82
V CTY - TERRA ALTA	2-127-042	402507.8	1664530.0	3955.75
V CTY -SWALLOWS	2-127-042	406854.8	1661388.0	0.00
V CTY - ?	2-127-042	398902.9	1679083.0	0.00
V CTY - HLND CTRY EST	2-127-042	401440.8	1664331.0	17104.97
V CTY - HLND CTRY EST	2-127-042	401618.6	1664330.0	17104.97
V CTY - W ORANGE CITY	2-127-042	395515.3	1674851.0	695.92
V CTY - SWALLOWS	2-127-042	406499.6	1661490.0	0.00
V CTY - SWALLOWS	2-127-042	401166.6	1661402.0	0.00
V CTY - SWALLOWS	2-127-042	406855.1	1661489.0	0.00
V CTY - CASSADAGA	2-127-042	424500.5	1685185.0	3003.44
DELAND-BRANDYWINE	2-127-042	398315.2	1724738.0	61607.21
DELAND-SPRING GARDEN	2-127-042	396359.2	1723329.0	1721.48
DELAND-SPRING GARDEN	2-127-042	396536.7	1723328.0	1721.48
DELAND-LONGLEAF PLANT.	2-127-042	409956.3	1694811.0	16042.78
DELAND-TOMOKA WOODS	2-127-042	412752.1	1751669.0	1574.98
DELAND-WOODLAND MANR	2-127-042	397529.0	1729285.0	7801.62
DELAND-GLENWOOD EST	2-127-042	393519.5	1723236.0	2087.76
DELAND-HOLIDAY HILLS	2-127-042	398684.3	1696961.0	3259.83
DELAND-HOLIDAY HILLS	2-127-042	398594.7	1696658.0	3259.83
ELLWOOD TITCOMB	2-127-043	430372.7	1690526.0	6103.25
CITY OF EDGEWATER	2-127-051	520604.4	1689660.0	19995.21
	2-127-051	519982.9	1689357.0	19995.21
	2-127-051	519450.1	1689154.0	19995.21
	2-127-051	518828.5	1689053.0	19995.21
	2-127-051	518384.5	1688952.0	19995.21
	2-127-051	513414.7	1678143.0	19995.21
	2-127-051	512792.8	1678142.0	19995.21
	2-127-051	512437.5	1678041.0	19995.21
	2-127-051	511993.3	1678041.0	19995.21
	2-127-051	517145.9	1678346.0	19995.21
	2-127-051	516790.1	1679255.0	19995.21
FALCON DEVEL-PINE RUN	2-127-O51	462824.0	1815824.0	0.00
HOWARD S. DORR	2-127-054	454558.5	1640899.0	1204.59
	2-127-054	454380.4	1640697.0	1204.59
TYMBER CREEK UTIL.	2-127-056	459435.6	1792900.0	13478.87
DELTONA WOODS	2-127-056	423686.6	1678015.0	3479.60
THE TRAILS INC.	2-127-061	453144.6	1790887.0	42722.76
LAKE HELEN	2-127-064	425660.5	1687909.0	15786.39
	2-127-064	425315.6	1693162.0	15786.39
HACIENDA DEL RIO	2-127-066	537765.3	1669473.0	7508.61
NATIONAL GARDENS	2-127-066	466370.6	1822487.0	1428.78
	2-127-066	465838.9	1821680.0	1428.78

	2-127-066	466103.8	1821073.0	1428.78
	2-127-066	467166.2	1821476.0	1428.78
	2-127-066	466457.2	1820366.0	1428.78
	2-127-066	467431.1	1820769.0	1428.78
	2-127-066	467429.8	1819254.0	1428.78
	2-127-066	467429.4	1818850.0	1428.78
	2-127-066	465747.1	1818145.0	1428.78
	2-127-066	466366.7	1818144.0	1428.78
	2-127-066	465923.7	1817639.0	1428.78
	2-127-066	466011.3	1816629.0	1428.78
	2-127-066	466719.7	1817033.0	1428.78
	2-127-066	466188.1	1816427.0	1428.78
	2-127-066	466541.8	1816023.0	1428.78
	2-127-066	467250.3	1816426.0	1428.78
	2-127-066	466895.4	1815517.0	1428.78
	2-127-066	466983.7	1815214.0	1428.78
	2-127-066	467160.4	1814911.0	1428.78
	2-127-066	467957.5	1815415.0	1428.78
	2-127-066	468046.4	1815920.0	1428.78
	2-127-066	469288.1	1818949.0	1428.78
	2-127-066	469110.6	1818344.0	1428.78
	2-127-066	468844.8	1817940.0	1428.78
ORANGE CITY	2-127-067	404581.6	1676342.0	28642.59
	2-127-067	404581.1	1676140.0	28642.59
	2-127-067	404491.3	1675736.0	28642.59
SUNSHINE HOLIDAY PK	2-127-068	455838.1	1821488.0	9315.49
KOVE ASSOCIATION	2-127-077	445038.4	1637478.0	2142.70
	2-127-077	445038.1	1637276.0	2142.70
LEMON BLUFF	2-127-079	455879.5	1629788.0	1887.19
	2-127-079	455968.5	1629788.0	1887.19
VOLUSIA COUNTY -	2-127-079	546671.1	1653424.0	5653.54
GOLDEN BAY COLONY	2-127-079	546759.8	1653526.0	5653.54
HOLIDAY TRAILER PK	2-035-006	448966.2	1844223.0	1355.21
PLANTATION BAY	2-035-002	439763.8	1841813.0	2429.61
	2-035-002	439762.3	1840904.0	2429.61
	2-035-002	439495.6	1840096.0	2429.61
KINGSTON SHORES	--	472576.7	1837633.0	2966.82
L BERESFORD WATER ASSN	--	389456.6	1699411.0	23441.51

Table 6. 2010 municipal pumpage used in the three-dimensional model (extension of current pumpage) (all rates in cubic feet per day).

Municipality	Number	State Planar Coordinates X Coord	Y Coord	Rate
DELAND	2-127-001	404038.2	1707249.0	84053.12
WATER UTILITY	2-127-001	401994.1	1706345.0	84053.12
	2-127-001	401021.6	1707863.0	84053.12
	2-127-001	401110.3	1707863.0	84053.12
	2-127-001	397832.1	1710195.0	84053.12
	2-127-001	407504.8	1709059.0	84053.12
	2-127-001	402196.0	1715738.0	84053.12
	2-127-001	396406.1	1708077.0	84053.12
1990 constr.	2-127-001	398793.1	1704435.0	84053.12
	2-127-001	404207.3	1703916.0	84053.12
	2-127-001	404206.8	1703714.0	84053.12
HOLLY HILL	2-127-002	484939.9	1784396.0	2620.08
EASTERN WF	2-127-002	485117.0	1784093.0	2620.08
	2-127-002	485294.0	1783689.0	2620.08
	2-127-002	485471.6	1784800.0	2620.08
	2-127-002	484408.5	1784700.0	2620.08
	2-127-002	482990.8	1784094.0	2620.08
WESTERN WF	2-127-002	461629.5	1773101.0	22457.80
	2-127-002	461895.8	1773606.0	22457.80
	2-127-002	462250.7	1774009.0	22457.80
	2-127-002	462694.0	1774211.0	22457.80
	2-127-002	461631.9	1775424.0	22457.80
	2-127-002	462163.0	1774918.0	22457.80
	2-127-002	463402.4	1773705.0	22457.80
OR. CITY CTRY VILLAGE	2-127-004	415950.8	1675002.0	51791.08
SO ST UTIL:	2-127-008	506124.5	1711168.0	3609.63
SUGAR MILL EST	2-127-008	506124.6	1710865.0	3609.63
	2-127-008	506302.1	1710966.0	3609.63
	2-127-008	506479.6	1710966.0	3609.63
"" 1990 CONSTR.	2-127-008	506302.2	1710461.0	3609.63
	2-127-008	506479.7	1710562.0	3609.63
	2-127-008	505591.9	1711976.0	3609.63
	2-127-008	505680.7	1711673.0	3609.63
V CTY - IND HBR	2-127-009	544886.4	1659078.0	5494.10
PORT ORANGE	2-127-009	457955.5	1736744.0	63204.16
WESTERN WF	2-127-009	457862.4	1732805.0	63204.16
	2-127-009	457593.9	1730684.0	63204.16
	2-127-009	457504.8	1730381.0	63204.16
	2-127-009	457592.1	1729068.0	63204.16
	2-127-009	457946.5	1728664.0	63204.16
	2-127-009	456001.0	1734120.0	63204.16
	2-127-009	455911.0	1733009.0	63204.16
	2-127-009	455998.5	1731999.0	63204.16
	2-127-009	456174.7	1730888.0	63204.16
	2-127-009	453960.6	1734022.0	63204.16
	2-127-009	454491.3	1732708.0	63204.16
	2-127-009	454046.4	1731597.0	63204.16

	2-127-009	457947.6	1729674.0	63204.16
	2-127-009	454222.4	1730486.0	63204.16
EASTERN WF	2-127-009	491132.0	1745711.0	7292.79
	2-127-009	491132.1	1746216.0	7292.79
	2-127-009	491132.2	1746721.0	7292.79
	2-127-009	491132.1	1746014.0	7292.79
	2-127-009	490599.9	1745610.0	7292.79
	2-127-009	491132.6	1748236.0	7292.79
	2-127-009	491132.7	1748741.0	7292.79
	2-127-009	491132.8	1749246.0	7292.79
	2-127-009	490689.5	1749448.0	7292.79
	2-127-009	490334.8	1749448.0	7292.79
	2-127-009	489891.5	1749448.0	7292.79
	2-127-009	489093.4	1749448.0	7292.79
	2-127-009	488916.1	1749448.0	7292.79
DELTONA	2-127-009	417788.1	1661868.0	116020.8
	2-127-009	413161.8	1659858.0	116020.8
	2-127-009	422067.5	1668323.0	116020.8
	2-127-009	428260.6	1653868.0	116020.8
	2-127-009	417606.8	1660252.0	116020.8
	2-127-009	417784.8	1660353.0	116020.8
	2-127-009	424447.7	1658723.0	116020.8
	2-127-009	424713.2	1658116.0	116020.8
	2-127-009	424270.7	1659127.0	116020.8
	2-127-009	441983.3	1675155.0	116020.8
	2-127-009	424447.7	1658723.0	116020.8
	2-127-009	441983.6	1675357.0	116020.8
	2-127-009	442161.2	1675256.0	116020.8
	2-127-009	418695.9	1670754.0	116020.8
	2-127-009	441438.5	1667581.0	116020.8
SPRUCE CREEK	2-127-014	483673.8	1724907.0	26847.85
	2-127-014	484295.2	1725513.0	26847.85
NEW SMYRNA	2-127-021	513319.8	1695414.0	73099.74
GLENCOE WF	2-127-021	512520.6	1695413.0	73099.74
	2-127-021	511721.4	1695413.0	73099.74
	2-127-021	513320.1	1694606.0	73099.74
	2-127-021	512520.9	1694605.0	73099.74
	2-127-021	511721.7	1694605.0	73099.74
	2-127-021	512521.1	1693797.0	73099.74
SAMSULA WF	2-127-021	475583.2	1699863.0	73099.74
	2-127-021	474162.6	1699864.0	73099.74
	2-127-021	473186.2	1700269.0	73099.74
	2-127-021	472565.0	1700572.0	73099.74
	2-127-021	471322.3	1701078.0	73099.74
	2-127-021	470701.1	1701483.0	73099.74
HALIFAX PLANTATION	2-127-027	453475.1	1842702.0	4779.87
	2-127-027	452060.1	1842906.0	4779.87
DAYTONA BCH	2-127-032	478107.8	1765916.0	0.00
EASTERN WF	2-127-032	477221.2	1765513.0	0.00
MARION ST WP	2-127-032	476511.9	1765109.0	0.00
7 WELLS INACTIV	2-127-032	475182.4	1765110.0	0.00
	2-127-032	474473.0	1764606.0	0.00
	2-127-032	473852.3	1764303.0	0.00
	2-127-032	472522.4	1763799.0	0.00

	2-127-032	471990.3	1763496.0	40986.74
	2-127-032	471192.3	1763093.0	40986.74
	2-127-032	469862.3	1762589.0	40986.74
	2-127-032	464897.4	1761482.0	40986.74
	2-127-032	464187.8	1760978.0	40986.74
WESTERN WF	2-127-032	462768.7	1760272.0	126591.1
BRENNAN WP	2-127-032	461794.5	1761081.0	126591.1
11 WELLS	2-127-032	458588.6	1747752.0	126591.1
	2-127-032	458145.0	1747551.0	126591.1
	2-127-032	457169.1	1747148.0	126591.1
	2-127-032	456370.6	1746846.0	126591.1
	2-127-032	455305.9	1746342.0	126591.1
	2-127-032	454507.4	1746040.0	126591.1
	2-127-032	454242.4	1746848.0	126591.1
	2-127-032	453800.3	1747960.0	126591.1
	2-127-032	453269.3	1748769.0	126591.1
Western wf	2-127-032	451854.4	1751800.0	126591.1
1988 constr.	2-127-032	451145.9	1752407.0	126591.1
	2-127-032	450969.5	1753115.0	126591.1
	2-127-032	451147.8	1753922.0	126591.1
	2-127-032	450971.8	1754933.0	126591.1
	2-127-032	451061.9	1756044.0	126591.1
	2-127-032	449910.0	1756449.0	126591.1
	2-127-032	453265.4	1745638.0	126591.1
	2-127-032	452916.9	1750587.0	126591.1
	2-127-032	452296.8	1751093.0	126591.1
ORMOND BCH	2-127-034	479276.3	1795409.0	38297.56
DIVISION AVE	2-127-034	479364.9	1795308.0	38297.56
	2-127-034	478832.6	1793692.0	38297.56
	2-127-034	478478:6	1794197.0	38297.56
	2-127-034	478301.6	1794399.0	38297.56
	2-127-034	478124.3	1794096.0	38297.56
	2-127-034	476175.6	1793794.0	38297.56
	2-127-034	475643.9	1793290.0	38297.56
	2-127-034	475023.8	1793088.0	38297.56
	2-127-034	478479.7	1796116.0	38297.56
	2-127-034	478125.3	1795914.0	38297.56
	2-127-034	475821.9	1794704.0	38297.56
SR 40 WF	2-127-034	467318.6	1793397.0	38297.56
	2-127-034	464038.3	1789966.0	38297.56
	2-127-034	467939.9	1794912.0	38297.56
	2-127-034	468293.6	1794305.0	38297.56
	2-127-034	462089.2	1789564.0	38297.56
HUDSON WF	2-127-034	450487.7	1791092.0	38297.56
	2-127-034	450488.9	1792002.0	38297.56
	2-127-034	450490.1	1792911.0	38297.56
	2-127-034	450491.2	1793719.0	38297.56
	2-127-034	450492.4	1794628.0	38297.56
	2-127-034	450493.6	1795537.0	38297.56
	2-127-034	450494.8	1796446.0	38297.56
	2-127-034	451552.9	1792909.0	38297.56
	2-127-034	451997.0	1793818.0	38297.56
	2-127-034	451998.1	1794727.0	38297.56
	2-127-034	452001.2	1797151.0	38297.56

	2-127-034	449515.9	1792912.0	38297.56
	2-127-034	448718.7	1792913.0	38297.56
JOHN KNOX VILL.	2-127-038	407780.8	1676637.0	6329.21
	2-127-038	407869.6	1676636.0	6329.21
	2-127-038	408491.8	1676736.0	6329.21
V CTY - OR CITY IND	2-127-042	405548.3	1672097.0	0.00
V CTY - FOUR TOWNS	2-127-042	404205.6	1668162.0	42322.91
V CTY - FOUR TOWNS	2-127-042	404478.5	1670686.0	42322.91
V CTY - LAKE MARIE	2-127-042	400182.2	1658880.0	16962.13
V CTY - LAKE MARIE	2-127-042	400093.1	1658779.0	16962.13
V CTY - BREEZEWOOD	2-127-042	406249.4	1668156.0	21441.65
V CTY - TERRA ALTA	2-127-042	402507.8	1664530.0	7178.96
V CTY -SWALLOWS	2-127-042	406854.8	1661388.0	0.00
V CTY - ?	2-127-042	398902.9	1679083.0	0.00
V CTY - HLND CTRY EST	2-127-042	401440.8	1664331.0	31005.05
V CTY - HLND CTRY EST	2-127-042	401618.6	1664330.0	31005.05
V CTY - W ORANGE CITY	2-127-042	395515.3	1674851.0	1259.98
V CTY - SWALLOWS	2-127-042	406499.6	1661490.0	0.00
V CTY - SWALLOWS	2-127-042	401166.6	1661402.0	0.00
V CTY - SWALLOWS	2-127-042	406855.1	1661489.0	0.00
V CTY - CASSADAGA	2-127-042	424500.5	1685185.0	5640.61
DELAND-BRANDYWINE	2-127-042	398315.2	1724738.0	109552.4
DELAND-SPRING GARDEN	2-127-042	396359.2	1723329.0	2921.03
DELAND-SPRING GARDEN	2-127-042	396536.7	1723328.0	2921.03
DELAND-LONGLEAF PLANT.	2-127-042	409956.3	1694811.0	34587.21
DELAND-TOMOKA WOODS	2-127-042	412752.1	1751669.0	3519.89
DELAND-WOODLAND MANR	2-127-042	397529.0	1729285.0	21709.03
DELAND-GLENWOOD EST	2-127-042	393519.5	1723236.0	4578.42
DELAND-HOLIDAY HILLS	2-127-042	398684.3	1696961.0	6937.22
DELAND-HOLIDAY HILLS	2-127-042	398594.7	1696658.0	6937.22
ELLWOOD TITCOMB	2-127-043	430372.7	1690526.0	56605.91
CITY OF EDGEWATER	2-127-051	520604.4	1689660.0	56605.91
	2-127-051	519982.9	1689357.0	56605.91
	2-127-051	519450.1	1689154.0	56605.91
	2-127-051	518828.5	1689053.0	56605.91
	2-127-051	518384.5	1688952.0	56605.91
	2-127-051	513414.7	1678143.0	56605.91
	2-127-051	512792.8	1678142.0	56605.91
	2-127-051	512437.5	1678041.0	56605.91
	2-127-051	511993.3	1678041.0	56605.91
	2-127-051	517145.9	1678346.0	56605.91
	2-127-051	516790.1	1679255.0	56605.91
FALCON DEVEL-PINE RUN	2-127-O51	462824.0	1815824.0	0.00
HOWARD S. DORR	2-127-054	454558.5	1640899.0	2183.23
	2-127-054	454380.4	1640697.0	2183.23
TYMBER CREEK UTIL.	2-127-056	459435.6	1792900.0	23965.28
DELTONA WOODS	2-127-056	423686.6	1678015.0	6307.23
THE TRAILS INC.	2-127-061	453144.6	1790887.0	77432.01
LAKE HELEN	2-127-064	425660.5	1687909.0	38605.23
	2-127-064	425315.6	1693162.0	38605.23
HACIENDA DEL RIO	2-127-066	537765.3	1669473.0	13608.82
NATIONAL GARDENS	2-127-066	466370.6	1822487.0	2589.55
	2-127-066	465838.9	1821680.0	2589.55
	2-127-066	466103.8	1821073.0	2589.55

	2-127-066	467166.2	1821476.0	2589.55
	2-127-066	466457.2	1820366.0	2589.55
	2-127-066	467431.1	1820769.0	2589.55
	2-127-066	467429.8	1819254.0	2589.55
	2-127-066	467429.4	1818850.0	2589.55
	2-127-066	465747.1	1818145.0	2589.55
	2-127-066	466366.7	1818144.0	2589.55
	2-127-066	465923.7	1817639.0	2589.55
	2-127-066	466011.3	1816629.0	2589.55
	2-127-066	466719.7	1817033.0	2589.55
	2-127-066	466188.1	1816427.0	2589.55
	2-127-066	466541.8	1816023.0	2589.55
	2-127-066	467250.3	1816426.0	2589.55
	2-127-066	466895.4	1815517.0	2589.55
	2-127-066	466983.7	1815214.0	2589.55
	2-127-066	467160.4	1814911.0	2589.55
	2-127-066	467957.5	1815415.0	2589.55
	2-127-066	468046.4	1815920.0	2589.55
	2-127-066	469288.1	1818949.0	2589.55
	2-127-066	469110.6	1818344.0	2589.55
	2-127-066	468844.8	1817940.0	2589.55
ORANGE CITY	2-127-067	404581.6	1676342.0	122207.2
	2-127-067	404581.1	1676140.0	122207.2
	2-127-067	404491.3	1675736.0	122207.2
SUNSHINE HOLIDAY PK	2-127-068	455838.1	1821488.0	16883.67
KOVE ASSOCIATION	2-127-077	445038.4	1637478.0	4713.94
	2-127-077	445038.1	1637276.0	4713.94
LEMON BLUFF	2-127-079	455879.5	1629788.0	3420.40
	2-127-079	455968.5	1629788.0	3420.40
VOLUSIA COUNTY -	2-127-079	546671.1	1653424.0	10246.64
GOLDEN BAY COLONY	2-127-079	546759.8	1653526.0	10246.64
HOLIDAY TRAILER PK	2-035-006	448966.2	1844223.0	2322.17
PLANTATION BAY	2-035-002	439763.8	1841813.0	5445.27
	2-035-002	439762.3	1840904.0	5445.27
	2-035-002	439495.6	1840096.0	5445.27
KINGSTON SHORES	--	472576.7	1837633.0	5310.97
L BERESFORD WATER ASSN	--	389456.6	1699411.0	43879.57

Table 7. 2010 proposed and existing municipal pumpage used in the three-dimensional model (all rates in cubic feet per day).

Municipality	Number	State Planar Coordinates X Coord	Y Coord	Rate
DELAND	2-127-001	404038.2	1707249.0	84053.12
WATER UTILITY	2-127-001	401994.1	1706345.0	84053.12
	2-127-001	401021.6	1707863.0	84053.12
	2-127-001	401110.3	1707863.0	84053.12
	2-127-001	397832.1	1710195.0	84053.12
	2-127-001	407504.8	1709059.0	84053.12
	2-127-001	402196.0	1715738.0	84053.12
	2-127-001	396406.1	1708077.0	84053.12
1990 constr.	2-127-001	398793.1	1704435.0	84053.12
	2-127-001	404207.3	1703916.0	84053.12
	2-127-001	404206.8	1703714.0	84053.12
HOLLY HILL	2-127-002	484939.9	1784396.0	2620.08
EASTERN WF	2-127-002	485117.0	1784093.0	2620.08
	2-127-002	485294.0	1783689.0	2620.08
	2-127-002	485471.6	1784800.0	2620.08
	2-127-002	484408.5	1784700.0	2620.08
	2-127-002	482990.8	1784094.0	2620.08
WESTERN WF	2-127-002	461629.5	1773101.0	19650.58
	2-127-002	461895.8	1773606.0	19650.58
	2-127-002	462250.7	1774009.0	19650.58
	2-127-002	462694.0	1774211.0	19650.58
	2-127-002	461631.9	1775424.0	19650.58
	2-127-002	462163.0	1774918.0	19650.58
	2-127-002	463402.4	1773705.0	19650.58
HH - Proposed	2-127-002	462783.4	1775019.0	19650.58
OR. CITY CTRY VILLAGE	2-127-004	415950.8	1675002.0	51791.08
SO ST UTIL:	2-127-008	506124.5	1711168.0	3609.63
SUGAR MILL EST	2-127-008	506124.6	1710865.0	3609.63
	2-127-008	506302.1	1710966.0	3609.63
	2-127-008	506479.6	1710966.0	3609.63
"" 1990 CONSTR.	2-127-008	506302.2	1710461.0	3609.63
	2-127-008	506479.7	1710562.0	3609.63
	2-127-008	505591.9	1711976.0	3609.63
	2-127-008	505680.7	1711673.0	3609.63
V CTY - IND HBR	2-127-009	544886.4	1659078.0	5494.10
PORT ORANGE	2-127-009	457955.5	1736744.0	31602.08
WESTERN WF	2-127-009	457862.4	1732805.0	31602.08
	2-127-009	457593.9	1730684.0	31602.08
	2-127-009	457504.8	1730381.0	31602.08
	2-127-009	457592.1	1729068.0	31602.08
	2-127-009	457946.5	1728664.0	31602.08
	2-127-009	456001.0	1734120.0	31602.08
	2-127-009	455911.0	1733009.0	31602.08
	2-127-009	455998.5	1731999.0	31602.08
	2-127-009	456174.7	1730888.0	31602.08
	2-127-009	453960.6	1734022.0	31602.08
	2-127-009	454491.3	1732708.0	31602.08

	2-127-009	454046.4	1731597.0	31602.08
	2-127-009	457947.6	1729674.0	31602.08
	2-127-009	454222.4	1730486.0	31602.08
PO - proposed	2-127-009	453873.9	1735638.0	31602.08
	2-127-009	453873.9	1735638.0	31602.08
	2-127-009	453873.9	1735638.0	31602.08
	2-127-009	456083.8	1729070.0	31602.08
	2-127-009	456083.8	1729070.0	31602.08
	2-127-009	456083.8	1729070.0	31602.08
PO - proposed	2-127-009	422871.0	1756899.0	31602.08
	2-127-009	420211.3	1756905.0	31602.08
	2-127-009	425530.6	1756894.0	31602.08
	2-127-009	422877.2	1759929.0	31602.08
	2-127-009	420217.8	1759935.0	31602.08
	2-127-009	425536.6	1759924.0	31602.08
	2-127-009	422864.7	1753869.0	31602.08
	2-127-009	420204.9	1753874.0	31602.08
	2-127-009	425524.6	1753864.0	31602.08
EASTERN WF	2-127-009	491132.0	1745711.0	7292.79
	2-127-009	491132.1	1746216.0	7292.79
	2-127-009	491132.2	1746721.0	7292.79
	2-127-009	491132.1	1746014.0	7292.79
	2-127-009	490599.9	1745610.0	7292.79
	2-127-009	491132.6	1748236.0	7292.79
	2-127-009	491132.7	1748741.0	7292.79
	2-127-009	491132.8	1749246.0	7292.79
	2-127-009	490689.5	1749448.0	7292.79
	2-127-009	490334.8	1749448.0	7292.79
	2-127-009	489891.5	1749448.0	7292.79
	2-127-009	489093.4	1749448.0	7292.79
	2-127-009	488916.1	1749448.0	7292.79
DELTONA	2-127-009	417788.1	1661868.0	52736.73
	2-127-009	413161.8	1659858.0	52736.73
	2-127-009	422067.5	1668323.0	52736.73
	2-127-009	428260.6	1653868.0	52736.73
	2-127-009	417606.8	1660252.0	52736.73
	2-127-009	417784.8	1660353.0	52736.73
	2-127-009	424447.7	1658723.0	52736.73
	2-127-009	424713.2	1658116.0	52736.73
	2-127-009	424270.7	1659127.0	52736.73
	2-127-009	441983.3	1675155.0	52736.73
	2-127-009	424447.7	1658723.0	52736.73
	2-127-009	441983.6	1675357.0	52736.73
	2-127-009	442161.2	1675256.0	52736.73
	2-127-009	418695.9	1670754.0	52736.73
	2-127-009	441438.5	1667581.0	52736.73
DELT - PROPOSED	2-127-009	417876.5	1661665.0	52736.73
	2-127-009	431594.3	1678505.0	52736.73
	2-127-009	439595.1	1681825.0	52736.73
	2-127-009	442924.6	1651217.0	52736.73
	2-127-009	434571.8	1653553.0	52736.73
	2-127-009	438035.0	1651224.0	52736.73
	2-127-009	423991.1	1652664.0	52736.73
	2-127-009	438951.0	1667989.0	52736.73

	2-127-009	442657.6	1651015.0	52736.73
	2-127-009	434927.3	1653553.0	52736.73
	2-127-009	428210.2	1674168.0	52736.73
	2-127-009	439506.1	1681724.0	52736.73
	2-127-009	413073.2	1659959.0	52736.73
	2-127-009	417518.6	1660555.0	52736.73
	2-127-009	436386.5	1675467.0	52736.73
	2-127-009	428874.9	1649624.0	52736.73
	2-127-009	434749.0	1653250.0	52736.73
	2-127-009	421955.4	1657011.0	52736.73
SPRUCE CREEK	2-127-014	483673.8	1724907.0	10739.14
	2-127-014	484295.2	1725513.0	10739.14
SC - PROPOSED	2-127-014	484117.6	1725311.0	10739.14
	2-127-014	483496.3	1724705.0	10739.14
	2-127-014	484738.9	1725815.0	10739.14
NEW SMYRNA	2-127-021	513319.8	1695414.0	50015.61
GLENCOE WF	2-127-021	512520.6	1695413.0	50015.61
	2-127-021	511721.4	1695413.0	50015.61
	2-127-021	513320.1	1694606.0	50015.61
	2-127-021	512520.9	1694605.0	50015.61
	2-127-021	511721.7	1694605.0	50015.61
	2-127-021	512521.1	1693797.0	50015.61
SAMSULA WF	2-127-021	475583.2	1699863.0	50015.61
	2-127-021	474162.6	1699864.0	50015.61
	2-127-021	473186.2	1700269.0	50015.61
	2-127-021	472565.0	1700572.0	50015.61
	2-127-021	471322.3	1701078.0	50015.61
	2-127-021	470701.1	1701483.0	50015.61
NSB - PROPOSED	2-127-021	461912.7	1702702.0	50015.61
SR 44 WELLFIELD	2-127-021	461380.1	1702804.0	50015.61
	2-127-021	462358.2	1704318.0	50015.61
	2-127-021	461470.2	1704117.0	50015.61
	2-127-021	461914.7	1704722.0	50015.61
	2-127-021	461560.0	1705127.0	50015.61
HALIFAX PLANTATION	2-127-027	453475.1	1842702.0	4779.87
	2-127-027	452060.1	1842906.0	4779.87
DAYTONA BCH	2-127-032	478107.8	1765916.0	0.00
EASTERN WF	2-127-032	477221.2	1765513.0	0.00
MARION ST WP	2-127-032	476511.9	1765109.0	0.00
7 WELLS INACTIV	2-127-032	475182.4	1765110.0	0.00
	2-127-032	474473.0	1764606.0	0.00
	2-127-032	473852.3	1764303.0	0.00
	2-127-032	472522.4	1763799.0	0.00
	2-127-032	471990.3	1763496.0	40986.74
	2-127-032	471192.3	1763093.0	40986.74
	2-127-032	469862.3	1762589.0	40986.74
	2-127-032	464897.4	1761482.0	40986.74
	2-127-032	464187.8	1760978.0	40986.74
WESTERN WF	2-127-032	462768.7	1760272.0	102246.7
BRENNAN WP	2-127-032	461794.5	1761081.0	102246.7
11 WELLS	2-127-032	458588.6	1747752.0	102246.7
	2-127-032	458145.0	1747551.0	102246.7
	2-127-032	457169.1	1747148.0	102246.7
	2-127-032	456370.6	1746846.0	102246.7

	2-127-032	455305.9	1746342.0	102246.7
	2-127-032	454507.4	1746040.0	102246.7
	2-127-032	454242.4	1746848.0	102246.7
	2-127-032	453800.3	1747960.0	102246.7
	2-127-032	453269.3	1748769.0	102246.7
Western wf	2-127-032	451854.4	1751800.0	102246.7
1988 constr.	2-127-032	451145.9	1752407.0	102246.7
	2-127-032	450969.5	1753115.0	102246.7
	2-127-032	451147.8	1753922.0	102246.7
	2-127-032	450971.8	1754933.0	102246.7
	2-127-032	451061.9	1756044.0	102246.7
	2-127-032	449910.0	1756449.0	102246.7
	2-127-032	453265.4	1745638.0	102246.7
	2-127-032	452916.9	1750587.0	102246.7
	2-127-032	452296.8	1751093.0	102246.7
DB - PROPOSED	2-127-032	451241.6	1757861.0	102246.7
	2-127-032	450977.0	1758872.0	102246.7
	2-127-032	450712.4	1759882.0	102246.7
	2-127-032	450447.8	1760893.0	102246.7
	2-127-032	450183.2	1761903.0	102246.7
ORMOND BCH	2-127-034	479276.3	1795409.0	21677.86
DIVISION AVE	2-127-034	479364.9	1795308.0	21677.86
	2-127-034	478832.6	1793692.0	21677.86
	2-127-034	478478.6	1794197.0	21677.86
	2-127-034	478301.6	1794399.0	21677.86
	2-127-034	478124.3	1794096.0	21677.86
	2-127-034	476175.6	1793794.0	21677.86
	2-127-034	475643.9	1793290.0	21677.86
	2-127-034	475023.8	1793088.0	21677.86
	2-127-034	478479.7	1796116.0	21677.86
	2-127-034	478125.3	1795914.0	21677.86
	2-127-034	475821.9	1794704.0	21677.86
SR 40 WF	2-127-034	467318.6	1793397.0	21677.86
	2-127-034	464038.3	1789966.0	21677.86
	2-127-034	467939.9	1794912.0	21677.86
	2-127-034	468293.6	1794305.0	21677.86
	2-127-034	462089.2	1789564.0	21677.86
HUDSON WF	2-127-034	450487.7	1791092.0	21677.86
	2-127-034	450488.9	1792002.0	21677.86
	2-127-034	450490.1	1792911.0	21677.86
	2-127-034	450491.2	1793719.0	21677.86
	2-127-034	450492.4	1794628.0	21677.86
	2-127-034	450493.6	1795537.0	21677.86
	2-127-034	450494.8	1796446.0	21677.86
	2-127-034	451552.9	1792909.0	21677.86
	2-127-034	451997.0	1793818.0	21677.86
	2-127-034	451998.1	1794727.0	21677.86
	2-127-034	452001.2	1797151.0	21677.86
	2-127-034	449515.9	1792912.0	21677.86
	2-127-034	448718.7	1792913.0	21677.86
OB - PROPOSED	2-127-034	419696.7	1764986.0	21677.86
CENTRAL RECHARGE	2-127-034	420758.4	1764075.0	21677.86
WELLFIELD	2-127-034	421643.1	1763265.0	21677.86
	2-127-034	421994.9	1761951.0	21677.86

	2-127-034	422080.4	1760436.0	21677.86
	2-127-034	422165.7	1758820.0	21677.86
	2-127-034	422163.4	1757708.0	21677.86
	2-127-034	422160.3	1756193.0	21677.86
	2-127-034	422158.6	1755385.0	21677.86
	2-127-034	423768.8	1762452.0	21677.86
	2-127-034	424832.9	1762652.0	21677.86
	2-127-034	425719.1	1762549.0	21677.86
	2-127-034	426871.8	1762749.0	21677.86
	2-127-034	425544.2	1763762.0	21677.86
	2-127-034	425280.1	1764671.0	21677.86
	2-127-034	420039.4	1759430.0	21677.86
	2-127-034	419152.3	1759129.0	21677.86
	2-127-034	418000.3	1759333.0	21677.86
	2-127-034	417819.9	1757920.0	21677.86
	2-127-034	417639.2	1756405.0	21677.86
	2-127-034	417548.4	1755395.0	21677.86
OB - PROPOSED	2-127-034	441343.5	1777571.0	21677.86
RIMA RIDGE	2-127-034	441168.2	1778784.0	21677.86
JOHN KNOX VILL.	2-127-038	407780.8	1676637.0	6329.21
	2-127-038	407869.6	1676636.0	6329.21
	2-127-038	408491.8	1676736.0	6329.21
V CTY - OR CITY IND	2-127-042	405548.3	1672097.0	0.00
V CTY - FOUR TOWNS	2-127-042	404205.6	1668162.0	42322.91
V CTY - FOUR TOWNS	2-127-042	404478.5	1670686.0	42322.91
V CTY - LAKE MARIE	2-127-042	400182.2	1658880.0	16962.13
V CTY - LAKE MARIE	2-127-042	400093.1	1658779.0	16962.13
V CTY - BREEZEWOOD	2-127-042	406249.4	1668156.0	21441.65
V CTY - TERRA ALTA	2-127-042	402507.8	1664530.0	7178.96
V CTY -SWALLOWS	2-127-042	406854.8	1661388.0	0.00
V CTY - ?	2-127-042	398902.9	1679083.0	0.00
V CTY - HLND CTRY EST	2-127-042	401440.8	1664331.0	31005.05
V CTY - HLND CTRY EST	2-127-042	401618.6	1664330.0	31005.05
V CTY - W ORANGE CITY	2-127-042	395515.3	1674851.0	1259.98
V CTY - SWALLOWS	2-127-042	406499.6	1661490.0	0.00
V CTY - SWALLOWS	2-127-042	401166.6	1661402.0	0.00
V CTY - SWALLOWS	2-127-042	406855.1	1661489.0	0.00
V CTY - CASSADAGA	2-127-042	424500.5	1685185.0	5640.61
DELAND-BRANDYWINE	2-127-042	398315.2	1724738.0	109552.4
DELAND-SPRING GARDEN	2-127-042	396359.2	1723329.0	2921.03
DELAND-SPRING GARDEN	2-127-042	396536.7	1723328.0	2921.03
DELAND-LONGLEAF PLANT.	2-127-042	409956.3	1694811.0	34587.21
DELAND-TOMOKA WOODS	2-127-042	412752.1	1751669.0	3519.89
DELAND-WOODLAND MANR	2-127-042	397529.0	1729285.0	21709.03
DELAND-GLENWOOD EST	2-127-042	393519.5	1723236.0	4578.42
DELAND-HOLIDAY HILLS	2-127-042	398684.3	1696961.0	6937.22
DELAND-HOLIDAY HILLS	2-127-042	398594.7	1696658.0	6937.22
ELLWOOD TITCOMB	2-127-043	430372.7	1690526.0	56605.91
CITY OF EDGEWATER	2-127-051	520604.4	1689660.0	56605.91
	2-127-051	519982.9	1689357.0	56605.91
	2-127-051	519450.1	1689154.0	56605.91
	2-127-051	518828.5	1689053.0	56605.91
	2-127-051	518384.5	1688952.0	56605.91
	2-127-051	513414.7	1678143.0	56605.91

	2-127-051	512792.8	1678142.0	56605.91
	2-127-051	512437.5	1678041.0	56605.91
	2-127-051	511993.3	1678041.0	56605.91
	2-127-051	517145.9	1678346.0	56605.91
	2-127-051	516790.1	1679255.0	56605.91
FALCON DEVEL-PINE RUN	2-127-O51	462824.0	1815824.0	0.00
HOWARD S. DORR	2-127-054	454558.5	1640899.0	2183.23
	2-127-054	454380.4	1640697.0	2183.23
TYMBER CREEK UTIL.	2-127-056	459435.6	1792900.0	23965.28
DELTONA WOODS	2-127-056	423686.6	1678015.0	6307.23
THE TRAILS INC.	2-127-061	453144.6	1790887.0	77432.01
LAKE HELEN	2-127-064	425660.5	1687909.0	38605.23
	2-127-064	425315.6	1693162.0	38605.23
HACIENDA DEL RIO	2-127-066	537765.3	1669473.0	13608.82
NATIONAL GARDENS	2-127-066	466370.6	1822487.0	2589.55
	2-127-066	465838.9	1821680.0	2589.55
	2-127-066	466103.8	1821073.0	2589.55
	2-127-066	467166.2	1821476.0	2589.55
	2-127-066	466457.2	1820366.0	2589.55
	2-127-066	467431.1	1820769.0	2589.55
	2-127-066	467429.8	1819254.0	2589.55
	2-127-066	467429.4	1818850.0	2589.55
	2-127-066	465747.1	1818145.0	2589.55
	2-127-066	466366.7	1818144.0	2589.55
	2-127-066	465923.7	1817639.0	2589.55
	2-127-066	466011.3	1816629.0	2589.55
	2-127-066	466719.7	1817033.0	2589.55
	2-127-066	466188.1	1816427.0	2589.55
	2-127-066	466541.8	1816023.0	2589.55
	2-127-066	467250.3	1816426.0	2589.55
	2-127-066	466895.4	1815517.0	2589.55
	2-127-066	466983.7	1815214.0	2589.55
	2-127-066	467160.4	1814911.0	2589.55
	2-127-066	467957.5	1815415.0	2589.55
	2-127-066	468046.4	1815920.0	2589.55
	2-127-066	469288.1	1818949.0	2589.55
	2-127-066	469110.6	1818344.0	2589.55
	2-127-066	468844.8	1817940.0	2589.55
ORANGE CITY	2-127-067	404581.6	1676342.0	122207.2
	2-127-067	404581.1	1676140.0	122207.2
	2-127-067	404491.3	1675736.0	122207.2
SUNSHINE HOLIDAY PK	2-127-068	455838.1	1821488.0	16883.67
KOVE ASSOCIATION	2-127-077	445038.4	1637478.0	4713.94
	2-127-077	445038.1	1637276.0	4713.94
LEMON BLUFF	2-127-079	455879.5	1629788.0	3420.40
	2-127-079	455968.5	1629788.0	3420.40
VOLUSIA COUNTY -	2-127-079	546671.1	1653424.0	10246.64
GOLDEN BAY COLONY	2-127-079	546759.8	1653526.0	10246.64
HOLIDAY TRAILER PK	2-035-006	448966.2	1844223.0	2322.17
PLANTATION BAY	2-035-002	439763.8	1841813.0	5445.27
	2-035-002	439762.3	1840904.0	5445.27
	2-035-002	439495.6	1840096.0	5445.27
KINGSTON SHORES	--	472576.7	1837633.0	5310.97
L BERESFORD WATER ASSN	--	389456.6	1699411.0	43879.57

	2-127-051	512792.8	1678142.0	56605.91
	2-127-051	512437.5	1678041.0	56605.91
	2-127-051	511993.3	1678041.0	56605.91
	2-127-051	517145.9	1678346.0	56605.91
	2-127-051	516790.1	1679255.0	56605.91
FALCON DEVEL-PINE RUN	2-127-O51	462824.0	1815824.0	0.00
HOWARD S. DORR	2-127-054	454558.5	1640899.0	2183.23
	2-127-054	454380.4	1640697.0	2183.23
TYMBER CREEK UTIL.	2-127-056	459435.6	1792900.0	23965.28
DELTONA WOODS	2-127-056	423686.6	1678015.0	6307.23
THE TRAILS INC.	2-127-061	453144.6	1790887.0	77432.01
LAKE HELEN	2-127-064	425660.5	1687909.0	38605.23
	2-127-064	425315.6	1693162.0	38605.23
HACIENDA DEL RIO	2-127-066	537765.3	1669473.0	13608.82
NATIONAL GARDENS	2-127-066	466370.6	1822487.0	2589.55
	2-127-066	465838.9	1821680.0	2589.55
	2-127-066	466103.8	1821073.0	2589.55
	2-127-066	467166.2	1821476.0	2589.55
	2-127-066	466457.2	1820366.0	2589.55
	2-127-066	467431.1	1820769.0	2589.55
	2-127-066	467429.8	1819254.0	2589.55
	2-127-066	467429.4	1818850.0	2589.55
	2-127-066	465747.1	1818145.0	2589.55
	2-127-066	466366.7	1818144.0	2589.55
	2-127-066	465923.7	1817639.0	2589.55
	2-127-066	466011.3	1816629.0	2589.55
	2-127-066	466719.7	1817033.0	2589.55
	2-127-066	466188.1	1816427.0	2589.55
	2-127-066	466541.8	1816023.0	2589.55
	2-127-066	467250.3	1816426.0	2589.55
	2-127-066	466895.4	1815517.0	2589.55
	2-127-066	466983.7	1815214.0	2589.55
	2-127-066	467160.4	1814911.0	2589.55
	2-127-066	467957.5	1815415.0	2589.55
	2-127-066	468046.4	1815920.0	2589.55
	2-127-066	469288.1	1818949.0	2589.55
	2-127-066	469110.6	1818344.0	2589.55
	2-127-066	468844.8	1817940.0	2589.55
ORANGE CITY	2-127-067	404581.6	1676342.0	122207.2
	2-127-067	404581.1	1676140.0	122207.2
	2-127-067	404491.3	1675736.0	122207.2
SUNSHINE HOLIDAY PK	2-127-068	455838.1	1821488.0	16883.67
KOVE ASSOCIATION	2-127-077	445038.4	1637478.0	4713.94
	2-127-077	445038.1	1637276.0	4713.94
LEMON BLUFF	2-127-079	455879.5	1629788.0	3420.40
	2-127-079	455968.5	1629788.0	3420.40
VOLUSIA COUNTY -	2-127-079	546671.1	1653424.0	10246.64
GOLDEN BAY COLONY	2-127-079	546759.8	1653526.0	10246.64
HOLIDAY TRAILER PK	2-035-006	448966.2	1844223.0	2322.17
PLANTATION BAY	2-035-002	439763.8	1841813.0	5445.27
	2-035-002	439762.3	1840904.0	5445.27
	2-035-002	439495.6	1840096.0	5445.27
KINGSTON SHORES	--	472576.7	1837633.0	5310.97
L BERESFORD WATER ASSN	--	389456.6	1699411.0	43879.57

Table 8. Summary of the three-dimensional model parameter zonation.

Parameter Type	Zone Number	Value
Hydraulic Conductivity	1	20 ft/d
	2	30
	3	0.4
	4	20
	5	40
	6	25
	7	0.5
	8	86
	9	200
	10	1500
	11	5000
	12	5
	13	3600
	14	235
	15	100
	16	18
	17	0.63
	18	0.01
	19	55
	20	40
Leakance	1	0.00028 d^{-1}
	2	0.00006
	3	0.001
	4	0.0019
	5	0.0000291
	6	0.6
	7	0.00005
	8	0.0116
	9	0.00001
	10	0.000028
	11	0.00045
	12	0.0000018

Table 9. Published hydraulic parameter values.

Surficial aquifer

Parameter	Range	Reference
K_h	0.1 ft/d	Mercer (1984)
	10 ft/d	Tibbals (1990)
	$3x10^{-2}$ to 49 ft/d	Phelps (1990)
K_v	0.01 ft/d	Mercer (1984)
	$7.6x10^{-5}$ to $3.4x10^{-1}$ ft/d	Phelps (1990)
Leakance Coeff.	$1x10^{-6}$ to $1x10^{-4}$ d^{-1}	Tibbals (1990)

Upper Floridan aquifer

Parameter	Range	Reference
T	10,000 to 400,000 ft^2/d	Tibbals (1990)
K_h	68.5 to 400 ft/d	Mercer (1984)
S	$5x10^{-4}$ to $1x10^{-3}$	Tibbals (1990)
Leakance Coeff.	$5x10^{-5}$ d^{-1}	Tibbals (1990)

Lower *Floridan aquifer*

Parameter	Range	Reference
T	30,000 to 60,000 ft^2/d	Tibbals (1990)
K_h	75 to 150 ft/d	Mercer (1984)
S	$5x10^{-4}$ to $1x10^{-3}$	Tibbals (1990)

Table 10. Calibration target locations and observed water levels in the predevelopment (1955) three-dimensional model.

Target	Target Location Row	Column	Layer	Observed Hydraulic Head (ft msl)
V-0095	5	9	2	25.000
V-0008	57	51	2	20.500
V-0096	5	15	2	21.200
R-1	3	4	2	5.000
R-2	6	15	2	20.000
R-3	9	7	2	26.000
R-4	76	10	2	14.000
R-5	30	11	2	19.000
R-6	43	17	2	44.000
R-7	84	48	2	22.000
R-8	78	48	2	25.000
R-9	62	20	2	37.000
R-10	60	35	2	40.000
R-11	53	63	2	13.000
R-12	83	8	2	12.000
R-13	25	25	2	29.000
R-14	16	68	2	17.000
R-15	74	72	2	10.000

* R-# taken from Rutledge (1985)

Table 11. Comparison of simulated and observed water levels at calibration targets for the predevelopment (1955) three-dimensional model.

Target	Target Location			Hydraulic Head (ft msl)		Residual
	Row	Column	Layer	Observed	Simulated	Head (ft)
V-0095	5	9	2	25.000	26.169	-1.17
V-0008	57	51	2	20.500	26.590	-6.09
V-0096	5	15	2	21.200	20.394	0.806
R-1	3	4	2	5.000	2.678	2.32
R-2	6	15	2	20.000	22.579	-2.58
R-3	9	7	2	26.000	24.240	1.76
R-4	76	10	2	14.000	11.717	2.28
R-5	30	11	2	19.000	9.951	9.05
R-6	43	17	2	44.000	39.010	4.99
R-7	84	48	2	22.000	23.494	-1.49
R-8	78	48	2	25.000	26.541	-1.54
R-9	62	20	2	37.000	44.287	-7.29
R-10	60	35	2	40.000	36.376	3.62
R-11	53	63	2	13.000	18.779	-5.78
R-12	83	8	2	12.000	12.381	-0.381
R-13	25	25	2	29.000	36.371	-7.37
R-14	16	68	2	17.000	12.512	4.49
R-15	74	72	2	10.000	8.860	1.14

* R-# taken from Rutledge (1985)

Table 12. Comparison of simulated and observed spring rates for the three-dimensional model.

	Spring Location			Spring Rate (mgd)		Error %
Spring	Row	Column	Layer	Observed	Simulated	
Predevelopment (1955)						
Ponce De Leon	35	12	2	20	20.1	0.5
Blue Spring	76	6	2	103	99.1	-0.5
Gemini Spring	86	7	2	5.2	5.4	3.8
1988						
Ponce De Leon	35	12	2	16.2	16.2	0.0
Blue Spring	76	6	2	91.6	90.9	-0.8
Gemini Spring	86	7	2	4.96 (1986)	4.95	0.2

Table 13. Comparison of simulated and observed water levels at calibration targets for the 1988 three-dimensional model.

	Target Location			Hydraulic Head (ft msl)		Residual
Target	Row	Column	Layer	Observed	Simulated	Head (ft)
F-0252	12	25	1	24.160	20.248	3.91
V-0063	19	15	1	20.165	25.120	-4.96
V-0069	11	7	1	24.305	25.639	-1.33
V-0185	3	9	1	26.520	28.857	-2.34
V-0193	58	46	1	32.630	30.124	2.51
V-0197	81	7	1	68.690	67.341	1.35
V-0199	88	34	1	16.235	20.392	-4.16
285655081165602	78	10	1	14.500	12.879	1.62
291007081101613	47	40	1	35.470	35.835	-0.365
291353081160401	21	28	1	31.130	31.779	-0.649
F-0261	3	36	2	8.405	11.213	-2.81
F-0286	22	53	2	7.895	13.611	-5.72
V-0008	57	51	2	12.725	3.944	8.78
V-0062	19	15	2	24.585	24.871	-0.286
V-0064	4	10	2	23.620	26.719	-3.10
V-0065	9	5	2	13.310	14.036	-0.726
V-0066	11	7	2	21.850	24.593	-2.74
V-0068	10	6	2	17.460	18.849	-1.39
V-0081	60	22	2	36.160	35.076	1.08
V-0096	5	15	2	19.460	18.474	0.986
V-0098	51	63	2	2.955	0.574	-3.53
V-0099	54	58	2	0.150	0.908	-1.06
V-0155	3	5	2	5.520	4.982	0.538
V-0156	48	10	2	15.050	11.349	3.70
V-0184	3	9	2	26.210	27.493	-1.28
V-0187	54	64	2	1.490	0.985	0.505
V-0198	88	34	2	16.215	18.955	-2.74
V-0200	63	78	2	2.370	1.031	-3.40
V-0206	15	5	2	16.140	17.898	-1.76
V-0213	28	11	2	17.000	12.223	4.78
V-0217	17	12	2	22.850	24.425	-1.58
V-0012	60	22	4	30.095	24.165	5.93
285016081014101	91	35	2	15.865	14.164	1.70
285040081192101	86	3	2	17.345	14.463	2.88
285156081190302	85	5	2	11.850	12.423	-0.573
285221081095002	88	17	2	21.710	16.684	5.03
285359081161701	84	9	2	16.400	12.573	3.83
285452080551801	90	64	2	8.515	8.310	0.205
285655081165601	78	10	2	12.080	11.505	0.575
285700081021001	86	45	2	17.570	18.225	-0.655
285745081054001	85	34	2	28.790	23.670	5.12
285833080571701	87	64	2	4.935	5.855	-0.920
285859081191001	74	9	2	5.020	6.699	-1.68
285904080554601	87	70	2	5.245	3.598	1.65
285906081152002	76	15	2	31.025	23.701	7.32

285921080541001	87	76	2	6.585	2.118	4.47
285934081041801	83	42	2	24.195	21.929	2.27
285950080580101	86	63	2	4.585	5.159	-0.574
290047080593101	84	60	2	6.180	8.761	-2.58
290102080564201	85	70	2	4.200	4.053	0.147
290138081203202	64	9	2	9.985	9.822	0.163
290225081040301	77	47	2	20.545	17.453	3.09
290230081123401	72	20	2	34.205	35.430	-1.22
290308081182301	61	14	2	16.445	18.035	-1.59
290325080563401	81	75	2	1.870	3.172	-1.30
290447081102301	68	31	2	35.230	27.837	7.39
290456081044401	74	49	2	18.550	14.646	3.90
290534081175001	53	16	2	35.110	33.423	1.69
290550081162601	54	17	2	38.120	37.351	0.769
290626081013701	73	63	2	2.960	5.670	-2.71
290651080582802	74	75	2	2.075	3.455	-1.38
290723081210601	40	13	2	12.080	10.106	1.97
290737081220301	37	11	2	8.700	3.845	4.85
290806081013901	69	66	2	3.575	3.060	0.515
290923081174301	37	18	2	34.350	31.613	2.74
291006081101004	47	40	2	26.100	18.899	7.20
291032081065201	51	51	2	5.975	0.927	5.05
291036081175801	32	18	2	30.620	32.275	-1.65
291139081032401	52	66	2	2.370	0.443	-2.81
291149081190801	25	18	2	25.410	27.572	-2.16
291155081022901	52	70	2	2.500	0.242	-2.74
291258081313701	12	3	2	6.515	10.110	-3.60
291302081063801	41	57	2	7.380	2.123	5.26
291315081270301	14	8	2	26.285	28.832	-2.55
291332081191001	18	19	2	30.095	26.782	3.31
291421081012202	44	78	2	3.220	0.196	-3.02
291523081095001	25	49	2	14.805	15.321	-0.516
291712081032102	29	77	2	4.655	3.214	-1.44
291720081194401	13	21	2	19.035	19.345	-0.310
291818081190401	12	25	2	16.640	18.608	-1.97
291904081055501	18	71	2	1.525	6.857	-5.33
291949081065901	16	68	2	6.090	8.823	-2.73
292128081295401	2	10	2	31.390	30.354	1.04
292156081215001	3	22	2	9.625	11.618	-1.99
292245081074801	12	71	2	5.670	7.813	-2.14
292302081155901	5	43	2	12.255	15.626	-3.37
292421081072301	9	75	2	5.845	6.158	-0.313
292448081121301	4	59	2	16.735	17.464	-0.729

Table 14. Calibration target locations and chloride concentrations for the 1990 three-dimensional transport model.

Target	Target Location Row	Column	Layer	Observed Chloride Concentration (mg/L)
V-0185	3	9	1	134
V-0197	81	7	1	4
V-0063	19	15	1	9
F-0252	12	25	1	66
285655081165602	78	10	1	13
F-0276	12	25	2	32
F-0277	3	25	2	770
F-0261	3	36	2	3700
V-0144	13	10	2	16
V-0147	12	9	2	8
V-0155	3	5	2	1380
V-0165	90	20	2	48
V-0183	58	46	2	168
V-0184	3	9	2	22
V-0187	54	64	2	169
V-0198	88	34	2	55
V-0213	28	11	2	38
V-0225	12	8	2	8
V-0508	86	75	2	4430
V-0062	19	15	2	14
V-0064	4	10	2	15
V-0065	9	5	2	12
V-0068	10	6	2	9
V-0080	57	51	2	47
V-0081	60	22	2	14
V-0095	5	9	2	11
V-0096	5	15	2	16
V-0098	51	63	2	88
V-0099	54	58	2	45
285016081014101	91	35	2	44
285040081192101	86	3	2	480
285359081161701	84	9	2	10
285452080551801	90	64	2	78
285512081202801	78	5	2	735
285655081165601	78	10	2	10
285700081021001	86	45	2	14
285904080554601	87	70	2	210
285921080541001	87	76	2	240
285923081211601	72	7	2	840
290225081040301	77	47	2	11

290251081001401	79	61	2	280
290308081182301	61	14	2	13
290456081044401	74	49	2	74
290651080582802	74	75	2	460
290708081233101	37	9	2	2700
290737081220301	37	11	2	390
291032081065201	51	51	2	31
291036081175801	32	18	2	8
291113081050601	51	59	2	110
291155081022901	52	70	2	150
291258081313701	12	3	2	29
291302081063801	41	57	2	36
291421081012202	44	78	2	125
291523081095001	25	49	2	62
291913081224201	18	71	2	160
292302081155901	5	43	2	91
292448081121301	4	59	2	31

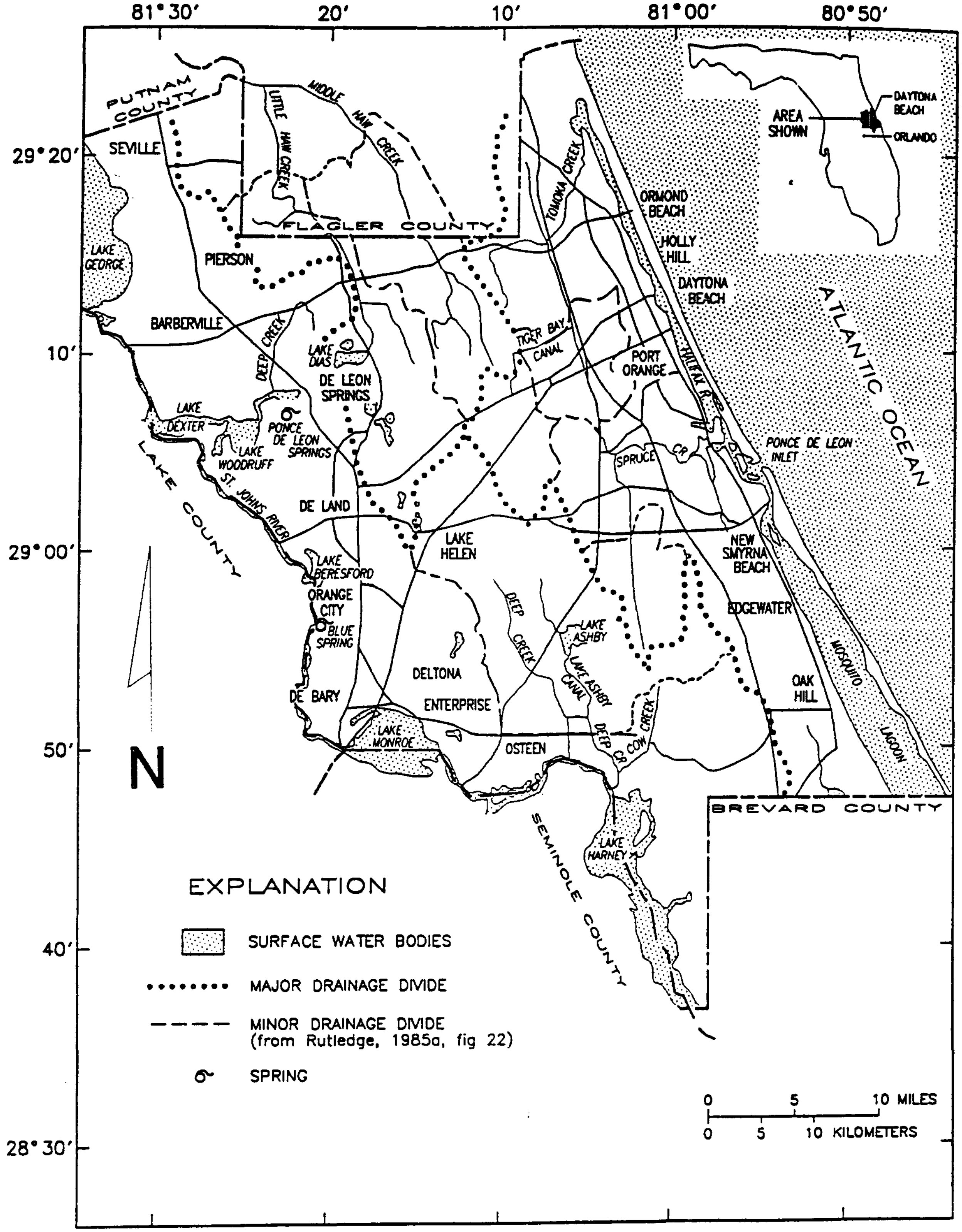

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Figure 1. Volusia County location map.

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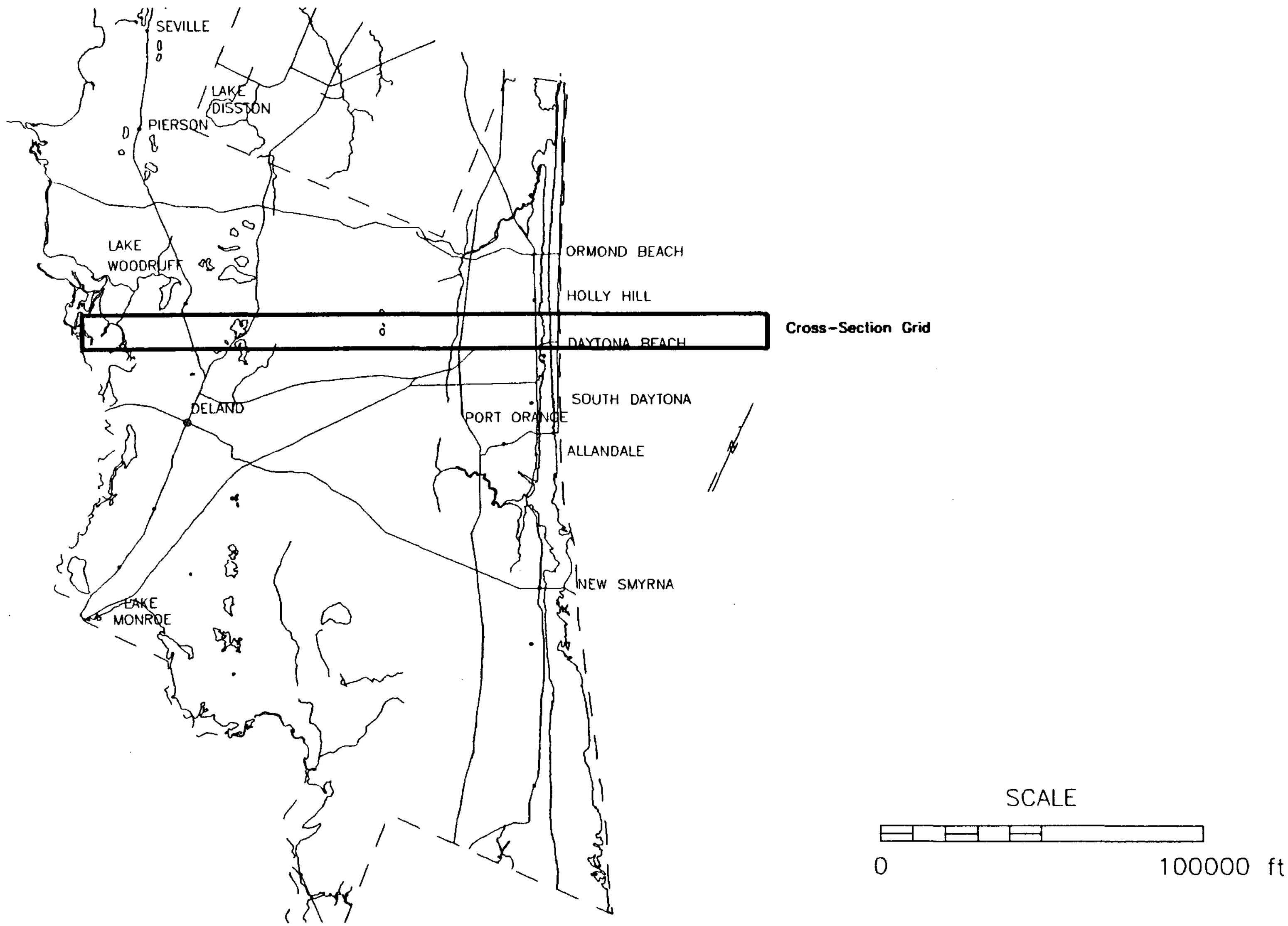

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Figure 2. Location of the cross-sectional model in Volusia County.

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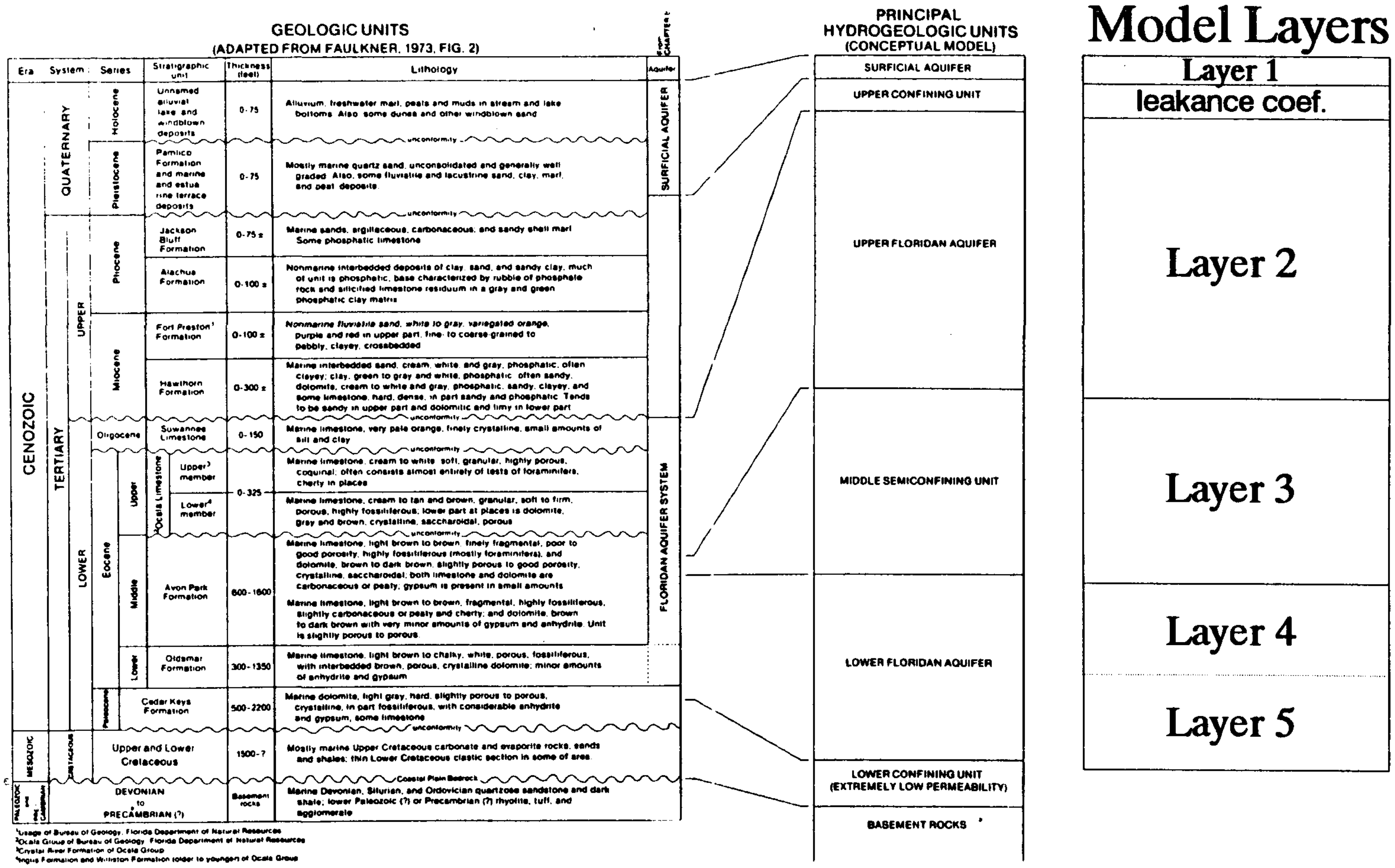

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Figure 3. Hydrogeologic section of the Floridan aquifer system (after Tibbals 1990).

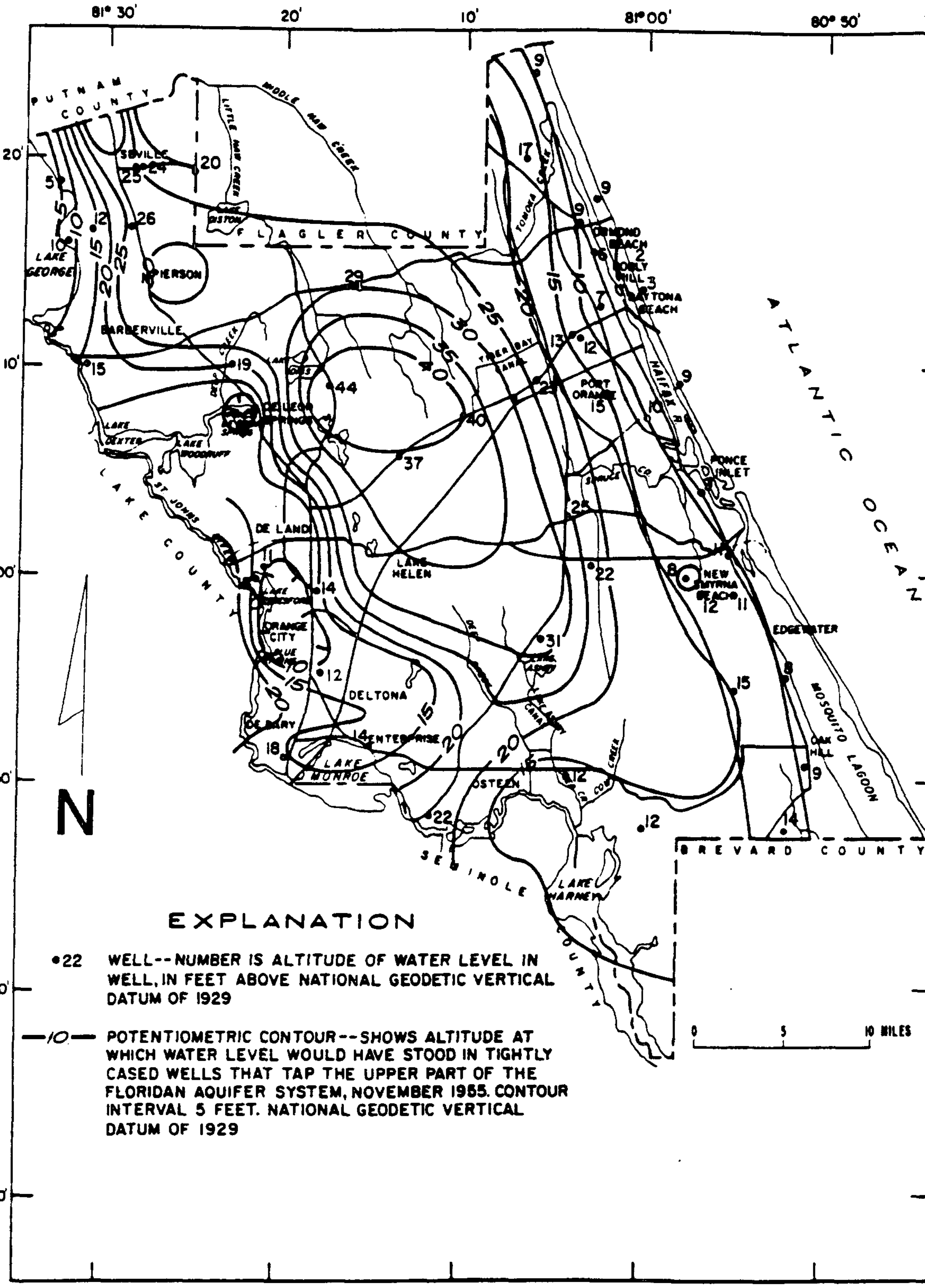

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Figure 4. Predevelopment potentiometric surface in the Upper Floridan aquifer (after Rutledge 1985).

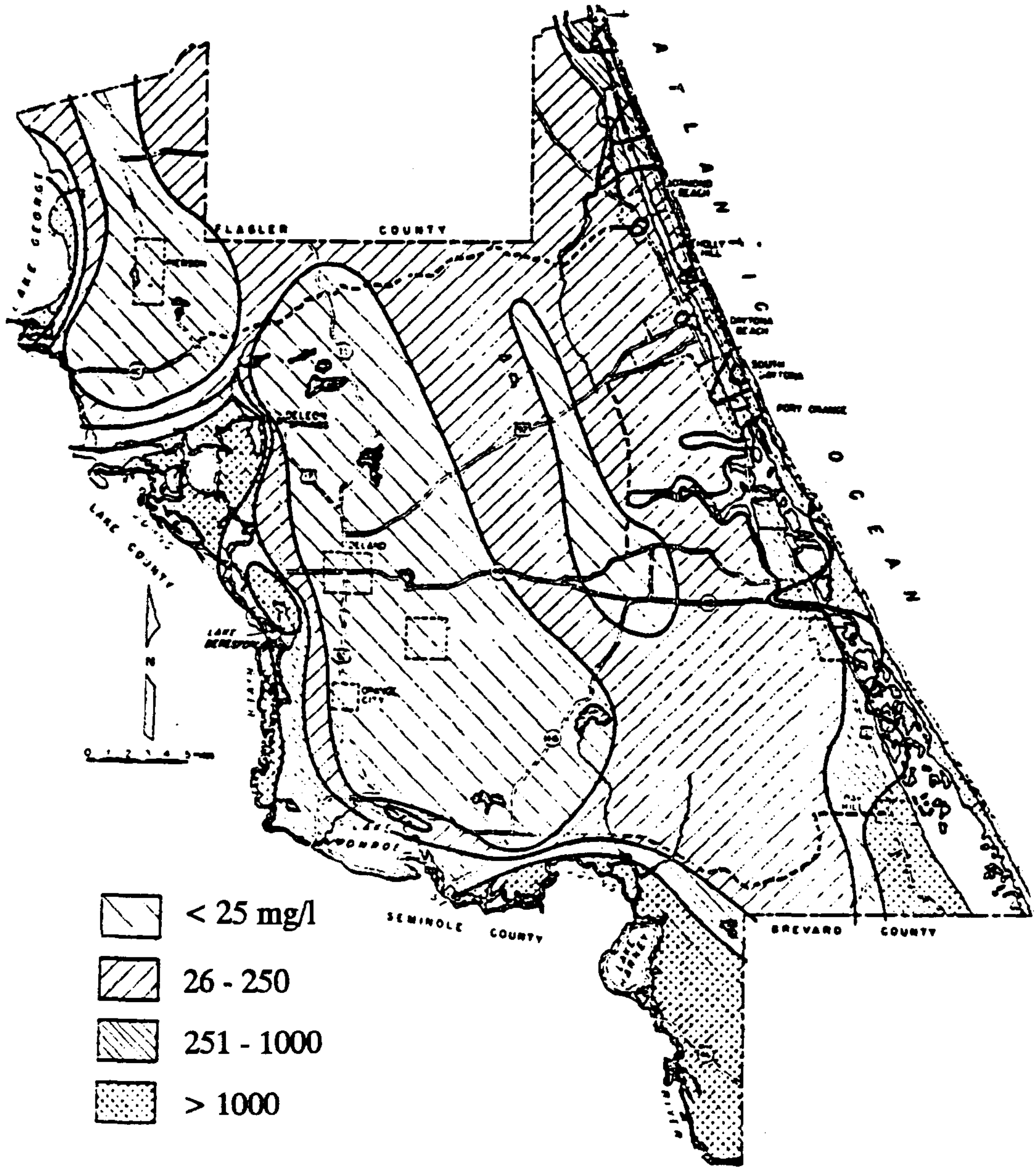

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Figure 5. Predevelopment chloride distribution in the Upper Floridan aquifer (after Wyrick 1960).

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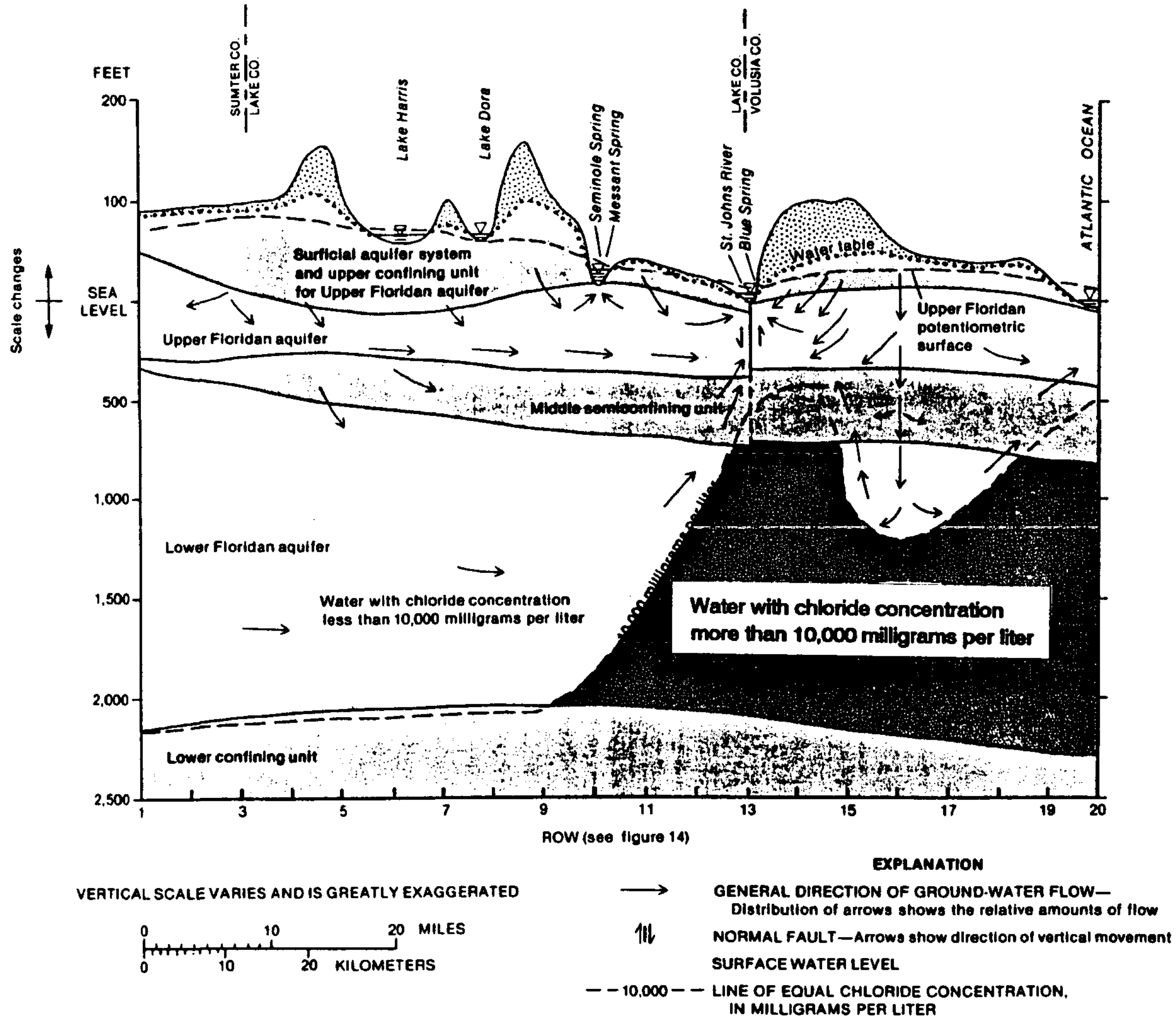

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Figure 6. Hydrogeologic units and ground-water flow along the cross section (after Tibbals 1990).

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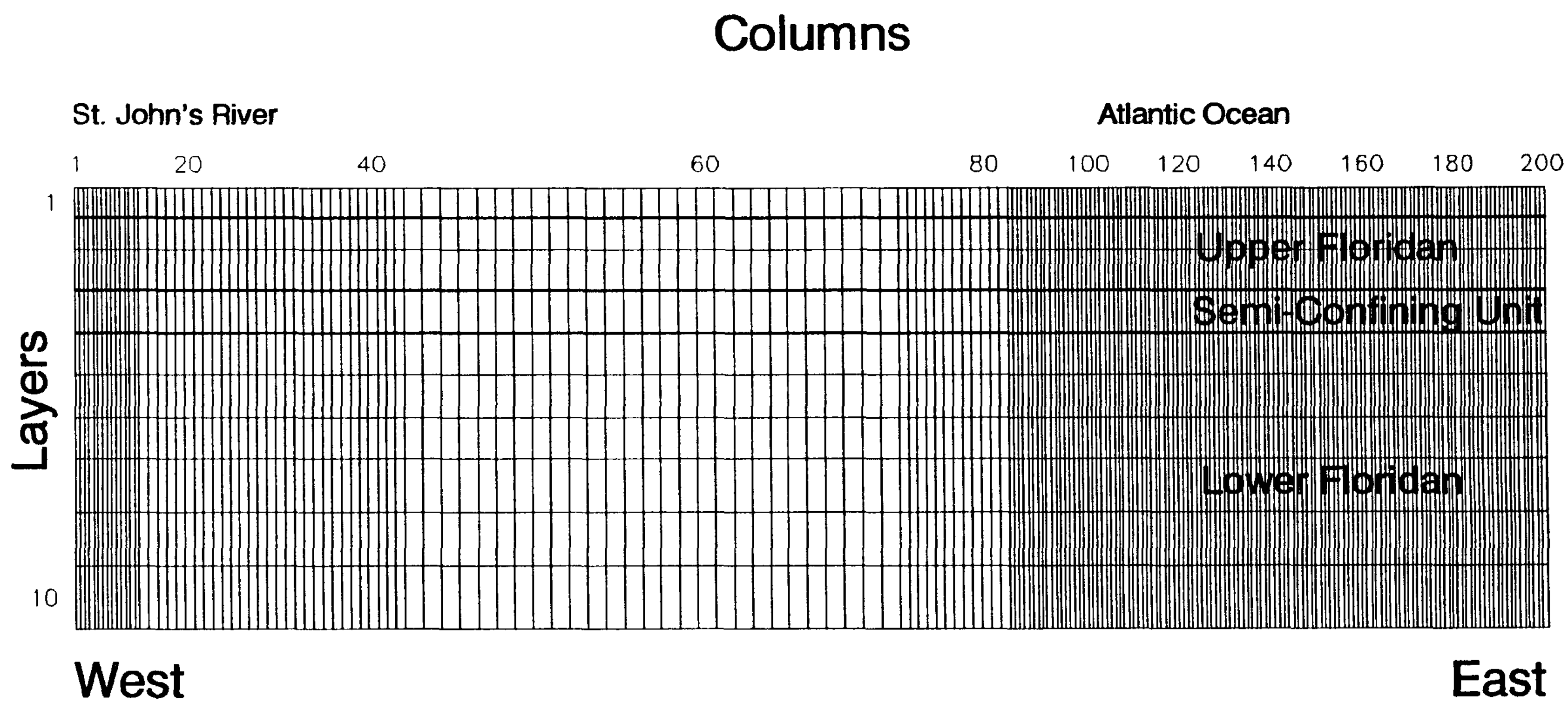

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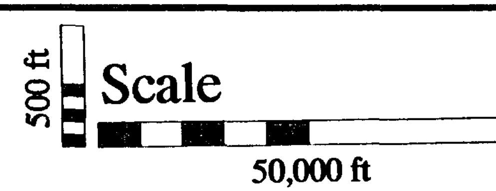
Figure 7. Base case cross-sectional model finite-difference grid.



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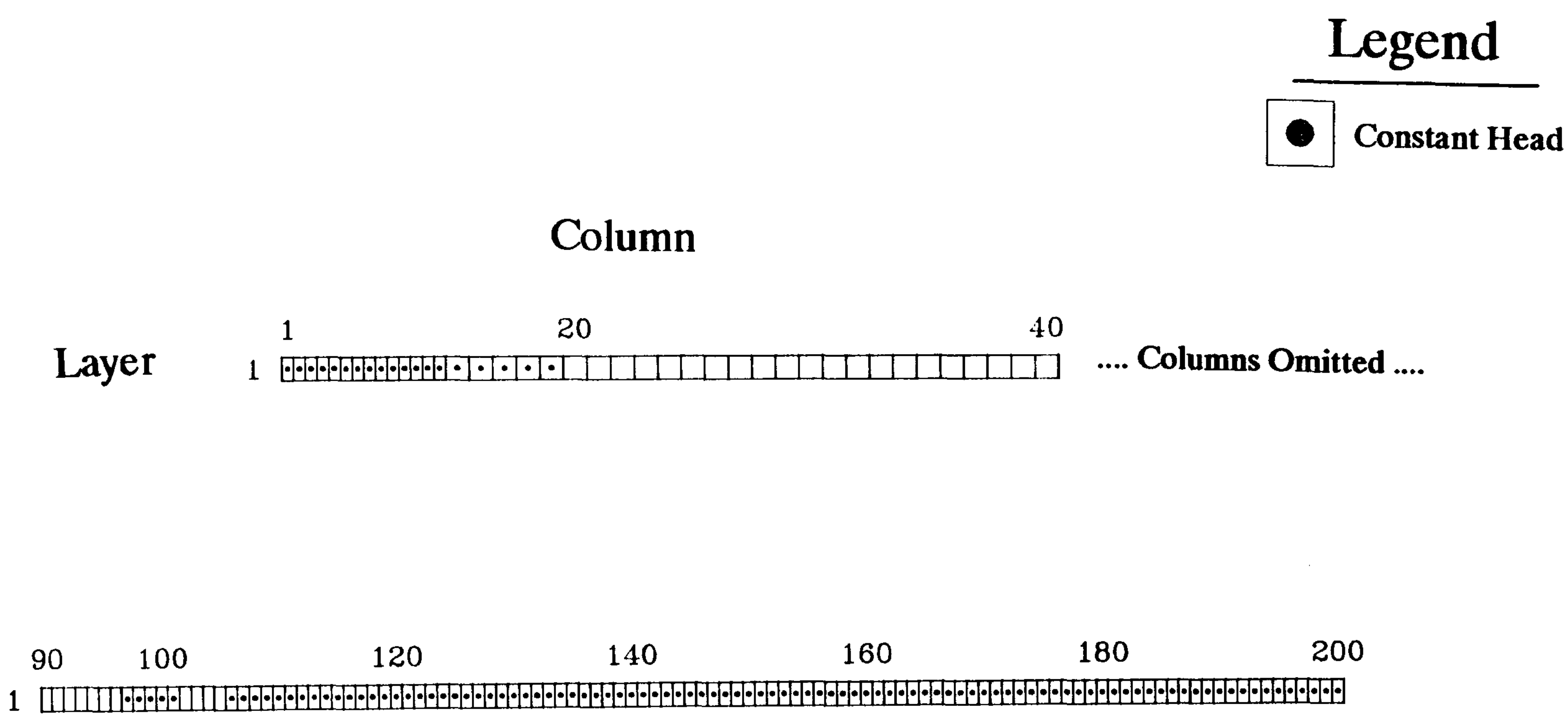

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Figure 8. Cross-sectional model boundary conditions and finite-difference grid (dots represent constant heads, model layer 1).

SCALE
0 2 mi

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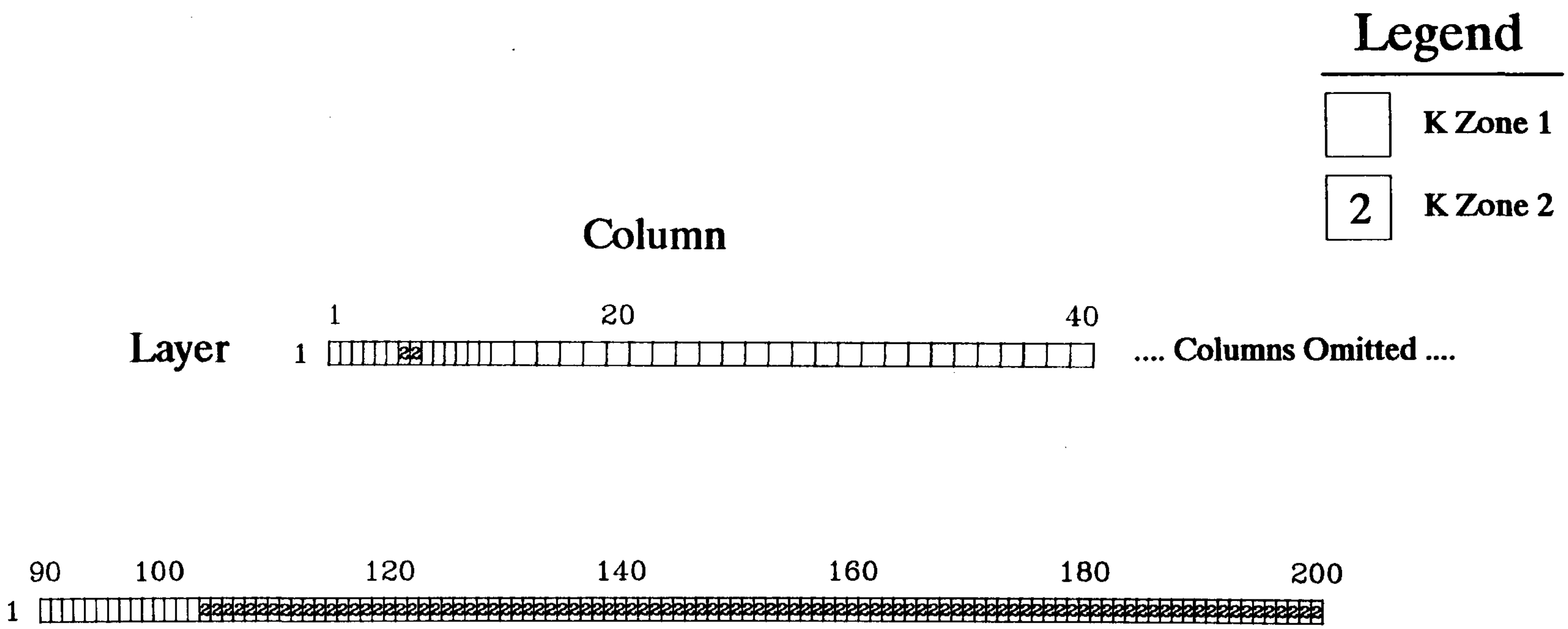

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Figure 9. Hydraulic conductivity zonation of the middle semi-confining unit, cross-sectional model layer 4.

SCALE

0 2 mi

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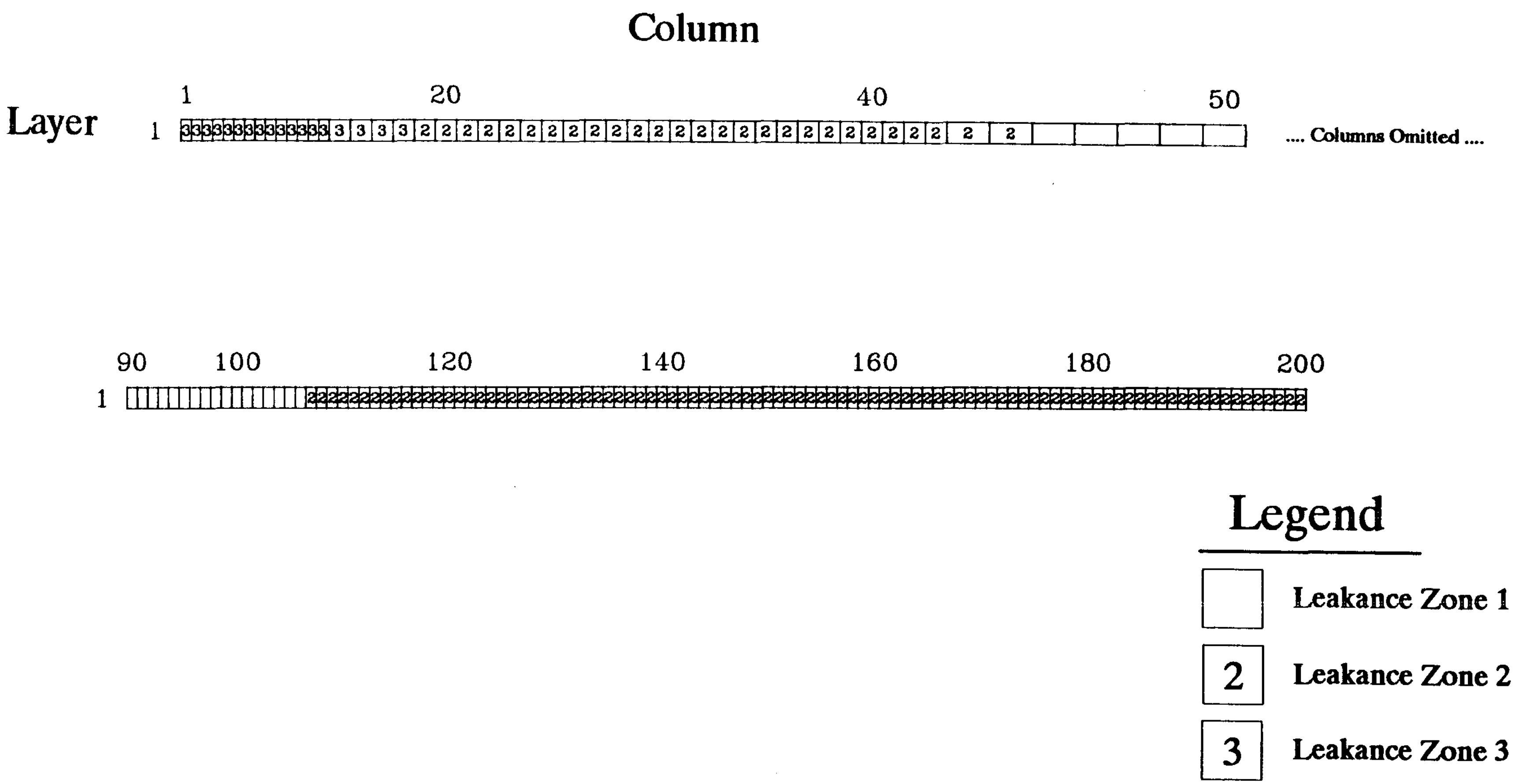

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Figure 10. Vertical leakance zonation of the confining unit at the base of the surficial aquifer, interface between cross-sectional model layers 1 and 2.

SCALE
0 2 mi

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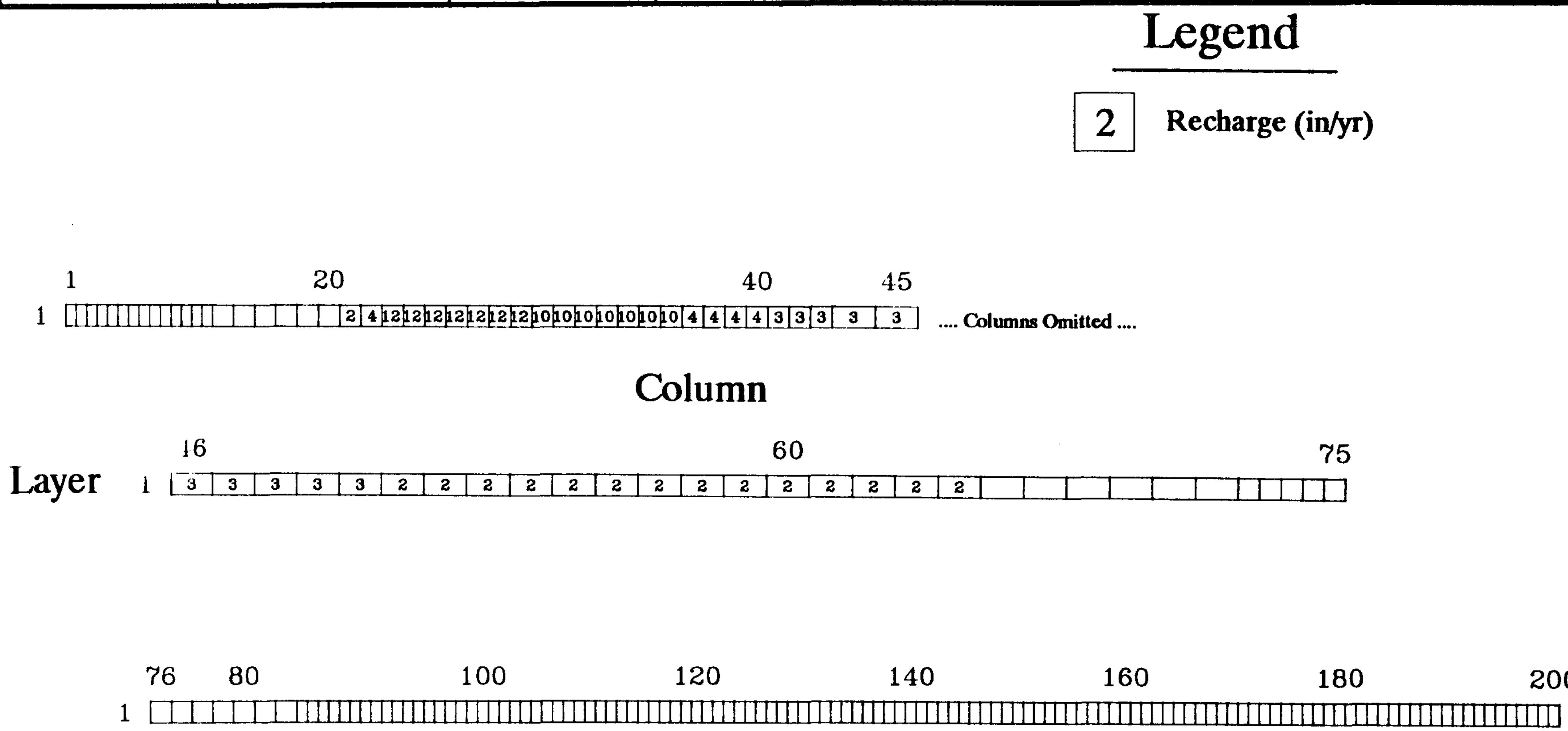

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Figure 11. Precipitation recharge zonation, cross-sectional model layer 1

SCALE
0 2 mi

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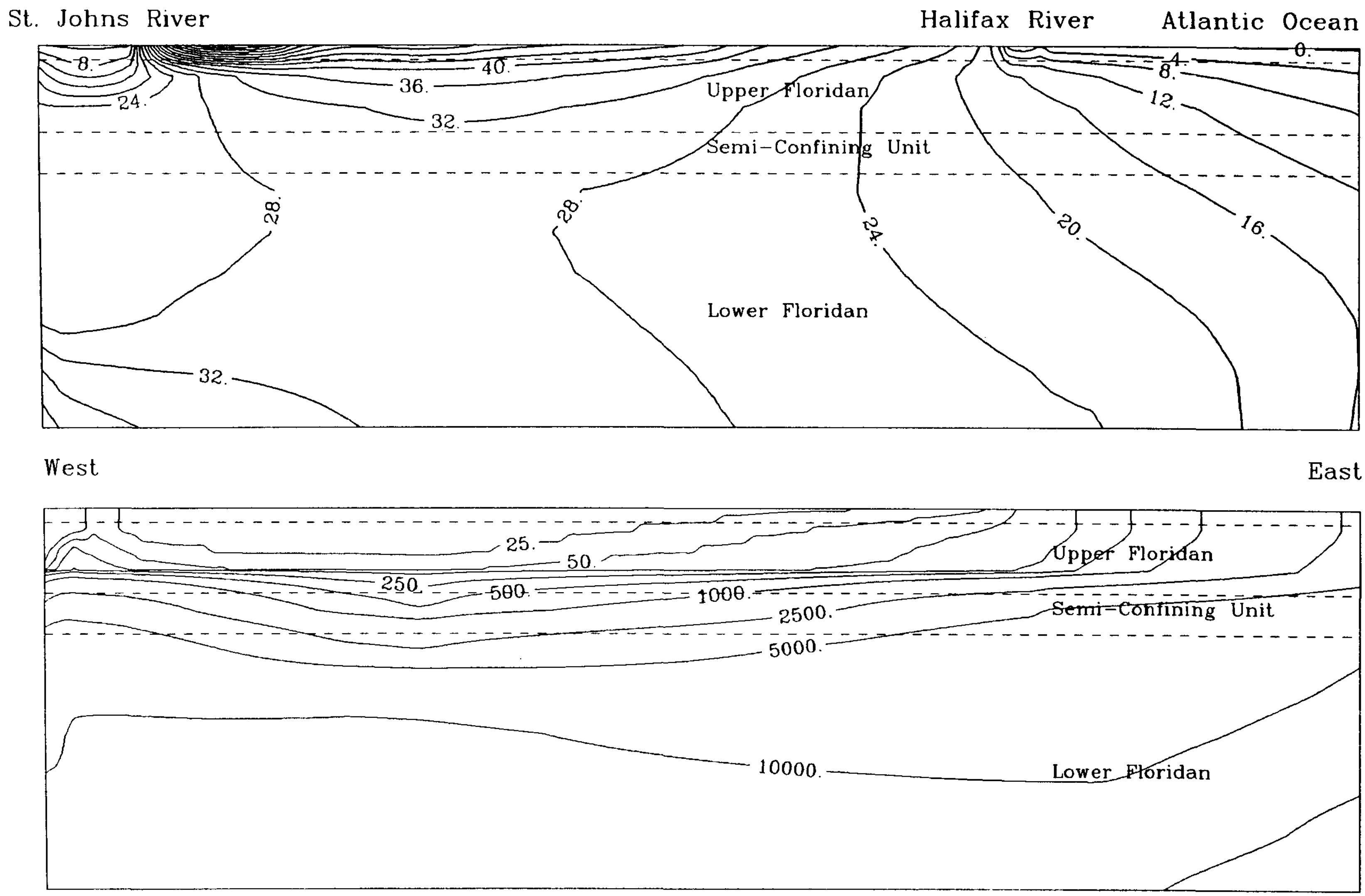

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Figure 12. Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution.

Scale
500 ft
50,000 ft

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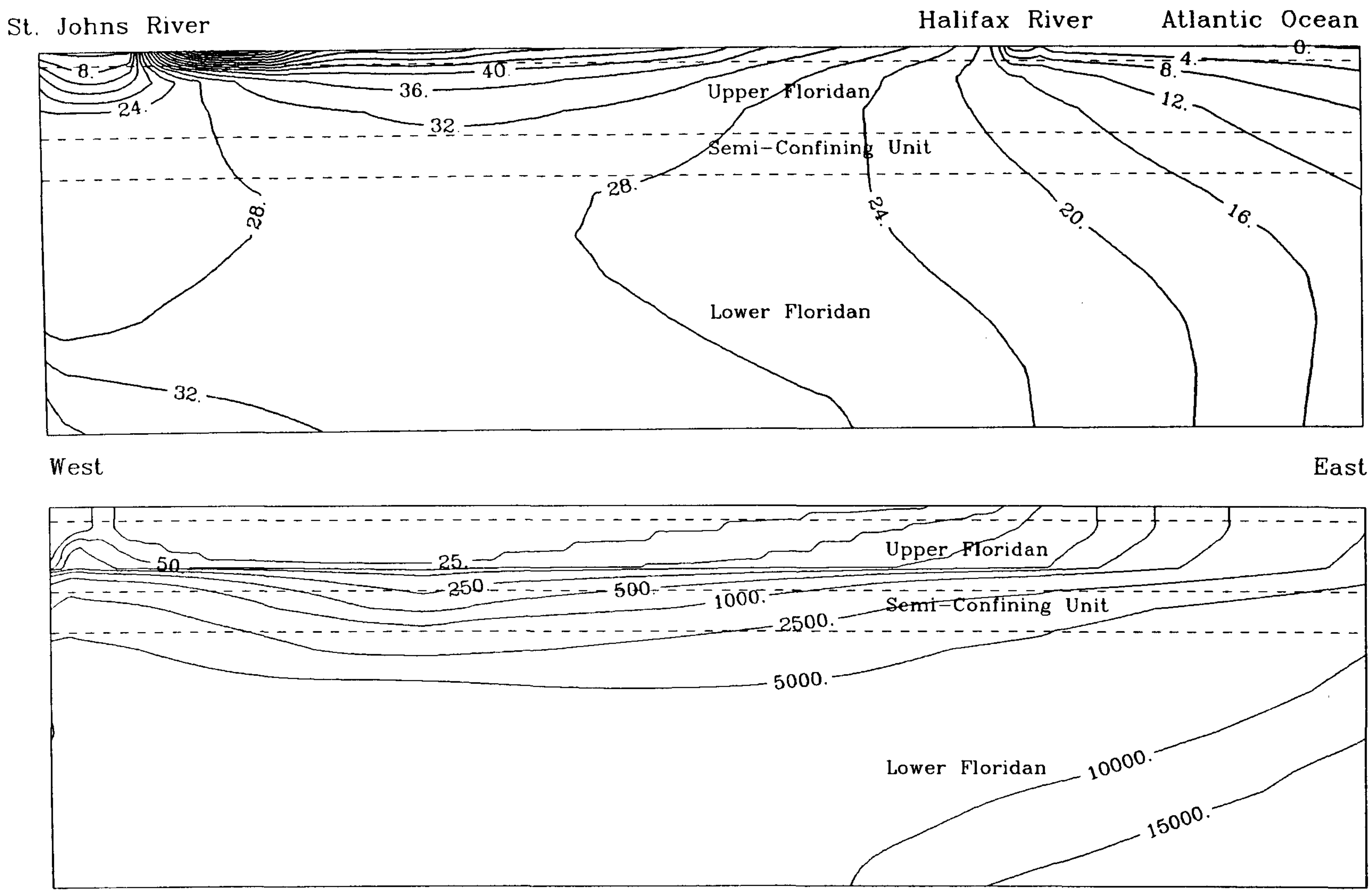

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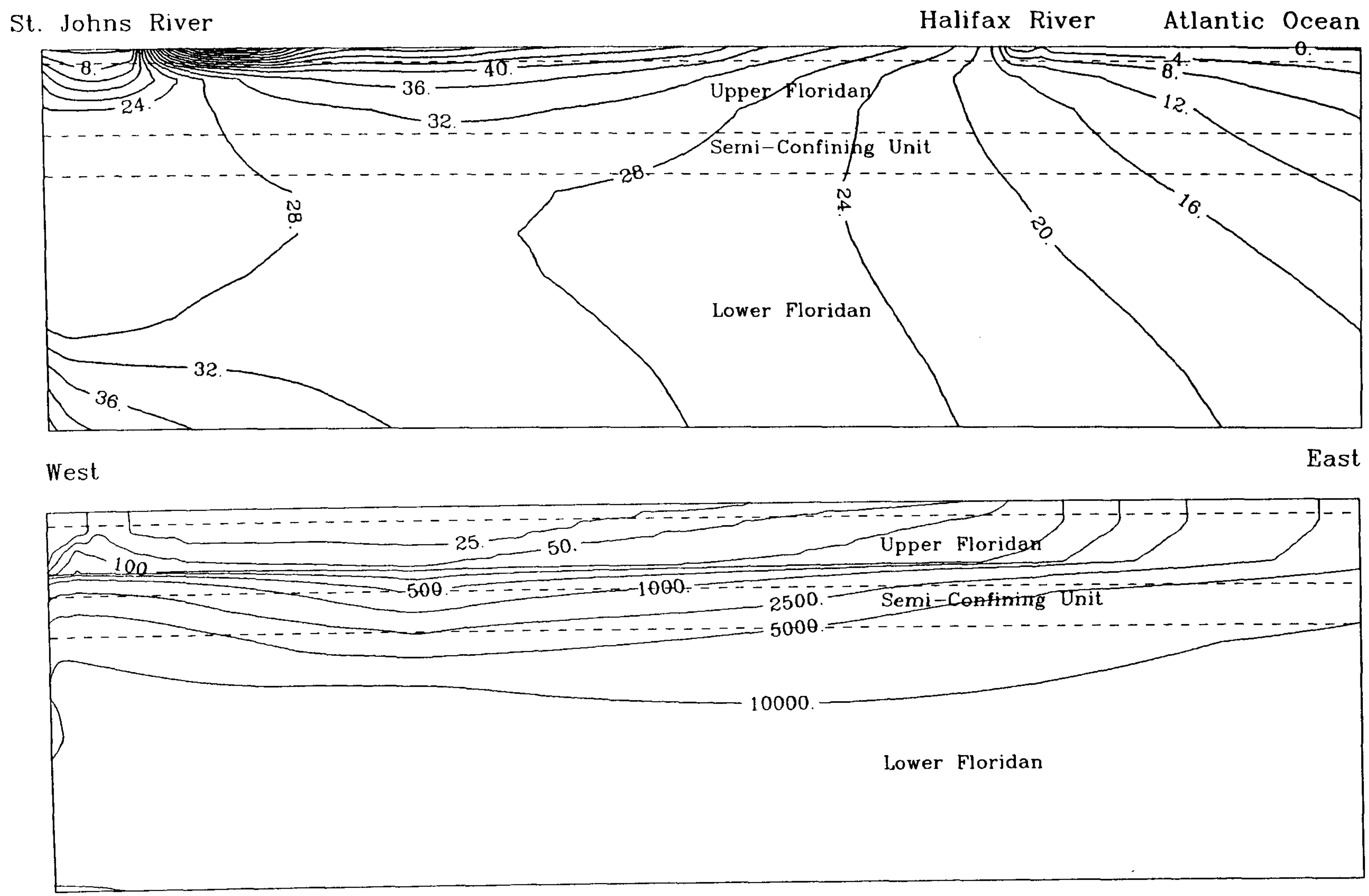
Figure 13. Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution with a 25% decrease in the chloride source concentration along the western model boundary.

500 ft

Scale

50,000 ft

DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:



GERAGHTY & MILLER, INC.
Environmental Services

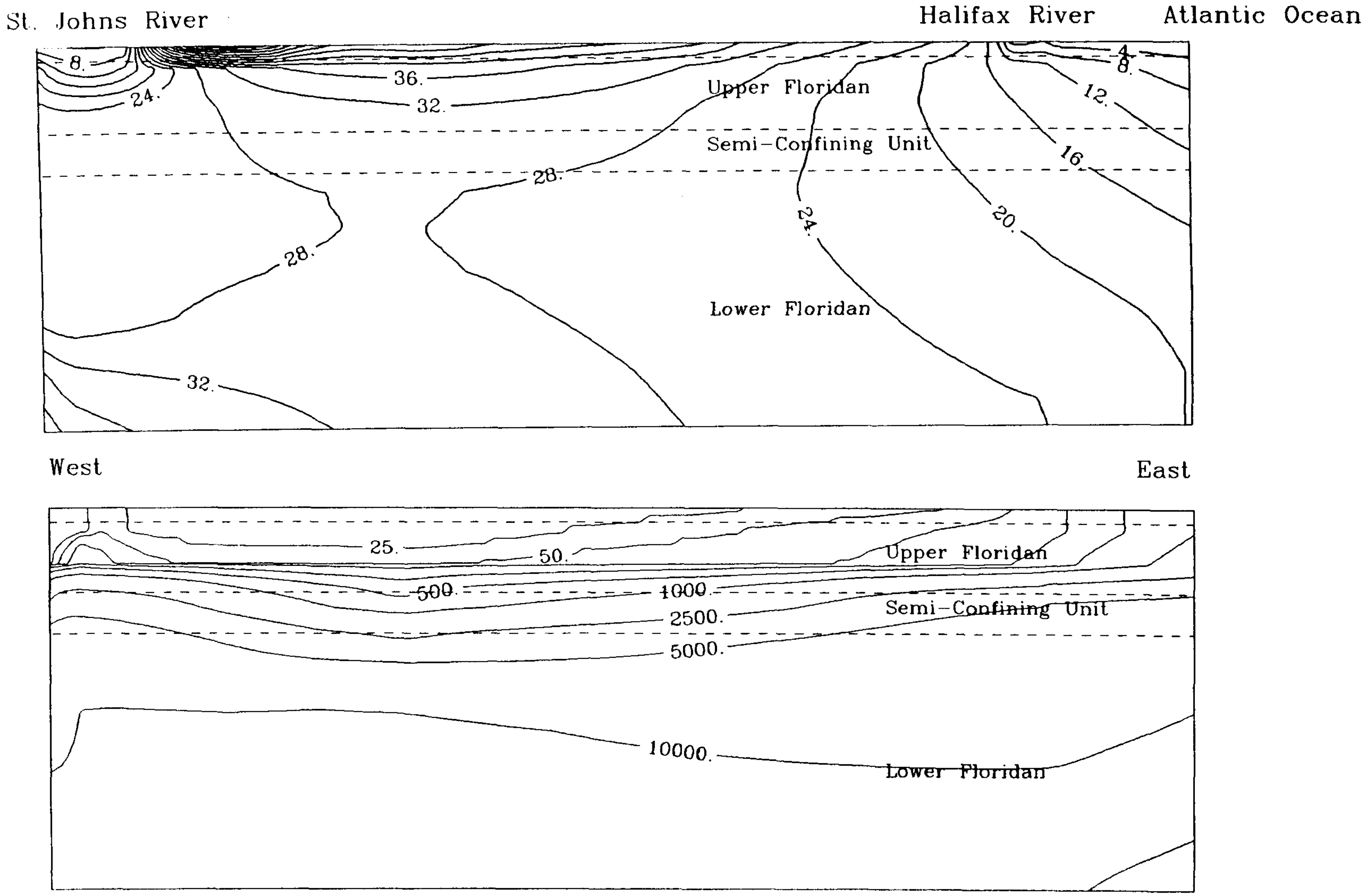
Figure 14. **Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution with a 25% increase in the chloride source concentration along the western model boundary.**

500 ft

Scale

50,000 ft

DWG DATE: | PRJCT NO.: | FILE NO.: | DRAWING: | CHECKED: | APPROVED: | DRAFTER:



GERAGHTY & MILLER, INC.
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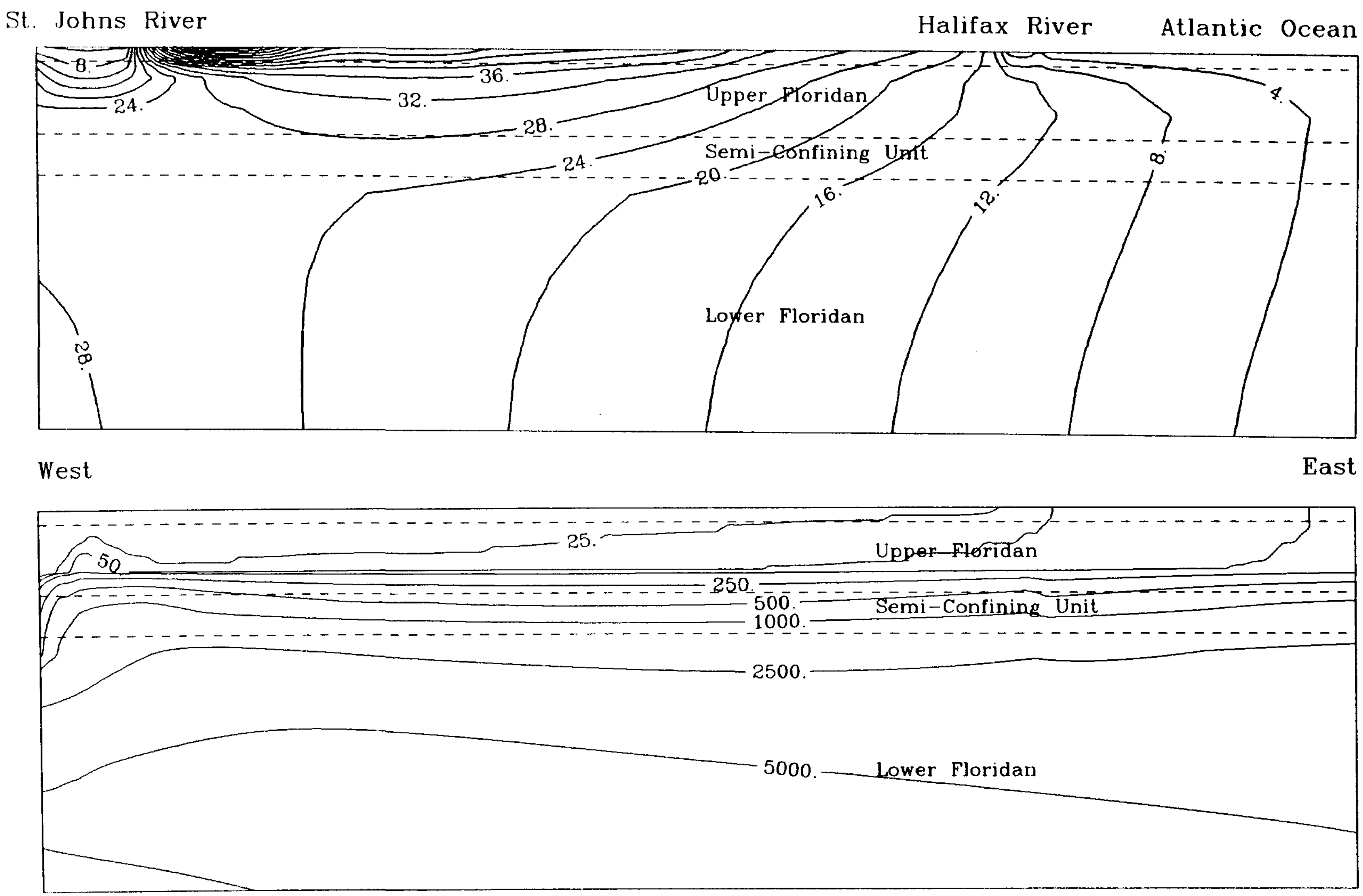
Figure 15. Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution with a six mile decrease in the extent of the eastern boundary.

500 ft
Scale
50,000 ft

DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:



GERAGHTY & MILLER, INC.
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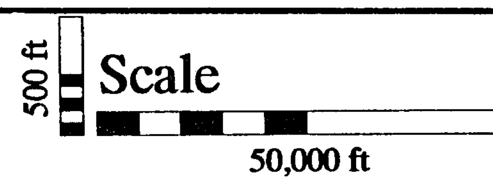
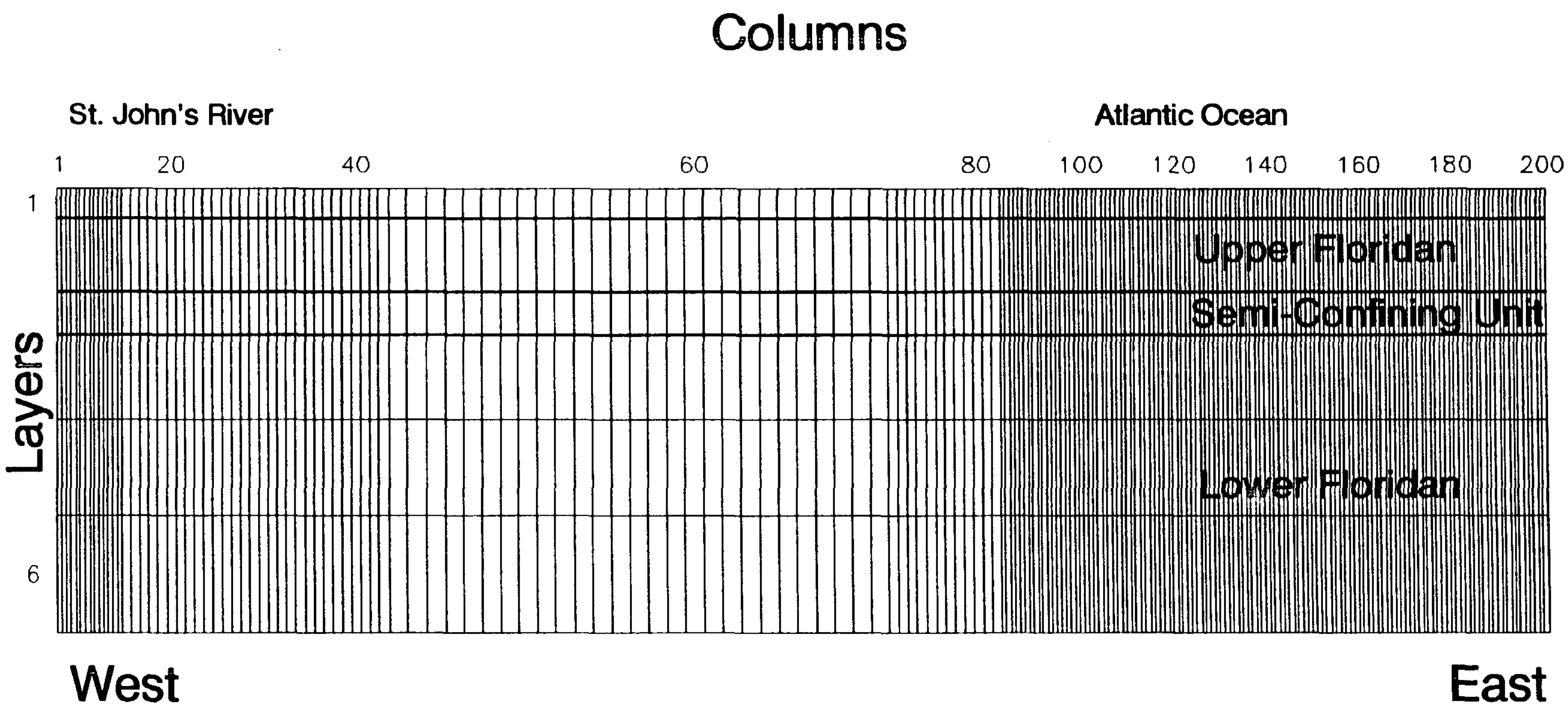
Figure 16. Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution neglecting the density constrast between freshwater and seawater.



DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:



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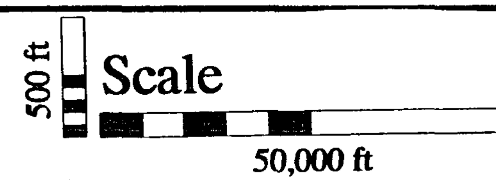
Environmental Services

Figure 17. Cross-sectional model finite-difference grid (six layer model).



DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:

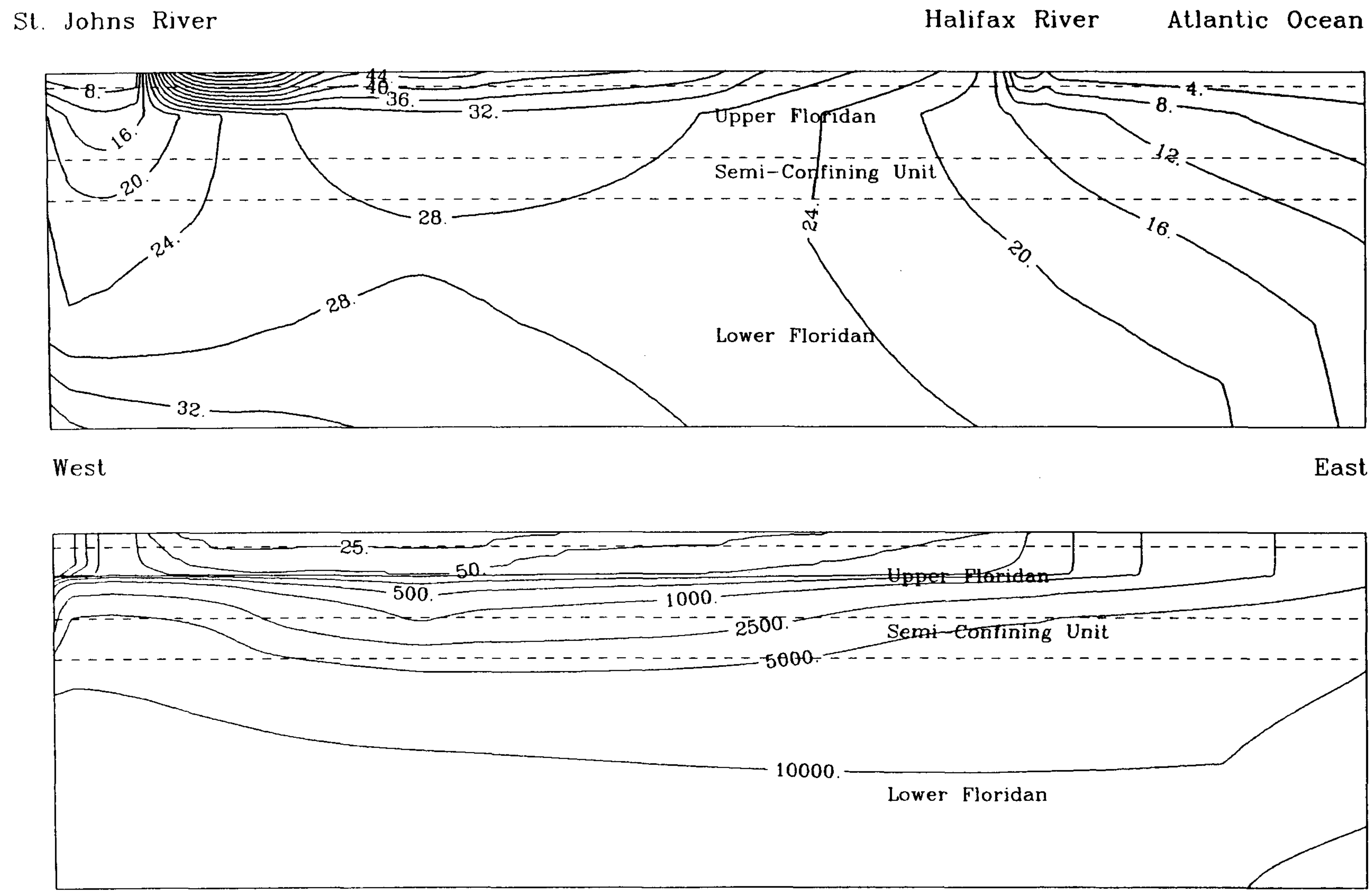


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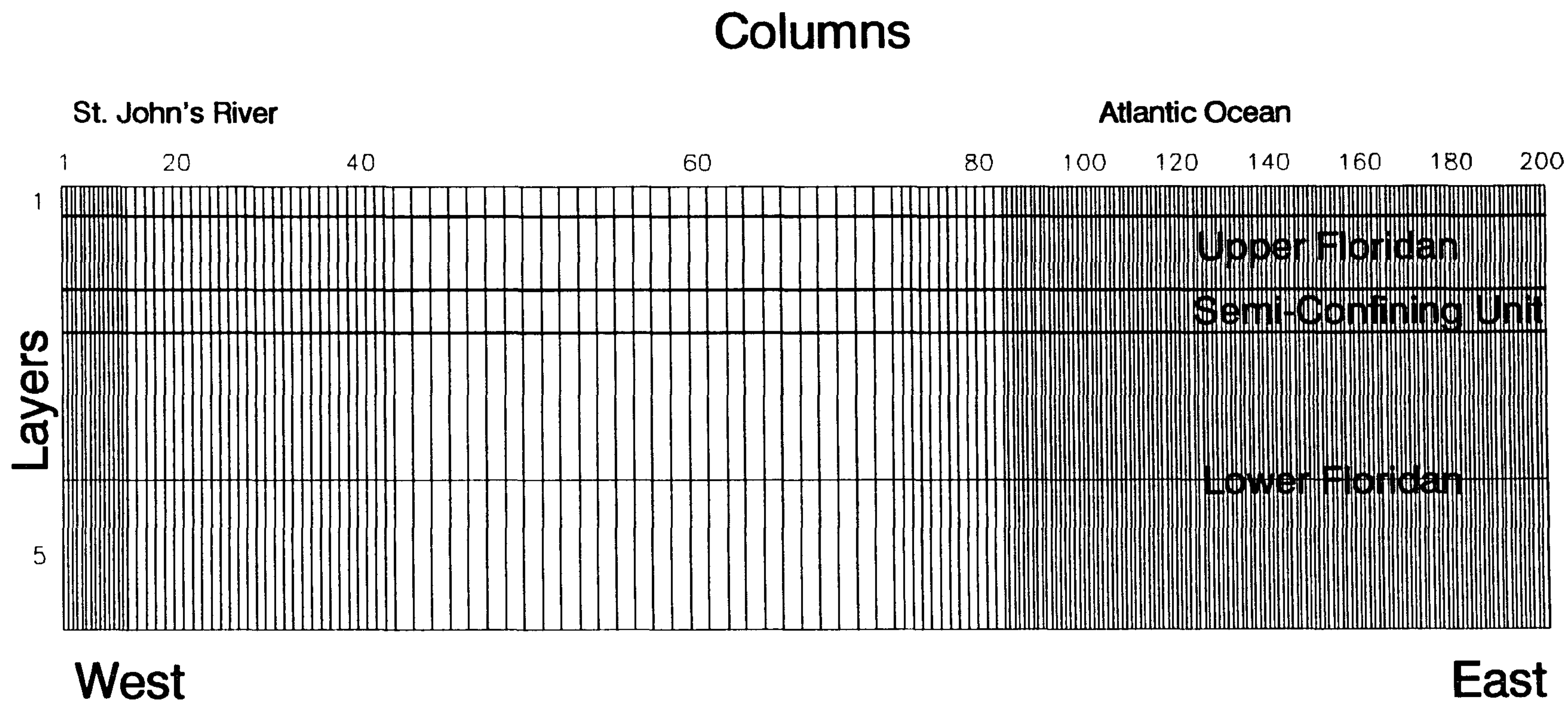
Figure 18. Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution (six layer model).

DWG DATE: | PRJCT NO.: | FILE NO.: | DRAWING: | CHECKED: | APPROVED: | DRAFTER:



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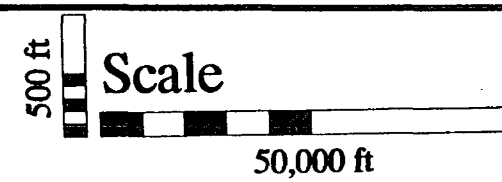
Environmental Services

Figure 19. Cross-sectional model finite-difference grid (five layer model).



DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:

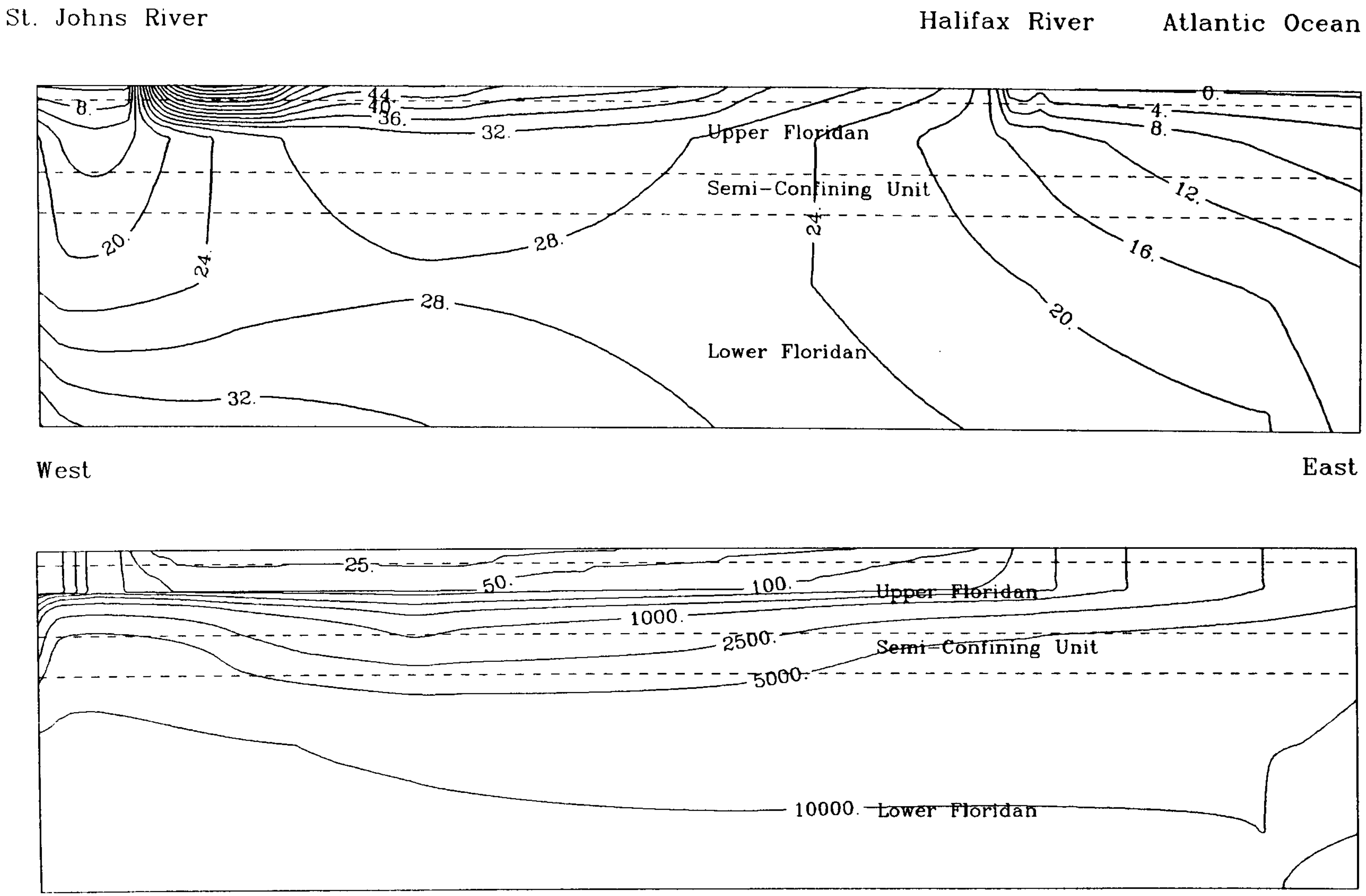


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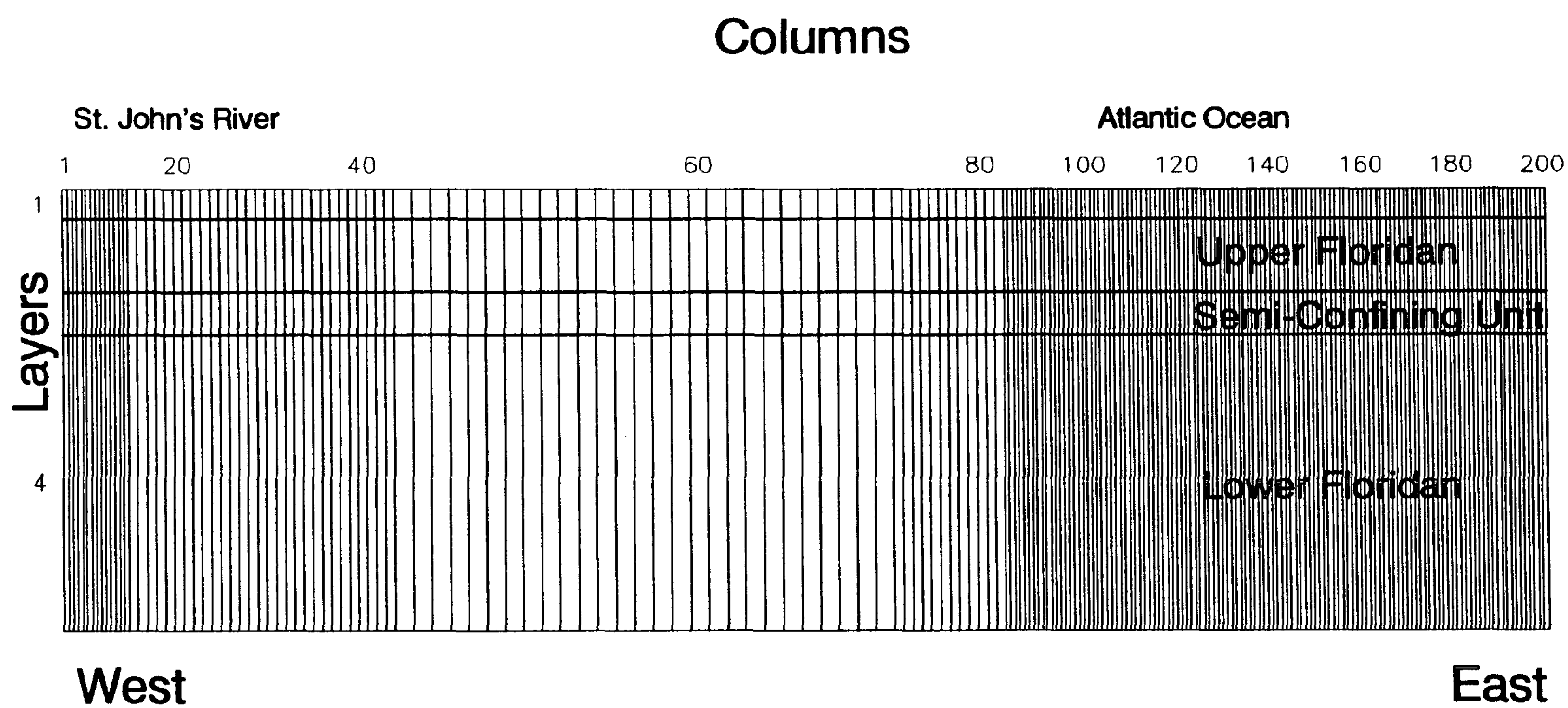
Figure 20. Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution (five layer model).

Scale
500 ft
50,000 ft



DWG DATE: | PRJCT NO.: | FILE NO.: | DRAWING: | CHECKED: | APPROVED: | DRAFTER:

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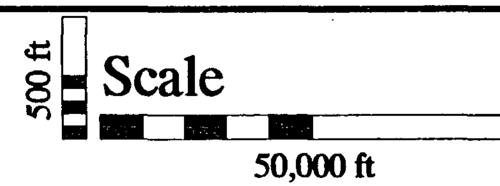
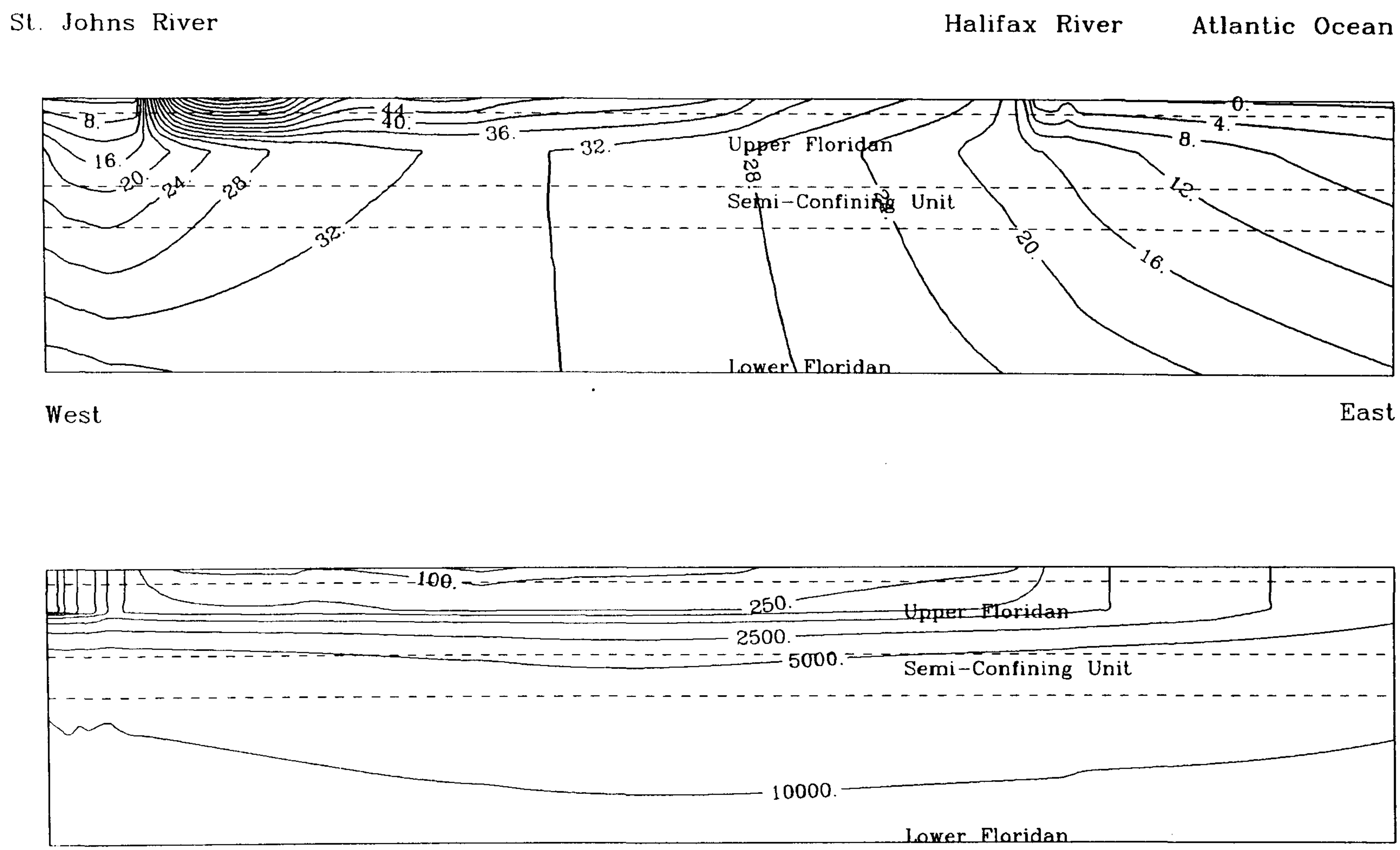
Environmental Services

Figure 21. Cross-sectional model finite-difference grid (four layer model).

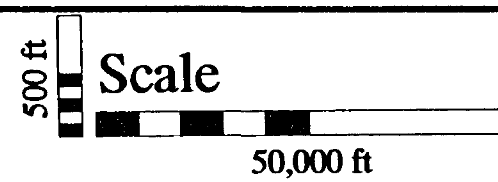


DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:

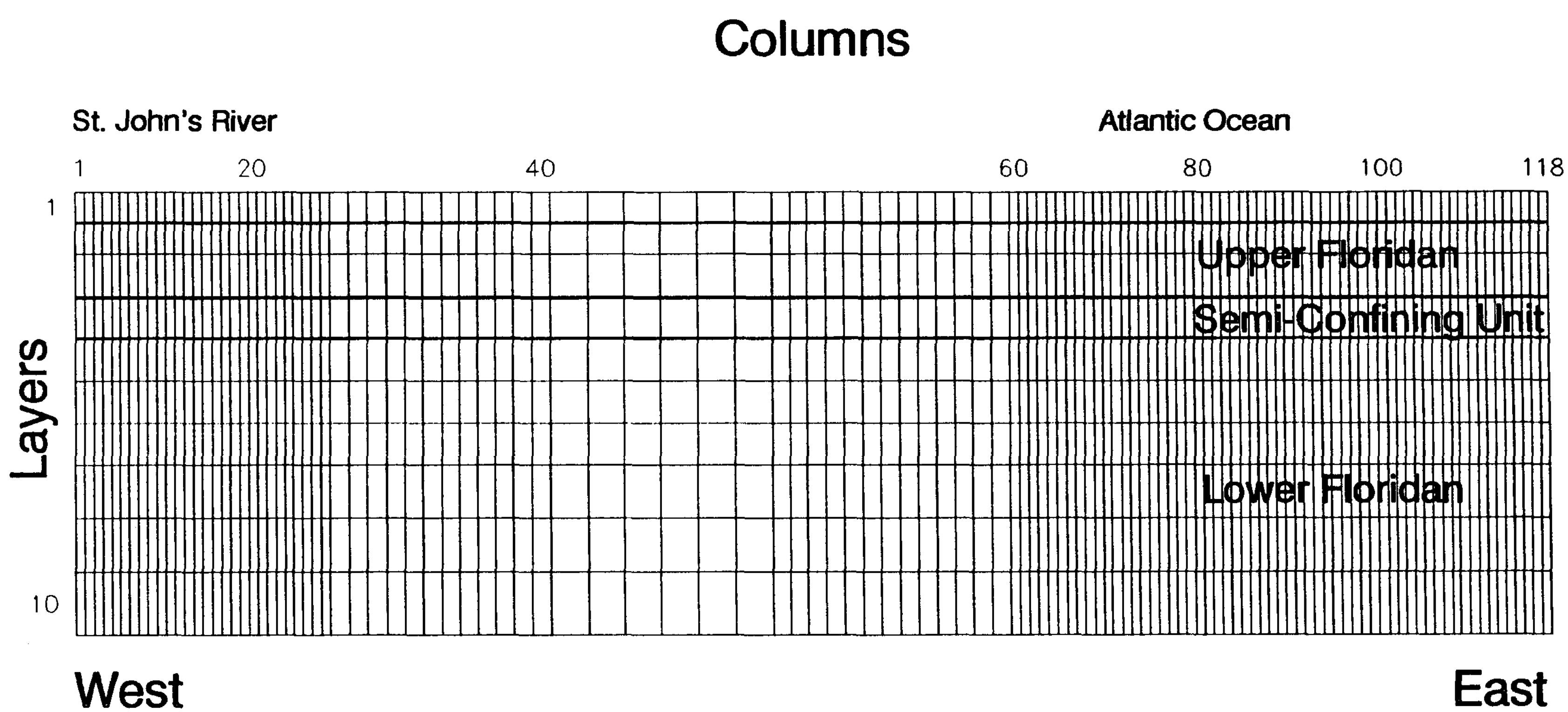


GERAGHTY & MILLER, INC.
Environmental Services

Figure 22. Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution (four layer model).

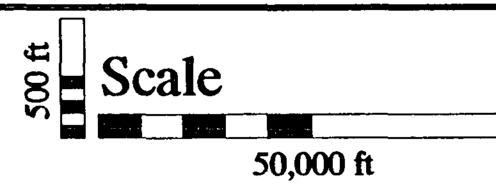


DWG DATE: | PRJCT NO.: | FILE NO.: | DRAWING: | CHECKED: | APPROVED: | DRAFTER:

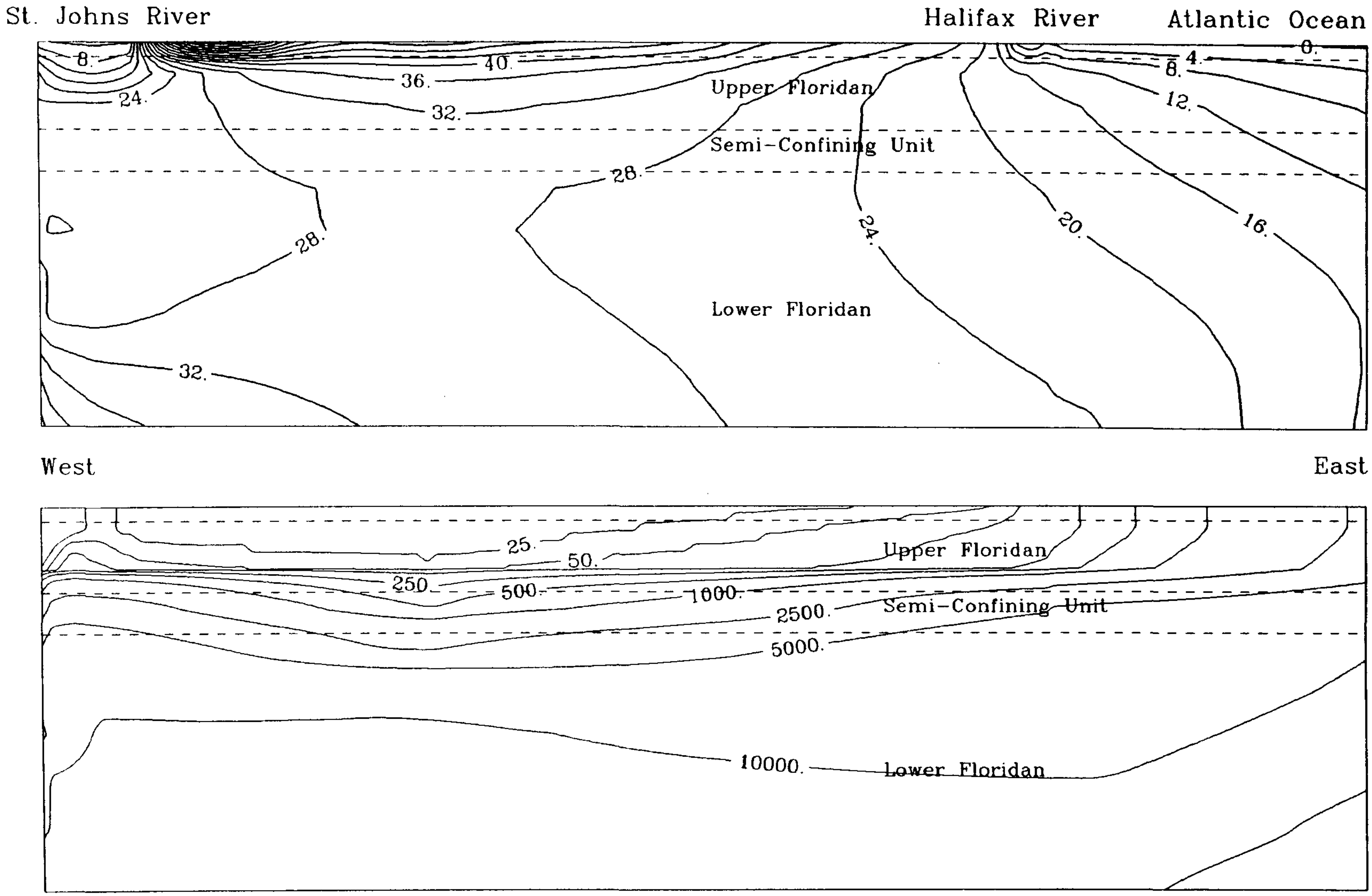


GERAGHTY & MILLER, INC.
Environmental Services

Figure 23. Cross-sectional model finite-difference grid (118 column model).



DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:



GERAGHTY & MILLER, INC.
Environmental Services

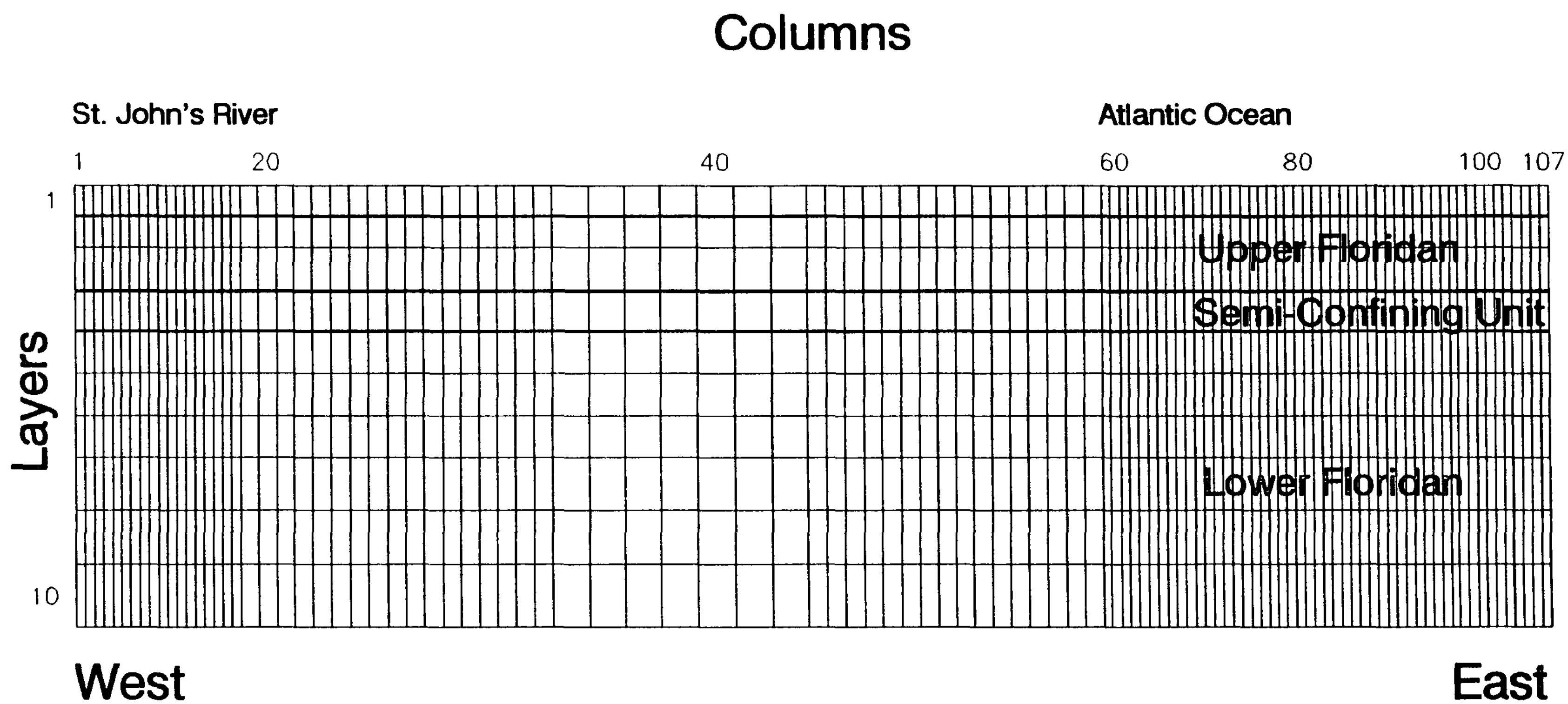
Figure 24. Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution (118 column model).

500 ft

Scale

50,000 ft

DWG DATE: | PRJCT NO.: | FILE NO.: | DRAWING: | CHECKED: | APPROVED: | DRAFTER:



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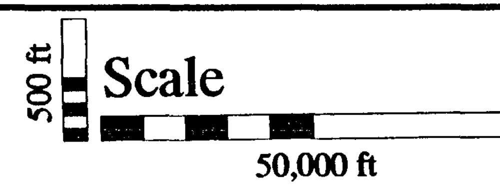
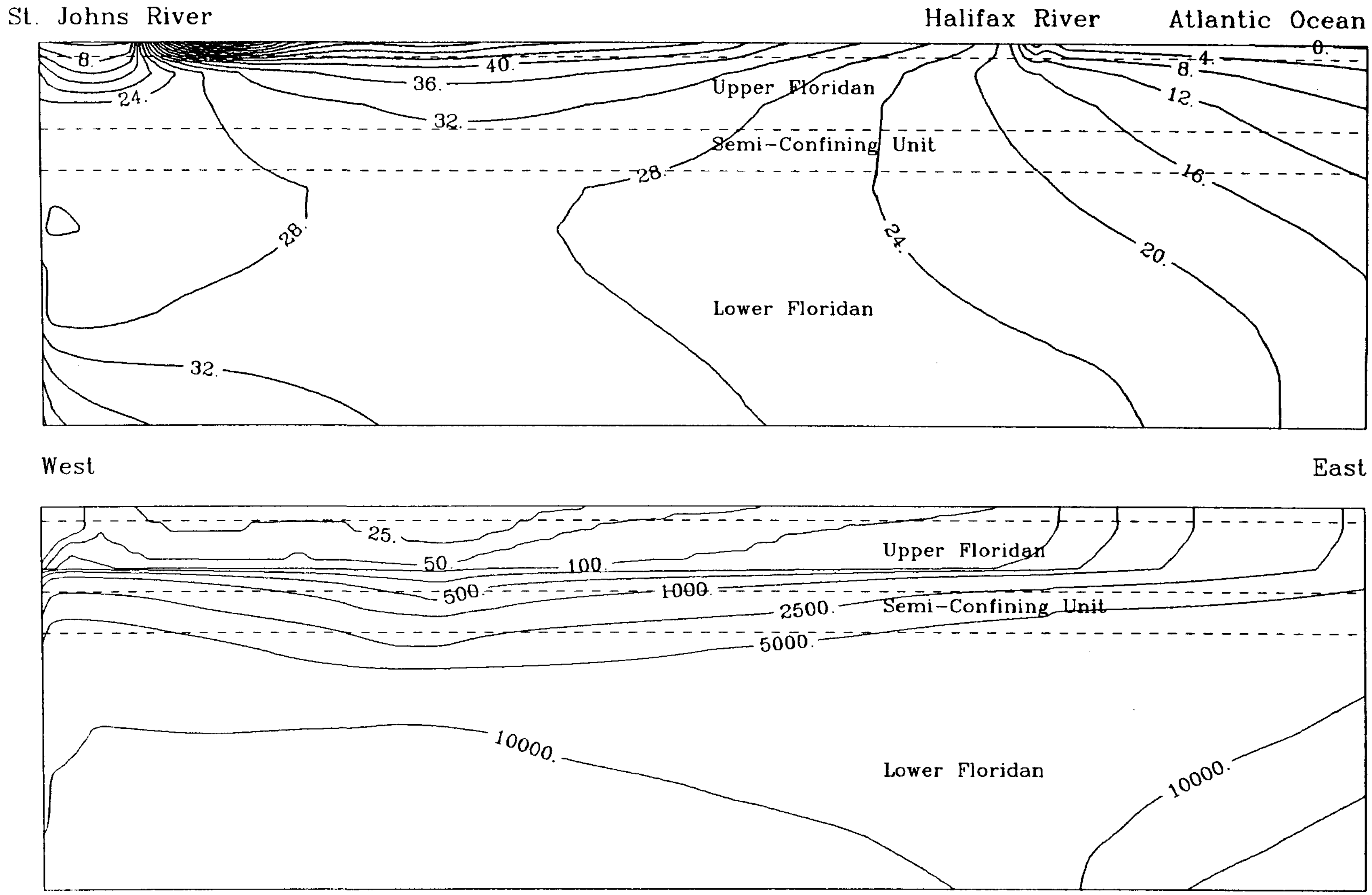
Environmental Services

Figure 25. Cross-sectional model finite-difference grid (107 column model).

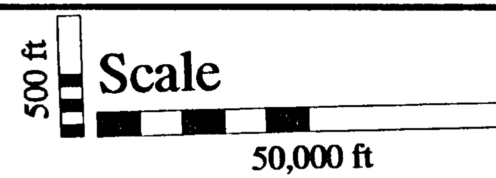


DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:

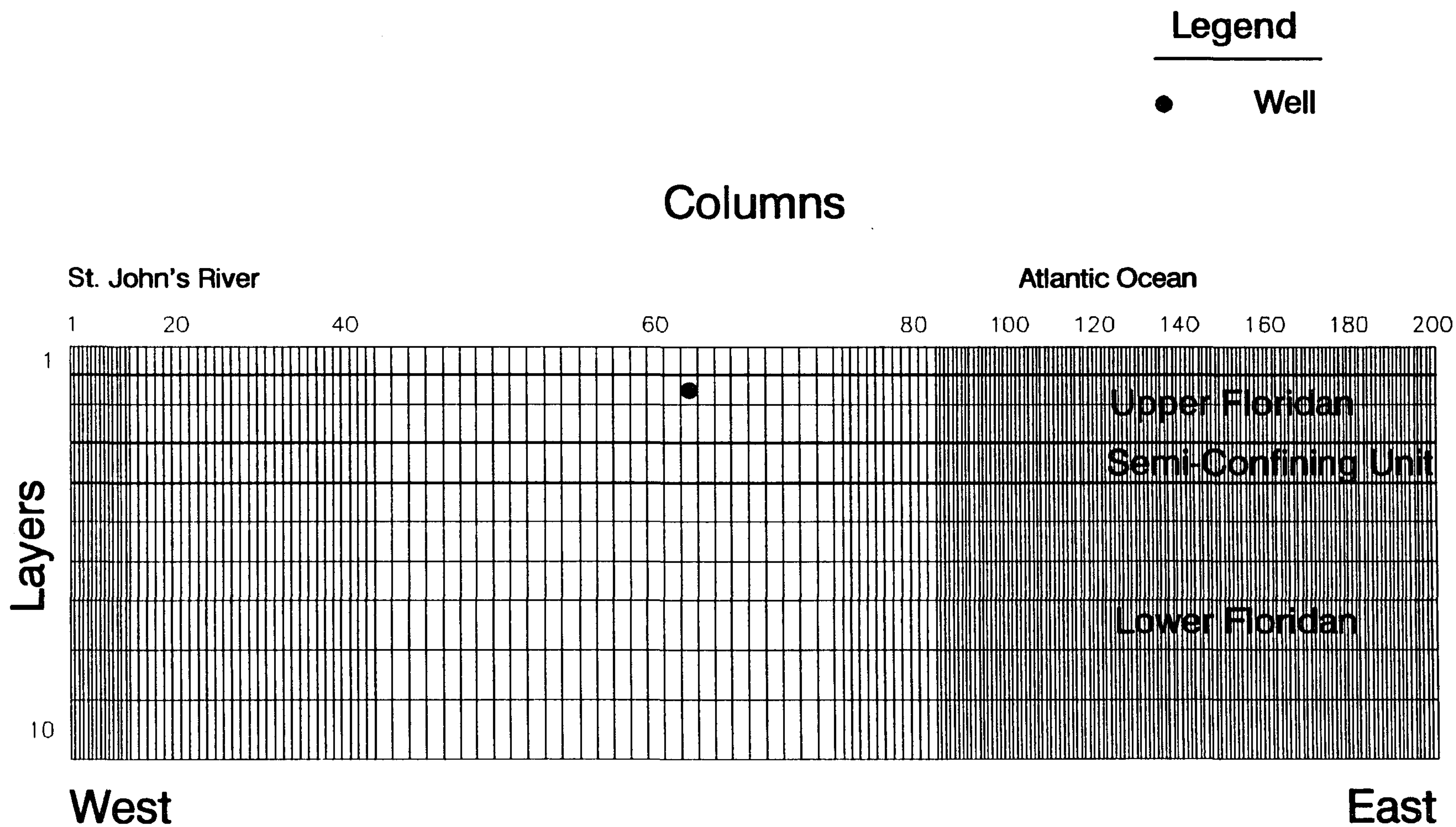


GERAGHTY & MILLER, INC.
Environmental Services

Figure 26. Cross-sectional model simulated steady-state predevelopment hydraulic head and chloride distribution (107 column model).



DWG DATE: | PRJCT NO.: | FILE NO.: | DRAWING: | CHECKED: | APPROVED: | DRAFTER:

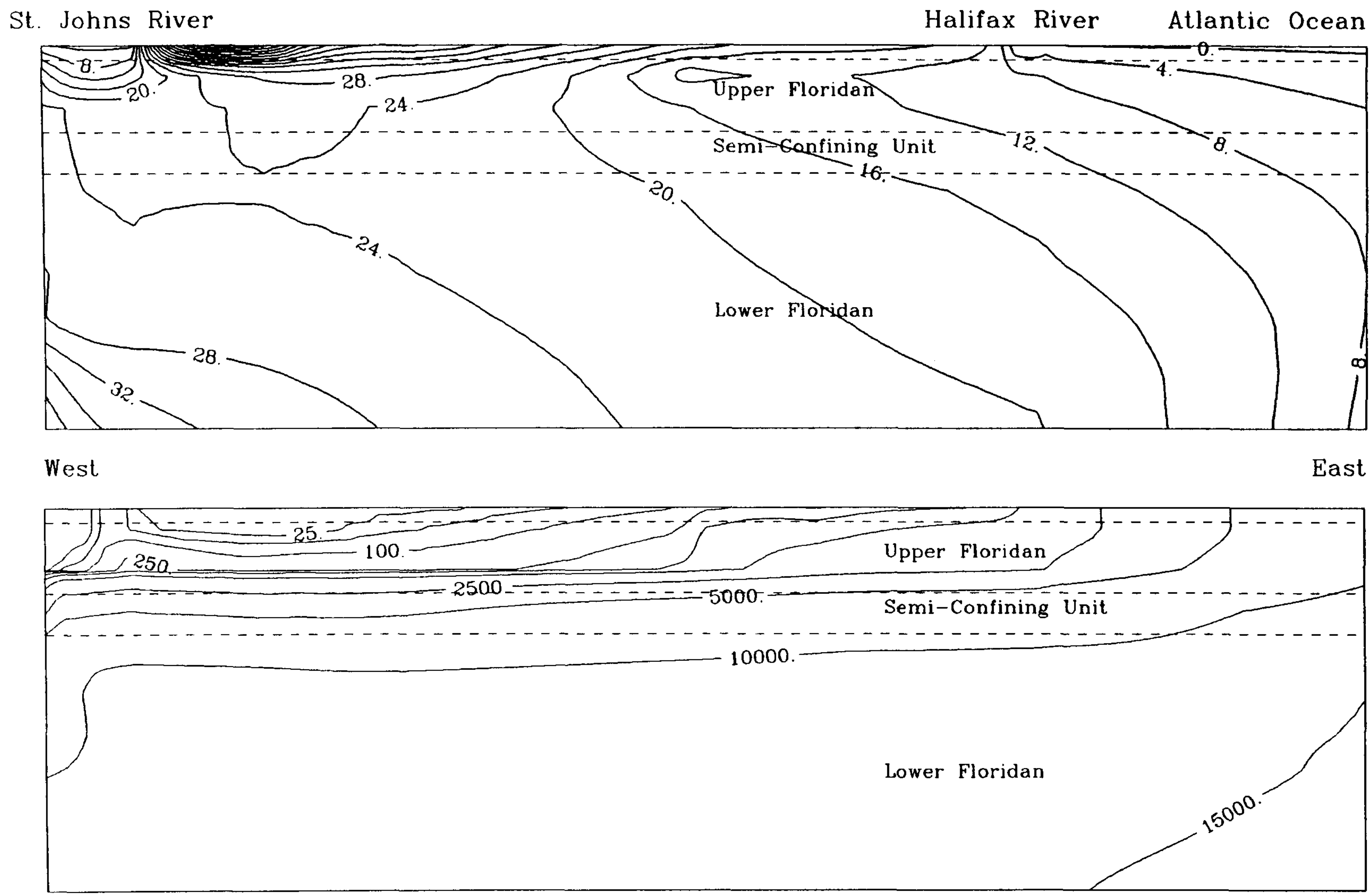


GERAGHTY & MILLER, INC.
Environmental Services

Figure 27. Base case cross-sectional model finite-difference grid showing the location of a hypothetical well.

500 ft
Scale
50,000 ft

DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:



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Environmental Services

Figure 28. Cross-sectional model simulated hydraulic head and chloride distribution, including the hypothetical wellfield.

Scale
500 ft
50,000 ft

DWG DATE: | PRJCT NO.: | FILE NO.: | DRAWING: | CHECKED: | APPROVED: | DRAFTER:

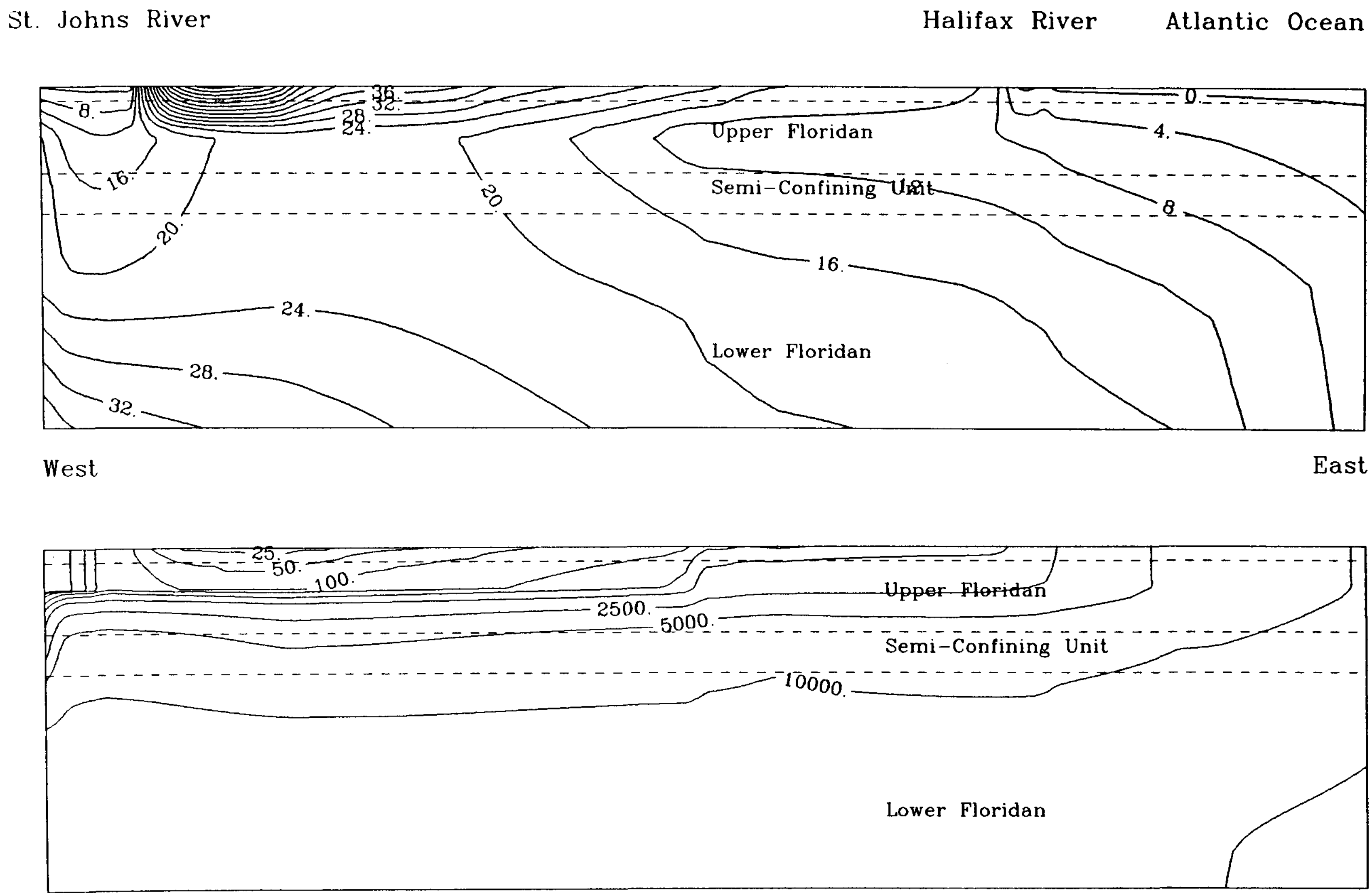

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Figure 29. Cross-sectional model simulated hydraulic head and chloride distribution, including the hypothetical wellfield (five layer model).

Scale
500 ft
50,000 ft

DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:

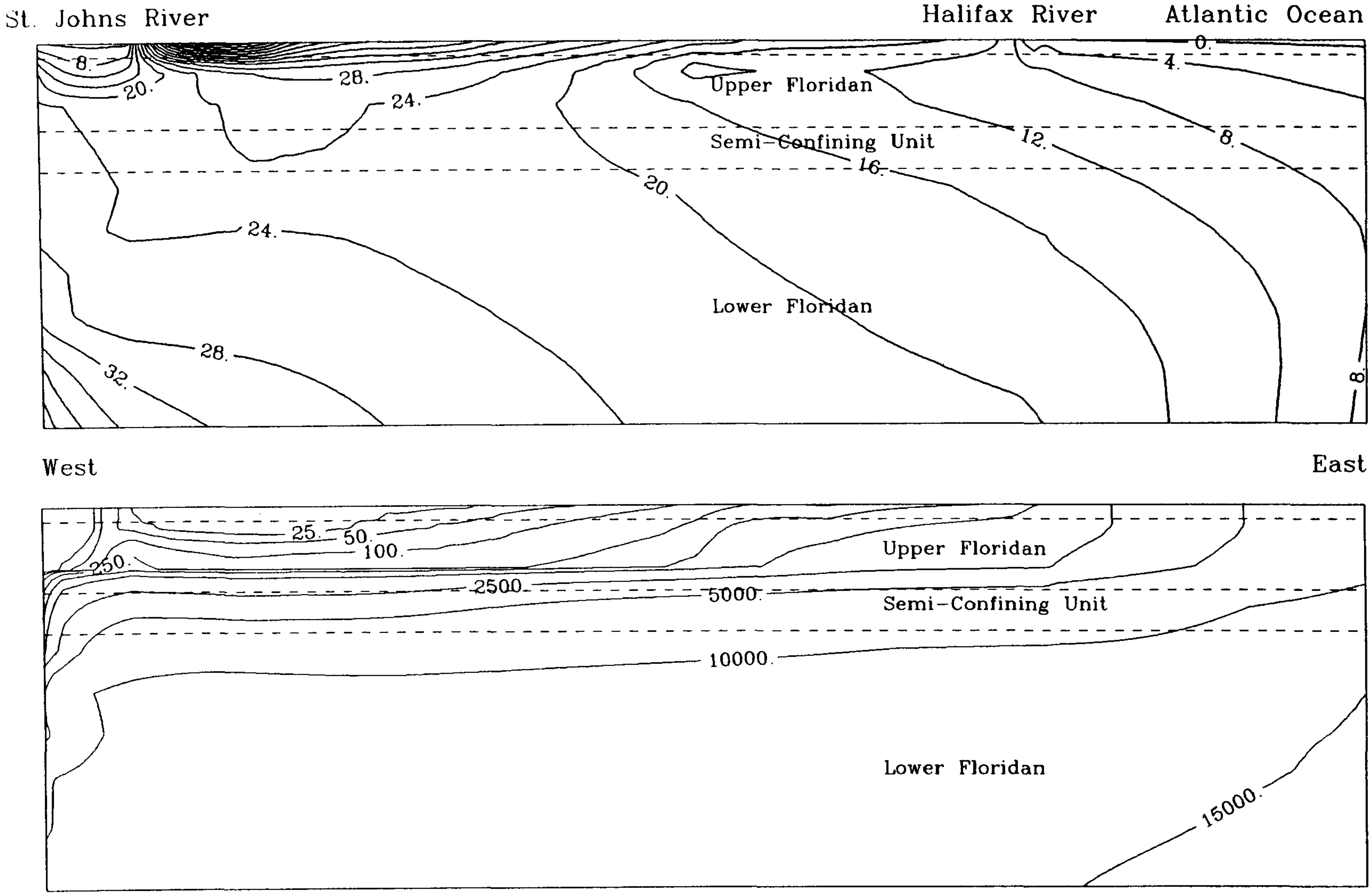

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Figure 30. Cross-sectional model simulated hydraulic head and chloride distribution, including the hypothetical wellfield (107 column model).

Scale

500 ft

50,000 ft

DWG DATE: | PRJCT NO.: | FILE NO.: | DRAWING: | CHECKED: | APPROVED: | DRAFTER:

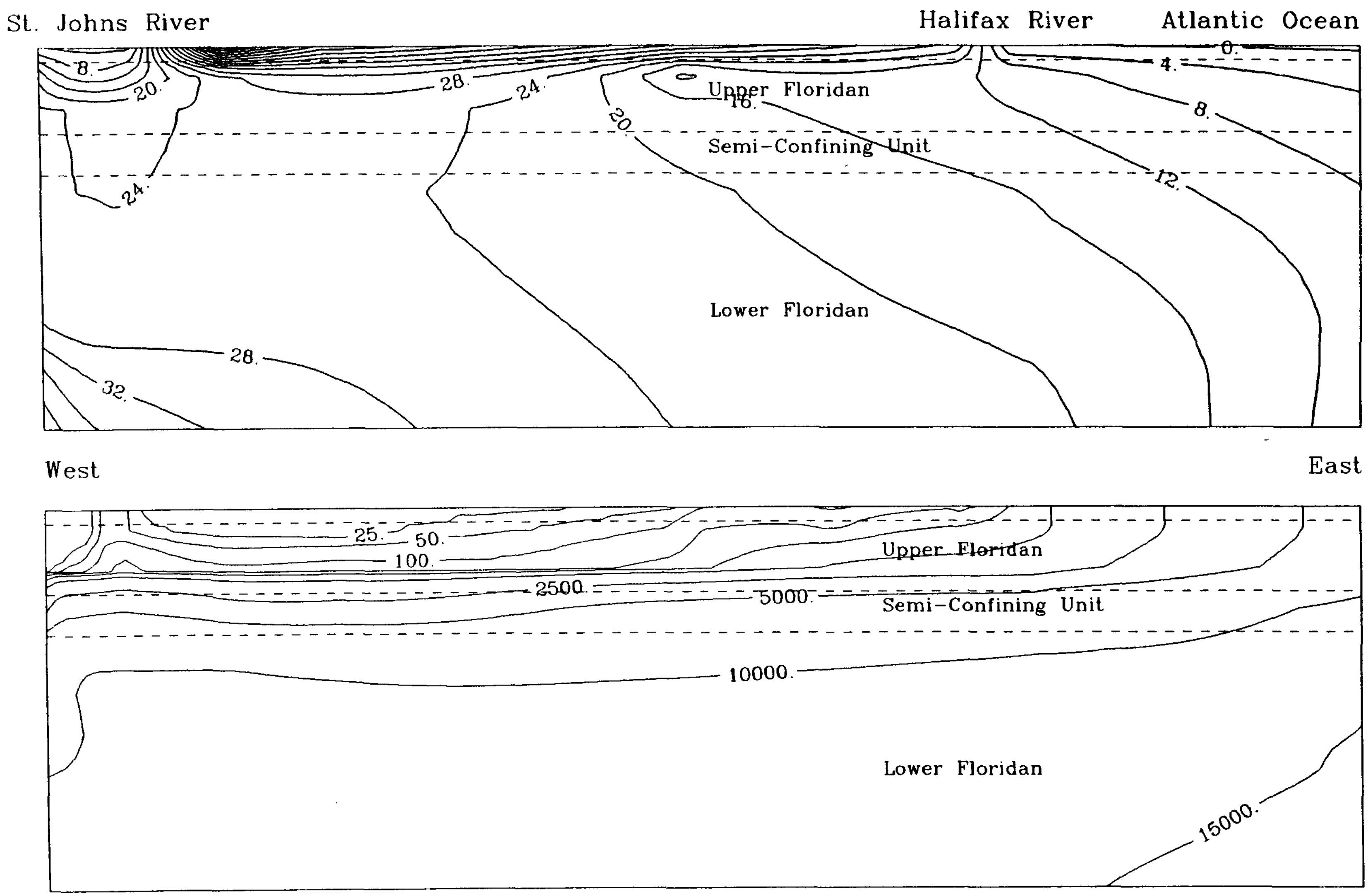

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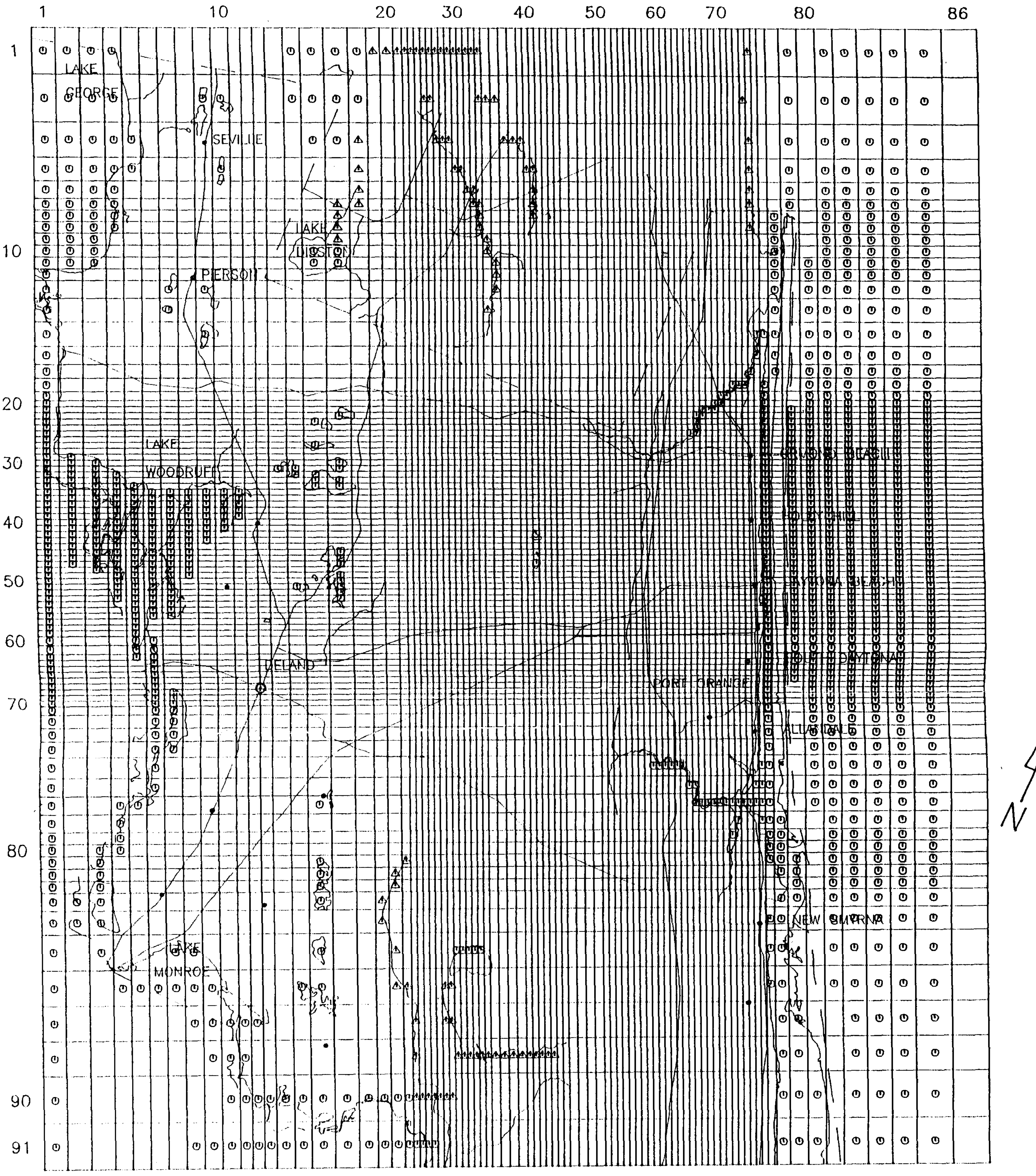
Figure 31. Cross-sectional model simulated hydraulic head and chloride distribution, including the hypothetical wellfield and fixing the surficial aquifer with constant heads.

500 ft

Scale

50,000 ft

DWG DATE: –	PRJCT NO.: –	FILE NO.: –	DRAWING: –	CHECKED: –	APPROVED: –	DRAFTER: –



Constant Head
Drain

SCALE
0 25000 FT

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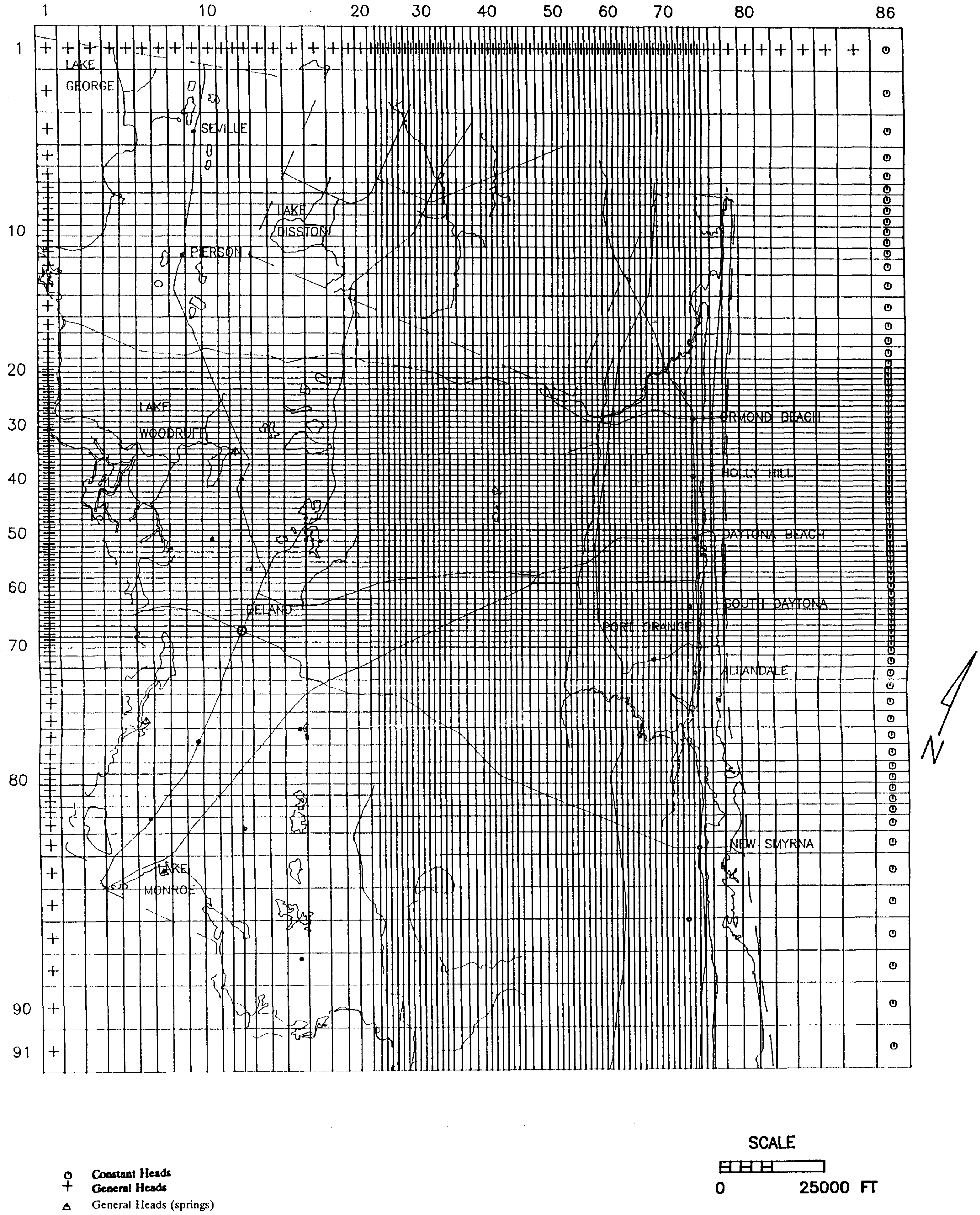
Figure 32. Finite-difference grid and boundary conditions in layer 1 (surficial aquifer) of the three-dimensional model.

DWG DATE: –	PRJCT NO.: –	FILE NO.: –	DRAWING: –	CHECKED: –	APPROVED: –	DRAFTER: –



GERAGHTY & MILLER, INC. *Environmental Services*

Figure 33. Finite-difference grid and boundary conditions in layer 2 (Upper Floridan) of the three-dimensional model.

DWG DATE: – | PRJCT NO.: – | FILE NO.: – | DRAWING: – | CHECKED: – | APPROVED: – | DRAFTER: –

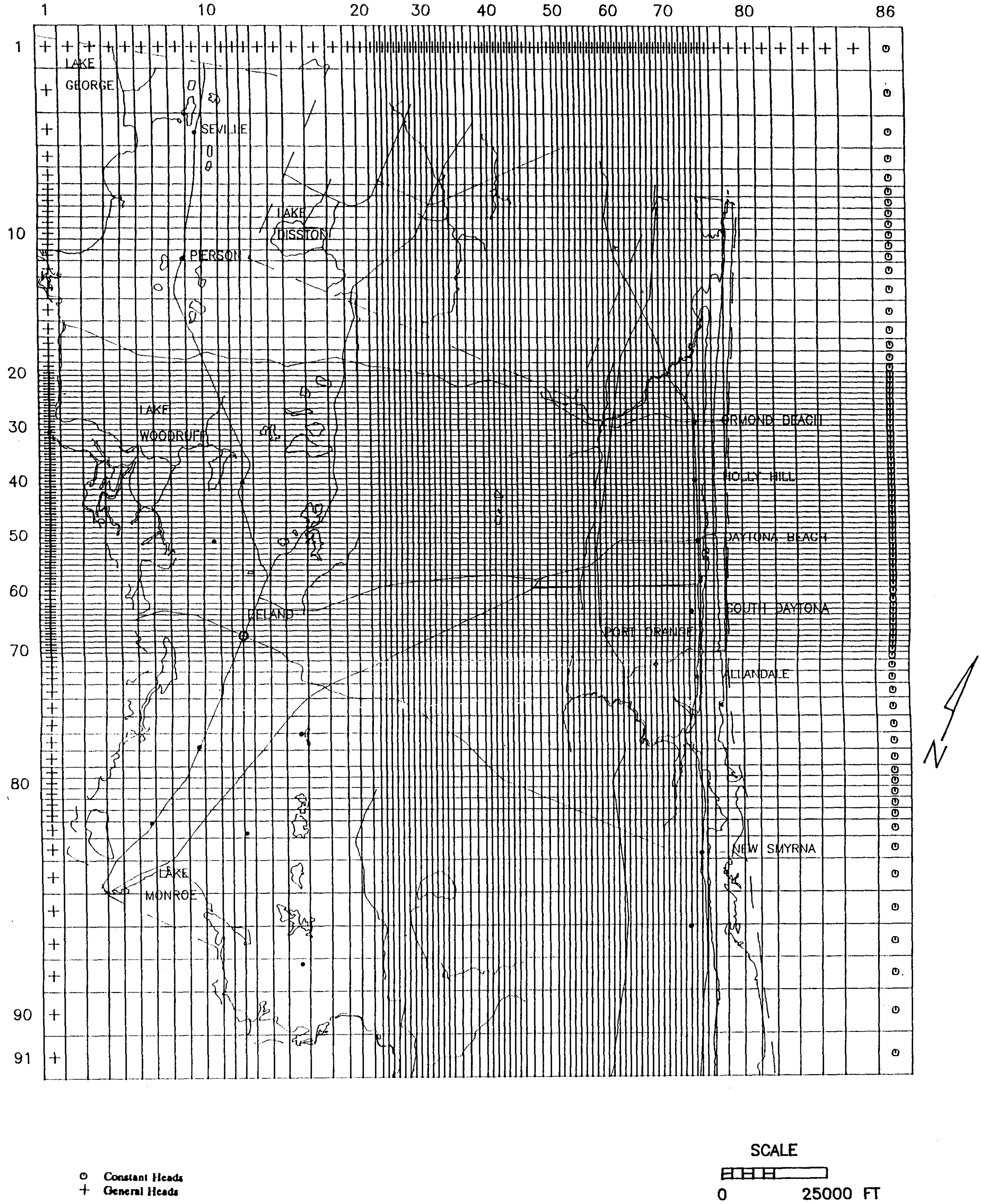


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Figure 34. Finite-difference grid and boundary conditions in layers 3 through 5 (Middle Semi-confining Unit and Lower Floridan) of the three-dimensional model.

DRAFTER:

APPROVED:

CHECKED:

DRAWING:

FILE NO.:

PRJCT NO.:

DWG DATE:

Parameter Type	Zone Number	Value
Hydraulic conductivity	1	20 ft/d
	2	30
	3	0.4
	4	20
	5	40
	6	25
	7	0.5
	8	86
	9	200
	10	1500
	11	5000
	12	5
	13	3600
	14	235
	15	100
	16	18
	17	0.63
	18	0.01
	19	55
	20	40

SCALE

0 35000 FT

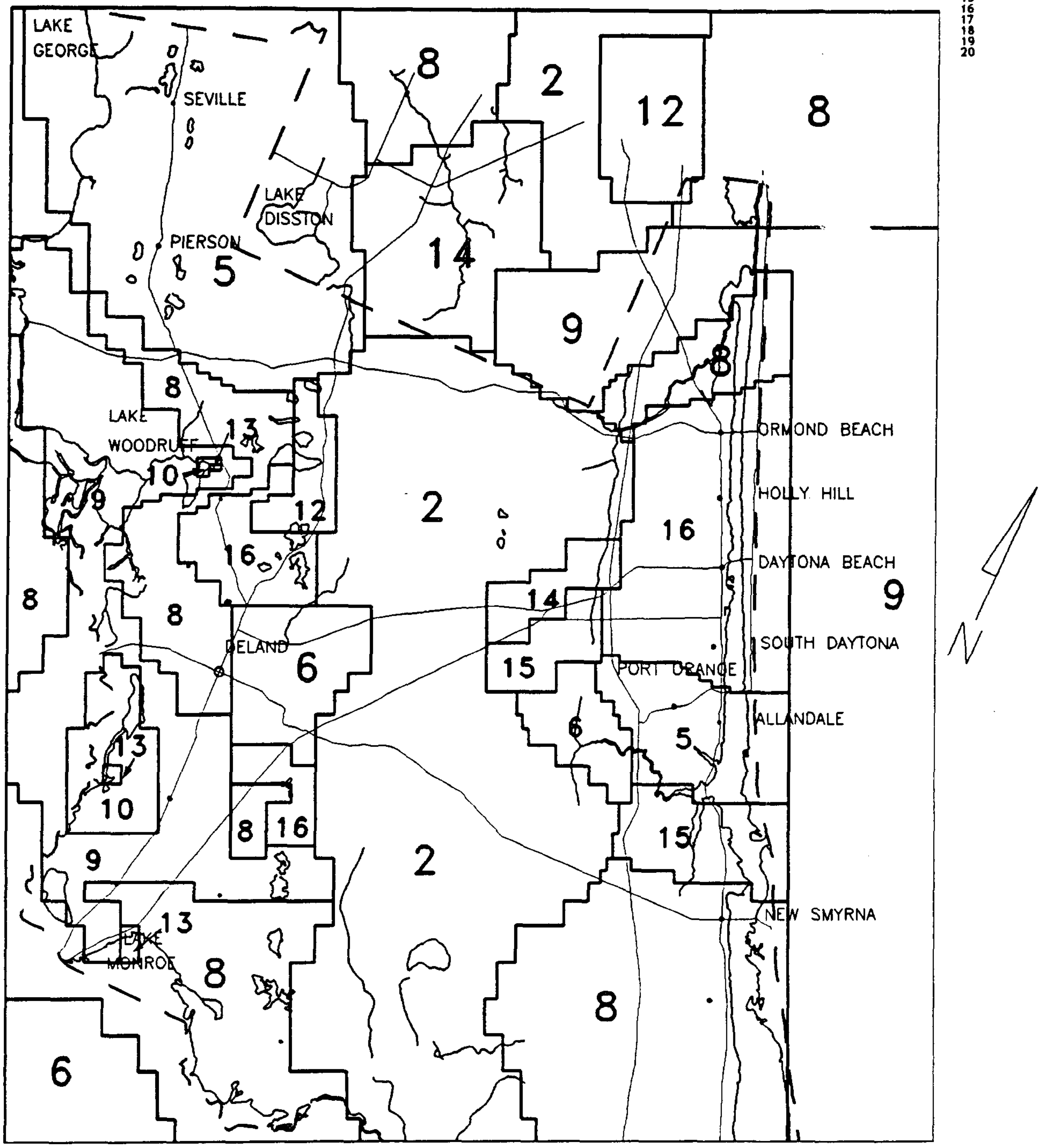

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Figure 35. Hydraulic conductivity zones in layer 2 (Upper Floridan aquifer) of the three-dimensional model.

FIGURE

Parameter Type	Zone Number	Value
Hydraulic Conductivity	1	20 ft/d
	2	30
	3	0.4
	4	20
	5	40
	6	25
	7	0.5
	8	86
	9	200
	10	1500
	11	5000
	12	5
	13	3600
	14	235
	15	100
	16	18
	17	0.63
	18	0.01
	19	55
	20	40

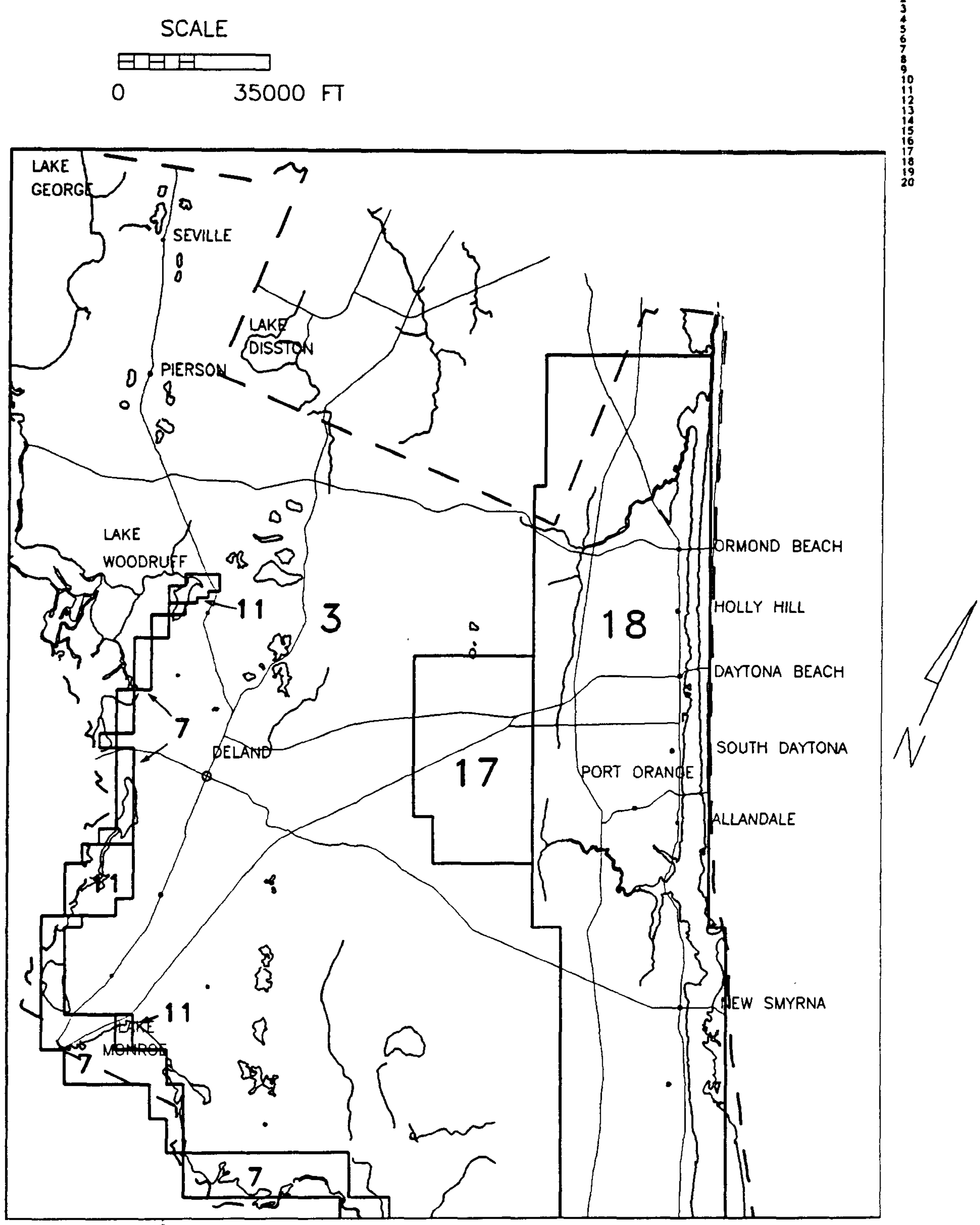

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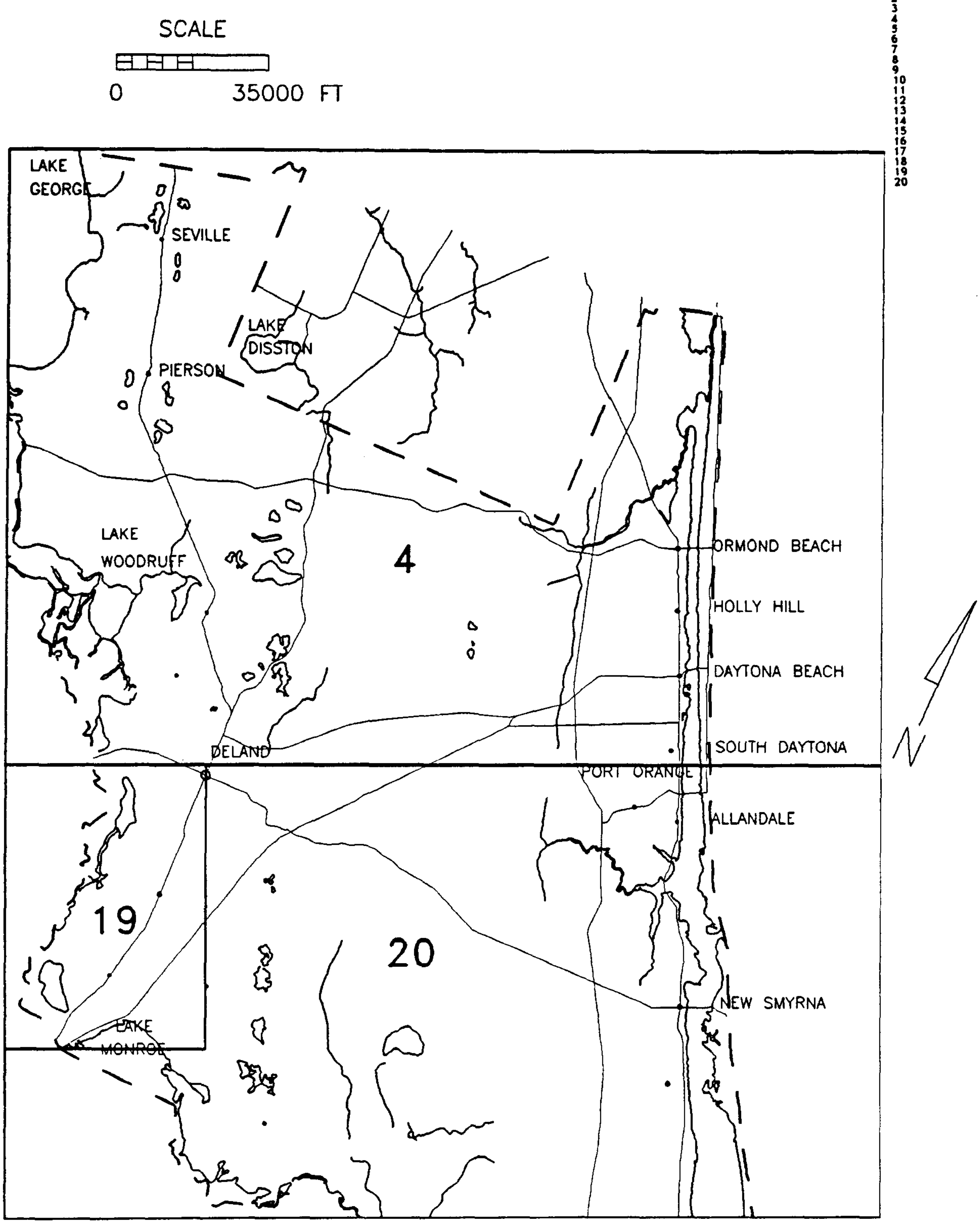
Figure 36. Hydraulic conductivity zones in layer 3 (Middle Semi-confining Unit) of the three-dimensional model.

FIGURE

Parameter Type	Zone Number	Value
Hydraulic conductivity	1	20 ft/d
	2	30
	3	0.4
	4	20
	5	40
	6	25
	7	0.5
	8	86
	9	200
	10	1500
	11	5000
	12	5
	13	3600
	14	235
	15	100
	16	18
	17	0.63
	18	0.01
	19	55
	20	40



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FILE NO.:

PRJCT NO.:

DWG DATE:

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Figure 37. Hydraulic conductivity zones in layers 4 and 5 (Lower Floridan aquifer) of the three-dimensional model.

FIGURE

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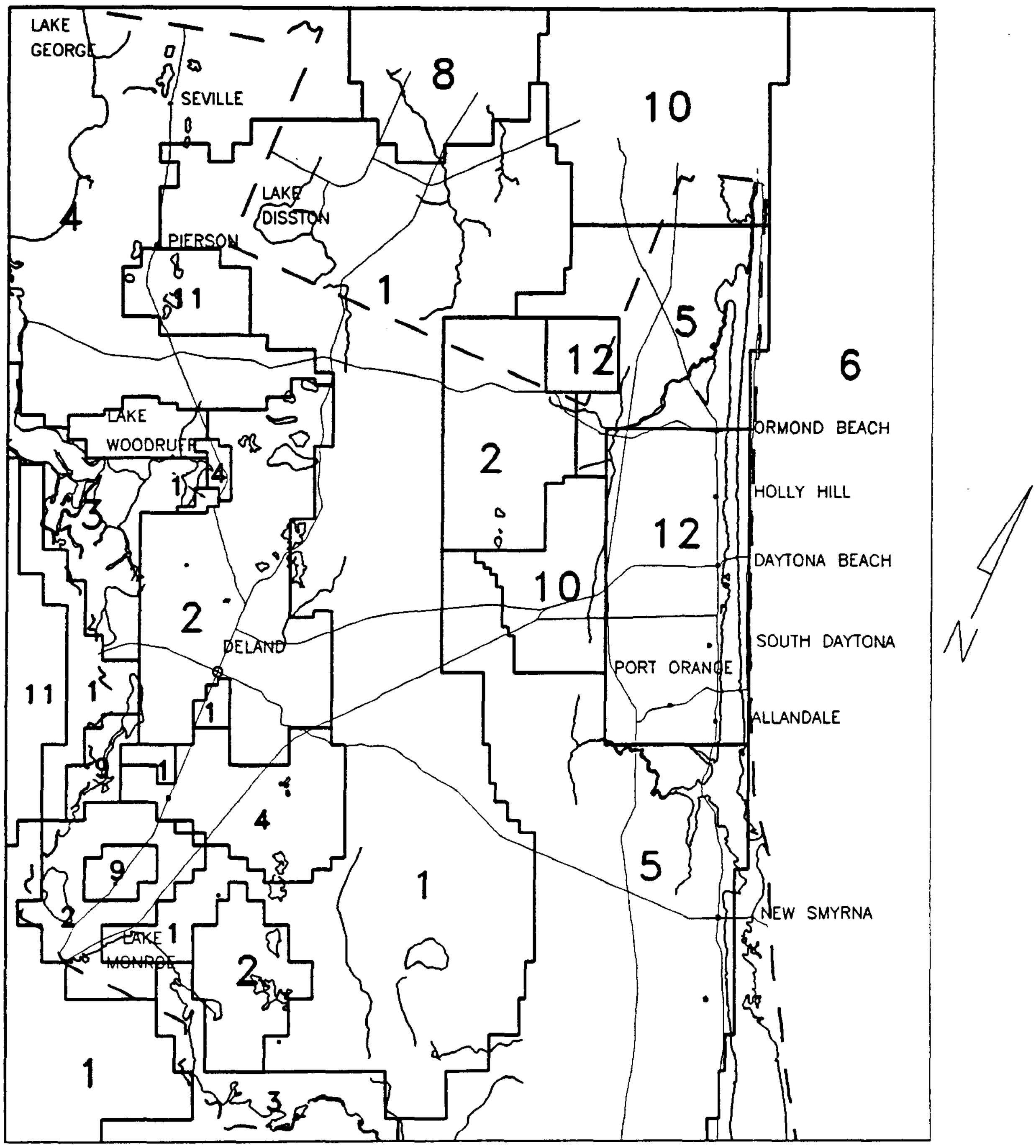
Parameter Type	Zone Number	Value
Leakance	1	0.00028 d^{-1}
	2	0.00006
	3	0.001
	4	0.0019
	5	0.0000291
	6	0.6
	7	0.00005
	8	0.0116
	9	0.00001
	10	0.000028
	11	0.00045
	12	0.0000018

SCALE

0 35000 FT



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Environmental Services

Figure 38. Vertical leakance zones in layer 1 (surficial aquifer) of the three-dimensional model.

FIGURE

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PRJCT NO.:
DWG DATE:

BRUNING 78505 FORM # 5489

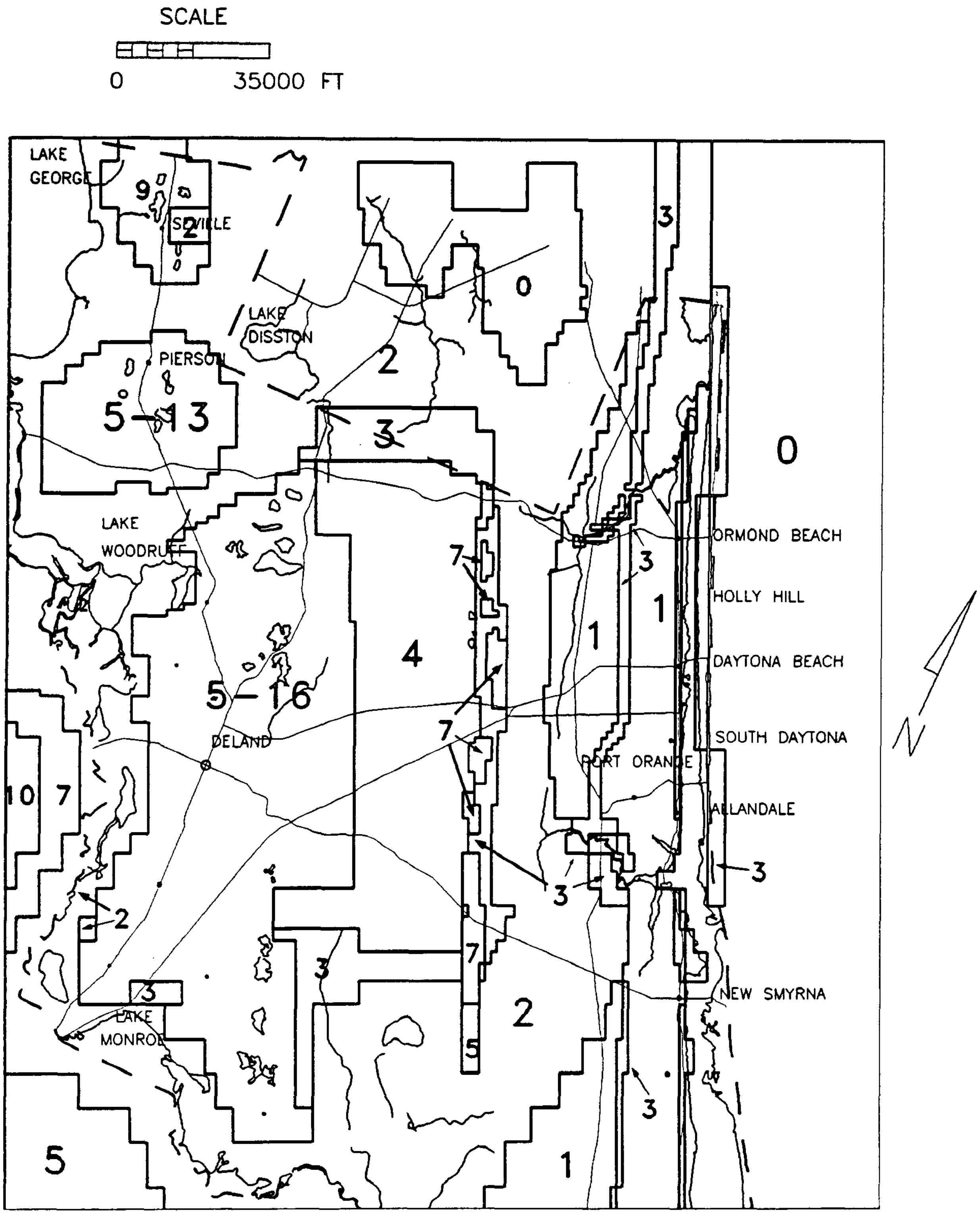

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Figure 39. Recharge zones in layer 1 (surficial aquifer) of the three-dimensional model (zone numbers represent recharge in inches per year).

FIGURE

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BRUNING 78505 FORM # 5489

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PRJCT NO.:

DWG DATE:

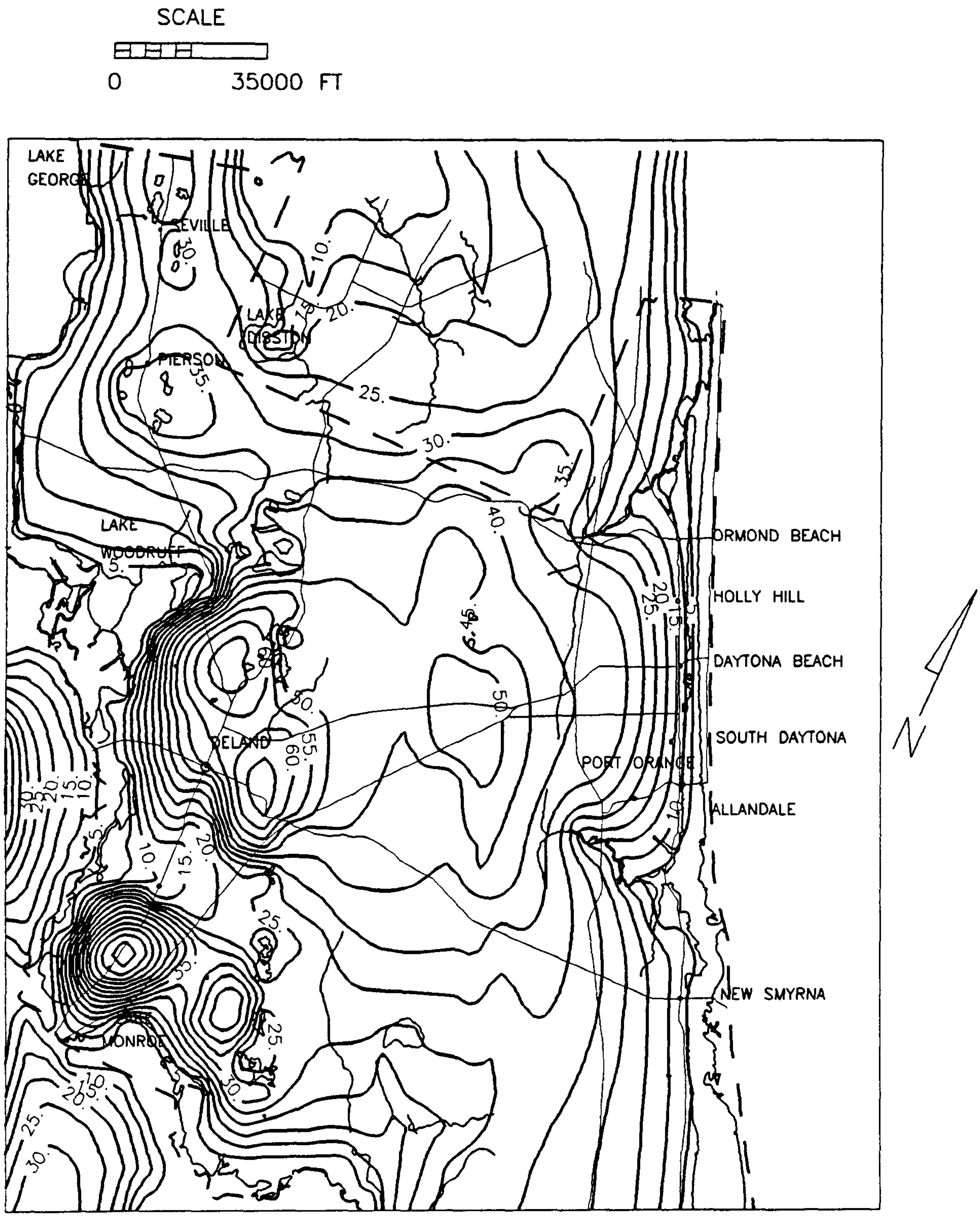

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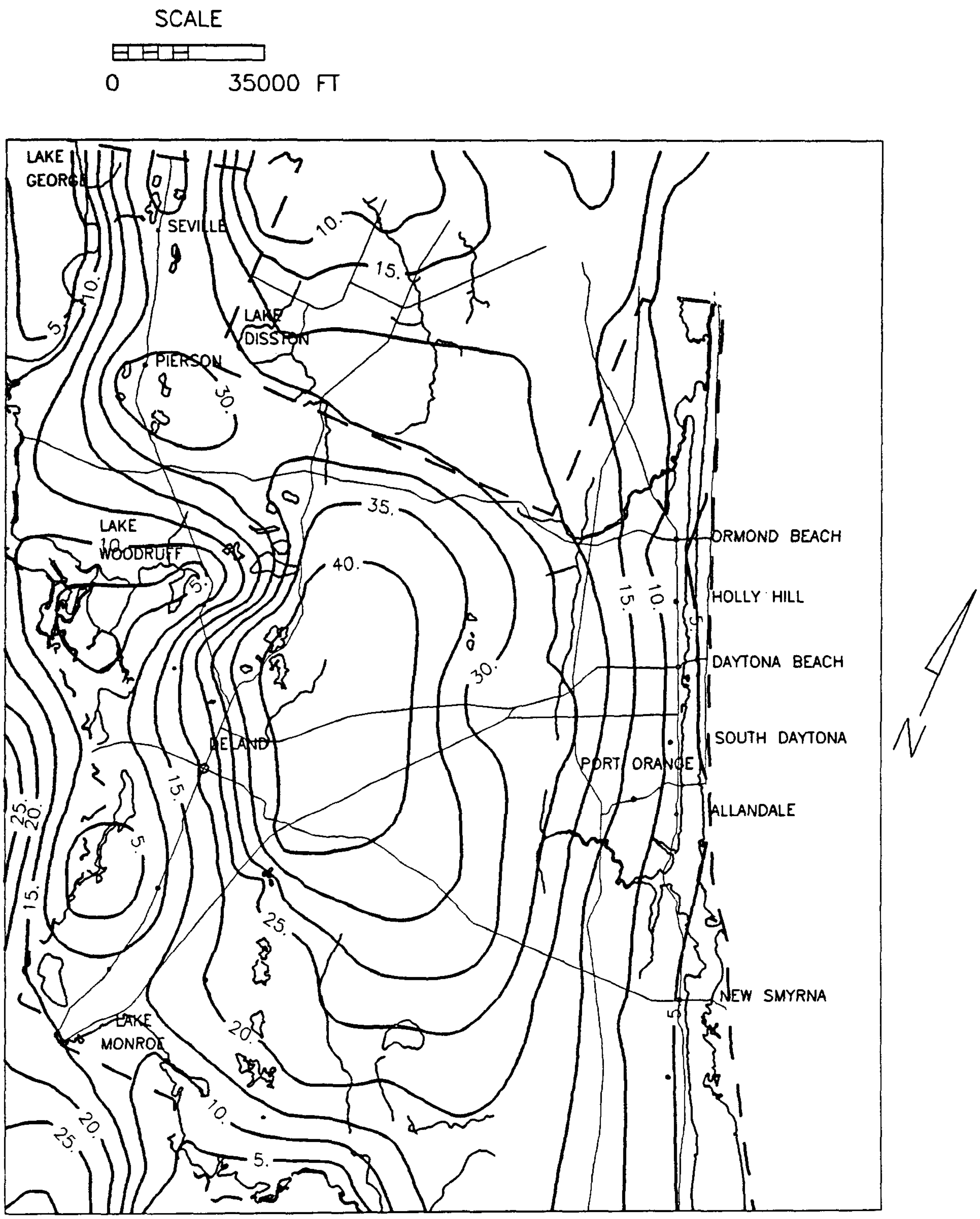
Figure 40. Simulated water-table contours for the predevelopment (1955) calibration in layer 1 (surficial aquifer).

FIGURE

BRUNING 78505 FORM # 5489



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DWG DATE:

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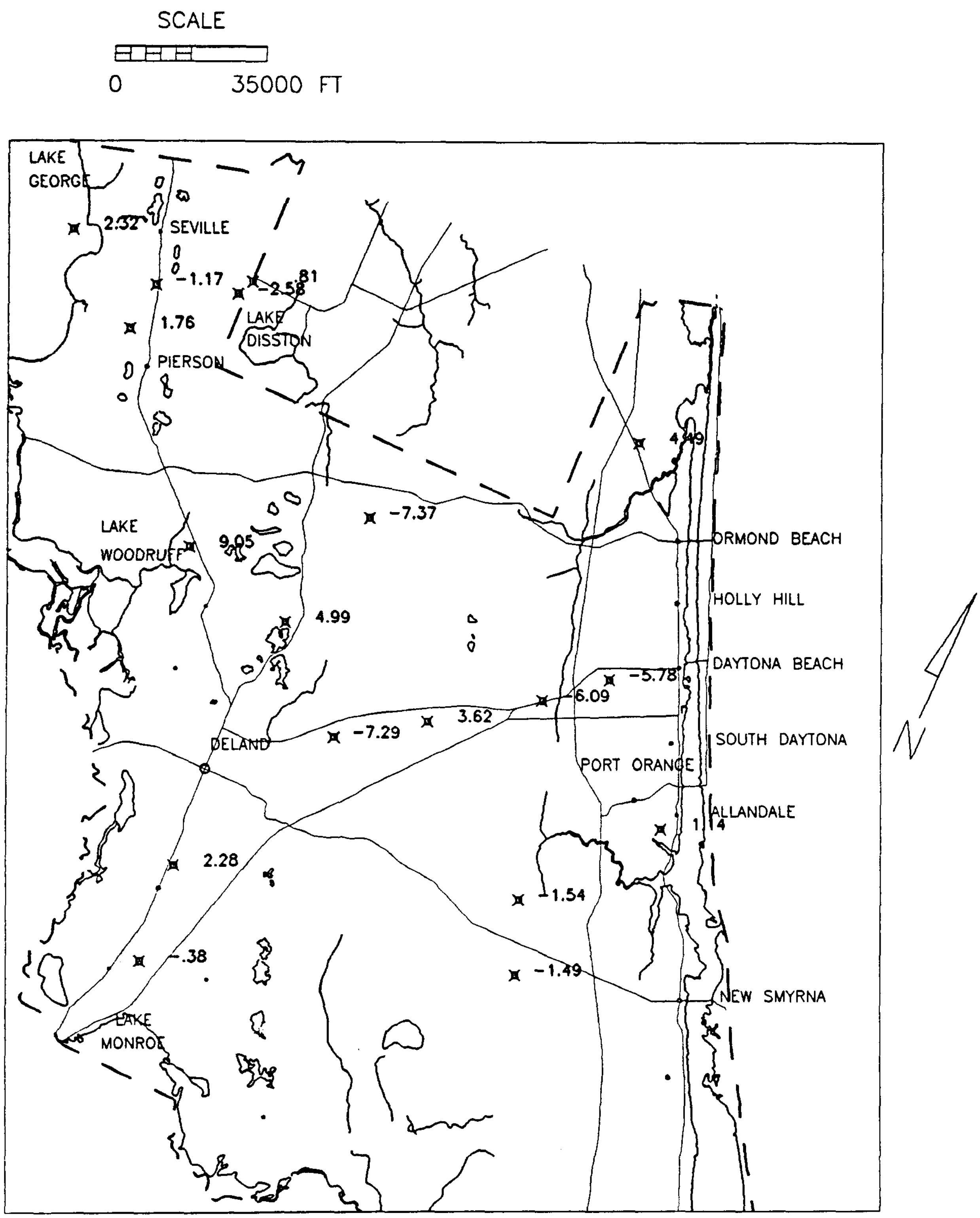
Environmental Services

Figure 41. Simulated potentiometric surface for the predevelopment (1955) calibration in layer 2 (Upper Floridan aquifer).

FIGURE

BRUNING 78505 FORM # 5489



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DWG DATE:

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Figure 42. Residuals for the predevelopment (1955) calibration in layer 2 (Upper Floridan aquifer).

FIGURE

BRUNING 78505 FORM # 5489

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PRJCT NO.:
DWG DATE:

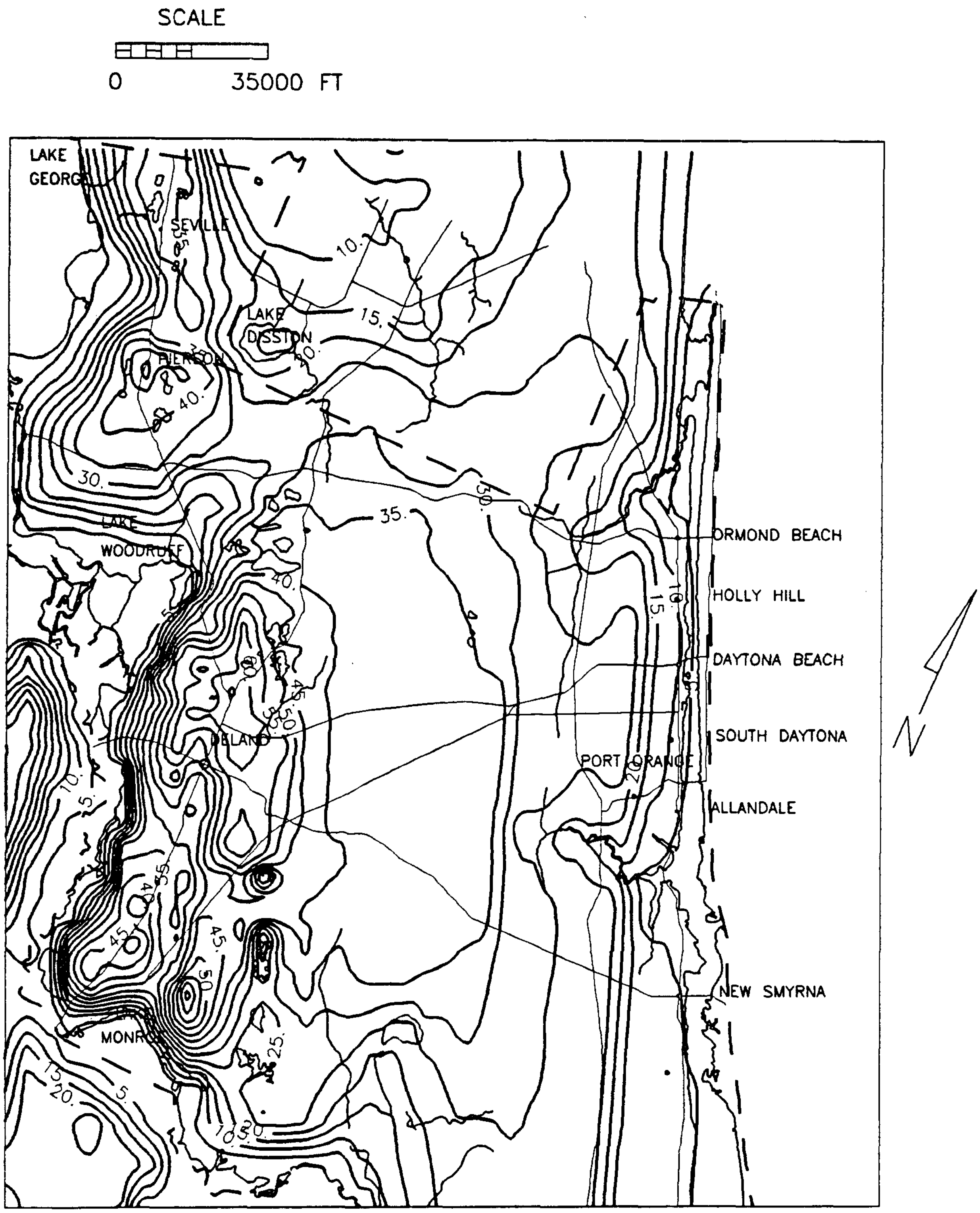

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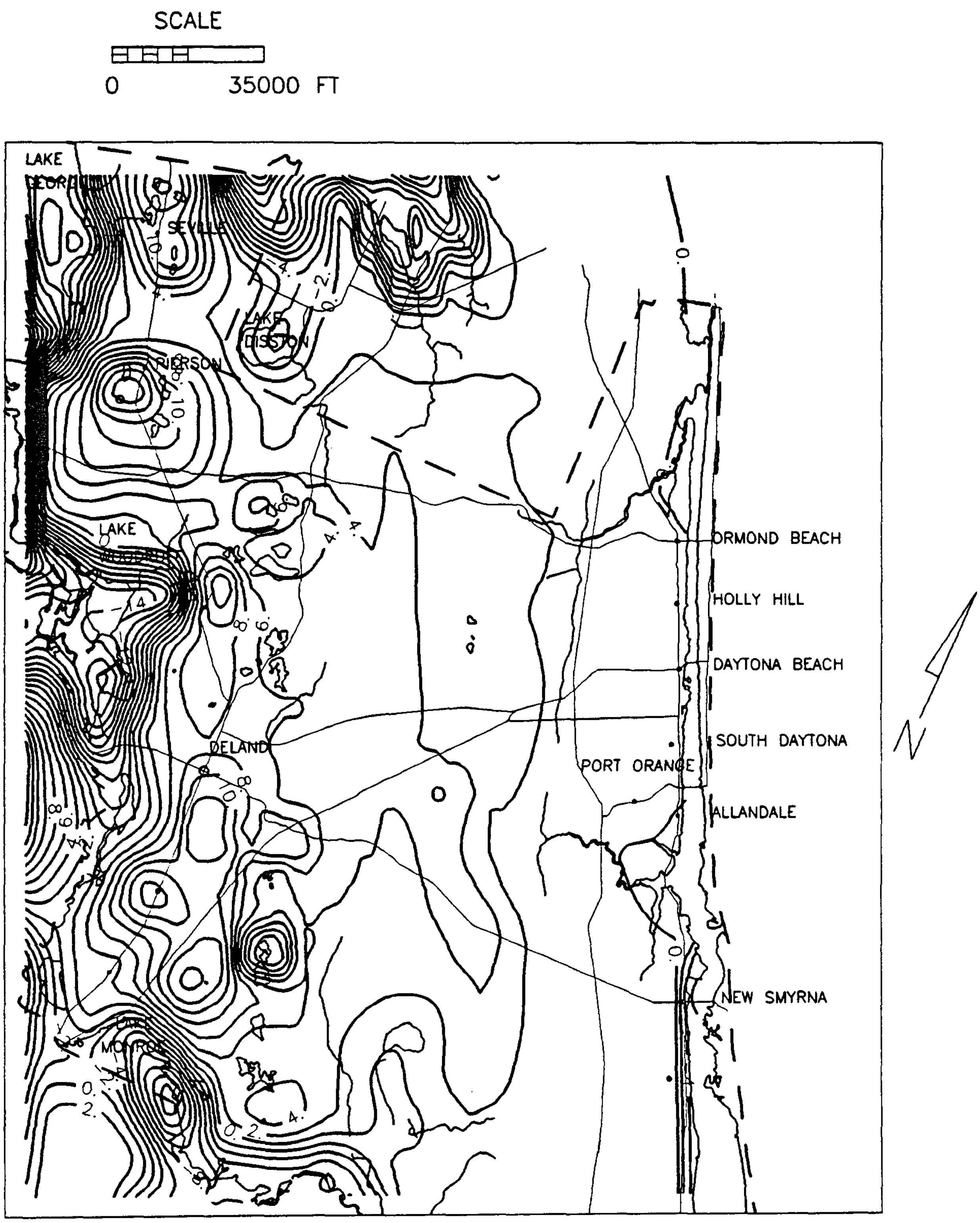
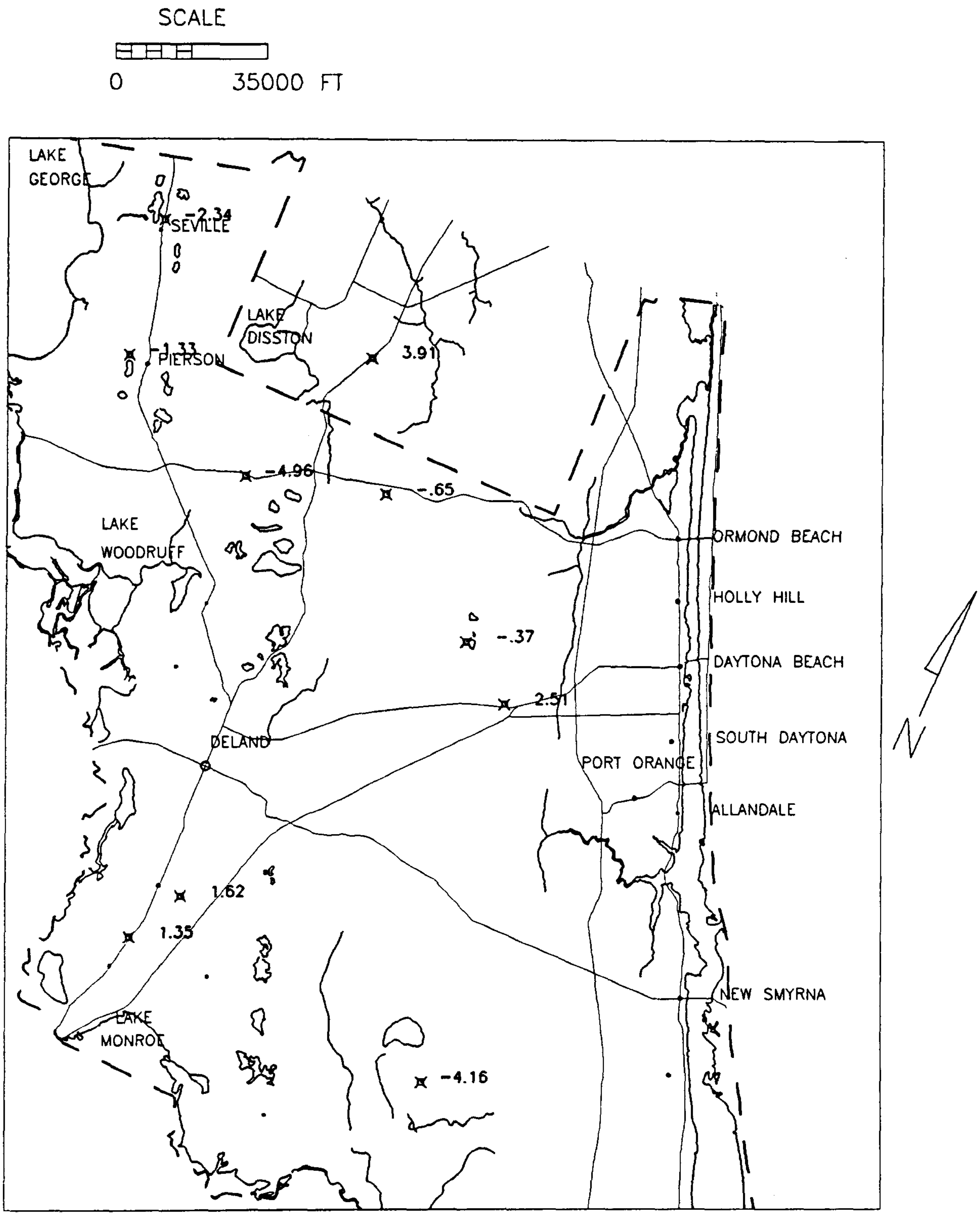
Figure 43. Postulated water-table contours in the surficial aquifer under predevelopment conditions.

FIGURE



FIGURE

Figure 44. Simulated recharge/discharge distribution through the top of layer 2 (Upper Floridan aquifer, predevelopment (1955) conditions, contours are inches per year).



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FILE NO.:
PRJCT NO.:
DWG DATE:

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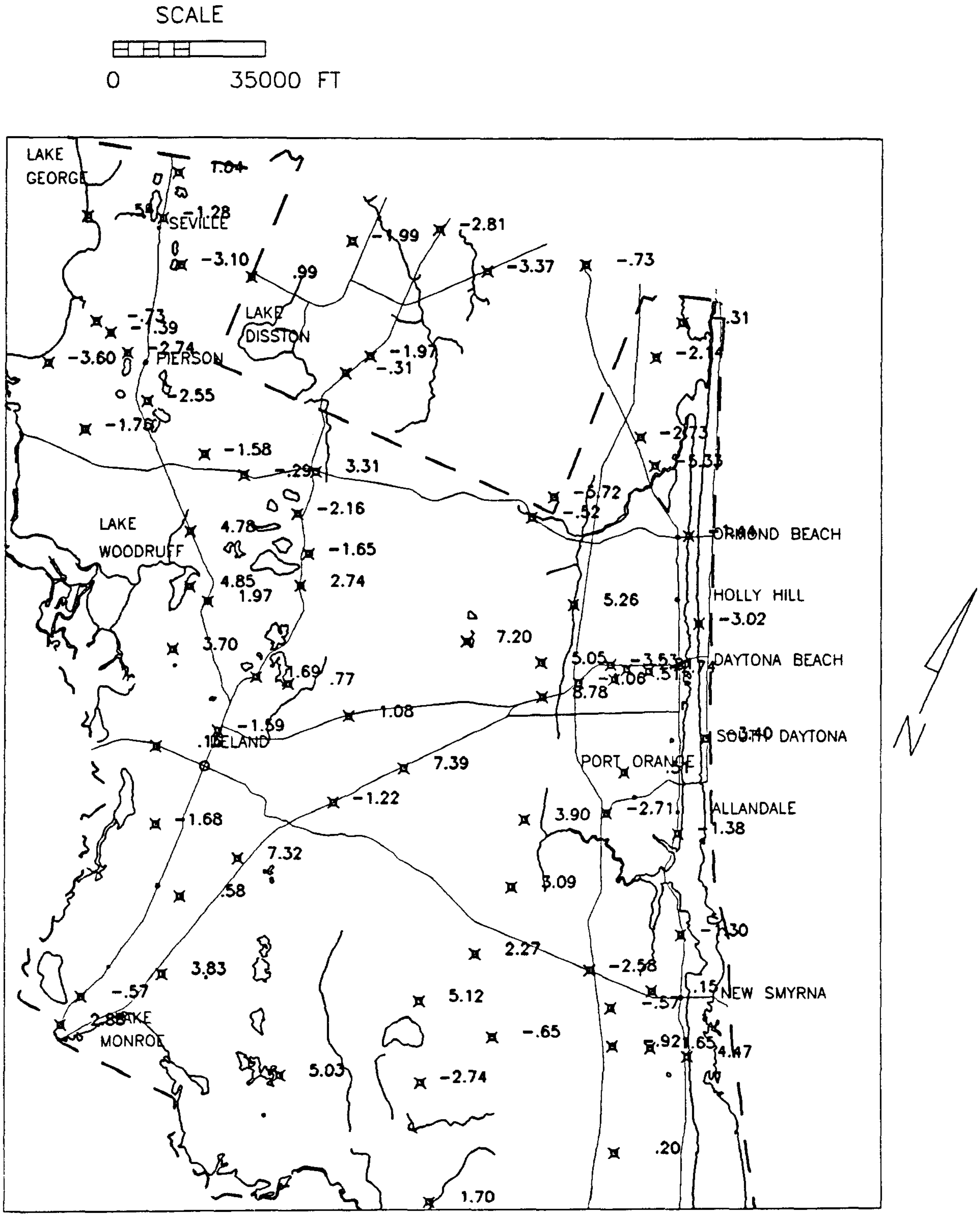
Figure 45. Residuals for the 1988 calibration in layer 1 (surficial aquifer).

FIGURE

BRUNING 78505 FORM # 5489



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FILE NO.:
PRJCT NO.:
DWG DATE:

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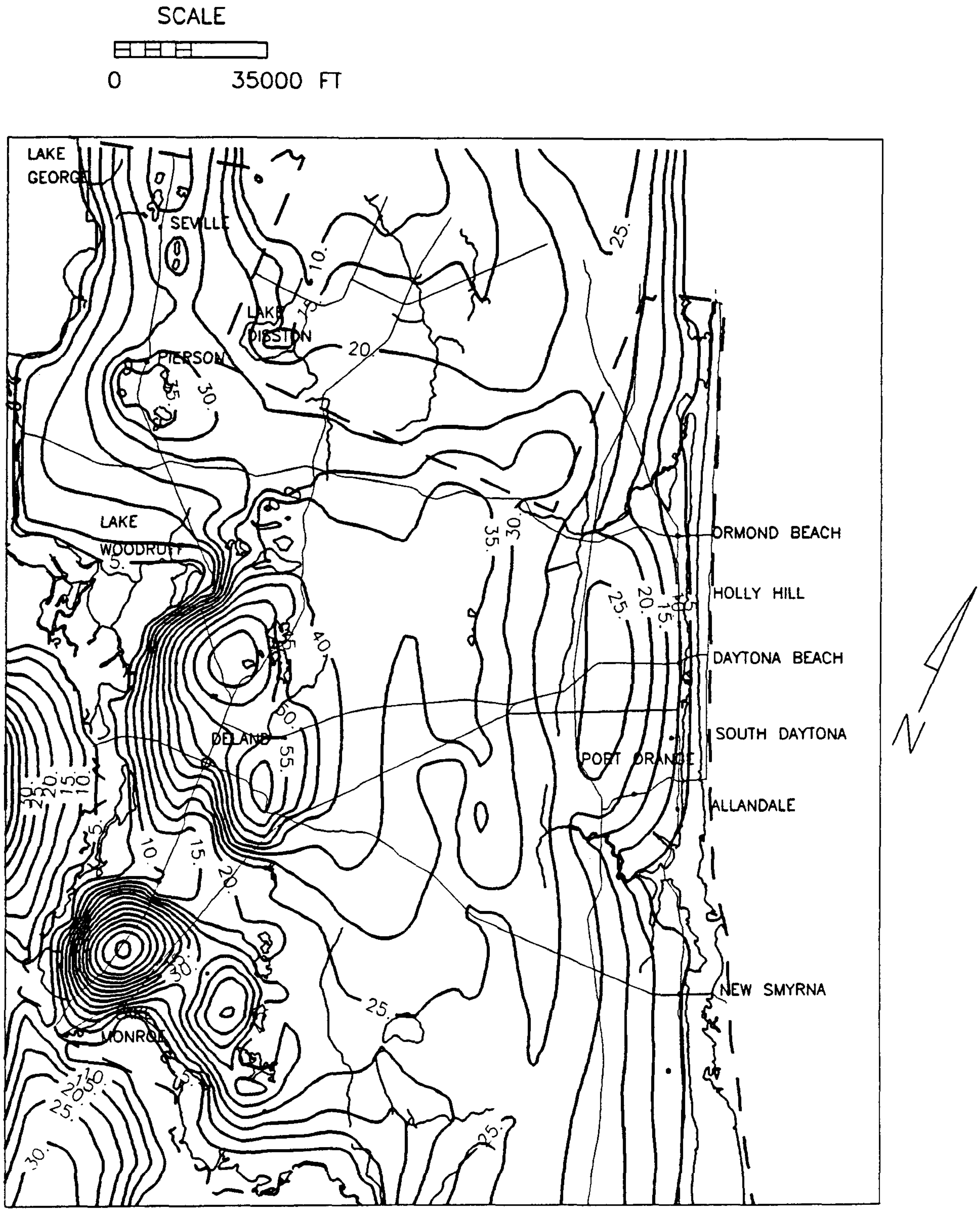
Figure 46. Residuals for the 1988 calibration in layer 2 (Upper Floridan aquifer).

FIGURE

BRUNING 78505 FORM # 5489



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DRAWING:

FILE NO.:

PRJCT NO.:

DWG DATE:

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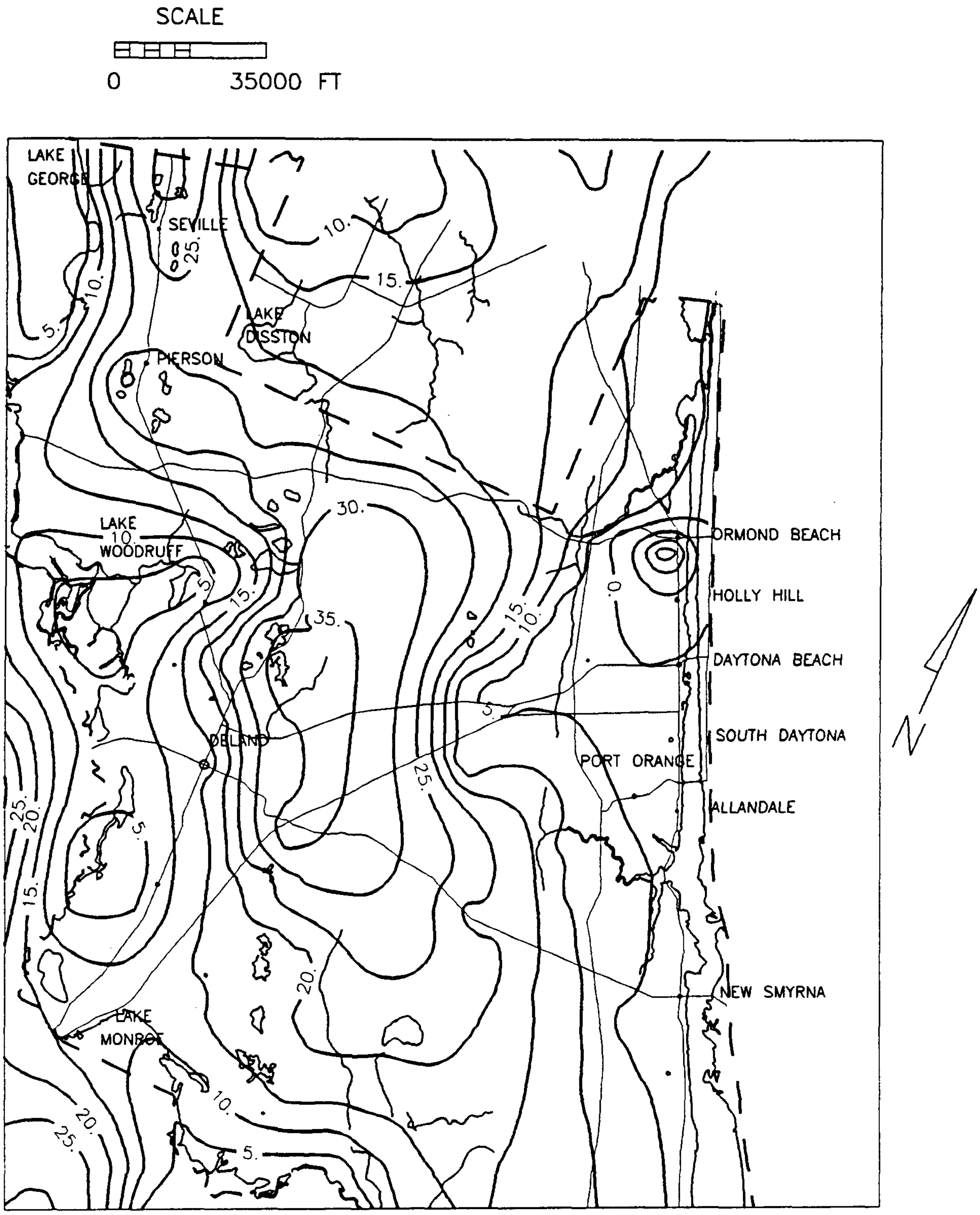
Figure 47. Simulated water-table contours for the 1988 calibration in layer 1 (surficial aquifer).

FIGURE

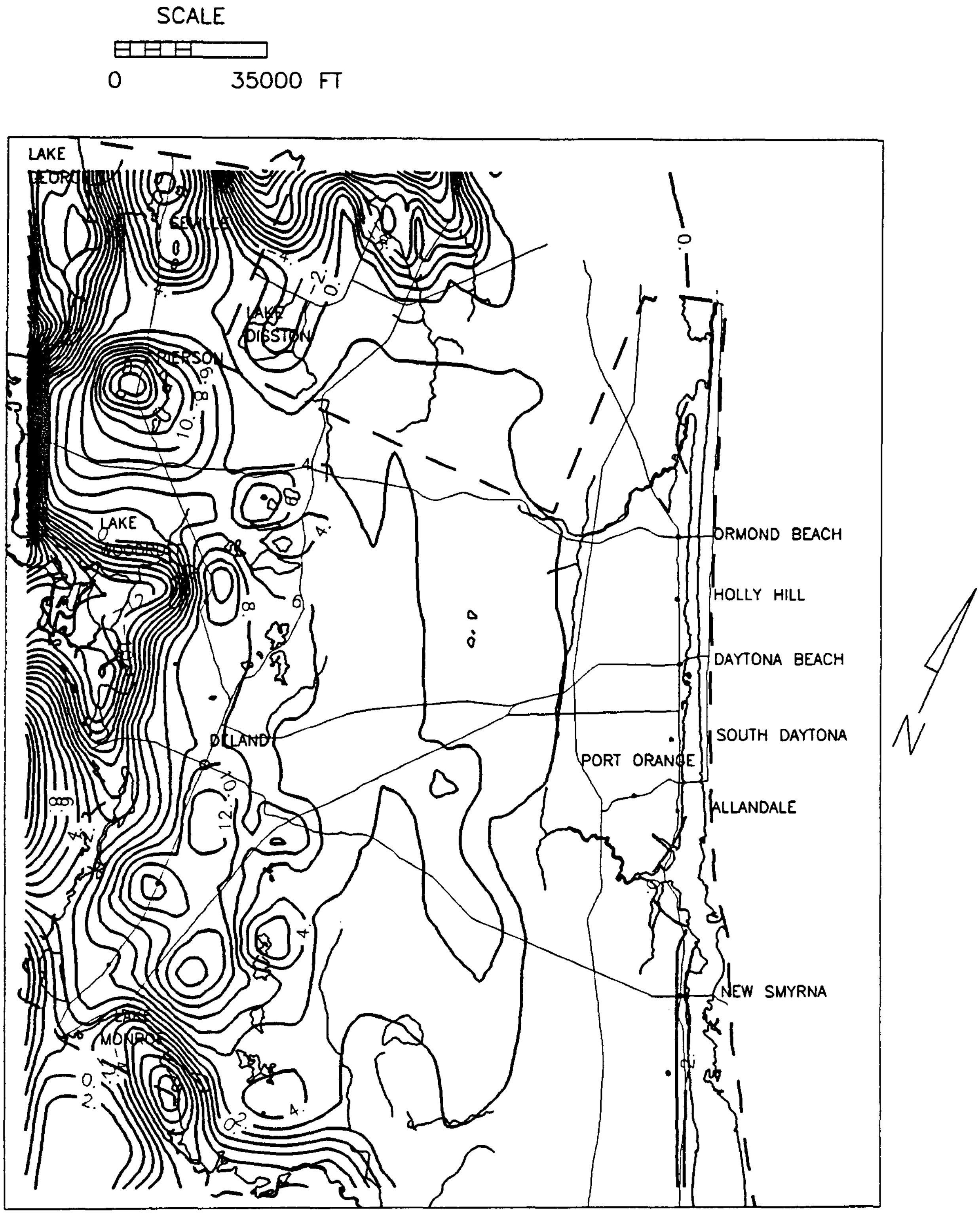
BRUNING 78505 FORM # 5489



GERAGHTY & MILLER, INC.
Environmental Services

Figure 48. Simulated potentiometric surface for the 1988 calibration in layer 2 (Upper Floridan aquifer).

FIGURE



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Environmental Services

Figure 49. Simulated recharge/discharge distribution through the top of layer 2 (Upper Floridan aquifer, 1988 conditions, contours are inches per year).

FIGURE

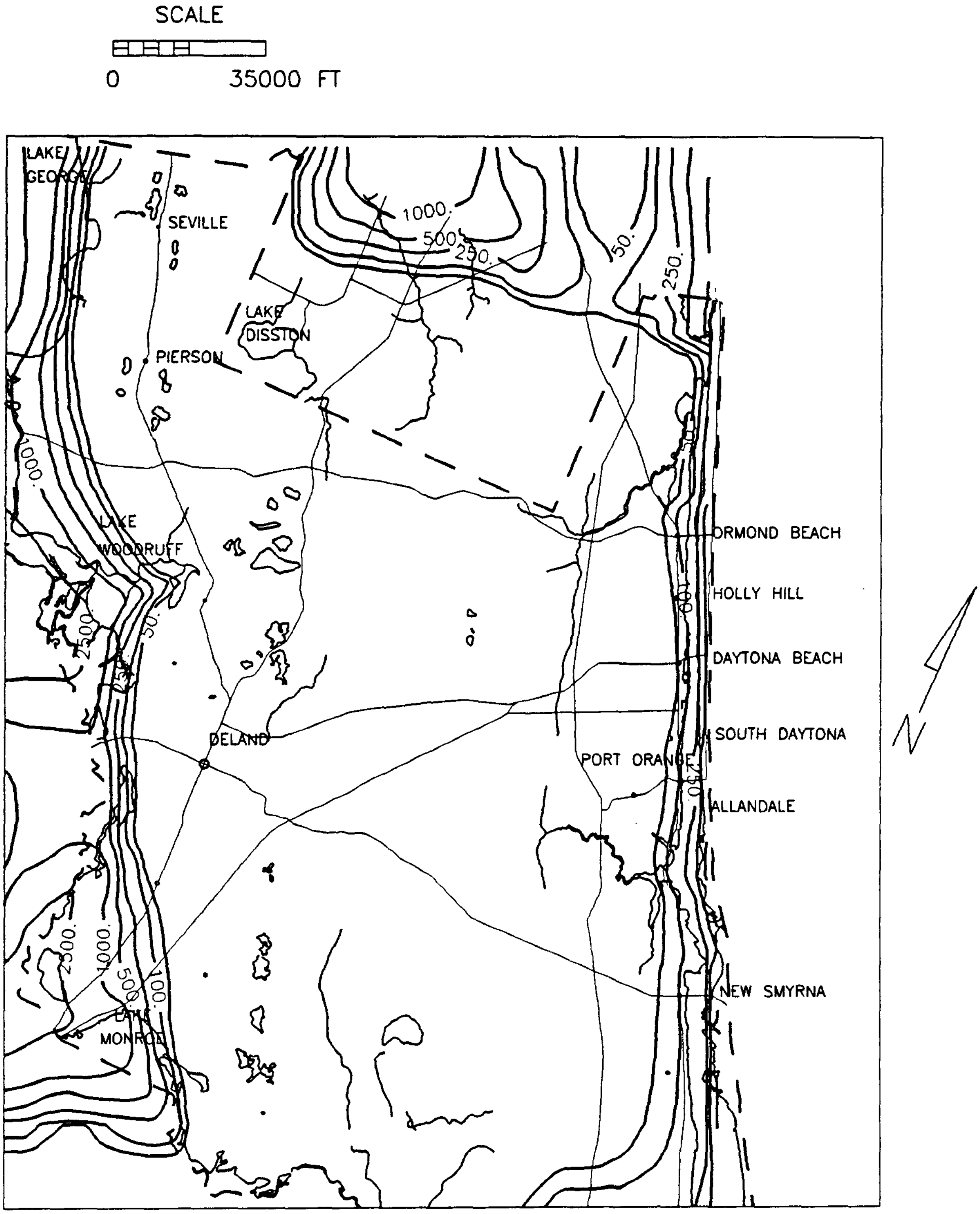

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Figure 50. Simulated chloride concentration contours for the predevelopment calibration in layer 1 (surficial aquifer) (concentrations in mg/L).

FIGURE

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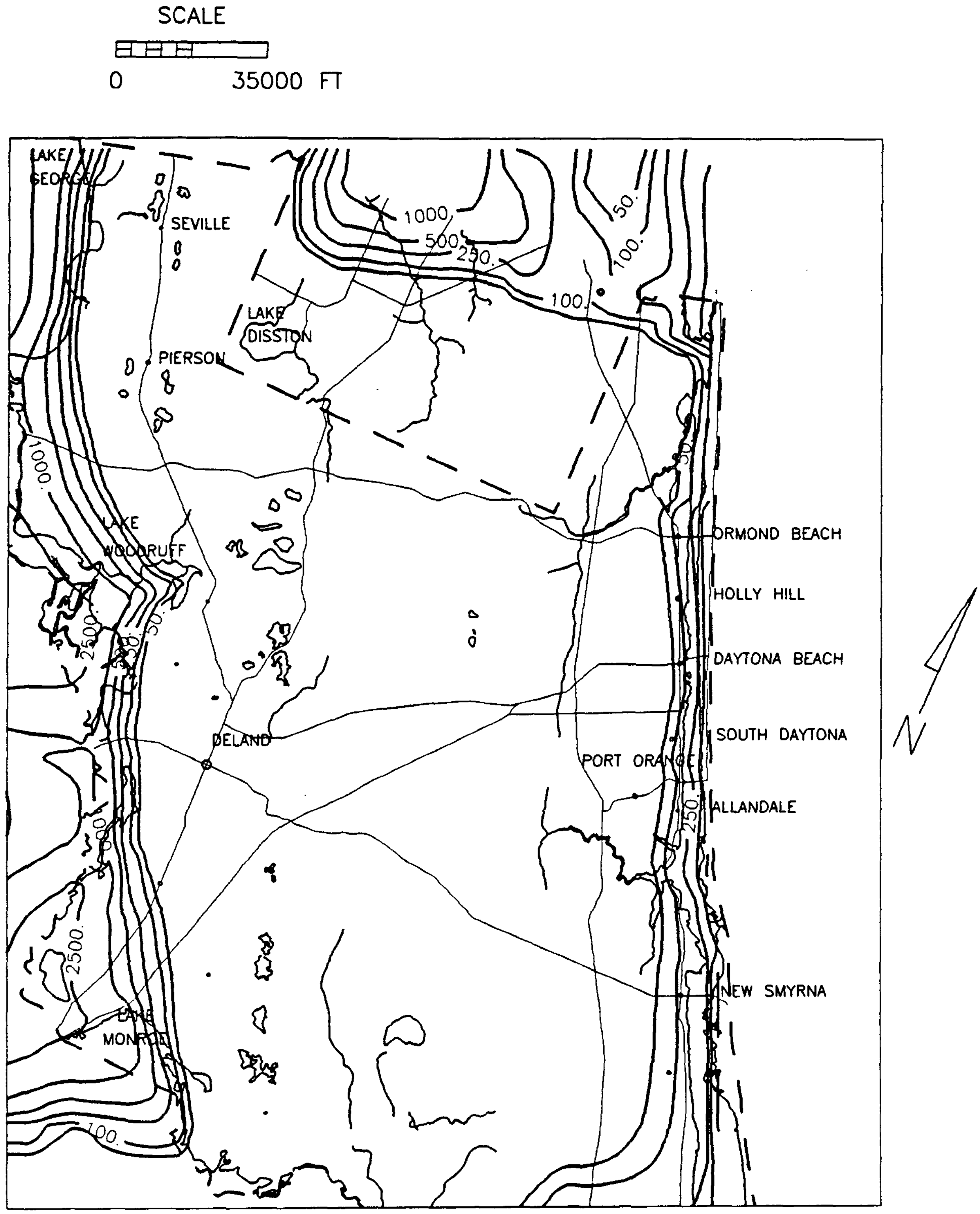

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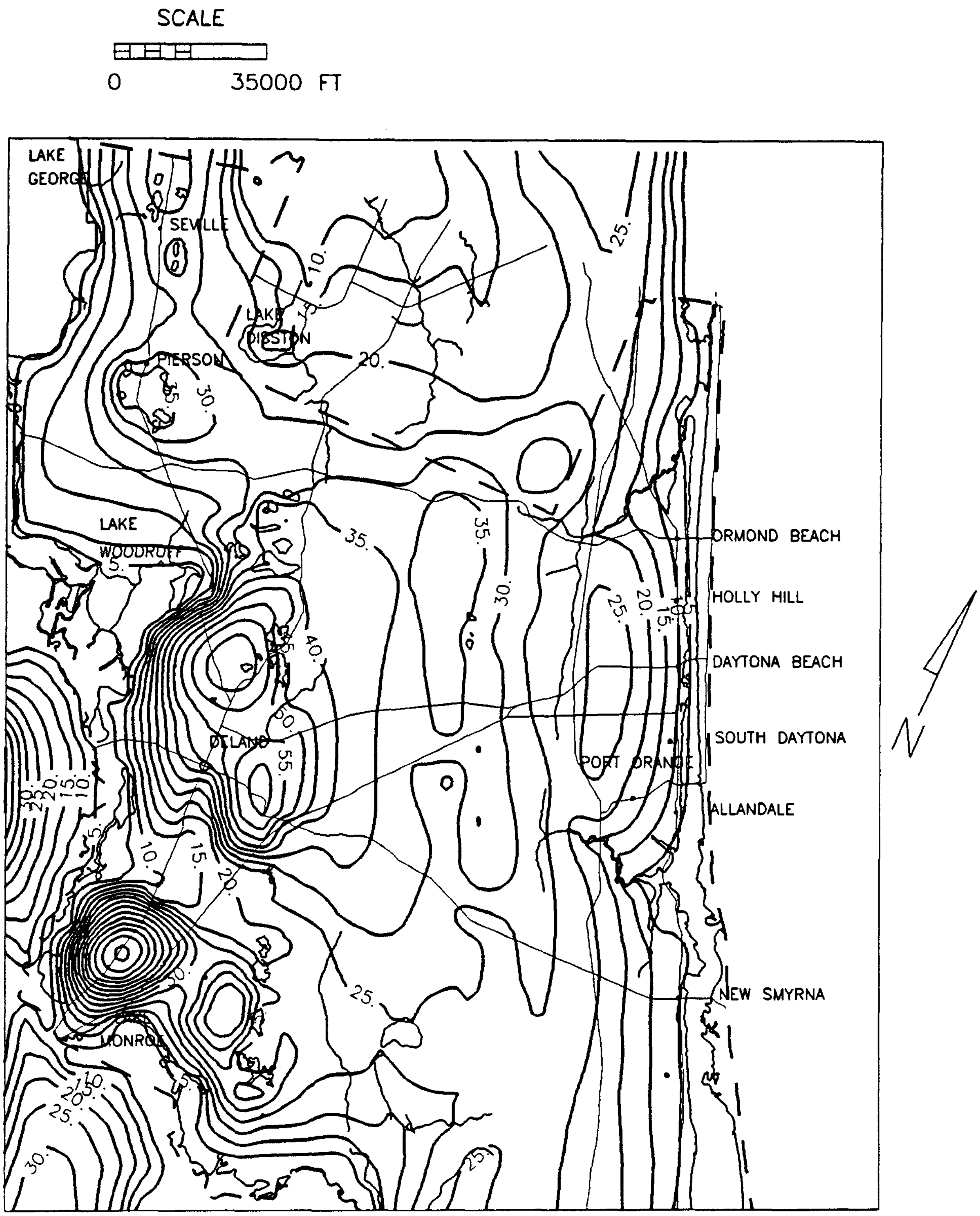
Environmental Services

Figure 51. Simulated chloride concentration contours for the predevelopment calibration in layer 2 (Upper Floridan aquifer) (concentrations in mg/L).

FIGURE



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DWG DATE:

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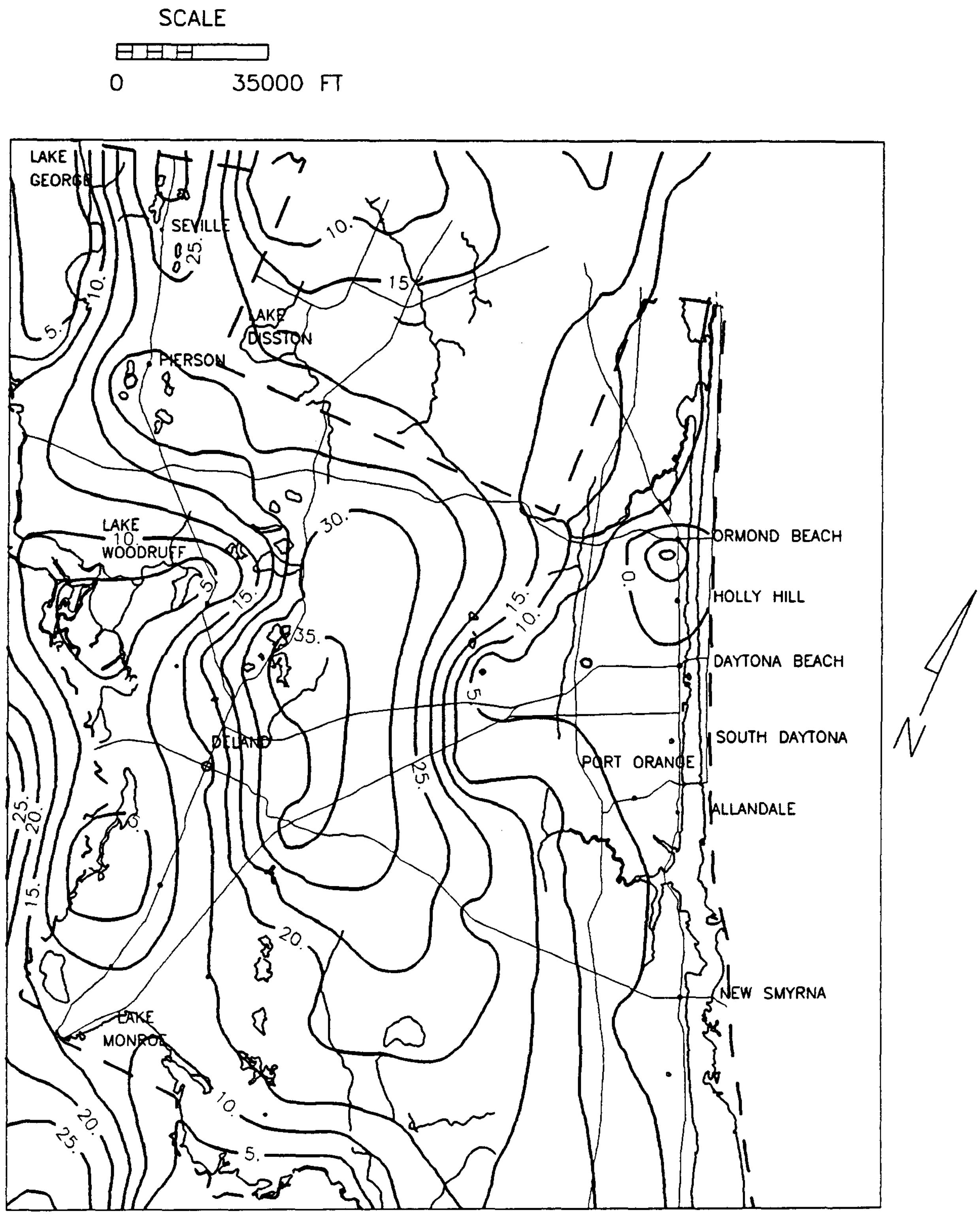
& MILLER, INC.
Environmental Services

Figure 52. Simulated water-table contours for 1990 conditions in layer 1 (surficial aquifer).

FIGURE

BRUNING 78505 FORM # 5489



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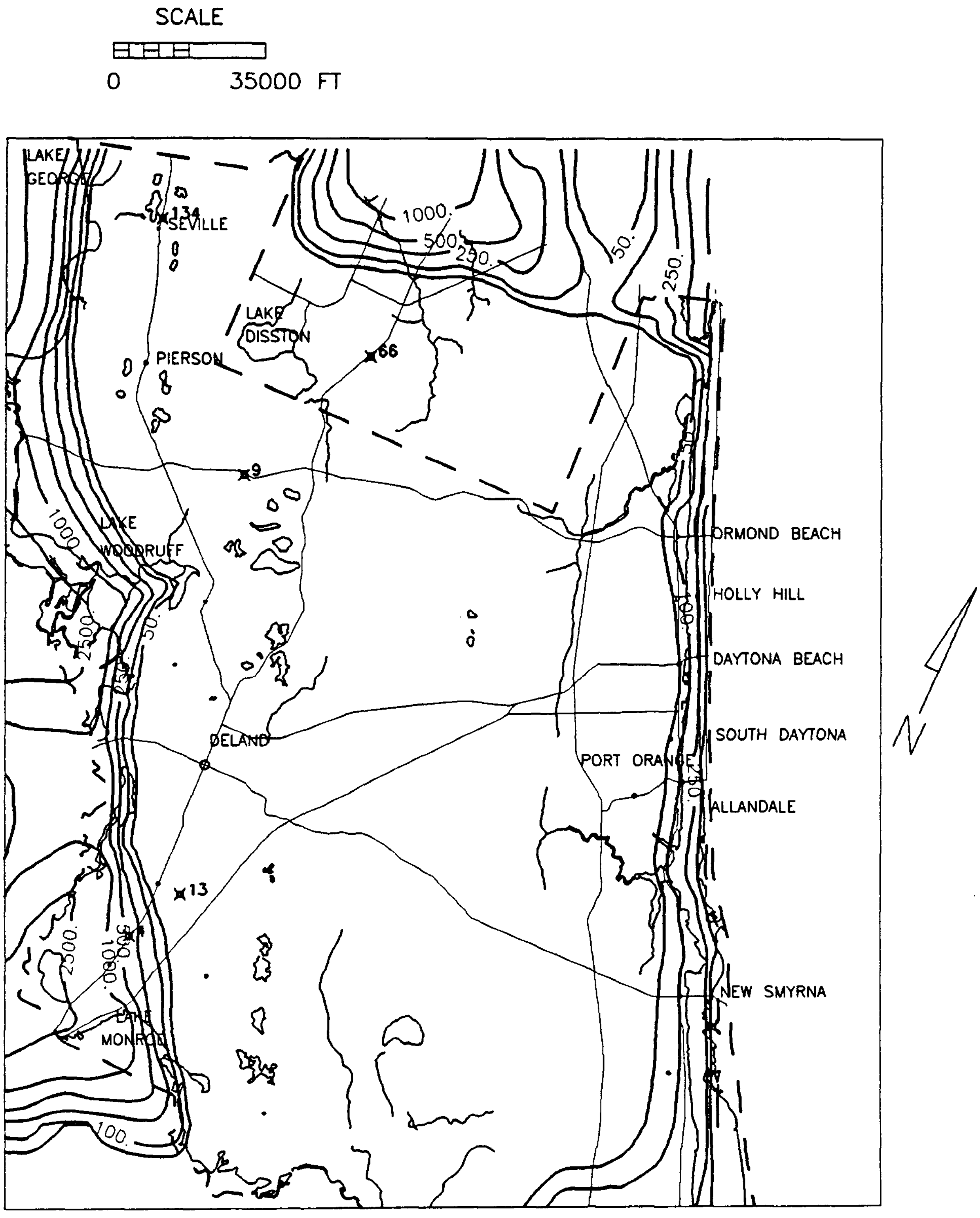
Environmental Services

Figure 53. Simulated potentiometric surface for 1990 conditions in layer 2 (Upper Floridan aquifer).

FIGURE

BRUNING 78505 FORM # 5489



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Environmental Services

Figure 54. Simulated chloride concentration contours for the transient 1990 chloride calibration in layer 1 (surficial aquifer) (concentrations in mg/L).

FIGURE

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BRUNING 78505 FORM # 5489

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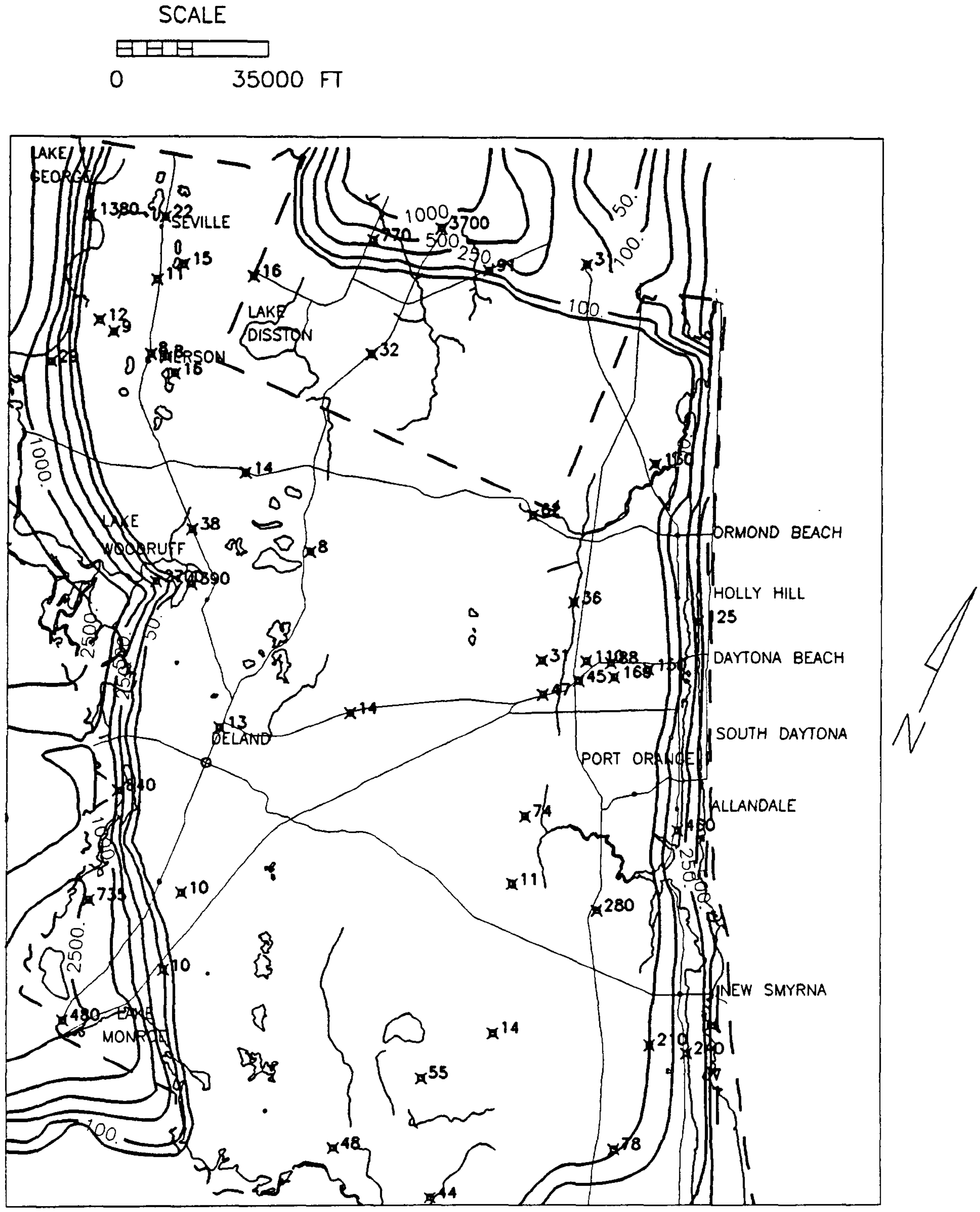
DWG DATE:



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Environmental Services

Figure 55. Simulated chloride concentration contours for the transient 1990 chloride calibration in layer 2 (Upper Floridan aquifer) (concentrations in mg/L).

FIGURE

BRUNING 78505 FORM # 5489

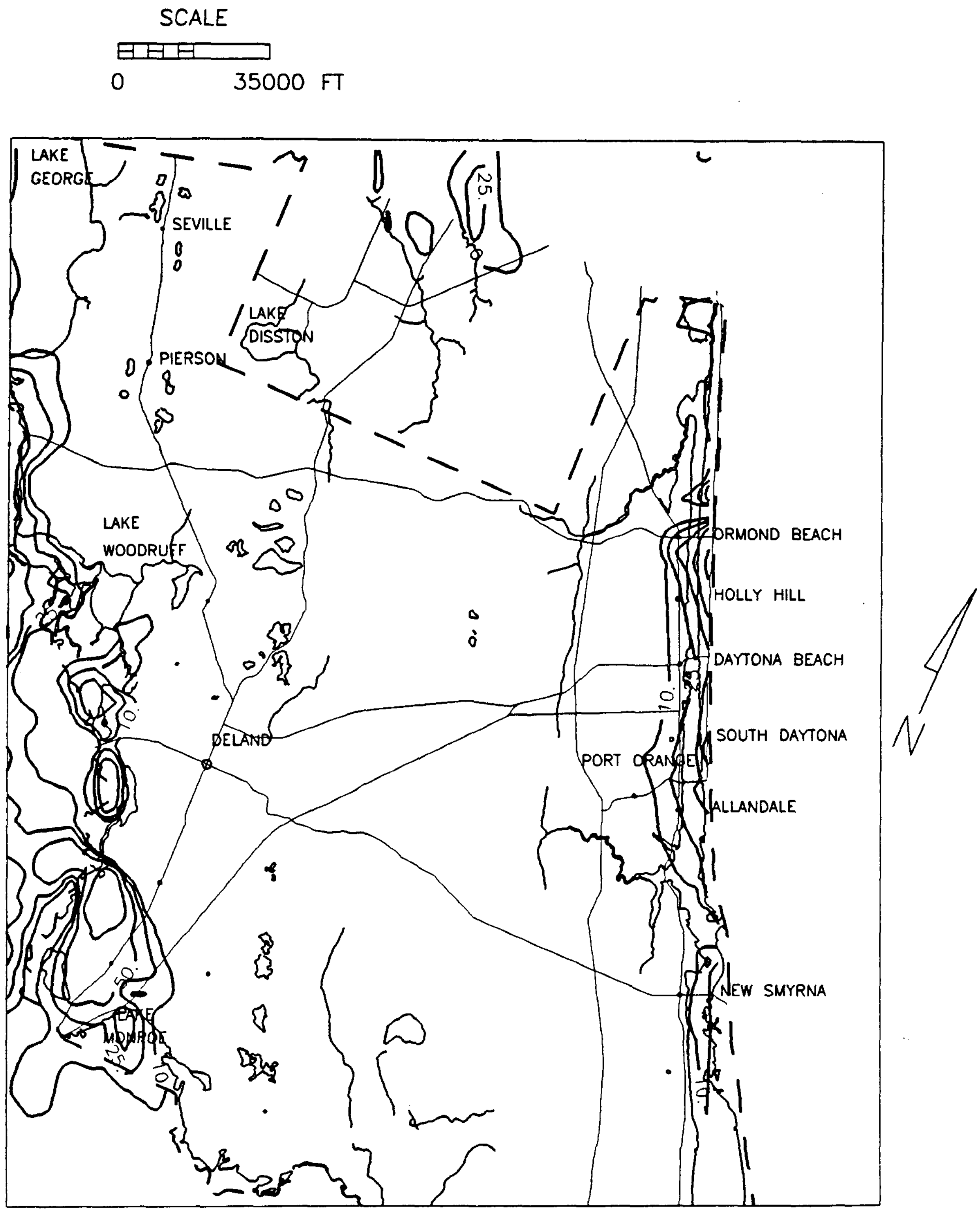

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Figure 56. Chloride concentration differences between simulated 1990 and predevelopment conditions in layer 2 (Upper Floridan aquifer) (concentrations in mg/L).

FIGURE

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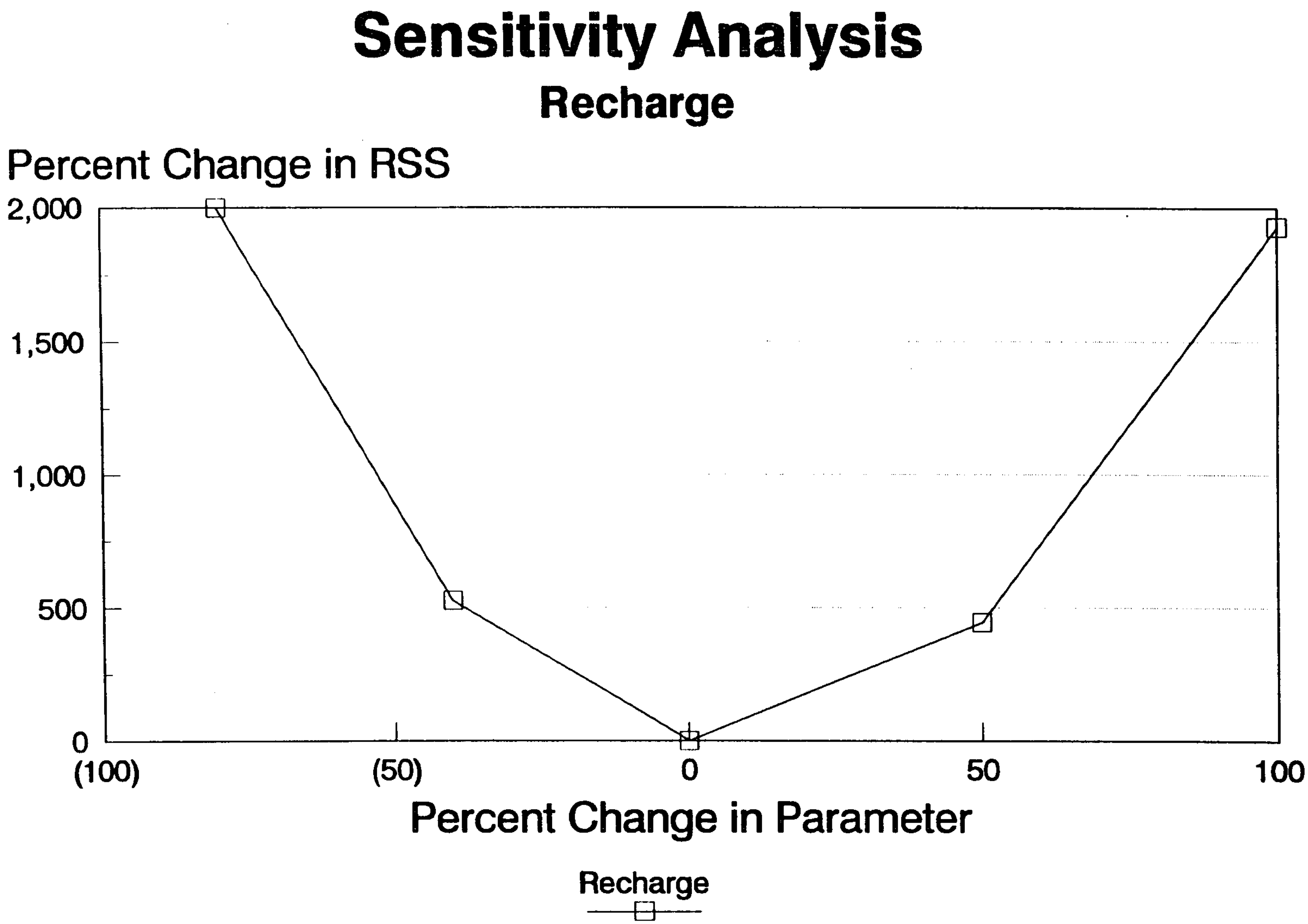

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Figure 57. Sensitivity of the 1988 calibration to changes in recharge.

FIGURE

BRUNING 78505 FORM # 5844

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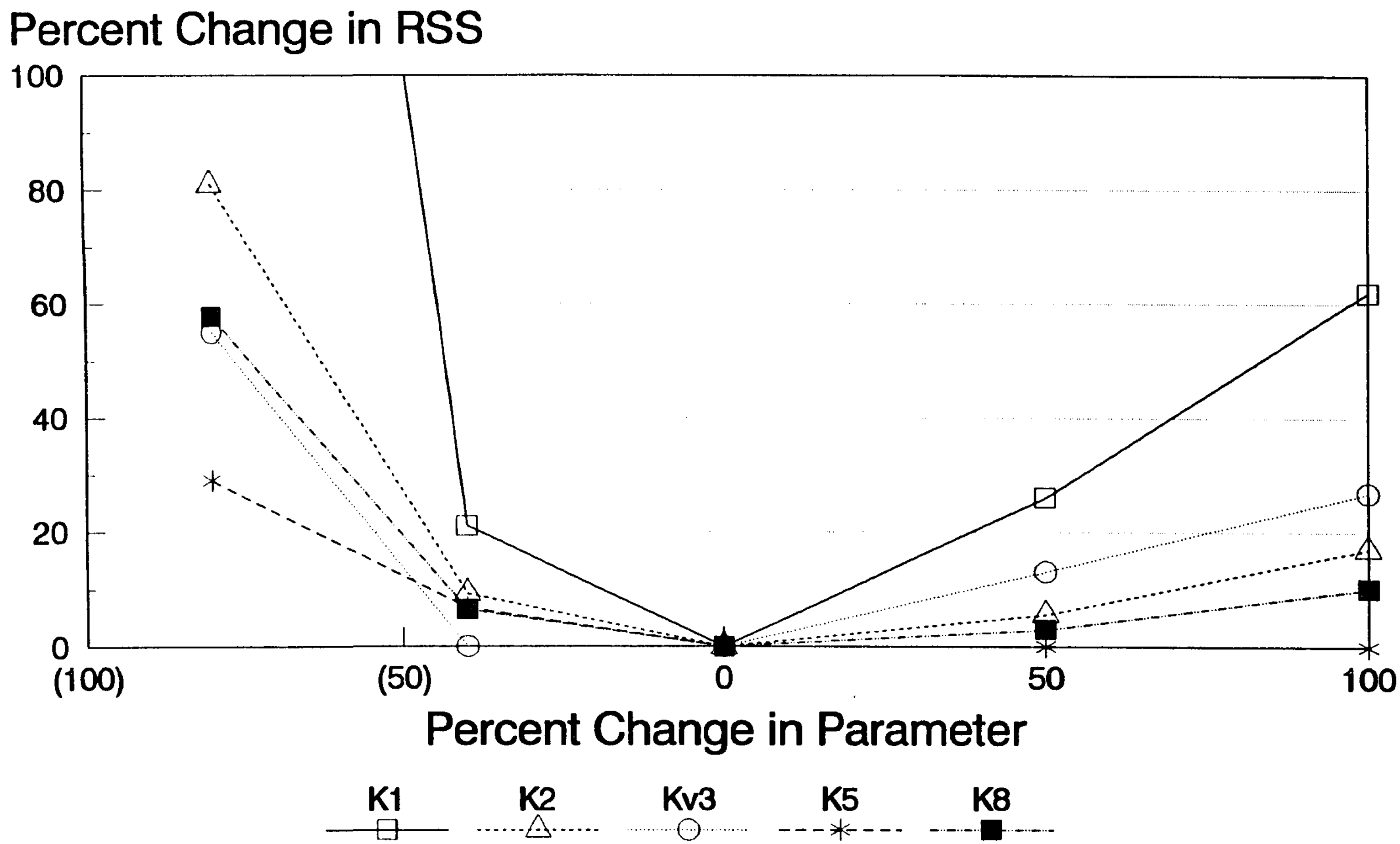
Sensitivity Analysis

Hydraulic Conductivity Zones



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Environmental Services

Figure 58. Sensitivity of the 1988 calibration to changes in hydraulic conductivity of zones 1, 2, 3, 5,and 8.

FIGURE

BRUNING 78505 FORM # 5844

DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:

Sensitivity Analysis

Hydraulic Conductivity Zones

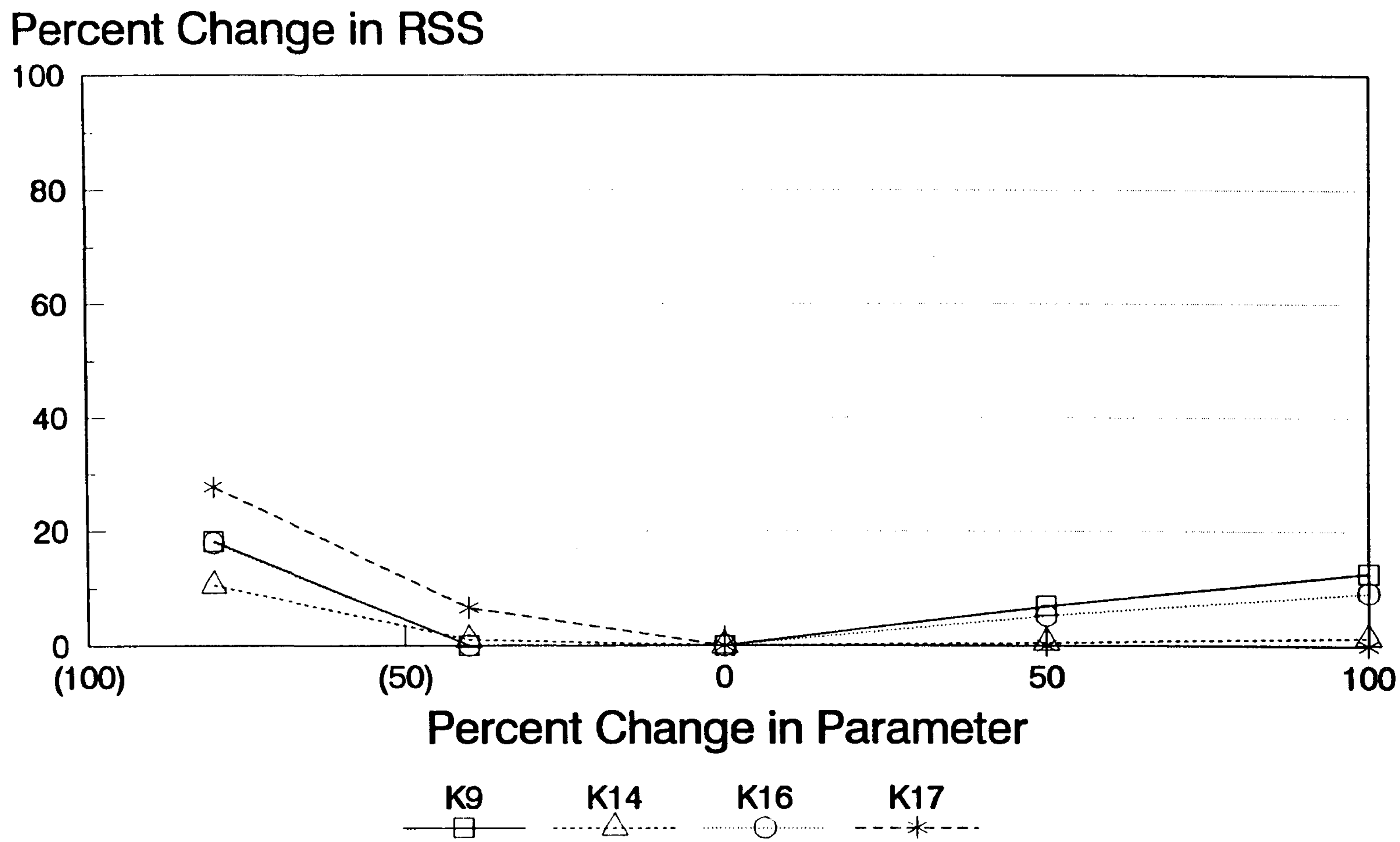

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Figure 59. Sensitivity of the 1988 calibration to changes in hydraulic conductivity of zones 9, 14, 16, and 17.

FIGURE

BRUNING 78505 FORM # 5844

DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:

Sensitivity Analysis

Leakance Coefficient Zones

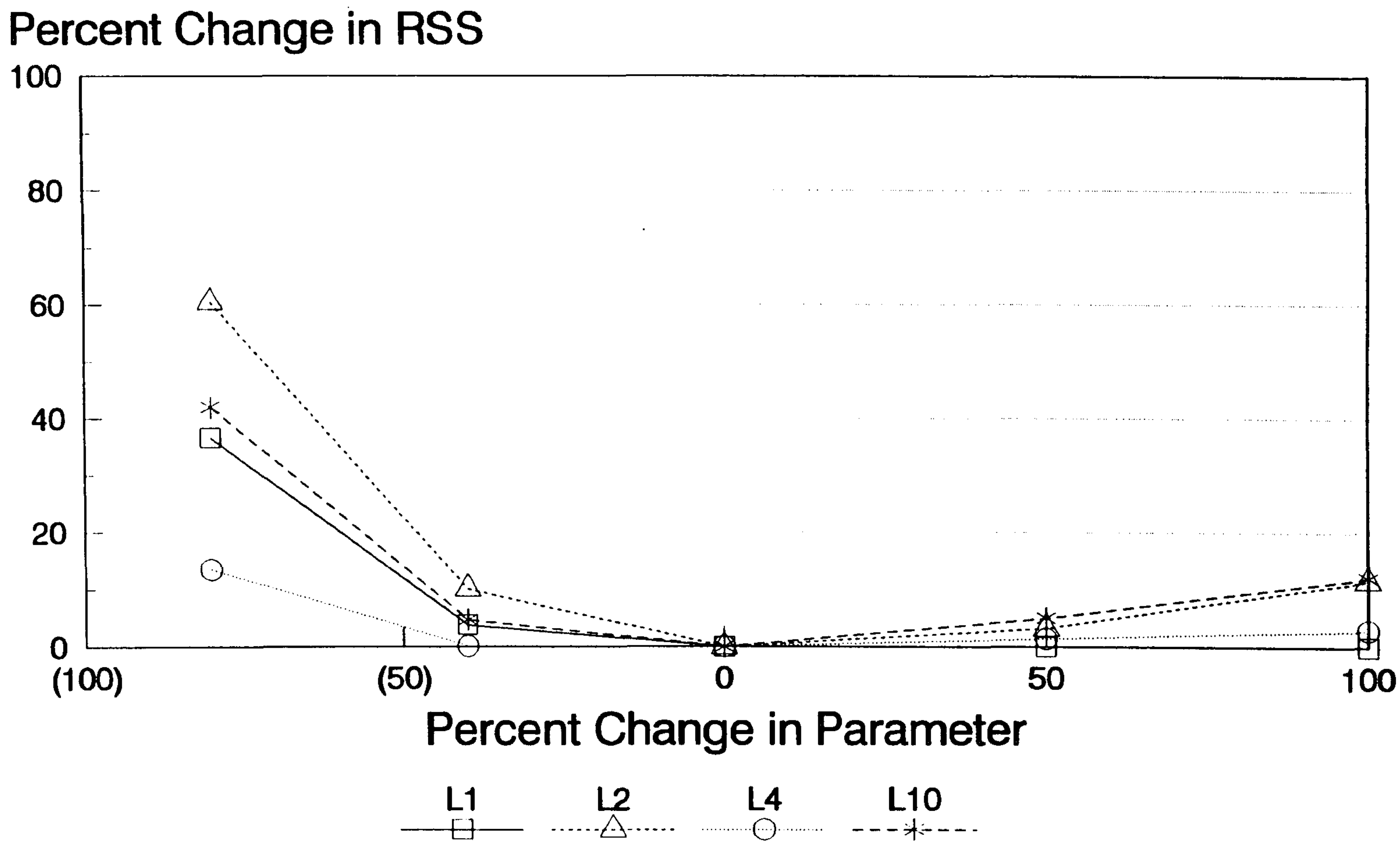

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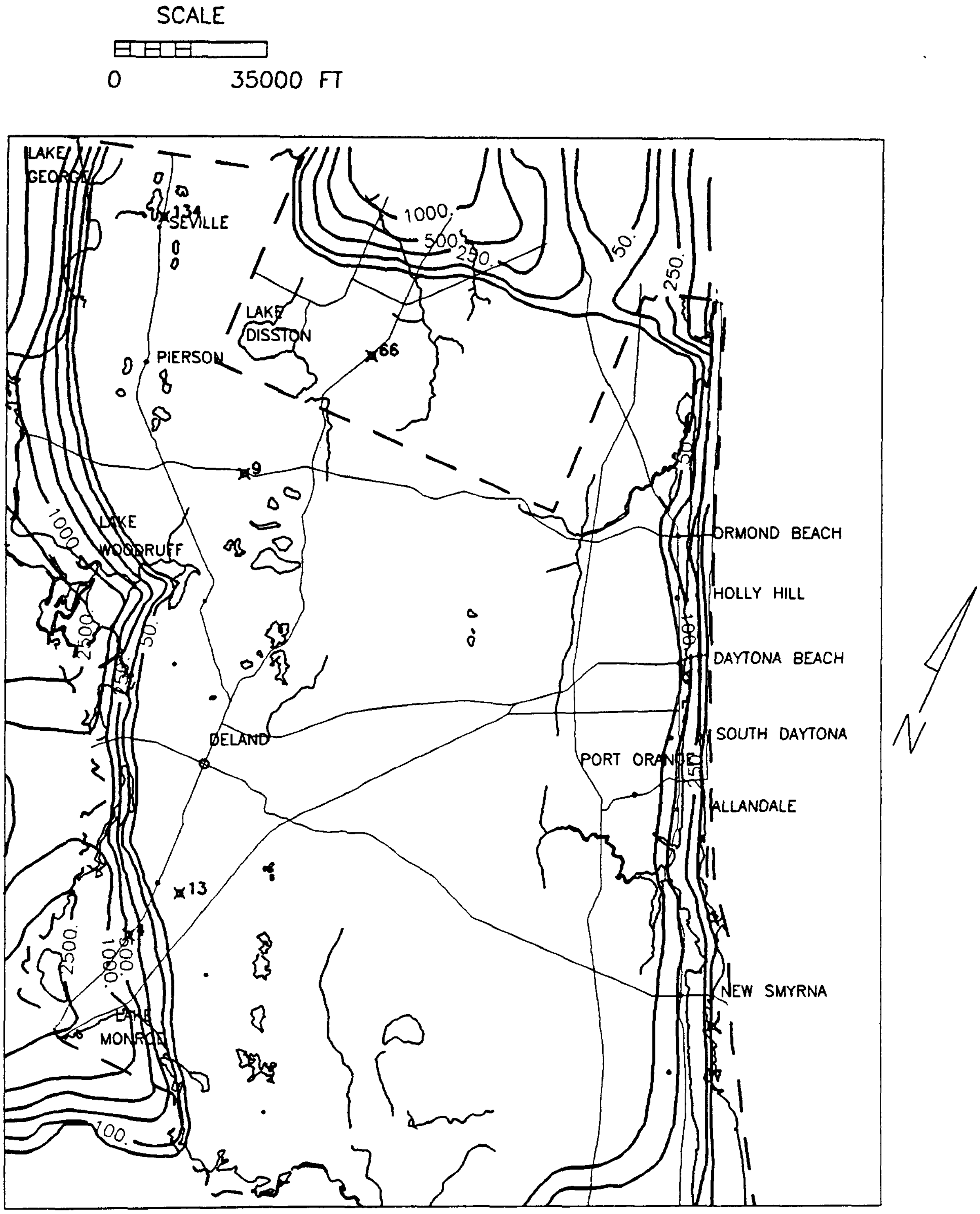
Figure 60. Sensitivity of the 1988 calibration to changes in vertical leakance of zones 1, 2, 4, and 10.

FIGURE

BRUNING 78505 FORM # 5844



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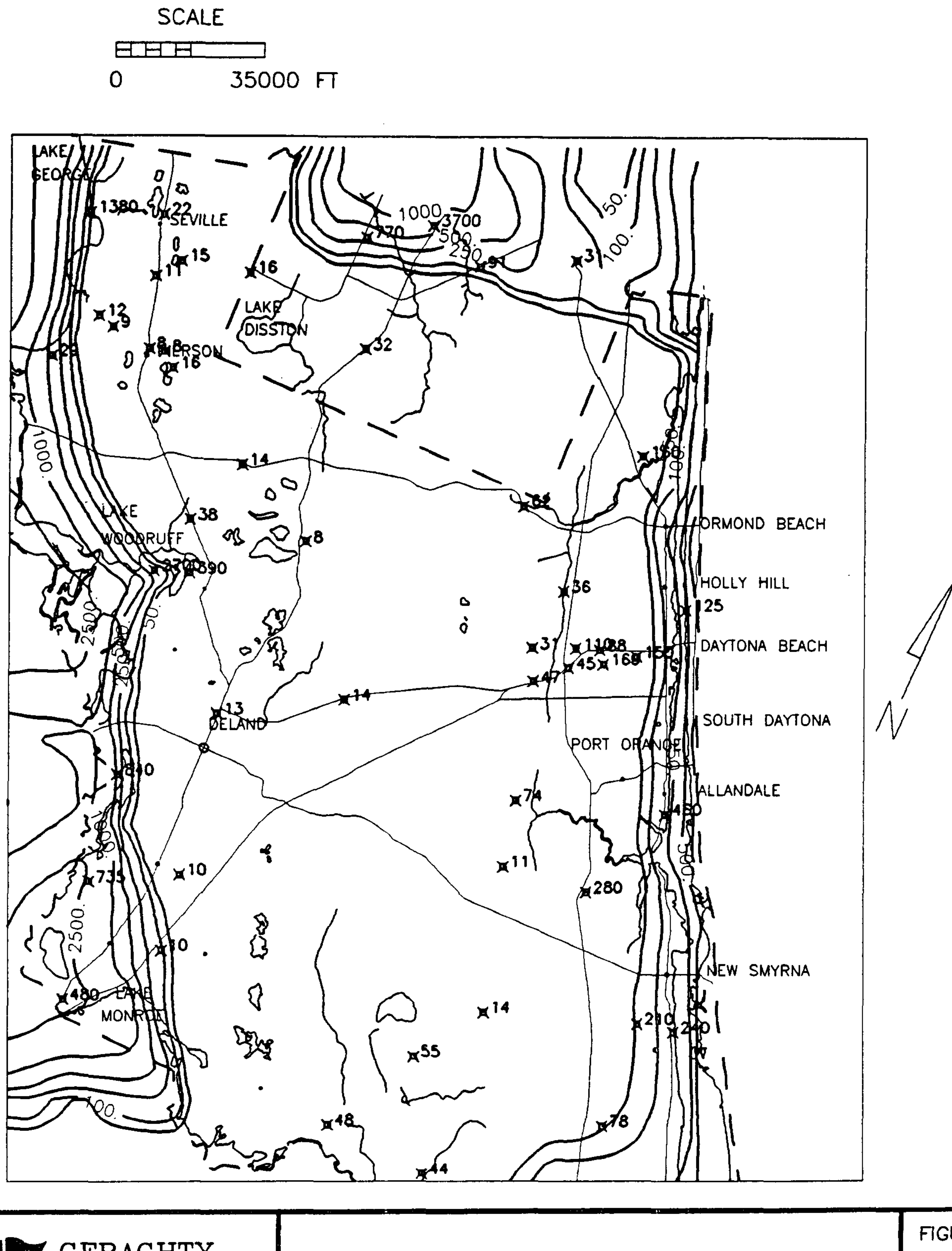
Environmental Services

Figure 61. Simulated chloride concentration contours for the transient 1990 chloride calibration in layer 1 (surficial aquifer) using a porosity of 10% (concentrations in mg/L).

FIGURE

BRUNING 78505 FORM # 5489



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Environmental Services

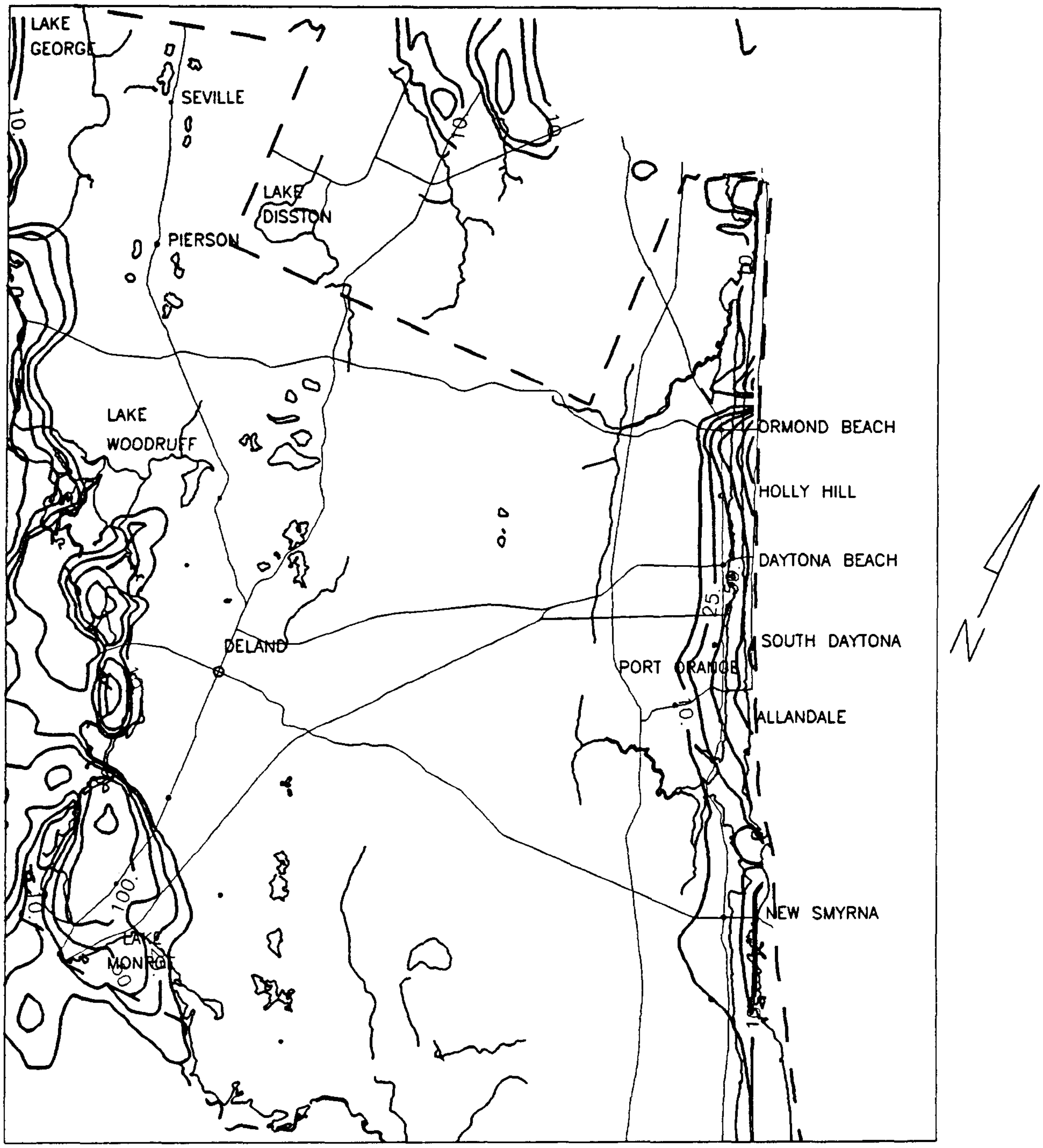
Figure 62. Simulated chloride concentration contours for the transient 1990 chloride calibration in layer 2 (Upper Floridan aquifer) using a porosity of 10% (concentrations in mg/L).

FIGURE

BRUNING 78505 FORM # 5489

SCALE

0 35000 FT



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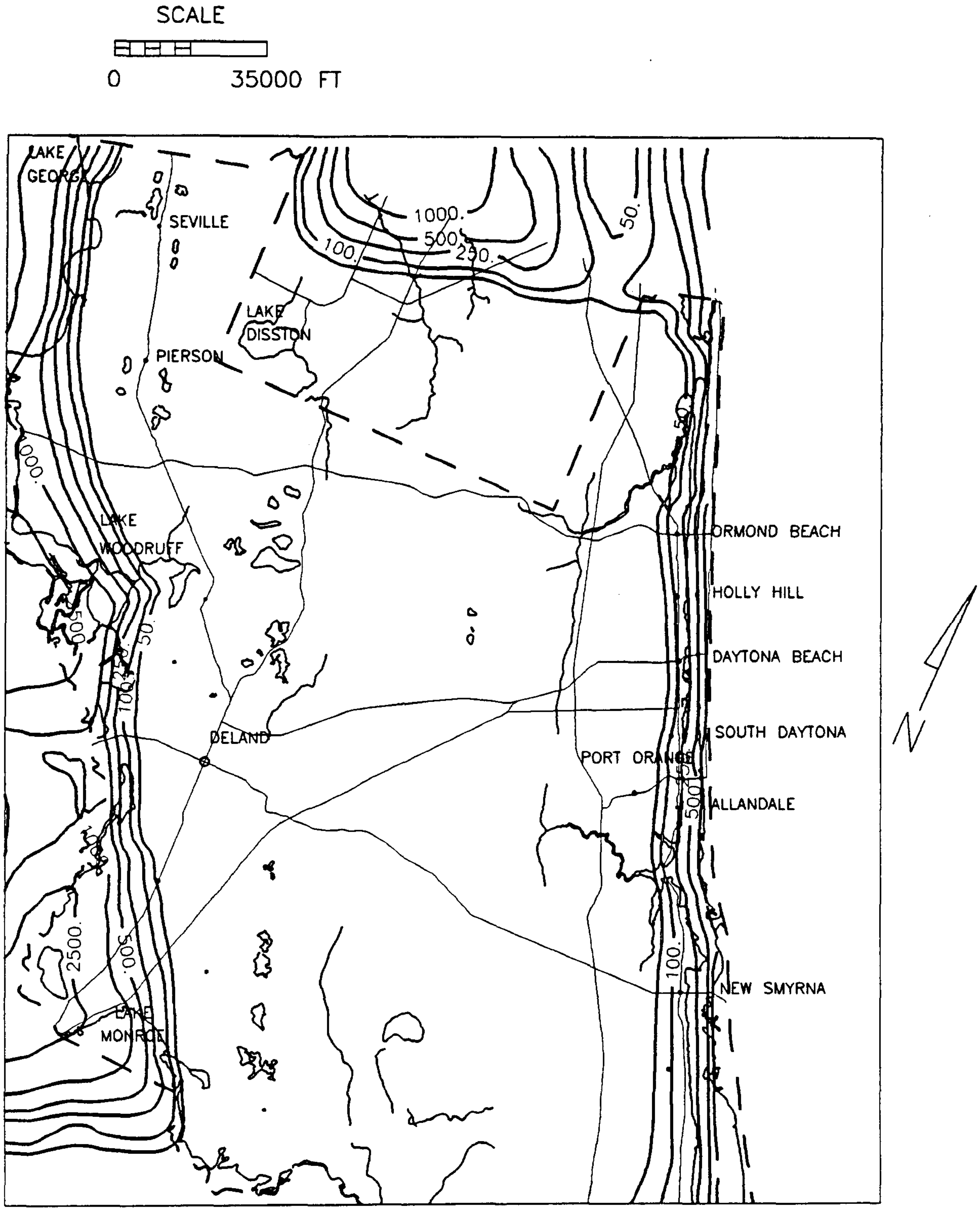
Environmental Services

Figure 63. Simulated chloride concentration differences between 1990 and predevelopment conditions in layer 2 (Upper Floridan aquifer) using a porosity of 10% (concentrations in mg/L).

FIGURE

BRUNING 78505 FORM # 5489



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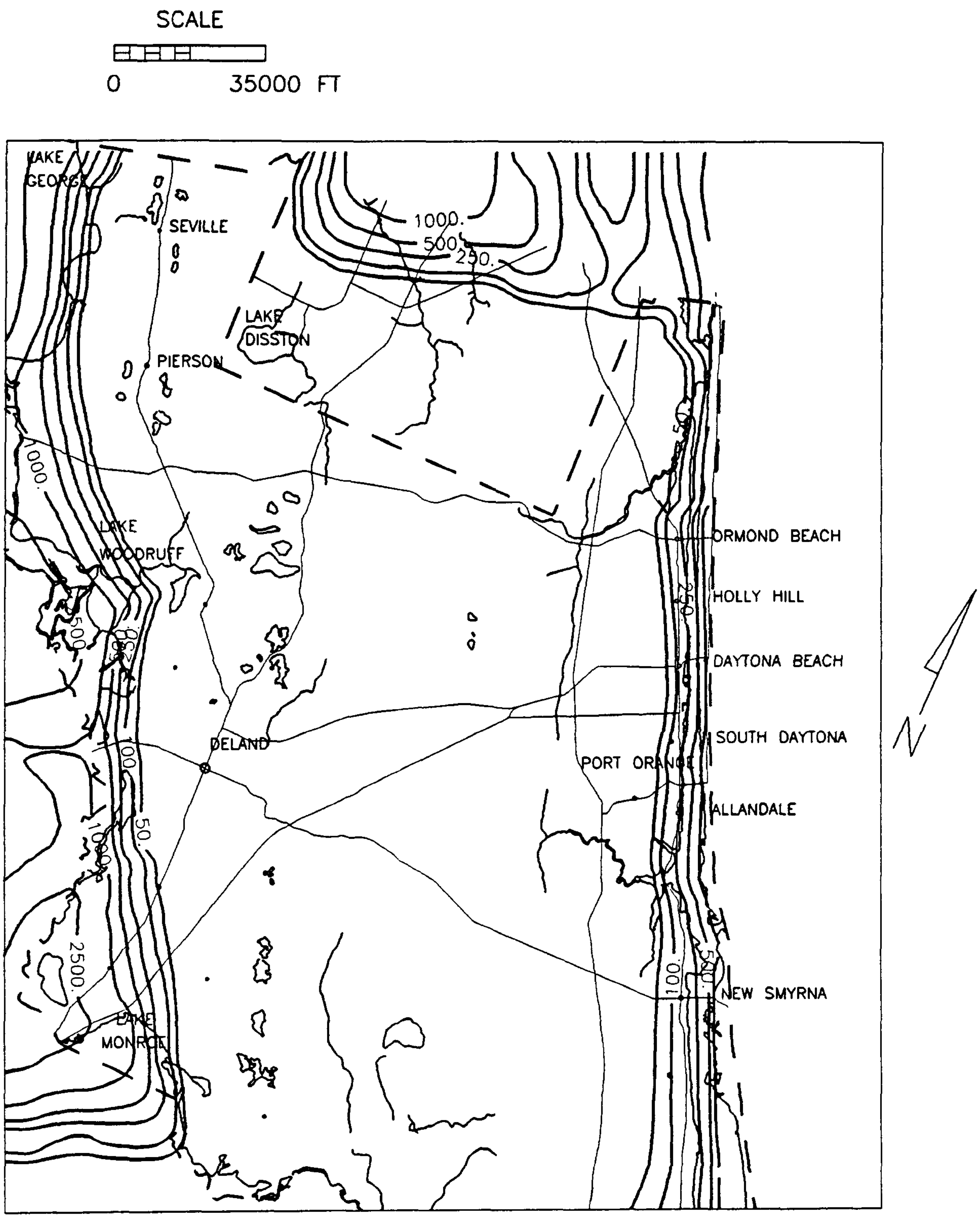
Environmental Services

Figure 64. Simulated chloride concentration contours for the predevelopment calibration in layer 1 (surficial aquifer) using a longitudinal dispersivity of 1500 ft and transverse dispersivity of 150 ft (concentrations in mg/L).

FIGURE

BRUNING 78505 FORM # 5489



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GERAGHTY & MILLER, INC.
Environmental Services

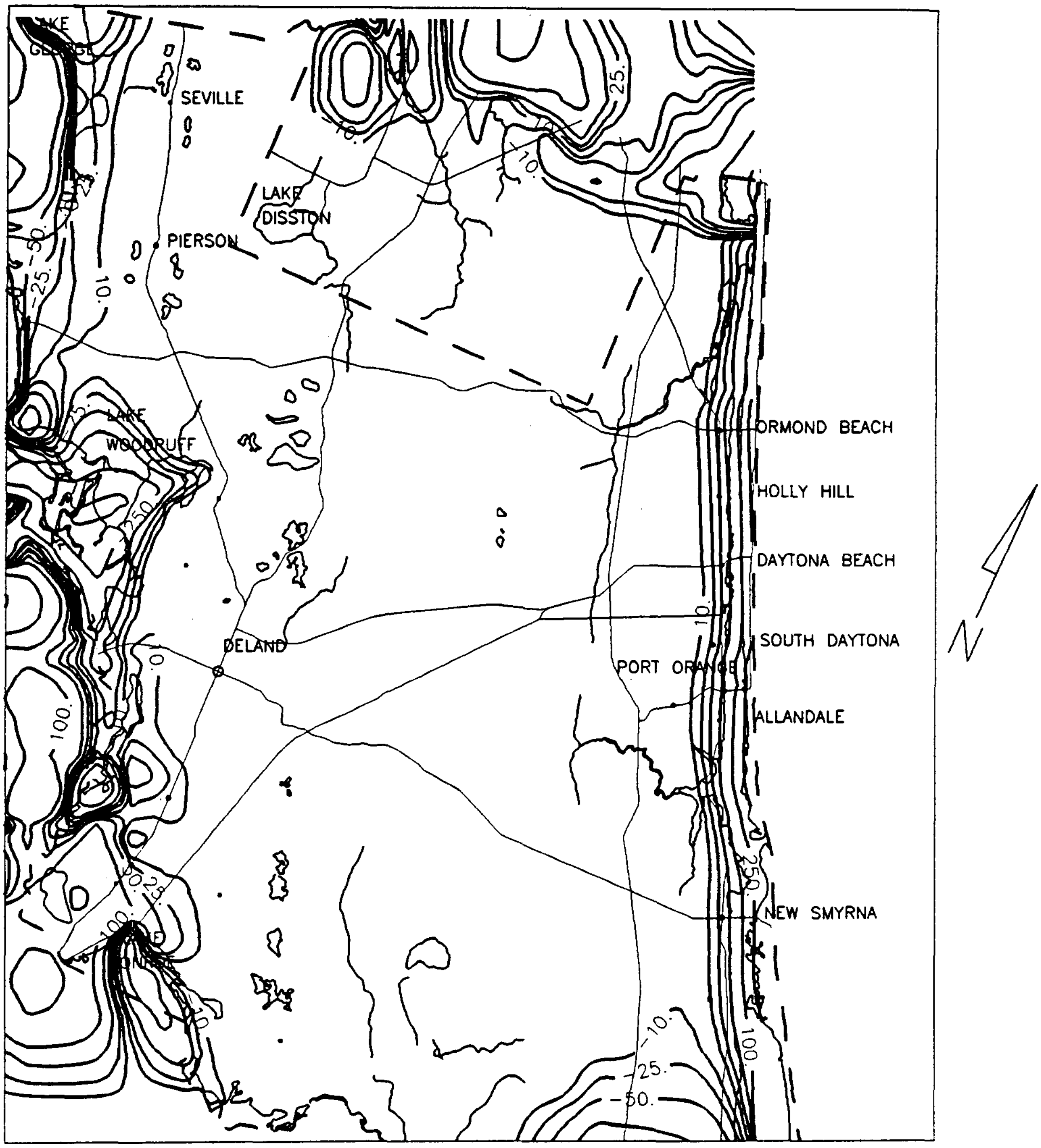
FIGURE

Figure 65. Simulated chloride concentration contours for the predevelopment calibration in layer 2 (Upper Floridan aquifer) using a longitudinal dispersivity of 1500 ft and transverse dispersivity of 150 ft (concentrations in mg/L).

BRUNING 78505 FORM # 5489

SCALE

0 35000 FT



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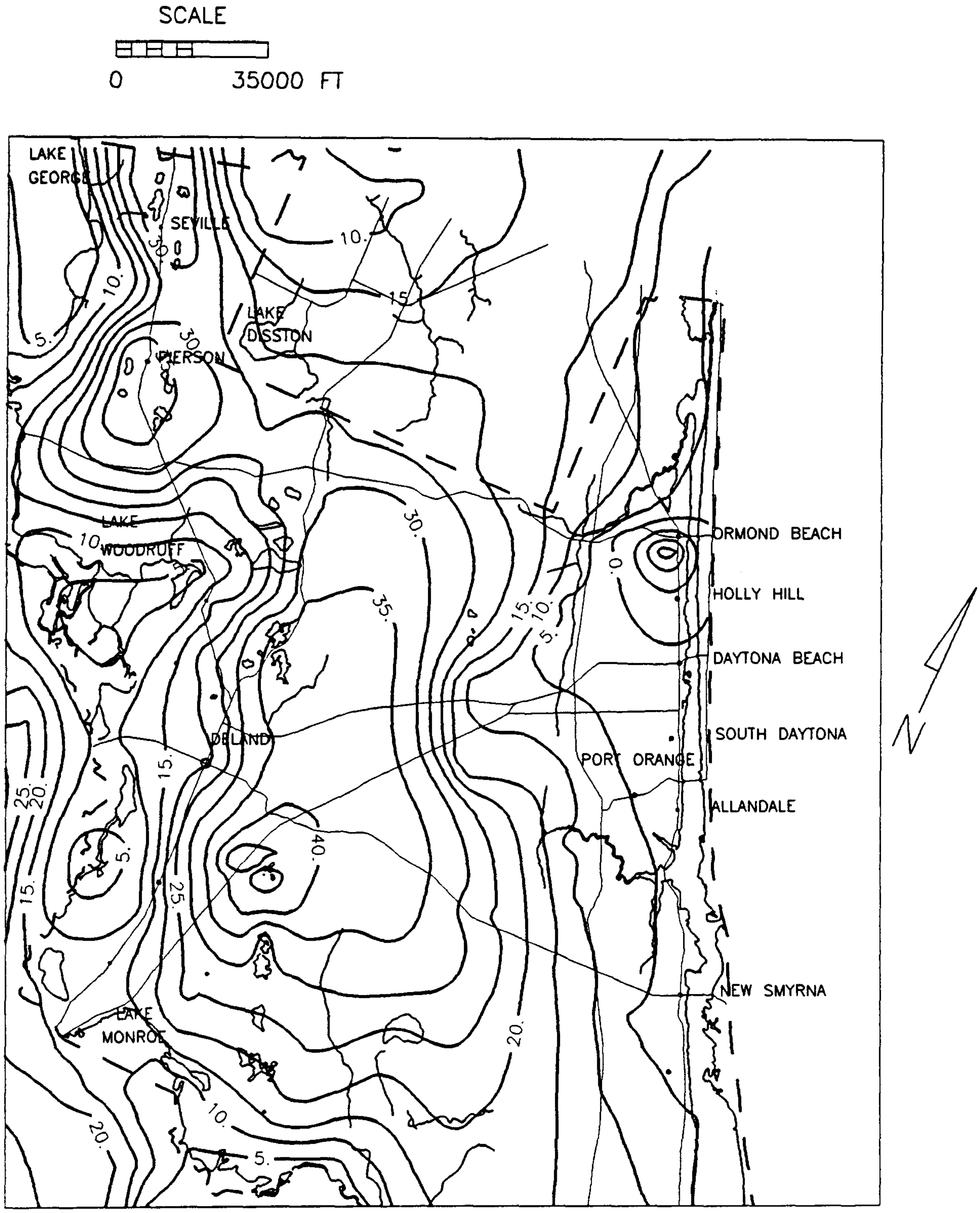
Environmental Services

Figure 66. Chloride concentration differences between the base case and increased dispersivity predevelopment conditions in layer 2 (Upper Floridan aquifer) (concentrations in mg/L).

FIGURE

BRUNING 78505 FORM # 5489



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Environmental Services

Figure 67. Simulated potentiometric surface for the 1988 calibration in layer 2 (Upper Floridan aquifer) with the water-table in layer 1 simulated as constant head boundary conditions.

FIGURE

BRUNING 78505 FORM # 5489

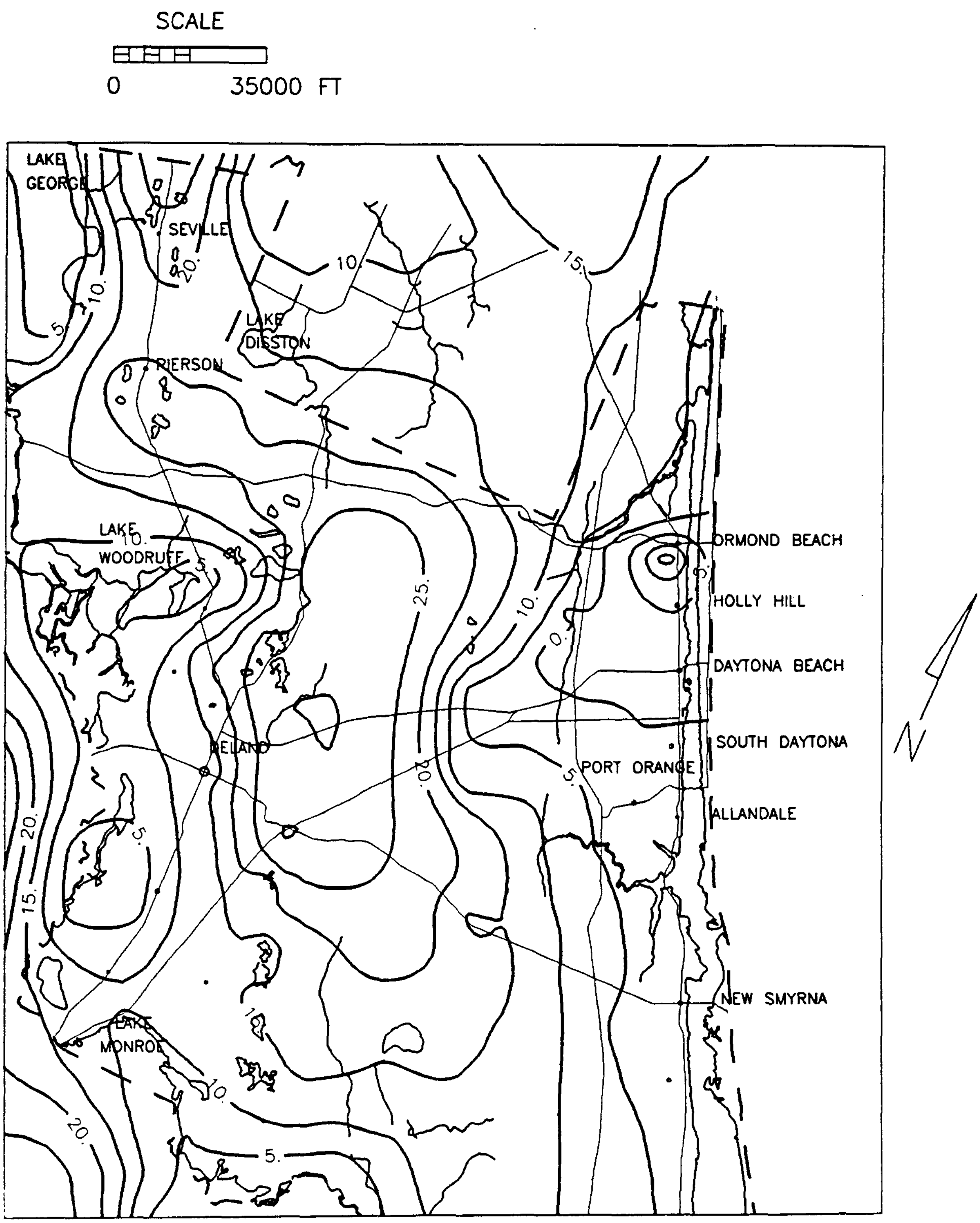

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Figure 68. Simulated potentiometric surface for the 1988 calibration in layer 2 (Upper Floridan aquifer) with the water-table removed and simulated predevelopment (1955) recharge/discharge flux applied directly to the Upper Floridan aquifer.

FIGURE

BRUNING 78505 FORM # 5489

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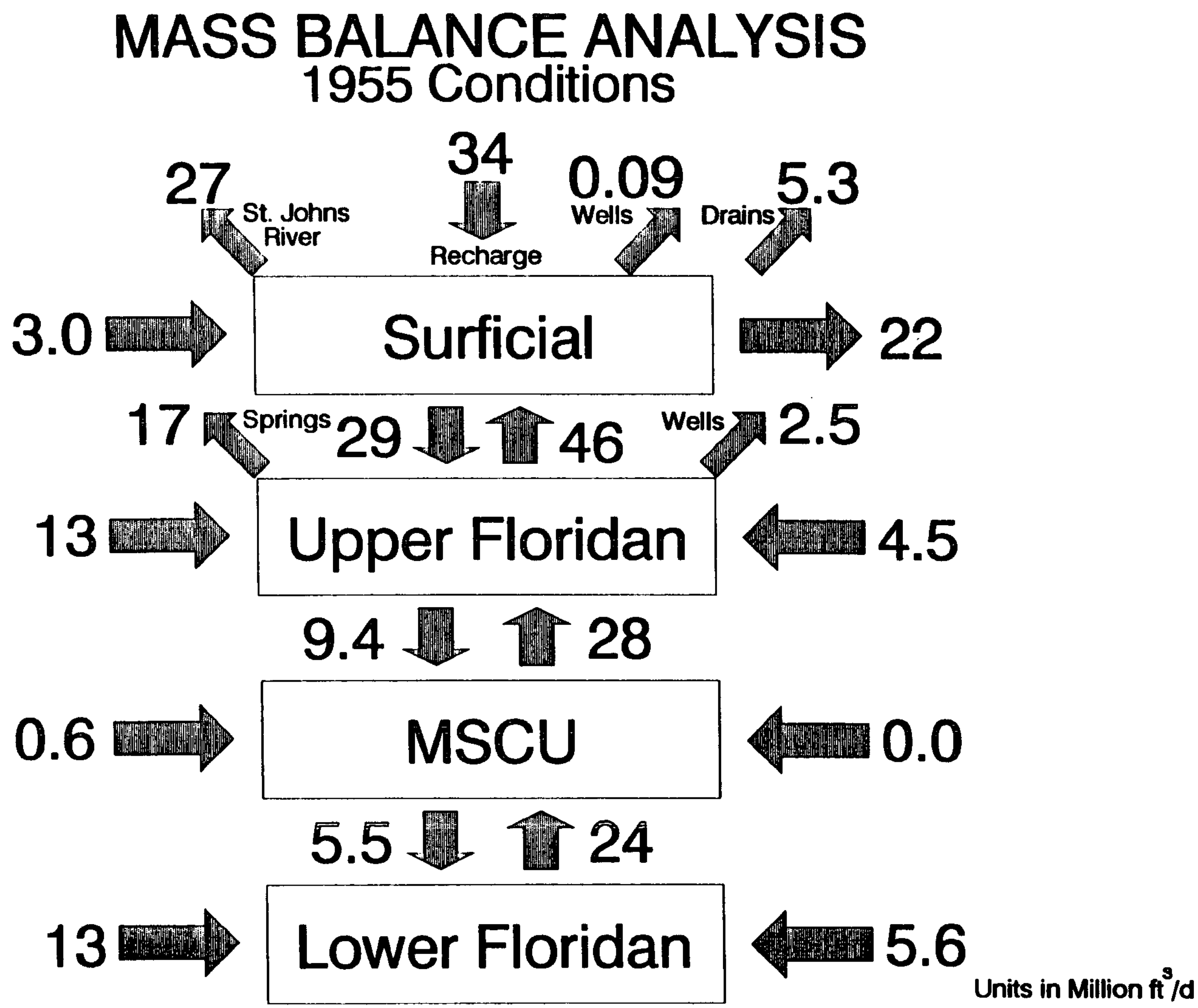

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Figure 69. Ground-water flow mass balance analysis for the predevelopment three-dimensional model.

FIGURE

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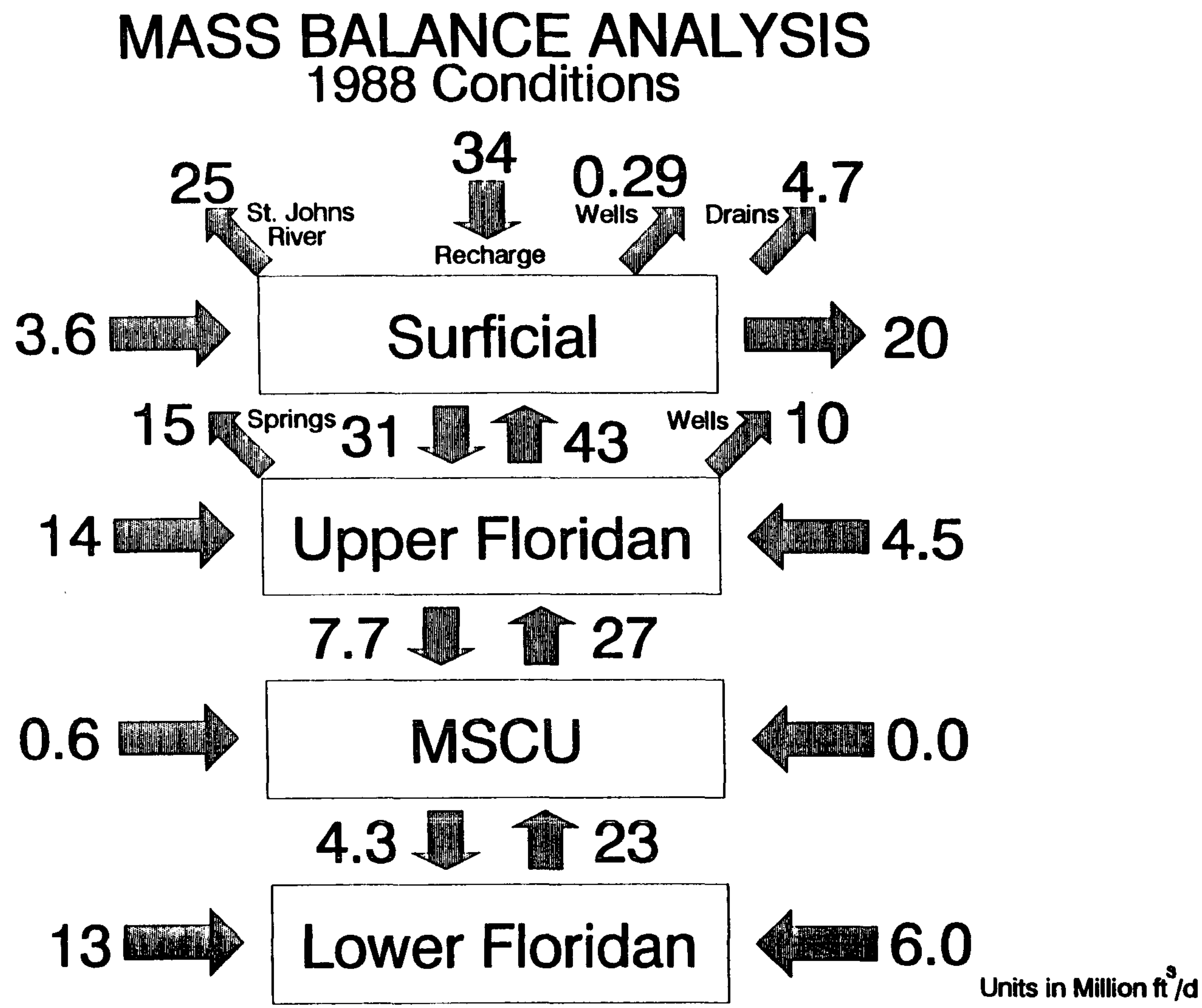

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Environmental Services

BRUNING 78505 FORM # 5844

Figure 70. Ground-water flow mass balance analysis for the 1988 three-dimensional model.

FIGURE

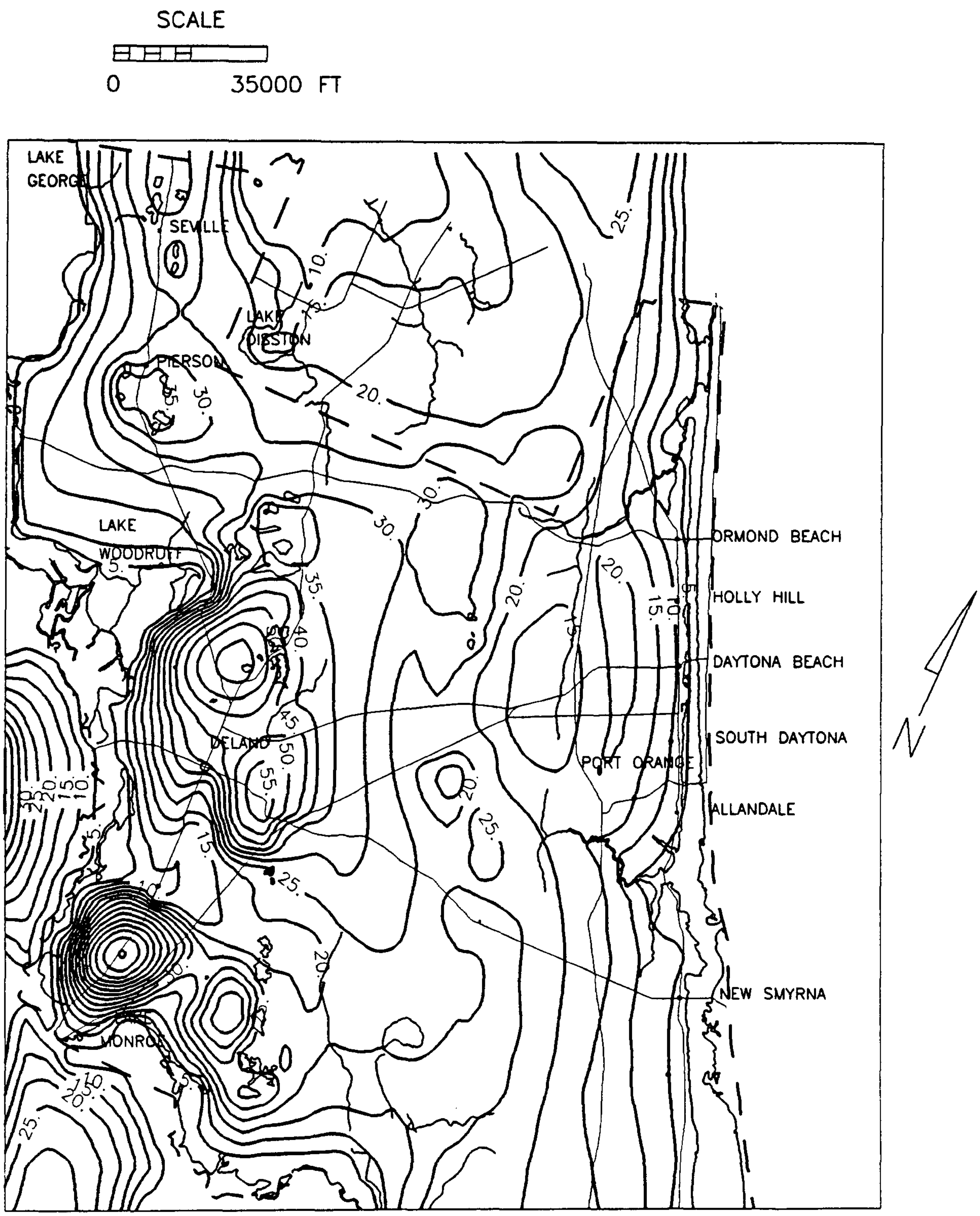

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Figure 71. Simulated water-table contours for 2010 conditions in layer 1 (surficial aquifer)(pumping from existing wellfields only).

FIGURE

BRUNING 78505 FORM # 5489

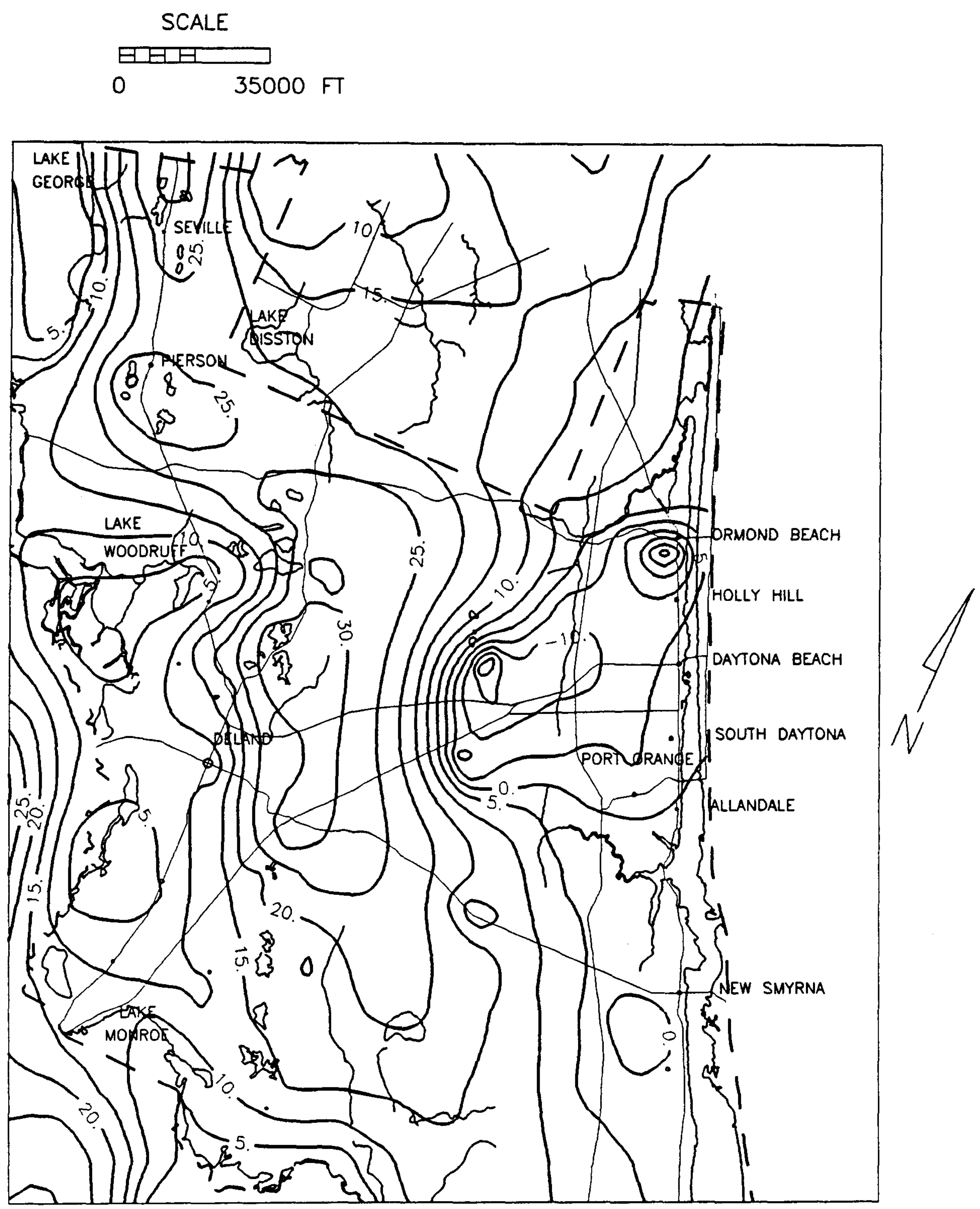

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Figure 72. Simulated potentiometric surface for 2010 conditions in layer 2 (Upper Floridan aquifer)(pumping from existing wellfields only).

FIGURE

BRUNING 78505 FORM # 5489

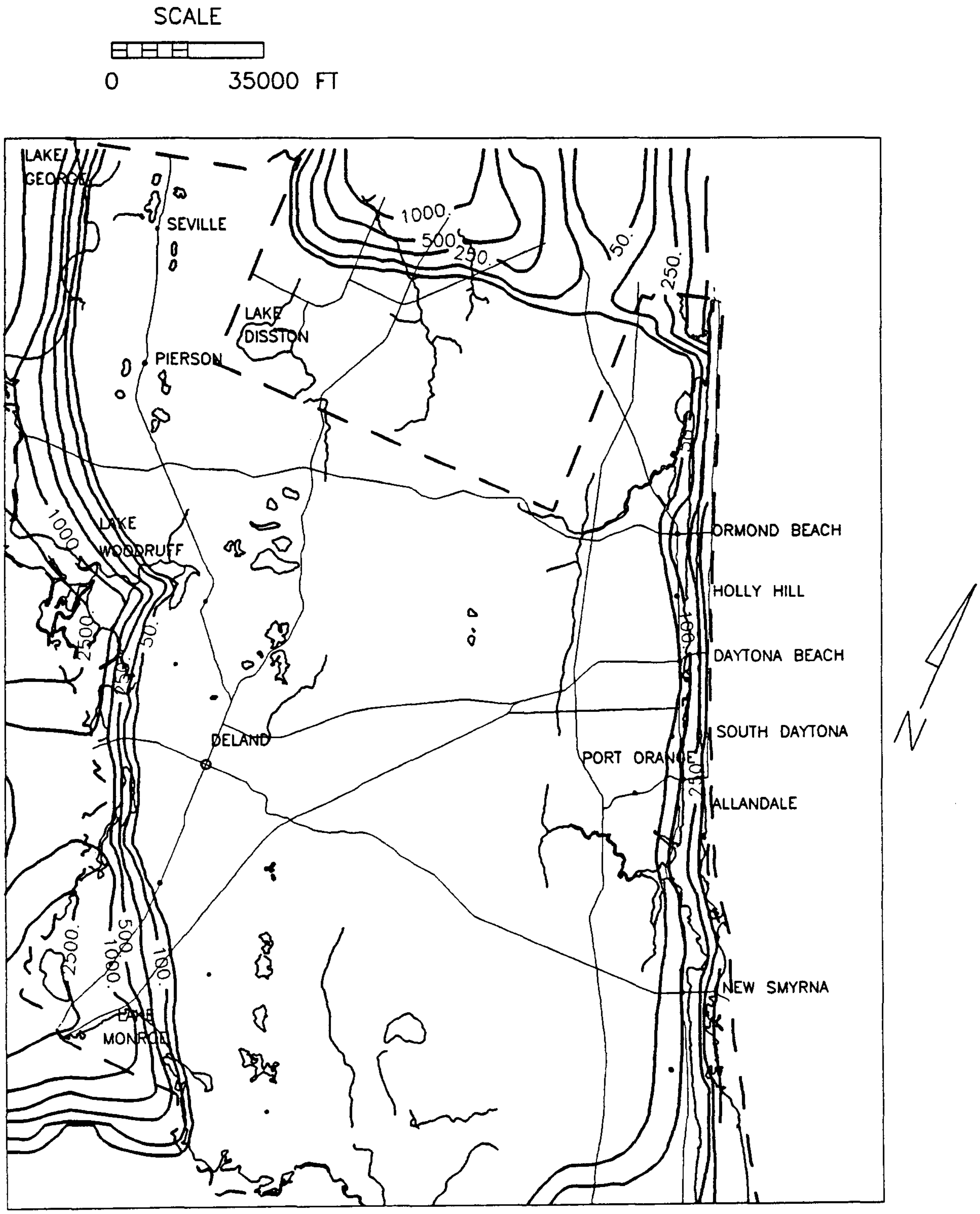

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Figure 73. Simulated chloride concentration contours for the transient 2010 simulation in layer 1 (surficial aquifer) (concentrations in mg/L)(pumping from existing wellfields only).

FIGURE

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BRUNING 78505 FORM # 5489

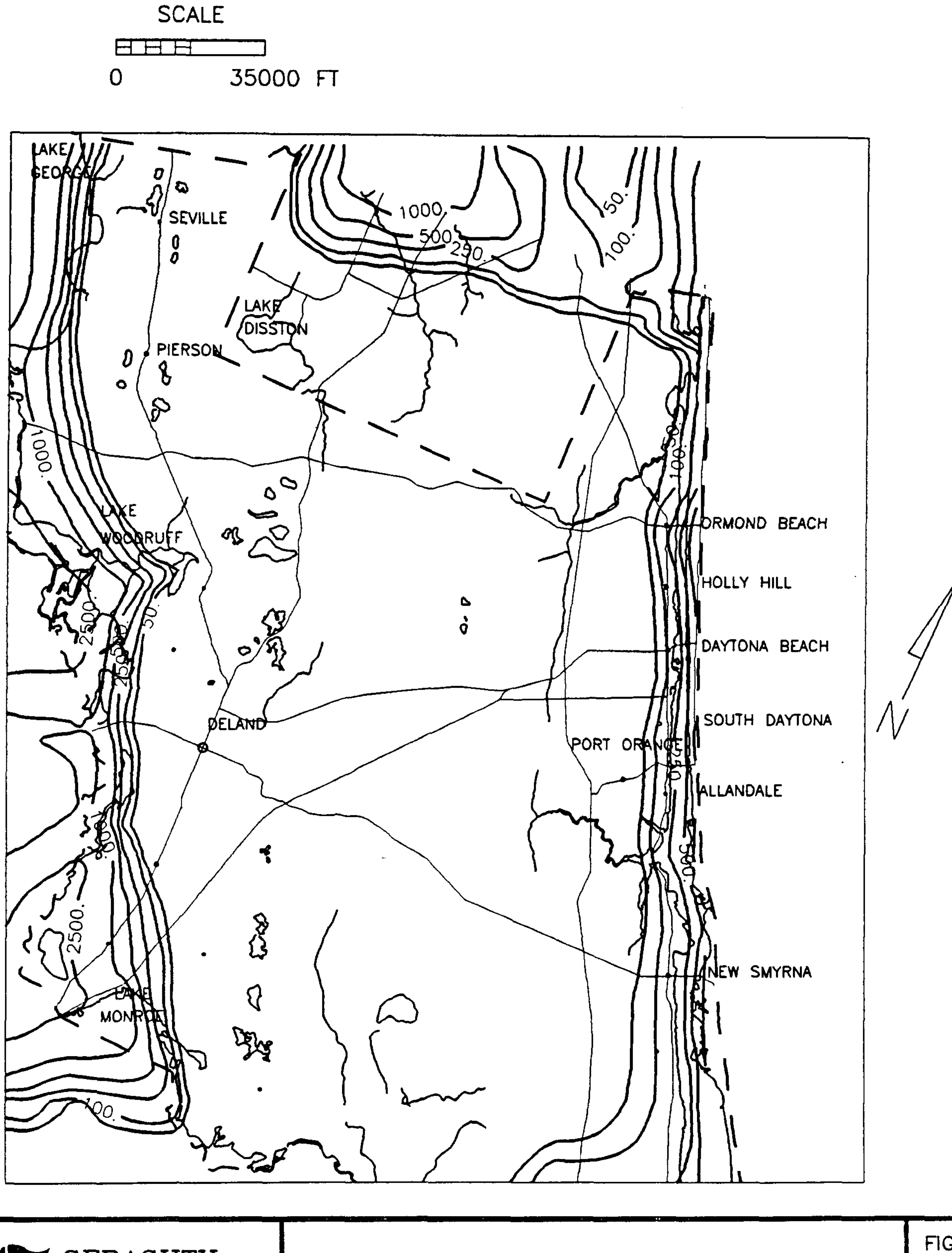

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Figure 74. Simulated chloride concentration contours for the transient 2010 simulation in layer 2 (Upper Floridan aquifer) (concentrations in mg/L)(pumping from existing wellfields only).

FIGURE

BRUNING 78505 FORM # 5489

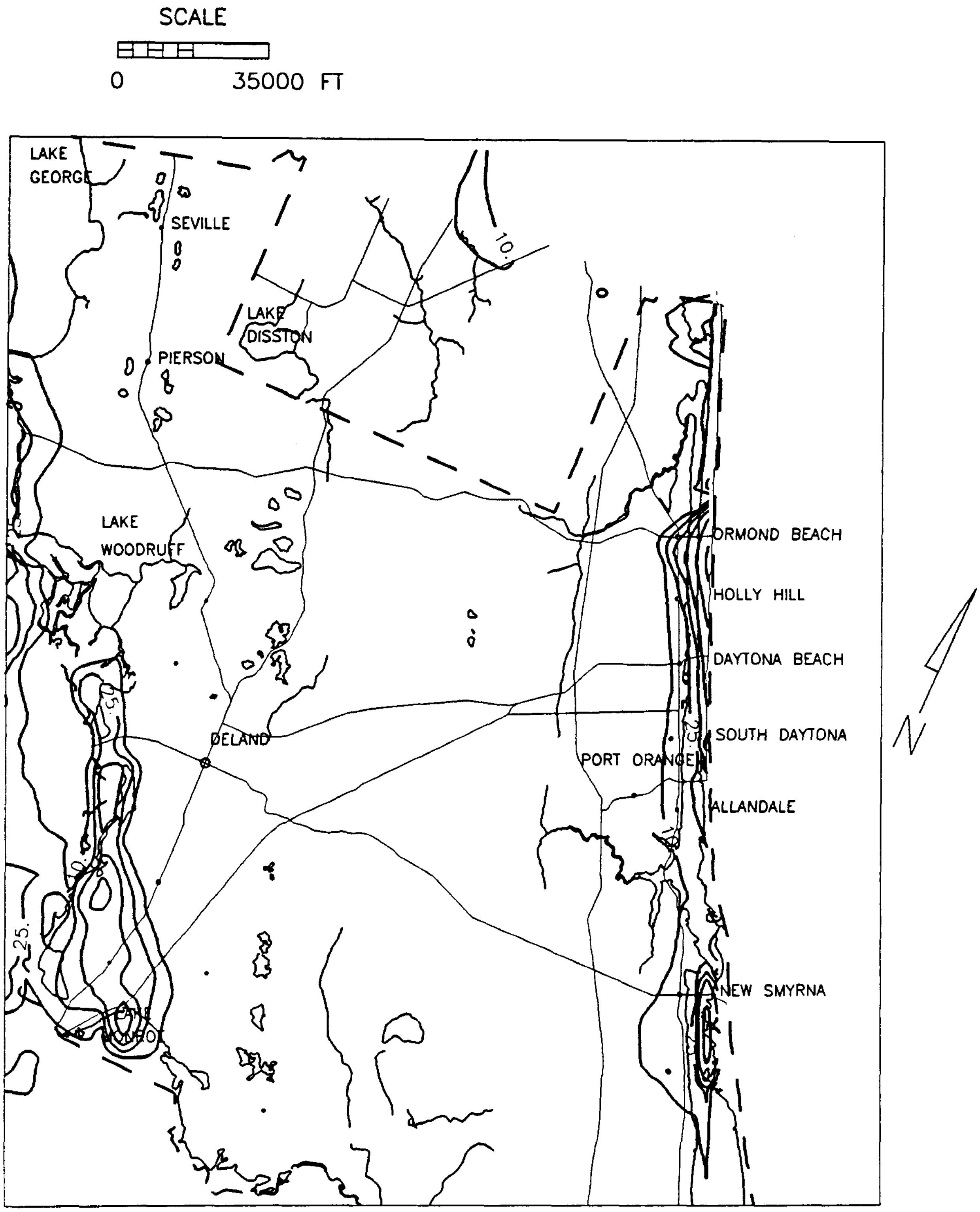

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Figure 75. Chloride concentration differences between simulated 2010 and 1990 conditions in layer 2 (Upper Floridan aquifer) (concentrations in mg/L)(pumping from existing wellfields only).

FIGURE

BRUNING 78505 FORM # 5489

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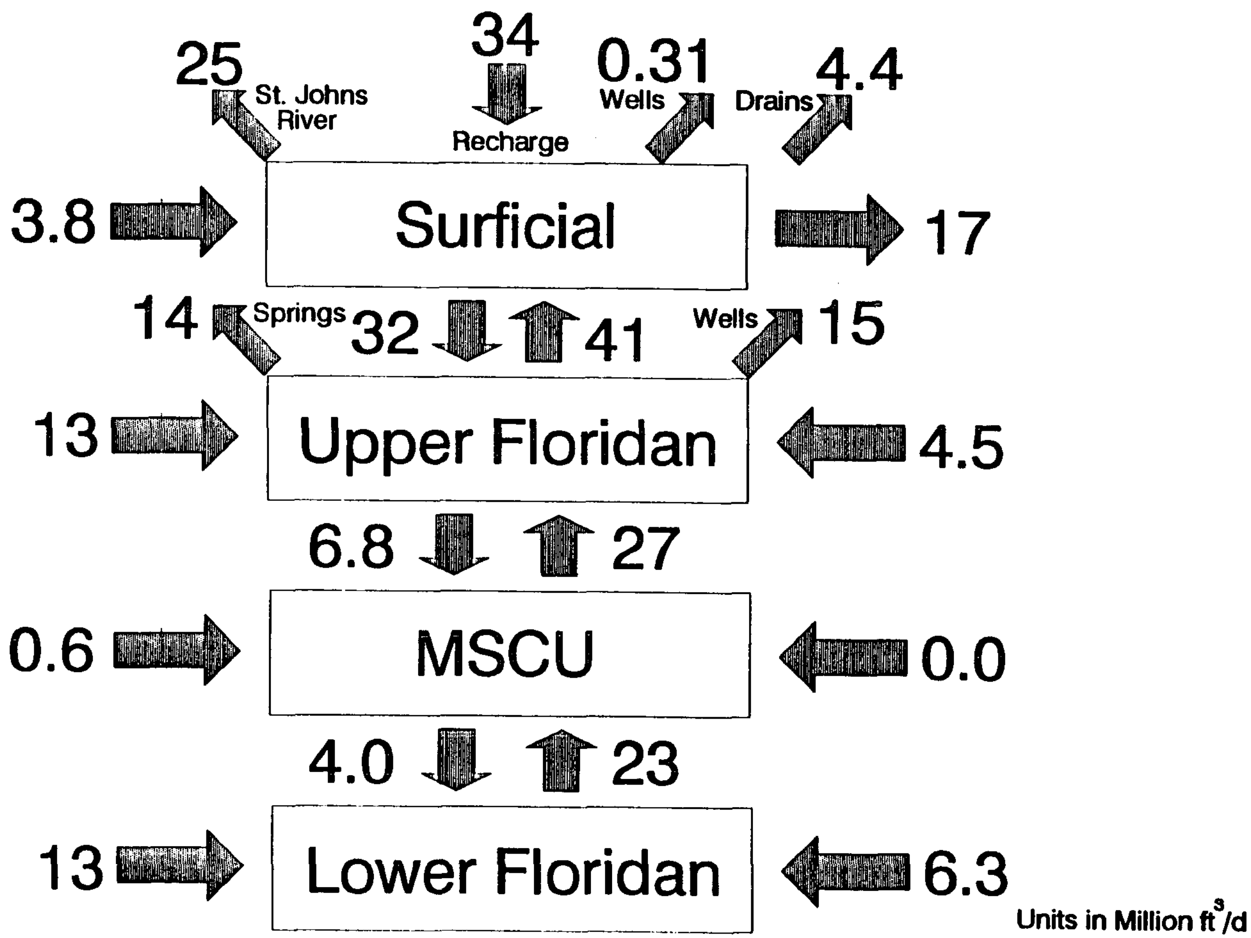
MASS BALANCE ANALYSIS
Extension of Current Pumping to 2010



BRUNING 78505 FORM # 5844

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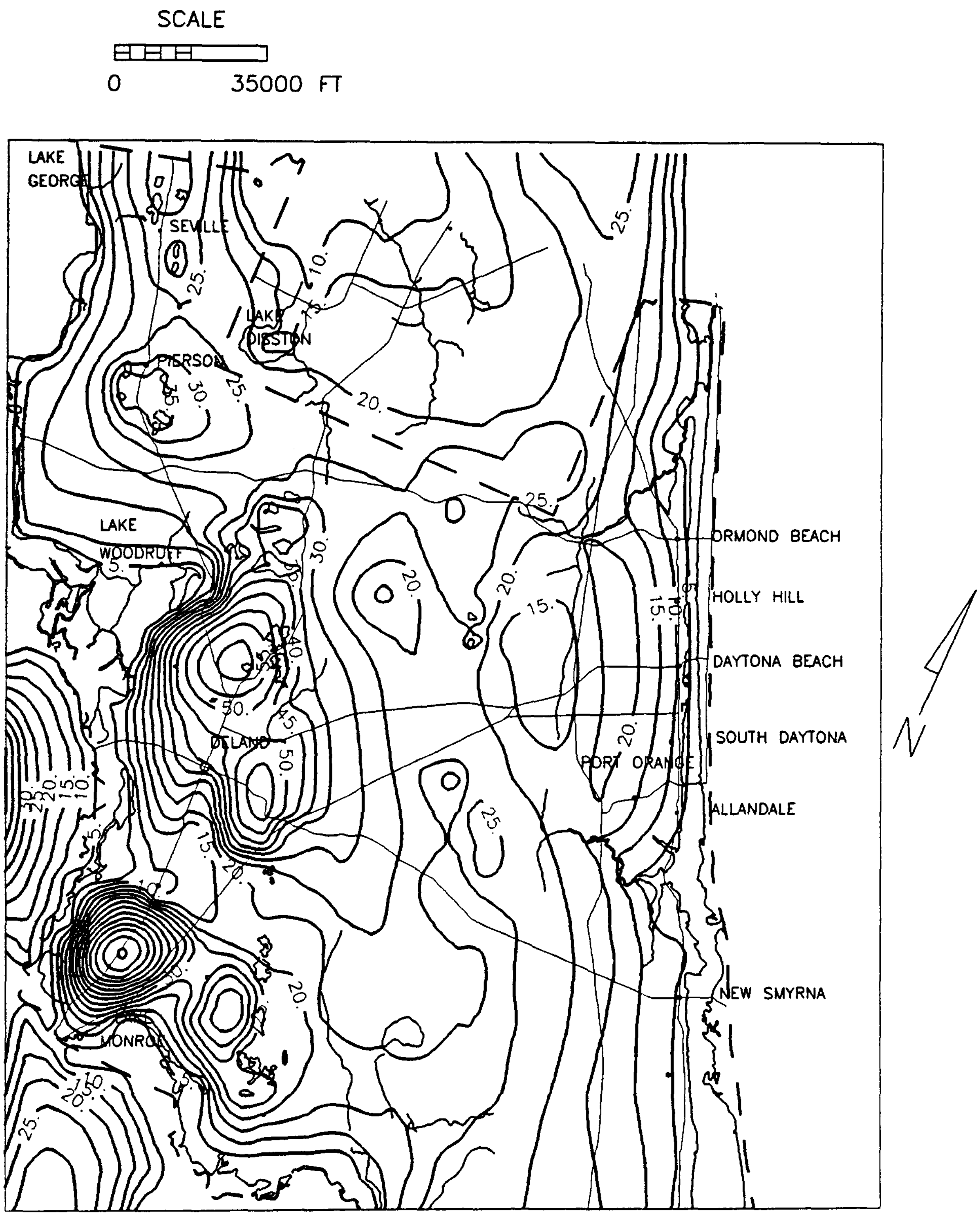
Environmental Services

Figure 76. Ground-water flow mass balance analysis for the 2010 three-dimensional model (pumping from existing wellfields only).

FIGURE



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Environmental Services

Figure 77. Simulated water-table contours for 2010 conditions in layer 1 (surficial aquifer)(pumping from existing and proposed wellfields).

FIGURE

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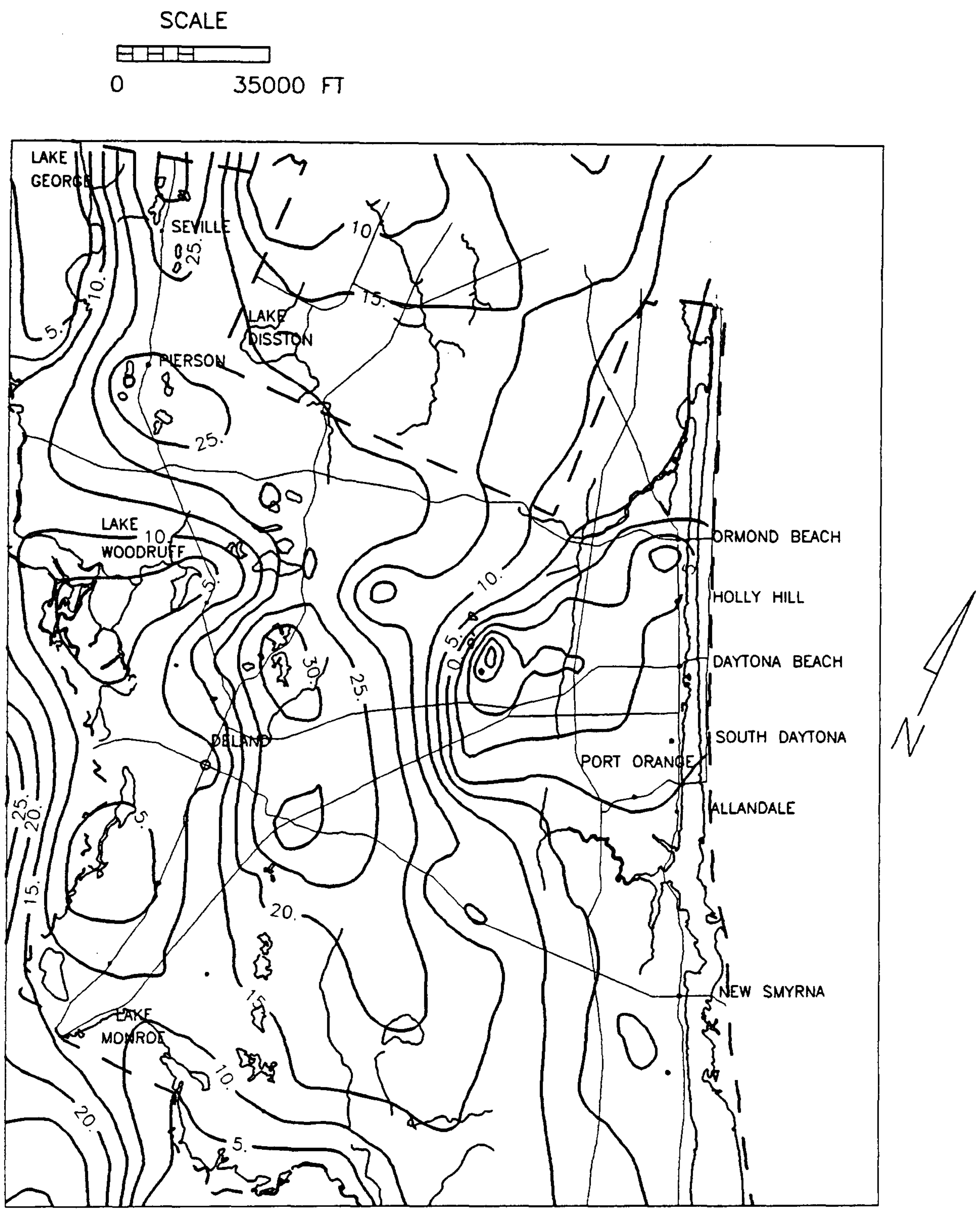
BRUNING 78505 FORM # 5489



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Environmental Services

Figure 78. Simulated potentiometric surface for 2010 conditions in layer 2 (Upper Floridan aquifer)(pumping from existing and proposed wellfields).

FIGURE

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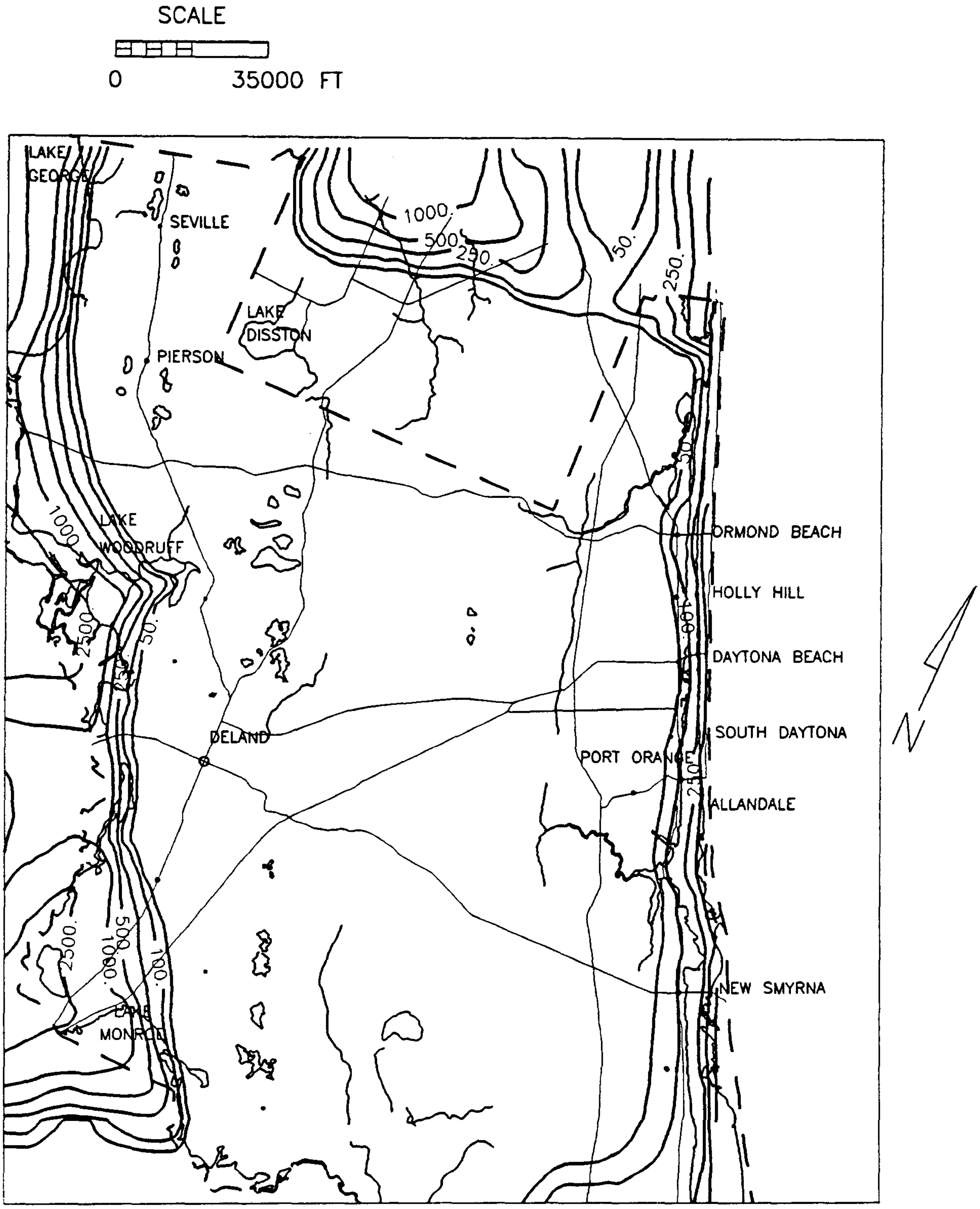

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Figure 79. Simulated chloride concentration contours for the transient 2010 simulation in layer 1 (surficial aquifer) (concentrations in mg/L)(pumping from existing and proposed wellfields).

FIGURE

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BRUNING 78505 FORM # 5489

SCALE

0 35000 FT

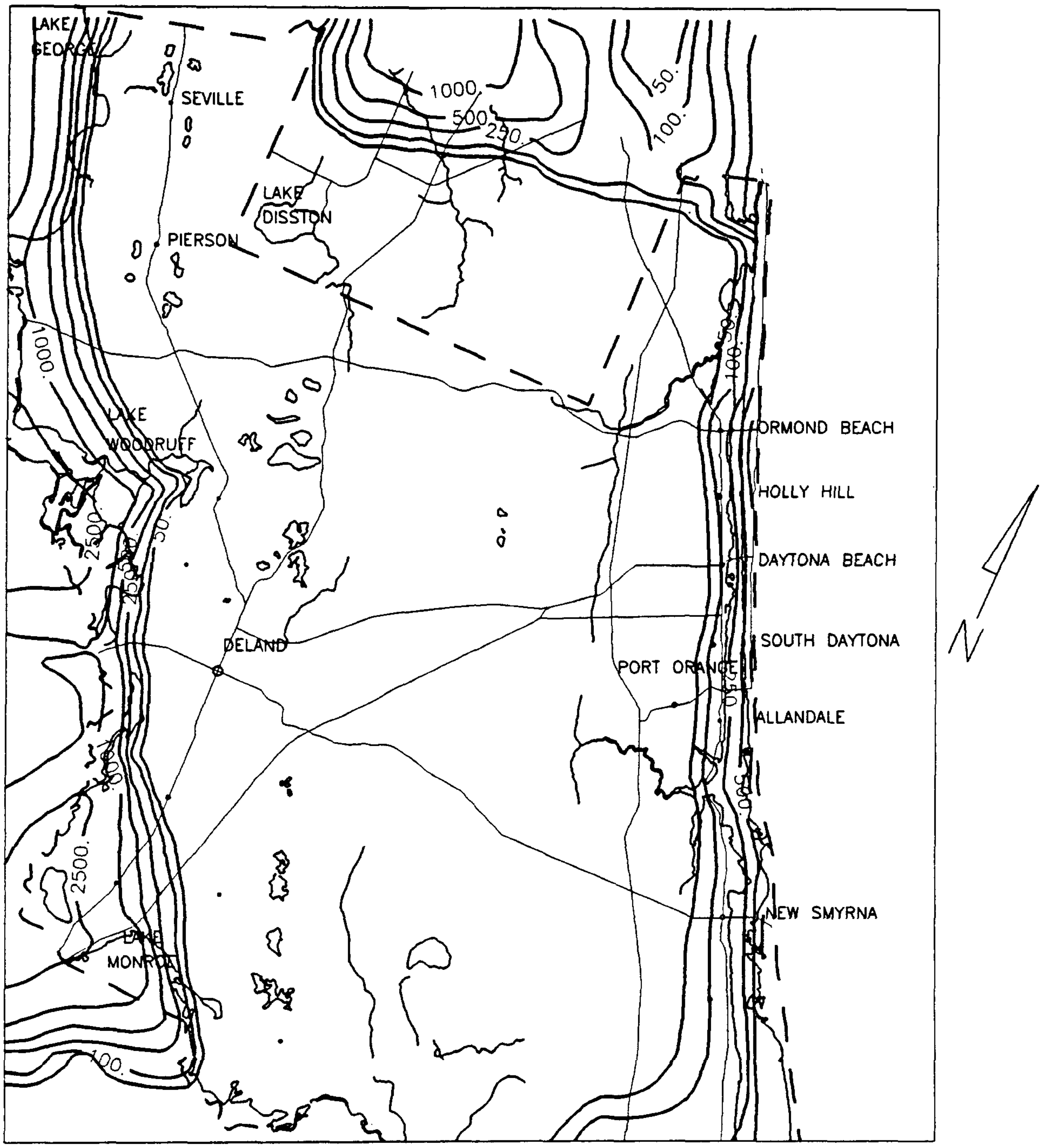

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Figure 80. Simulated chloride concentration contours for the transient 2010 simulation in layer 2 (Upper Floridan aquifer) (concentrations in mg/L)(pumping from existing and proposed wellfields).

FIGURE

BRUNING 78505 FORM # 5489

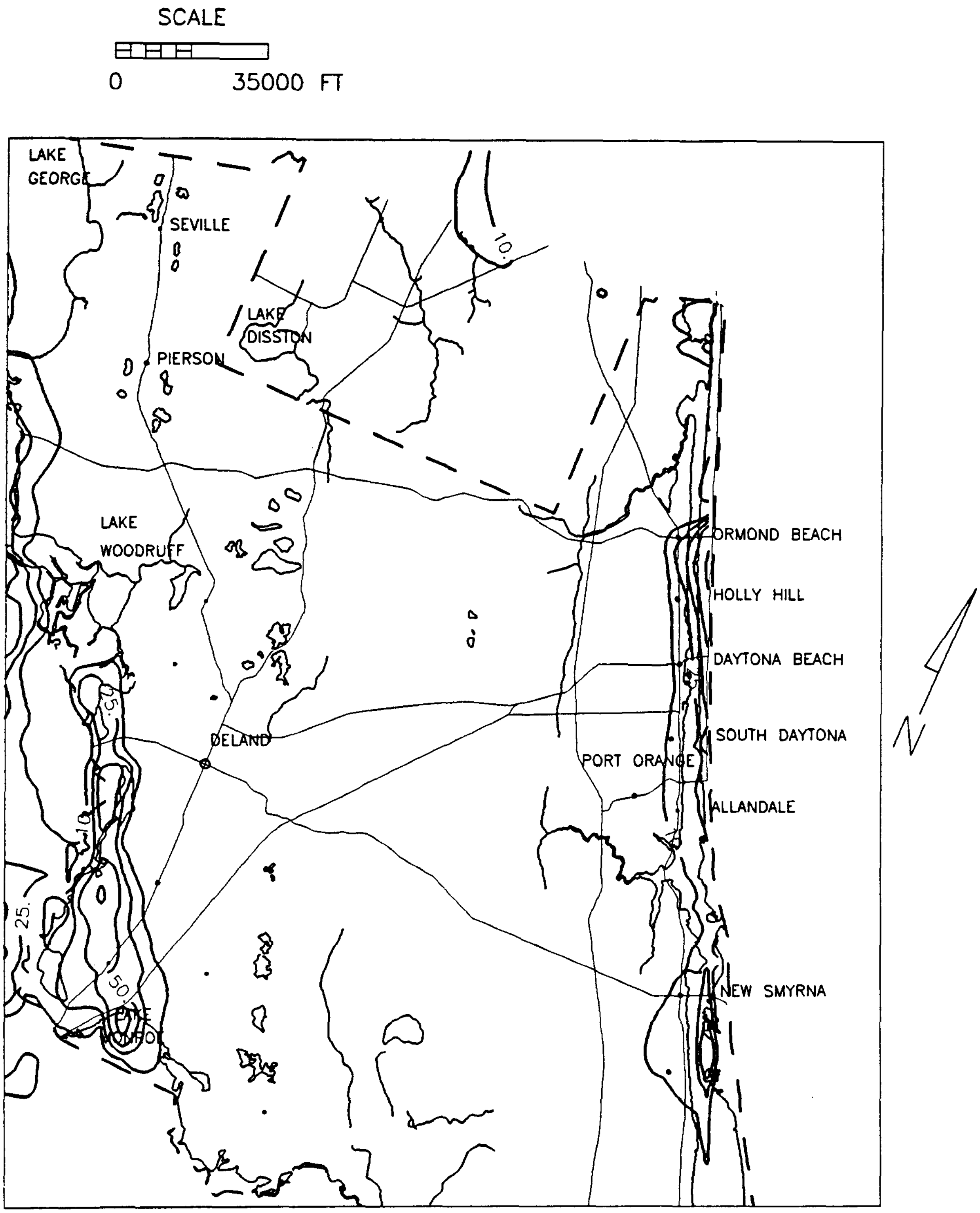

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Figure 81. Simulated chloride concentration differences between simulated 2010 and 1990 conditions in layer 2 (Upper Floridan aquifer) (concentrations in mg/L) (pumping from existing and proposed wellfields).

FIGURE

BRUNING 78505 FORM # 5489

DWG DATE:	PRJCT NO.:	FILE NO.:	DRAWING:	CHECKED:	APPROVED:	DRAFTER:

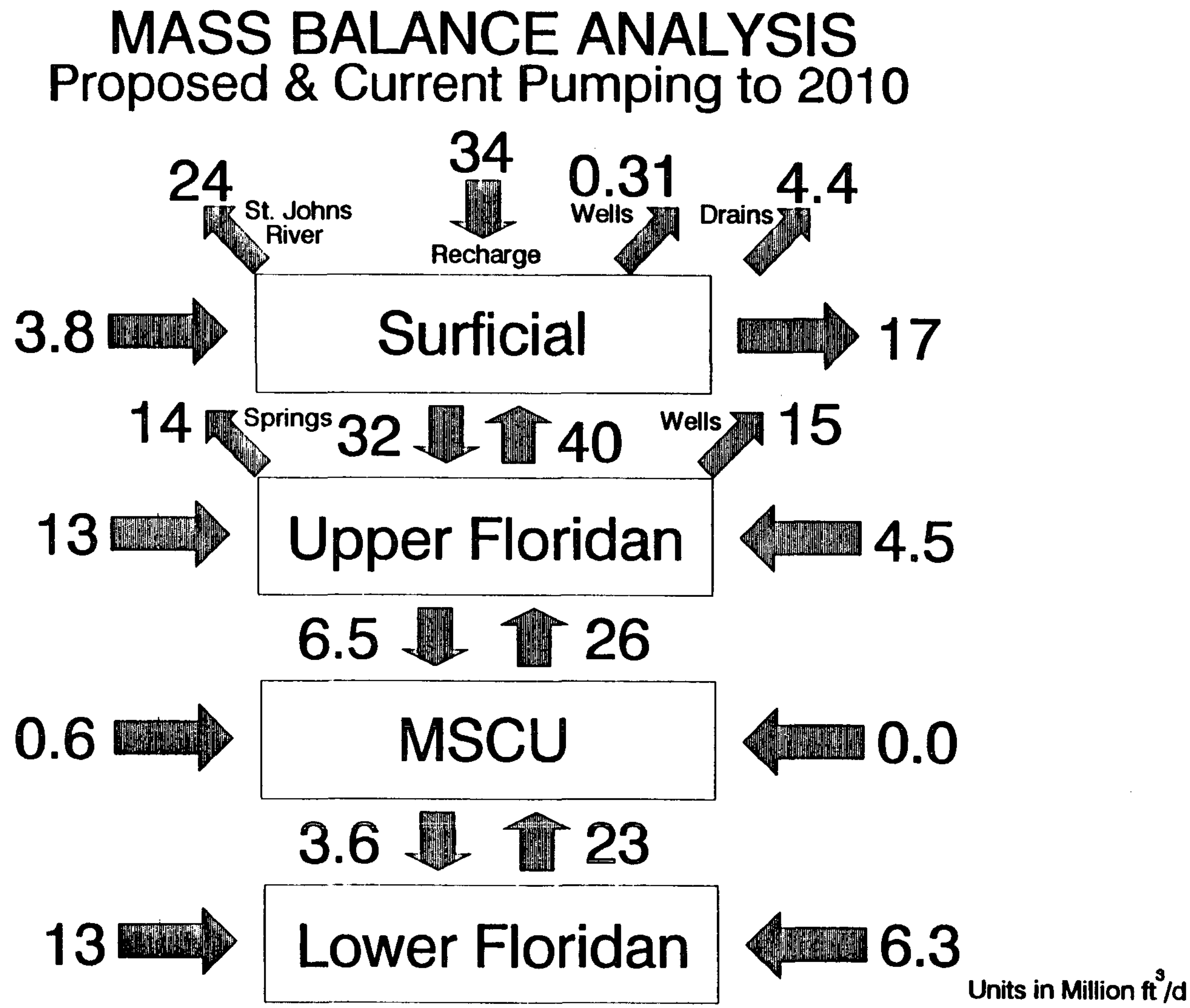

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Figure 82. Ground-water flow mass balance analysis for the 2010 three-dimensional model (pumping from existing and proposed wellfields).

FIGURE

BRUNING 78505 FORM # 5844