Special Publication SJ92-SP20

WEKIVA RIVER BASIN GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELING STUDY

Phase II: Cross-Sectional Groundwater Flow and Solute Transport Model Development

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June 21, 1991

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EXECUTIVE SUMMARY

A two-dimensional cross-sectional groundwater flow and saltwater transport model of a portion of the Wekiva River Basin was developed to assess mechanisms of saltwater intrusion. The current study is the second phase of a project designed to provide the St. Johns River Water Management District with a tool to aid in the establishment of minimum groundwater levels within the basin. The first phase involved development of a regional three-dimensional groundwater flow model, Phase III will involve development of a subregional three-dimensional groundwater flow and saltwater transport model. The current study is a necessary precursor to Phase III and helps to define the controlling factors on saltwater intrusion in this area.

A two-dimensional vertical cross-section running from southwest near Seminole Springs to northeast near the St. Johns River was chosen for the analysis. This section includes both the Upper and Lower Floridan aquifers and incorporates the effect of leakage to or from the surficial aquifer. The model is capable of analyzing the flow and transport of variable density saltwater. A satisfactory match to available field data was obtained by using measured and published hydrologic parameters in the model.

An extensive analysis of uncertainty in hydrologic parameters, flow system boundaries, and general flow conceptualization was performed. This effort, known as sensitivity analysis, involved a series of 19 simulations in which parameters or boundaries were independently varied. The results of the sensitivity analysis indicate that the hydraulic conductivity of the upper confining unit is an important factor in governing the extent and rate of saltwater intrusion. The degree of variability of hydraulic conductivity as well as the areal extent of this unit could greatly influence saltwater transport. Hydraulic conductivity zonation in the aquifers also influences the extent and rate of saltwater intrusion.

A significant data gap exists with regard to assessing current groundwater conditions and predicting future responses. The location of the saltwater wedge with depth is poorly known. Very limited data

exist to ascertain how deep and how far inland saltwater is present. This is an important aspect in analyzing whether water resources are in danger of contamination. Data on the location of the saltwater wedge could be obtained by construction of deep monitoring wells or through geophysical techniques.

Even with this uncertainty, it appears that an adequate understanding of the system exists and current modeling technology is sufficient to develop a three-dimensional model of the subregional system. This model can be updated and revised as data becomes available.

1 INTRODUCTION

1.1 BACKGROUND

The Wekiva River basin is located in east-central Florida and incorporates parts of Seminole, Orange, and Lake Counties (Figure 1.1). The major components of the Wekiva River system include the Wekiva River, Black Water Creek, Rock Springs and Rock Springs Run, Wekiva Springs and Wekiva Springs Run, and the Little Wekiva River.

Extensive and expanding development within Orange and Seminole counties is being accompanied by demands on the groundwater resources of the Wekiva River basin. Pumping from the Floridan aquifer system within and in the vicinity of the basin results in lowering of the potentiometric surface of the aquifer which, in turn, can result in reductions in spring flows within the basin. Springs represent the major source of base flow to the Wekiva River and adequate spring flows are essential to the proper functioning of the ecosystem of the basin.

Lowering of the potentiometric surface of the Floridan aquifer within the basin as a result of increased withdrawals could also result in further degradation of basin groundwater resources due to encroachment of groundwater with unacceptable chloride concentrations. Portions of the Floridan aquifer in the Wekiva River basin already contain water with chloride concentrations in excess of 250 milligrams per liter (mg/L), the result of past encroachment by ancient seas. Enlargement of these areas could conceivably occur by lateral movement of water within the aquifer from areas of higher chloride concentrations to areas of lower chloride concentrations. Enlargement of these areas might also occur by vertical upconing of water from the lower portions of the Floridan aquifer system.

1.2 OBJECTIVES

This report presents the results of the second phase of a three-phase study of the Wekiva River basin. The overall objective of the study is to provide the St. Johns River Water Management District with a tool to aid in the establishment of minimum groundwater levels

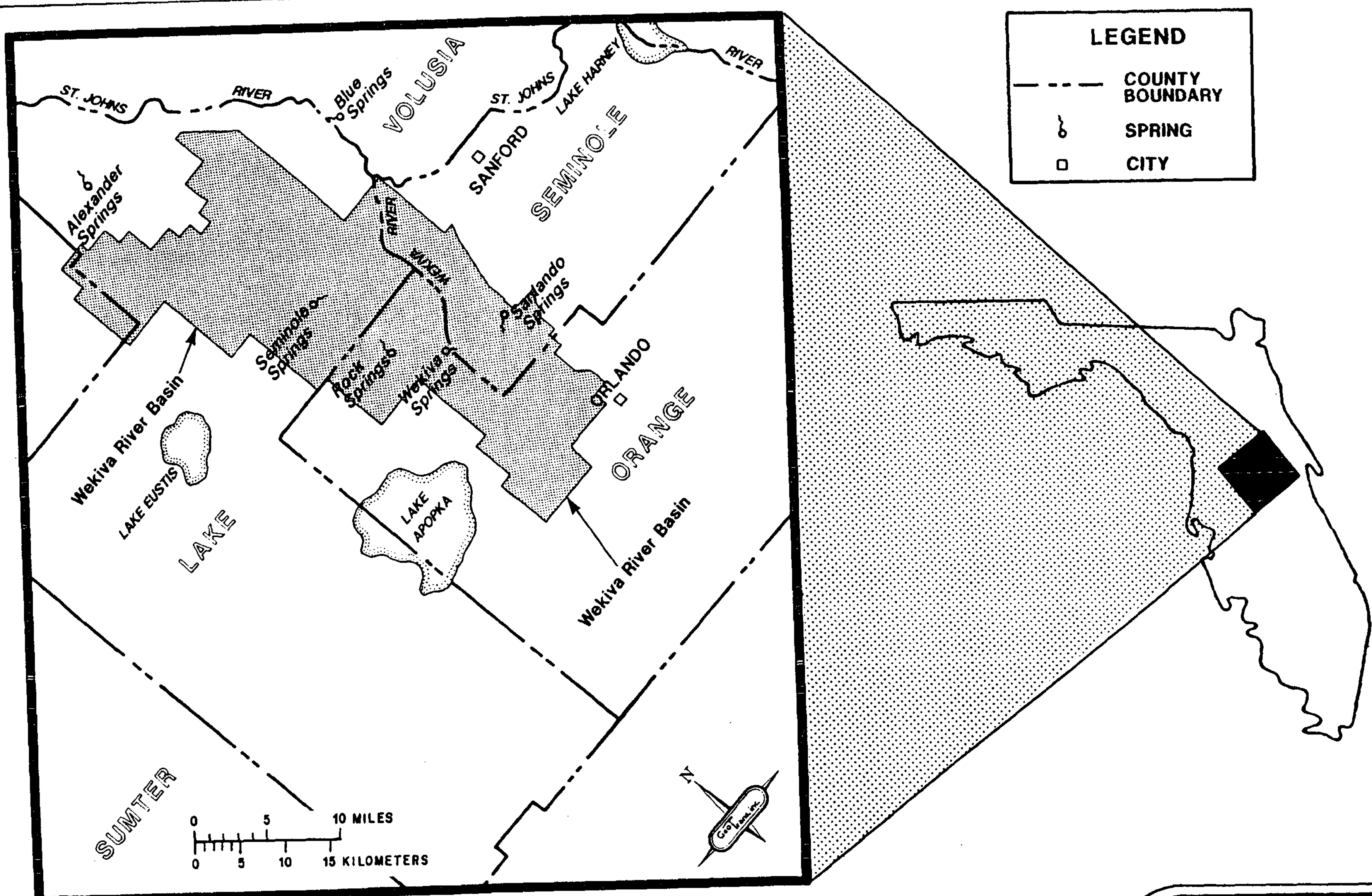

Figure 1.1. Location of study area.

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within the basin to protect the quality of its water resources. Emphasis is on the Floridan aquifer system.

The specific objectives of the study, as defined by the District, include the determination of the effects of existing and proposed groundwater withdrawals within the project area on the following:

- The potentiometric surface of the Upper Floridan aquifer within the project area;
- The flow magnitudes of various springs within the project area;
- The potential for lateral migration of saline water (water with chloride concentrations greater than 250 mg/L) within the Floridan aquifer system of the project area; and,
- The potential for vertical upconing of saline water within the Floridan aquifer system of the project area.

The objective of Phase I was to develop a three-dimensional groundwater flow model of the Floridan aquifer system that encompasses the Wekiva River basin. This regional-scale model will be used to determine boundary flows and boundary conditions for two- and three-dimensional flow and saltwater transport models of a smaller sub-regional area. Phase I was completed in May, 1991.

The second phase of the study involves developing a two-dimensional cross-sectional model through the study area. This model incorporates the additional complexity of variable density groundwater flow and is capable of modeling saltwater transport. Specific tasks associated with Phase II include:

- Construct a two-dimensional vertical cross-sectional model using an improved version of the SWICHA (GeoTrans, 1991a) code.
- Perform sensitivity analysis and transient simulations to compare the response of the groundwater flow system to changes in aquifer parameters and boundary conditions.
- Prepare a report which discusses the methodology, results, and conclusions of the study including recommendations on

the reliability of the model and suggestions for additional data collection.

This report is submitted at the conclusion of Phase II and includes discussion on the three items given above.

One of the main objectives of this phase of the study is to preview and resolve problems that will be encountered in developing the three-dimensional transport model for Phase III. Specific problems include:

- Transport boundary conditions;
- Vertical and horizontal grid spacing;
- Sensitivity of results to parameter variations and uncertainty; and
- Calibration of an inherently transient system to a steady state condition.

2 HYDROGEOLOGY OF STUDY AREA

The discussions in this section are paraphrased from Tibbals (1990).

2.1 REGIONAL HYDROGEOLOGY

2.1.1 Surficial Aquifer Framework

The uppermost water-bearing formation in the Wekiva River Basin is the surficial aquifer. Throughout most of the project area, the surficial aquifer typically consists of fine to medium quartz sands containing varying amounts of silt, clay, and loose shell. Water in the surficial aquifer is unconfined. In the swampy lowlands and flatlands, the water table is generally at or near land surface throughout most of the year. In the rolling highlands, the water table is generally a subdued reflection of the topography but can be several tens of feet below land surface. At depths usually less than 50 ft below the water table, the sands of the surficial aquifer grade into the less permeable clayey or silty sands of the Hawthorn Formation that act as the overlying confining unit for the limestones of the Floridan aquifer system. The Hawthorn Formation ranges in thickness from 0 to 150 feet (ft) in the project area (Miller, 1986).

2.1.2 Floridan Aquifer System Framework

The Floridan aquifer system is composed of a sequence of limestone and dolomitic limestone that ranges in thickness from about 2,000 ft in the northwest part of the study area to about 2,400 ft in the extreme southwest part. The top of the Floridan is defined as the first occurrence of vertically persistent, permeable, consolidated, carbonate rocks. The top of the Floridan aquifer system ranges between +50 to -100 ft MSL throughout the project area (Scott and Hajishafie, 1980).

The faults shown on the top of the Floridan aquifer system in Figure 2.1 are believed to have little vertical displacement and

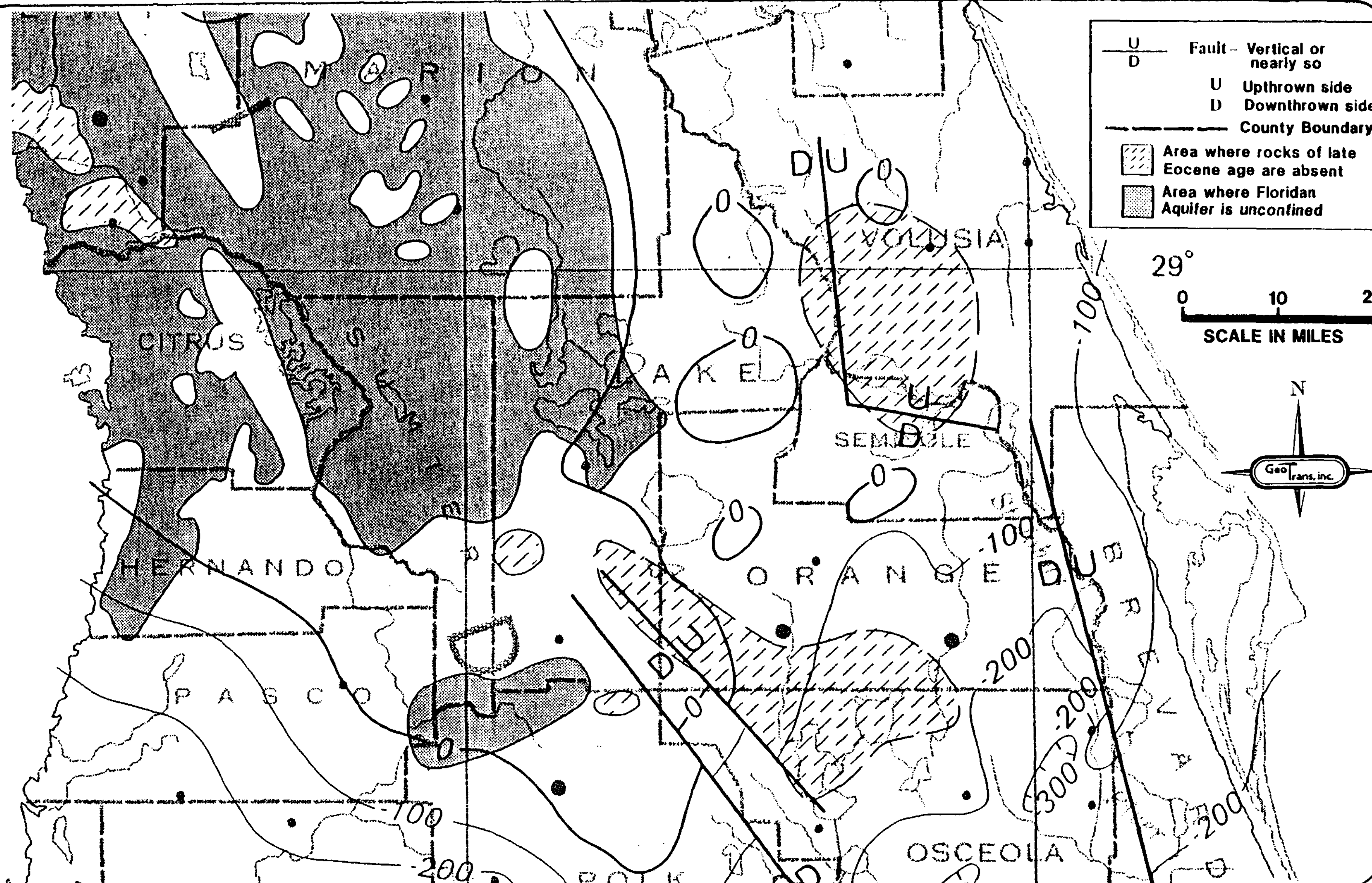

Figure 2.1. Altitude of the top of the Floridan aquifer relative to mean sea level, in feet (from Miller, 1986).

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probably extend only into the Upper Floridan. The exception is the fault that trends north-south along the St. Johns River between Volusia and Lake Counties. Tibbals (1990) asserts that this fault provides a good connection between the Upper and Lower Floridan aquifers in this area.

In addition to the relief on the top of the Floridan caused by faults, considerable relief is caused by subsurface subsidence. The surface expression of such subsidence is often in the form of closed or nearly closed topographic depressions that, in some instances, contain lakes. Subsurface subsidence is caused by the gradual dissolution of limestone and the collapse of the overlying sediments into the volume previously occupied by the limestone. The collapse of the overlying sediments can be subtle, affect large areas, and occur over a long period of time, or it can be quite pronounced, affect relatively small areas, and occur suddenly. Almost all occurrences of sinkholes are in areas of the Floridan aquifer system where recharge rates are high and, generally, where the depth to the top of the Floridan is less than 200 ft.

The base of the Floridan aquifer system is defined as the first occurrence of vertically persistent beds of anhydride or, in their absence, the top of the transition of the generally permeable carbonate sequence of rocks to the much less permeable gypsiferous and anhydrous carbonate beds. These beds have very low permeability and serve as the hydraulic base of the Floridan aquifer system. In the study area, the base of the Floridan ranges from about 2,000 ft below sea level in the northwest to about 2,400 ft below sea level in the extreme southwest (Figure 2.2).

The geologic formations that make up the Floridan aquifer system in the project area are, from top to bottom, Eocene rocks comprising the Ocala Limestone (where present), the Avon Park Formation, the Oldsmar Formation, and Paleocene rocks of the upper Cedar Keys Formation. The base of the Floridan aquifer occurs within the lower part of the Cedar Keys formation (Miller, 1986). The Ocala Limestone constitutes the top of the Floridan aquifer system over most of the project area (Miller, 1986). The Ocala Limestone is absent and the

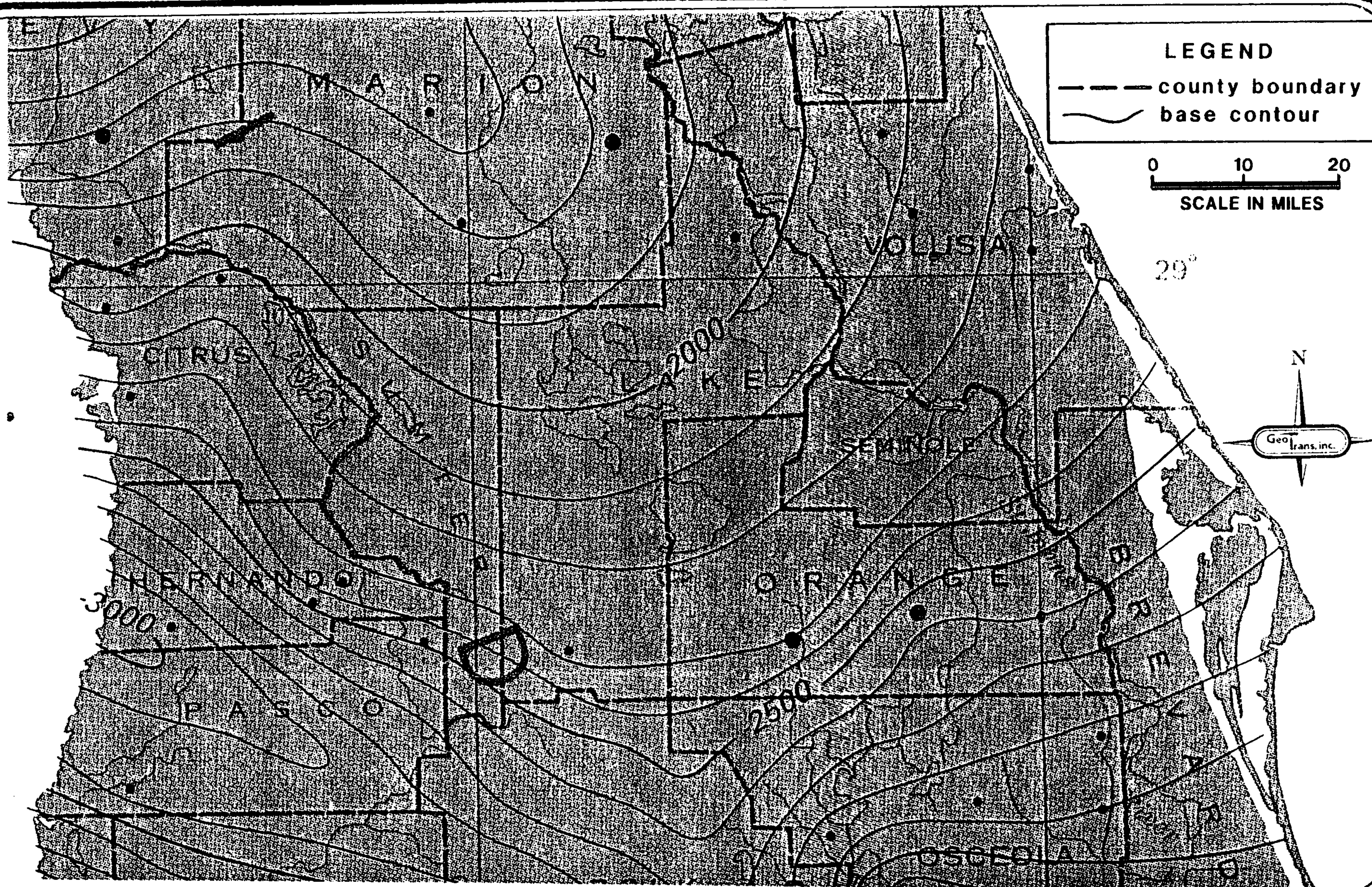

Figure 2.2. Altitude of the base of the Floridan aquifer relative to mean sea level, in feet (from Miller, 1986).

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Avon Park Formation constitutes the top of the Floridan in north Seminole and extreme northeast Lake Counties.

The Floridan aquifer system is divided on the basis of the vertical occurrence of two zones of relatively high permeability. These zones are commonly referred to as the "Upper Floridan" and "Lower Floridan" aquifers. According to Miller (1986), the Upper Floridan in the project area averages 350 feet in thickness while the Lower Floridan ranges between 1300 and 1500 feet thick. The Upper and Lower Floridan are separated by a less permeable, soft, chalky limestone and dolomitic limestone sequence referred to as the "middle semi-confining unit" (Figure 2.3). The unit is believed to be thinnest in the west part of the project area, but is as much as 500 ft thick in southern Seminole County. The middle semi-confining unit occurs at elevations between 300 and 350 ft below MSL. The middle semi-confining unit is leaky, and the hydraulic connection between the Upper and Lower Floridan aquifers varies from place to place (Tibbals, 1990). However, given the relatively little head differential between the upper and lower aquifers, typically less than 4-5 feet, it is apparent that this unit provides only minimal impedance to flow between them.

2.1.3 Aquifer Hydrology

Development of a reliable model of the Floridan aquifer system requires a thorough understanding of both the Floridan and surficial aquifers and how these two aquifers interact hydraulically.

The surficial aquifer is recharged by rainfall, irrigation, surface waters, septic tank effluent, and sewage or stormwater holding pond effluent. In areas where the potentiometric surface of the Upper Floridan aquifer is above the water table, there is upward leakage from the Upper Floridan. Water leaves the surficial aquifer by seepage to surface waters, by evapotranspiration where the water table is near land surface ($\leq$13 feet deep) (Tibbals, 1990), by pumpage, and, where the potentiometric surface of the Upper Floridan aquifer is below the water table, by downward leakage to the Floridan. In the

GEOLOGIC UNITS
(ADAPTED FROM FAULKNER, 1973, FIG. 2)

Era	System	Series	Stratigraphic unit	Thickness (feet)	Lithology	Aquifer (from Chapter B)
CENOZOIC	QUATERNARY	Holocene	Unnamed alluvial, lake, and windblown deposits	0-75	Alluvium, freshwater marl, peats and muds in stream and lake bottoms. Also, some dunes and other windblown sand.	SURFICIAL AQUIFER
			unconformity			
CENOZOIC	QUATERNARY	Pleistocene	Pamlico Formation and marine and estuarine terrace deposits	0-75	Mostly marine quartz sand, unconsolidated and generally well graded. Also, some fluviatile and lacustrine sand, clay, marl, and peat deposits.	SURFICIAL AQUIFER
			unconformity			
CENOZOIC	TERTIARY, UPPER	Pliocene	Jackson Bluff Formation	0-75 ±	Marine sands, argillaceous, carbonaceous; and sandy shell marl. Some phosphatic limestone.	
CENOZOIC	TERTIARY, UPPER	Pliocene	Alachua Formation	0-100 ±	Nonmarine interbedded deposits of clay, sand, and sandy clay; much of unit is phosphatic, base characterized by rubble of phosphate rock and silicified limestone residuum in a gray and green phosphatic clay matrix.	
CENOZOIC	TERTIARY, UPPER	Miocene	Fort Preston[1] Formation	0-100 ±	Nonmarine fluviatile sand, white to gray, variegated orange, purple and red in upper part, fine- to coarse-grained to pebbly, clayey, crossbedded.	
CENOZOIC	TERTIARY, UPPER	Miocene	Hawthorn Formation	0-300 ±	Marine interbedded sand, cream, white, and gray, phosphatic, often clayey, clay, green to gray and white, phosphatic, often sandy; dolomite, cream to white and gray, phosphatic, sandy, clayey; and some limestone, hard, dense, in part sandy and phosphatic. Tends to be sandy in upper part and dolomitic and limy in lower part.	
			unconformity			
CENOZOIC	TERTIARY, LOWER	Oligocene	Suwannee Limestone	0-150	Marine limestone, very pale orange, finely crystalline, small amounts of silt and clay.	FLORIDAN AQUIFER SYSTEM
			unconformity			
CENOZOIC	TERTIARY, LOWER	Eocene, Upper	Ocala Limestone[2]: Upper[3] member	0-325	Marine limestone, cream to white, soft, granular, highly porous, coquinal, often consists almost entirely of tests of foraminifers; cherty in places.	FLORIDAN AQUIFER SYSTEM
CENOZOIC	TERTIARY, LOWER	Eocene, Upper	Ocala Limestone[2]: Lower[4] member	0-325	Marine limestone, cream to tan and brown, granular, soft to firm, porous, highly fossiliferous, lower part at places is dolomite, gray and brown, crystalline, saccharoidal, porous.	FLORIDAN AQUIFER SYSTEM
			unconformity			
CENOZOIC	TERTIARY, LOWER	Eocene, Middle	Avon Park Formation	600-1600	Marine limestone, light brown to brown, finely fragmental, poor to good porosity, highly fossiliferous (mostly foraminifers); and dolomite, brown to dark brown, slightly porous to good porosity, crystalline, saccharoidal, both limestone and dolomite are carbonaceous or peaty, gypsum is present in small amounts. Marine limestone, light brown to brown, fragmental, highly fossiliferous, slightly carbonaceous or peaty and cherty; and dolomite, brown to dark brown with very minor amounts of gypsum and anhydrite. Unit is slightly porous to porous.	FLORIDAN AQUIFER SYSTEM
CENOZOIC	TERTIARY, LOWER	Eocene, Lower	Oldsmar Formation	300-1350	Marine limestone, light brown to chalky, white, porous, fossiliferous, with interbedded brown, porous, crystalline dolomite; minor amounts of anhydrite and gypsum.	
CENOZOIC	TERTIARY, LOWER	Paleocene	Cedar Keys Formation	500-2200	Marine dolomite, light gray, hard, slightly porous to porous, crystalline, in part fossiliferous, with considerable anhydrite and gypsum, some limestone.	
			unconformity			
MESOZOIC	CRETACEOUS		Upper and Lower Cretaceous	1500-?	Mostly marine Upper Cretaceous carbonate and evaporite rocks, sands and shales; thin Lower Cretaceous clastic section in some of area.	
			Coastal Plain Bedrock			
PALEOZOIC and PRE-CAMBRIAN			DEVONIAN to PRECAMBRIAN (?)	Basement rocks	Marine Devonian, Silurian, and Ordovician quartzose sandstone and dark shale; lower Paleozoic (?) or Precambrian (?) rhyolite, tuff, and agglomerate.	

[1]Usage of Bureau of Geology, Florida Department of Natural Resources
[2]Ocala Group of Bureau of Geology, Florida Department of Natural Resources

PRINCIPAL HYDROGEOLOGIC UNITS
(CONCEPTUAL MODEL)

- SURFICIAL AQUIFER
- UPPER CONFINING UNIT
- UPPER FLORIDAN AQUIFER
- MIDDLE SEMICONFINING UNIT
- LOWER FLORIDAN AQUIFER
- LOWER CONFINING UNIT (EXTREMELY LOW PERMEABILITY)
- BASEMENT ROCKS

Figure 2.3. Geologic and hydrogeologic units in the project area (from Tibbals, 1990).

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study area, the most important function of the surficial aquifer is to store water, some of which recharges the Upper Floridan aquifer. The surficial aquifer is little used as a source of water supply because, relative to the Floridan aquifer system, its permeability is low, resulting in relatively low yields to wells. Also, water from the surficial aquifer often contains high concentrations of dissolved iron and is sometimes highly colored.

Water enters, or recharges, the Floridan aquifer system in the project area by downward leakage from the surficial aquifer system to the Upper Floridan and by inflow from drainage wells.

In aquifer recharge areas, the water table in the surficial aquifer system is above the potentiometric surface of the Upper Floridan. The rate of recharge depends on the difference between hydraulic head in the surficial aquifer system and the Upper Floridan and on the thickness and permeability of the confining beds. Recharge rates are proportional to head difference and confining bed permeability and are inversely proportional to confining bed thickness. It is probable that, locally, recharge rates are as high as 20 in/yr (Tibbals, 1990).

In addition to natural downward leakage, recharge also occurs through about 400 drainage wells in the Orlando area (Kimrey and Fayard, 1984). These wells are constructed similarly to wells used for withdrawal; that is, they are cased to the top of the Upper Floridan aquifer and then drilled open-hole into the Upper Floridan. Drainage wells are generally used to control lake levels and to dispose of street runoff from storm sewers, but in the past they were used to drain wetlands, to dispose of surplus effluent from industrial sites, and to receive effluent from septic tanks. While estimates of the quantity of water entering the aquifer are as high as 50 million gallons per day (mgd), Tibbals (1990) used a rate of 33 mgd in his simulations.

Discharge from the Floridan aquifer system in the project area occurs by diffuse upward leakage in areas where the potentiometric surface is above the water table, by pumping or flowing wells, and by springs. In areas where the Upper Floridan aquifer potentiometric surface is above land surface, wells that tap the Upper Floridan flow at the surface.

Nineteen named Upper Floridan springs in the study area have discharges of 1 cubic foot per second (ft^3/s) or more. Five other sites of naturally occurring Upper Floridan discharge were confirmed by estimates based on low-flow stream-gaging measurements and water-quality analyses (Tibbals, 1990). In several areas, depressions in the potentiometric surface of the Upper Floridan indicate relatively large groundwater discharges by other than known springs. These areas include the St. Johns River and Lake Jessup.

Water quality within the study area is discussed by Tibbals (1990), Sprinkle (1982), and Klein (1971). Water in the Upper Floridan has generally low concentrations of total dissolved solids (less than 1000 mg/L), except along the course of the St. Johns River and its confluence with the Wekiva River (Figure 2.4). Tibbals (1990) states that flow in the aquifer is extremely sluggish in this area and therefore poor water quality could result from ancient occurrences of seawater. However, Tibbals (1990) believes that it is most likely that most of the brackish water being discharged at Blue Spring (near the present cross-section) is moving upward from depth in the vicinity of the spring. The quality of water in the Lower Floridan is not well defined. Much of the interpretation of water quality in the Lower Floridan is from interpolation and extrapolation of a few measurements. Most references are only able to distinguish between areas of poor quality water and areas of good quality water in the Lower Floridan without being able to quantify the zone of diffusion or an exact "interface".

Because analysis of potential movement of existing poor quality water in the Upper Floridan aquifer is an objective in this study, it is important to replicate water quality conditions in this aquifer. Chloride is the predominant anion in seawater and is often used as a tracer or indicator of saltwater intrusion. Chloride is therefore the modeled constituent of concern in this study. Sprinkle (1982) mapped chloride concentrations in the Upper Floridan (Figure 2.5). Tibbals

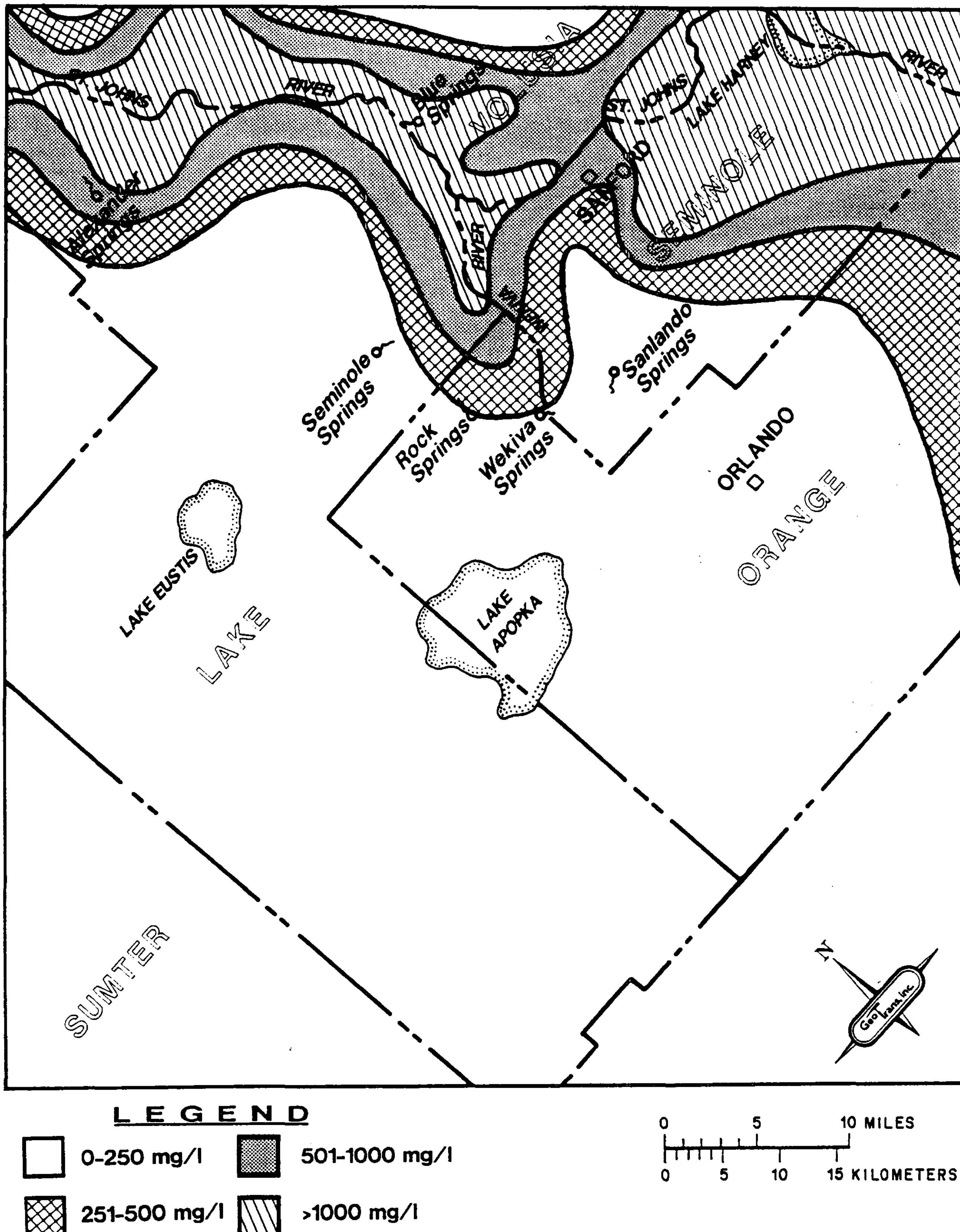

Figure 2.4. Total dissolved solids (mg/L) in the upper Floridan aquifer in the study area (adapted from Klein, 1975).

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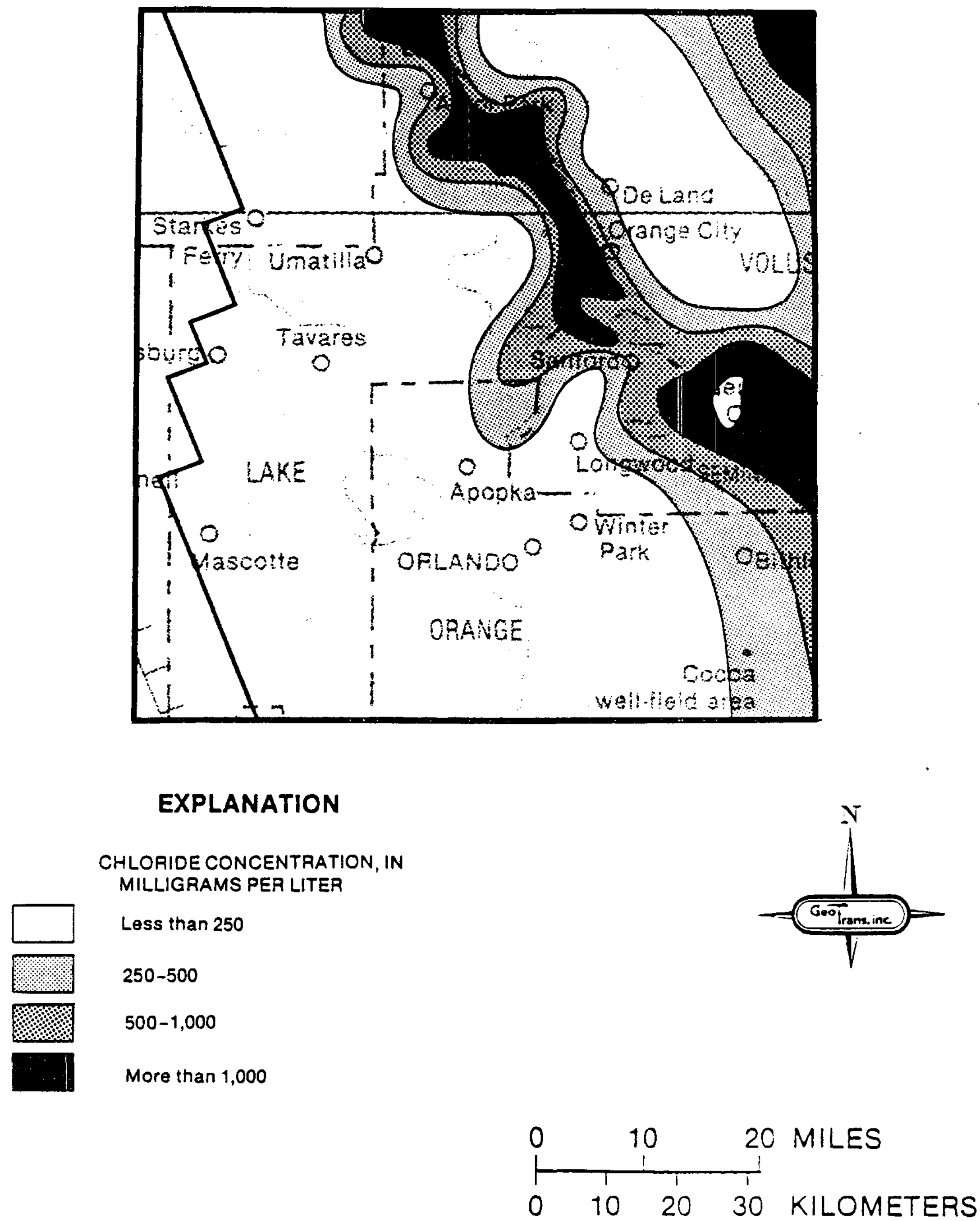

Figure 2.5. Chloride concentrations in the upper Floridan aquifer in the study area (adapted from Sprinkle, 1982).

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refined this analysis in mapping chloride concentrations in the upper 100 ft of the Upper Floridan (Figure 2.6). Klein (1975) shows depth to base of potable water in the Floridan aquifer system (Figure 2.7).

2.2 HYDROGEOLOGY ALONG CROSS-SECTIONS

Several criteria were used in the selection of a suitable cross-section through the Wekiva River Basin. The cross-section should:

1. Fall within the proposed boundaries of the three-dimensional transport model;
2. Be placed along a groundwater flow path which is relatively straight;
3. Be in an area where pumpage or other radial flow conditions are minimal; and
4. Be in an area somewhat typical of conditions to be encountered in the three-dimensional transport model.

Conditions 2 and 3 limited the locations considerably due to the abundance of springs in the model area. In addition to being difficult to quantify in a two-dimensional model, the springs tended to induce a great deal of curvature to groundwater flow paths in the area.

The cross-section which was selected is located in northeast Lake County and runs southwest to northeast through the Wekiva River Basin (Figure 2.8). This section corresponds to the right portion of row 6 of the regional flow model and is located near the edge of the proposed three-dimensional transport model. Tibbals (1990) showed a cross-section running approximately through this area (Figure 2.9). As is typical of much of the study area, concentrations along the St. Johns River are quite high in the Upper Floridan aquifer.

Concentrations decline further from the river. There is a distinct wedge of salty groundwater with concentrations in excess of 10,000 mg/L on the northeastern extent of the model in the Lower Floridan. This presumably also decreases to the southwest, but it is unclear where the saltwater interface is at depth and the extent of the zone of diffusion along the interface is uncertain.

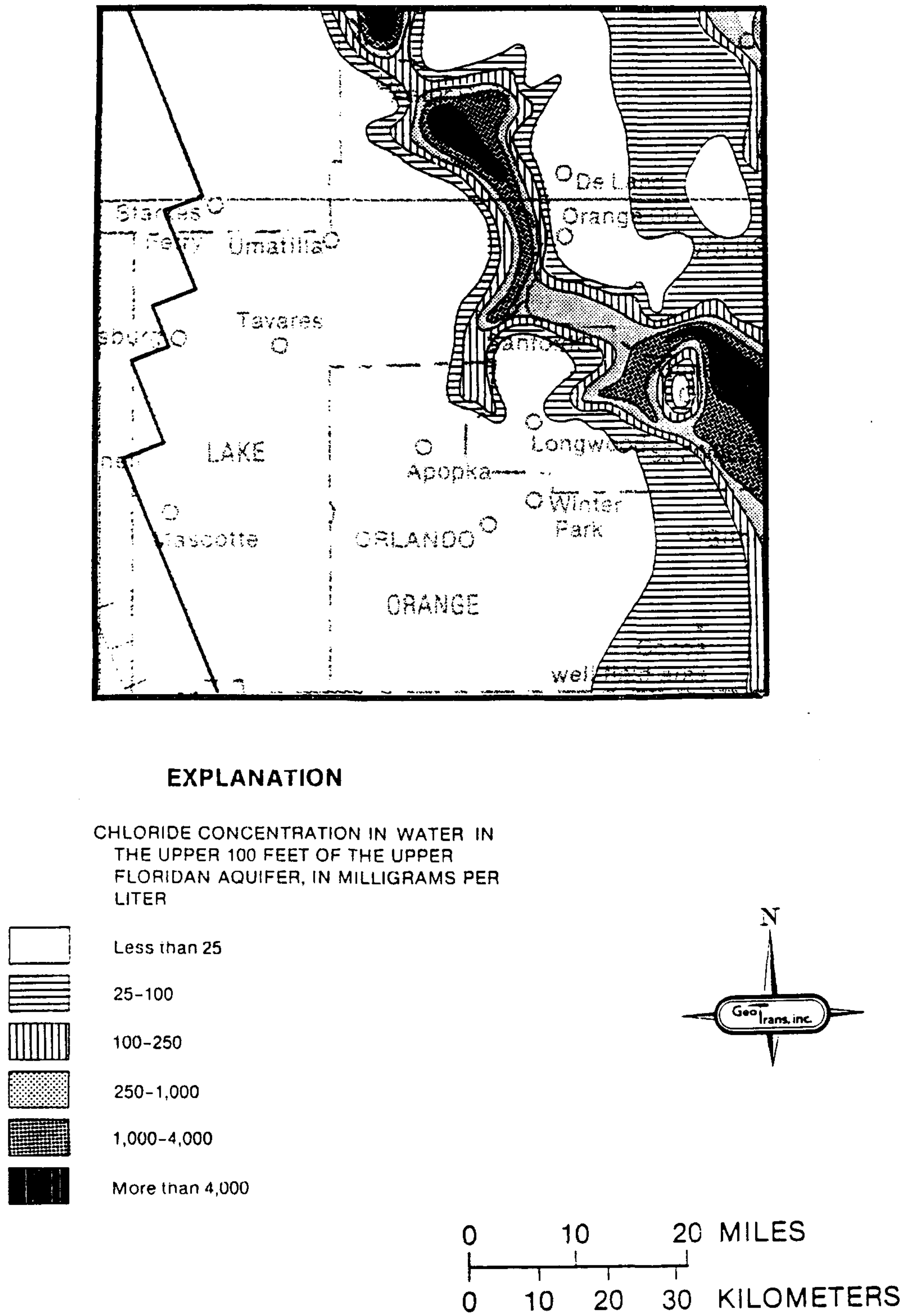

Figure 2.6. Chloride concentrations in the upper 100 ft of the upper Floridan aquifer in the study area (adapted from Tibbals, 1990).

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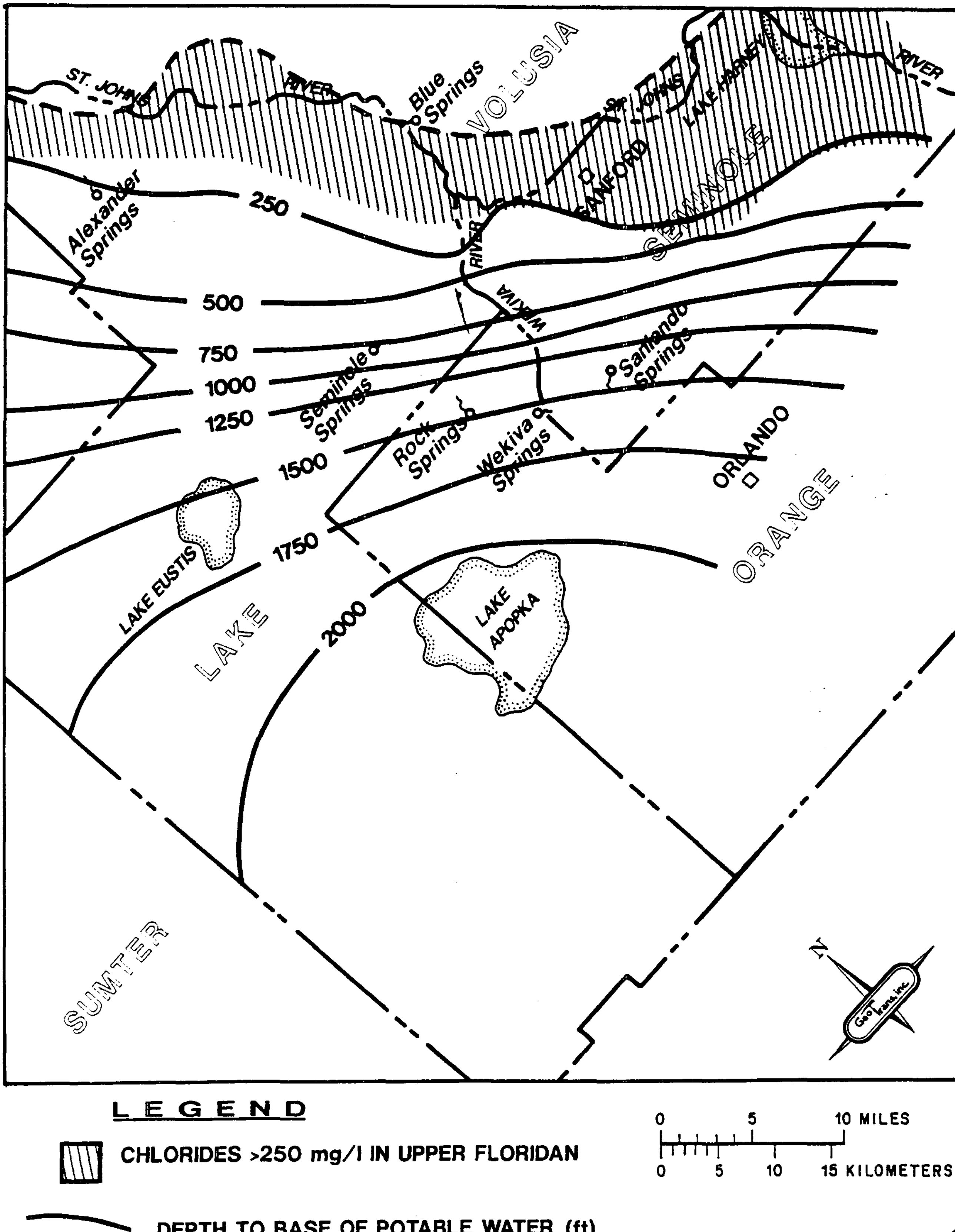

Figure 2.7. Depth to base of potable water in the Floridan aquifer system (adapted from Klein, 1975).

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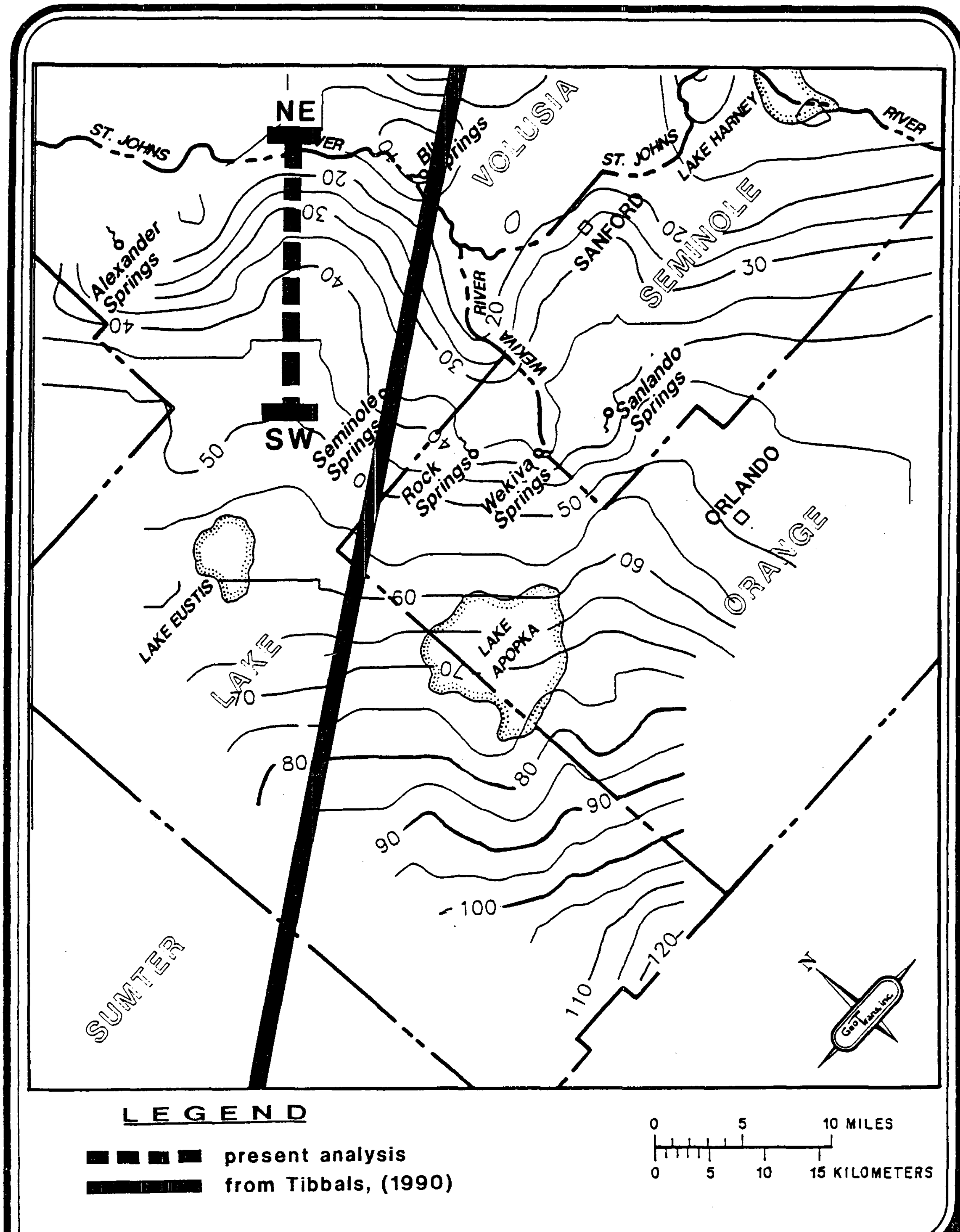

Figure 2.8. Location of the cross-section used in the present analysis.

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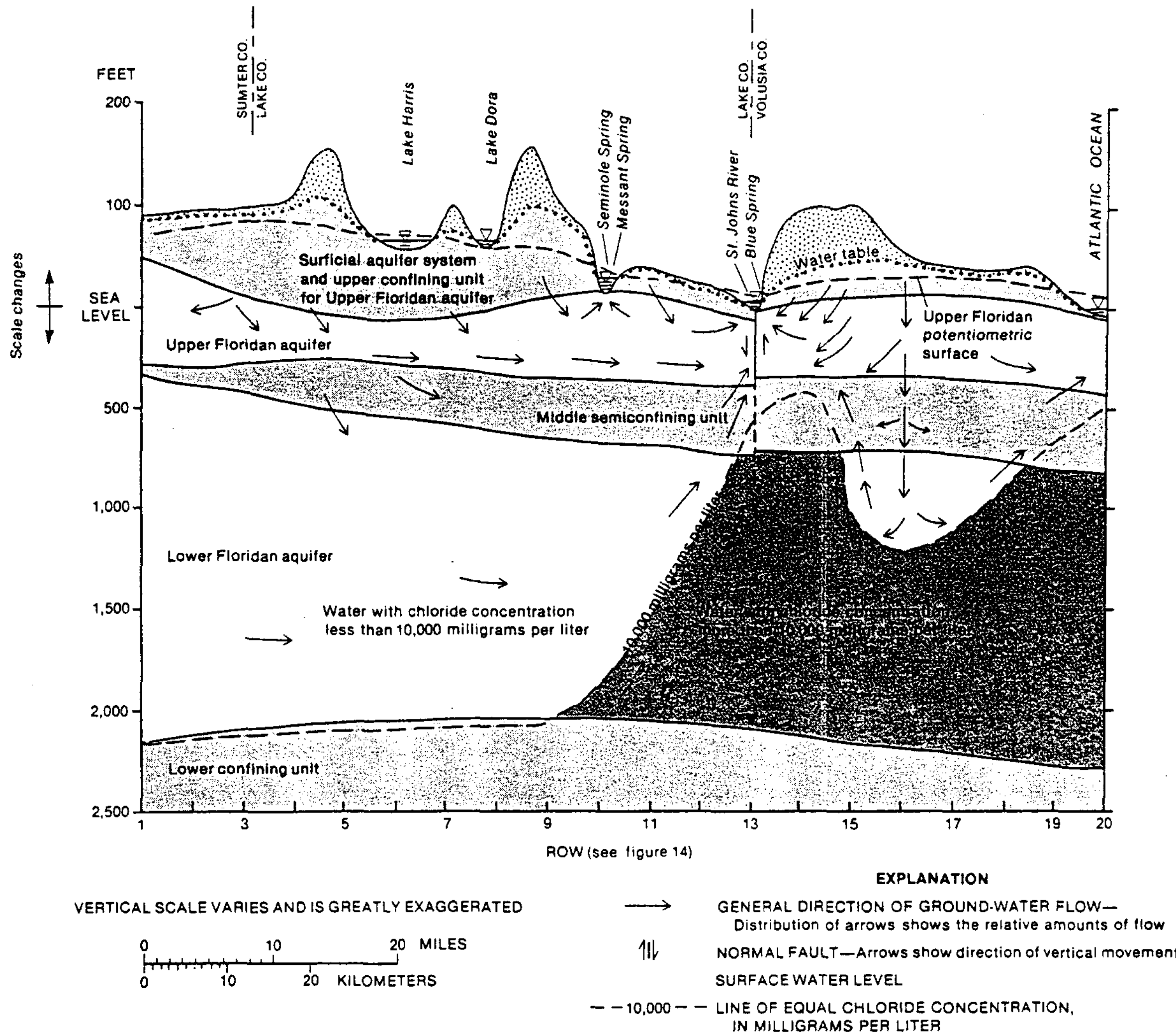

Figure 2.9. Regional cross-section through Blue Springs and Seminole Springs (adapted from Tibbals, 1990). Location of cross-section is shown in Figure 2.8.

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Several wells exist in the study area that have chloride data available (Figure 2.10). However much of this data is distant from the cross-section. The database as a whole will be more useful for the three-dimensional analysis to be performed in Phase III.

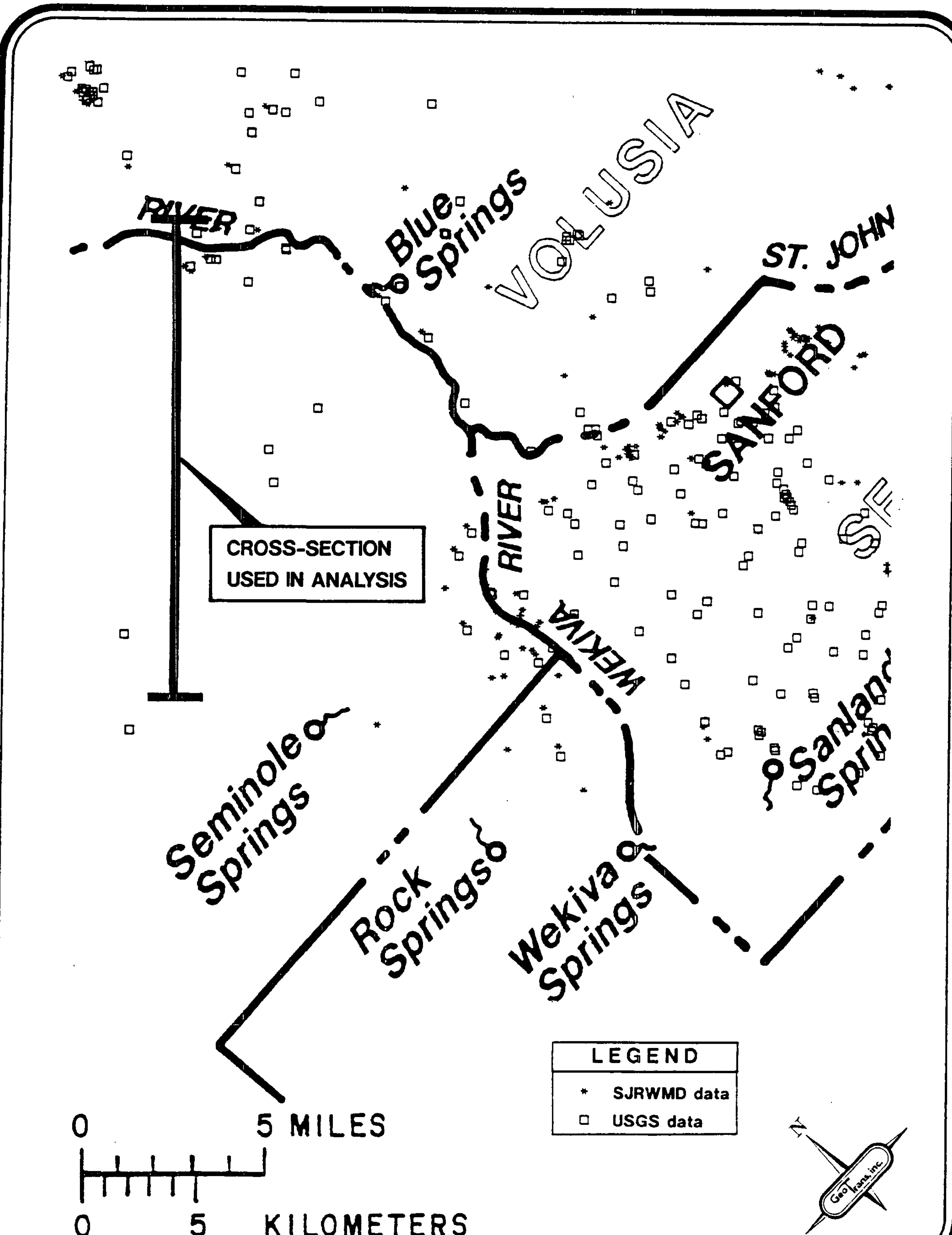

Figure 2.10. Chloride monitor wells used in the cross-sectional anlaysis.

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3 MODEL DEVELOPMENT

3.1 COMPUTER CODE

A solute transport code called SWICHA was used in this application. SWICHA is capable of modeling three-dimensional, variable density groundwater flow and solute transport. The code has been documented (GeoTrans, 1985 and 1991a), benchmarked (Huyakorn et al., 1987), and field tested (Andersen et al., 1986, Andersen et al., 1988, and GeoTrans 1991b) at three sites in Florida. Several modifications were made to SWICHA prior to this study, including: (1) addition of a mass balance calculation, (2) improved input/output, (3) improved computation of the non-linear under-relaxation factor, and (4) documentation revision. SWICHA is a public domain code which can be obtained through the International Ground Water Modeling Center.

The formulation of the governing equations and the numerical approximation used in the model are presented in detail in the SWICHA documentation and are summarized here. Two partial differential equations describe the problem of seawater intrusion in coastal aquifers. The first equation describes the flow of variable density fluid and the second equation describes the transport of dissolved salt. The two equations are coupled, that is, concentrations must be known to compute flow, while the flow field must be known to compute concentrations. This non-linearity is handled using an implicit Picard iterative scheme. The flow and transport equations are alternately solved until convergence is achieved. Hydraulic heads are posed in terms of reference or relative freshwater heads, defined as:

$$h = \frac{P}{\rho_o g} + Y$$

where P is fluid pressure, g is gravitational acceleration, ρ_o is the freshwater density, and Y is the elevation above a datum.

The equations are approximated using the Galerkin finite element technique. Spatial discretization is performed using a vertical slicing approach. Solving two-dimensional matrices interconnected in the third dimension circumvents computational and solution time problems due to a very large matrix. Simple rectangular and prism elements are used within each slice to avoid time-consuming numerical integration in computing element matrices. A slice-successive relaxation (SSR) scheme is used to solve the system of equations. Generally, over-relaxation is used for flow while under-relaxation is used for transport. Artificial dispersion can be added to the transport equation stiffness matrix to prevent exceedence of a critical Peclet number.

Boundary and initial conditions are specified for each of the equations. Boundary conditions of specified flux, specified head, and head dependent flux may be used for flow while specified mass flux and specified concentration may be used for transport. The head dependent flux boundary condition enables leakage to or from a stream or adjacent aquifer to be simulated without discretizing that particular feature.

Output from the model includes a listing of input data, iteration history, nodal connection data, relative freshwater heads, concentrations, Darcy velocities, and mass balances for flow and transport. Results may be plotted using standard commercially available graphics packages. Further details on SWICHA may be found in the model documentation (GeoTrans, 1991a).

3.2 CONCEPTUAL MODEL

The conceptual model for flow along the cross-section is shown in Figure 3.1. Groundwater flow is generally from southwest to northeast in the Floridan aquifer (see Figure 2.8). The St. Johns River provides a local discharge point for the surficial system, the Upper Floridan, and to some degree, the Lower Floridan. Flow in the Lower Floridan is generally toward the northeast, however.

Freshwater enters the Upper Floridan from the southwest and moves toward the northeast, mixing with residual saltwater contamination. Salty water from the Lower Floridan discharges through the semi-confining layer. A diffuse wedge of saltwater, with

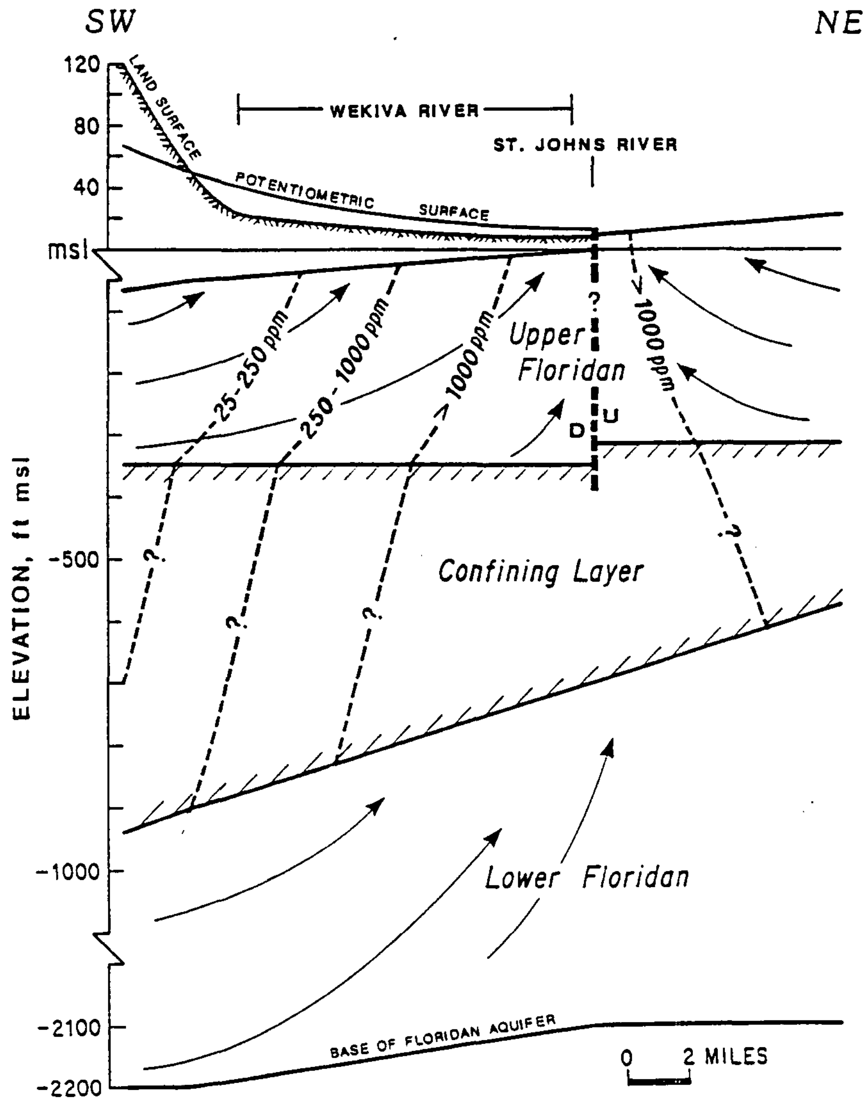

Figure 3.1. Conceptual model of the Floridan aquifer system in the vicinity of the cross-sectional model.

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concentrations generally decreasing toward the southwest and increasing with depth, is present across the cross-section. Data regarding concentrations in the Lower Floridan are very sparse and the configuration of the wedge is poorly known.

The surficial aquifer system provides downward leakage over much of the study area. This water is generally of low chloride concentration because it is derived primarily from precipitation recharge onto the surficial system. Shallow lakes and wetlands cover much of the surficial system in the study area.

The postulated fault shown near the St. Johns River in Figure 3.1 may provide an avenue for upward leakage into the river and surficial system. Given the other uncertainty associated with this boundary, the effect of the fault is not assessed further.

This qualitative description of groundwater flow is converted to a quantitative numerical model by discretizing into a finite-element mesh, assigning appropriate initial and boundary conditions, and assigning the required groundwater flow and transport parameters. This process is described in detail in the next section.

3.3 NUMERICAL MODEL CONFIGURATION

3.3.1 Boundary Conditions and Hydrogeologic Unit Geometry

The boundary conditions and hydrogeologic unit thicknesses upon which the cross-sectional model is based were derived from data provided by the SJRWMD, as well as information from studies by Miller (1986), Tibbals (1990), and GeoTrans (1991c). The finite element grid used in this model is shown in Figure 3.2. Also shown in this figure are layer thicknesses and boundary conditions. The grid consists of 61 columns representing a total of 80,000 ft along the cross-section and 19 rows representing a total of 2025 ft in the vertical direction. Individual grid spacing varies form 500 to 2000 ft horizontally and 50 to 200 ft vertically. Hydraulic heads and concentrations are computed at each node (intersection of column line and row line) and velocities are computed for each element (rectangle formed by four nodes).

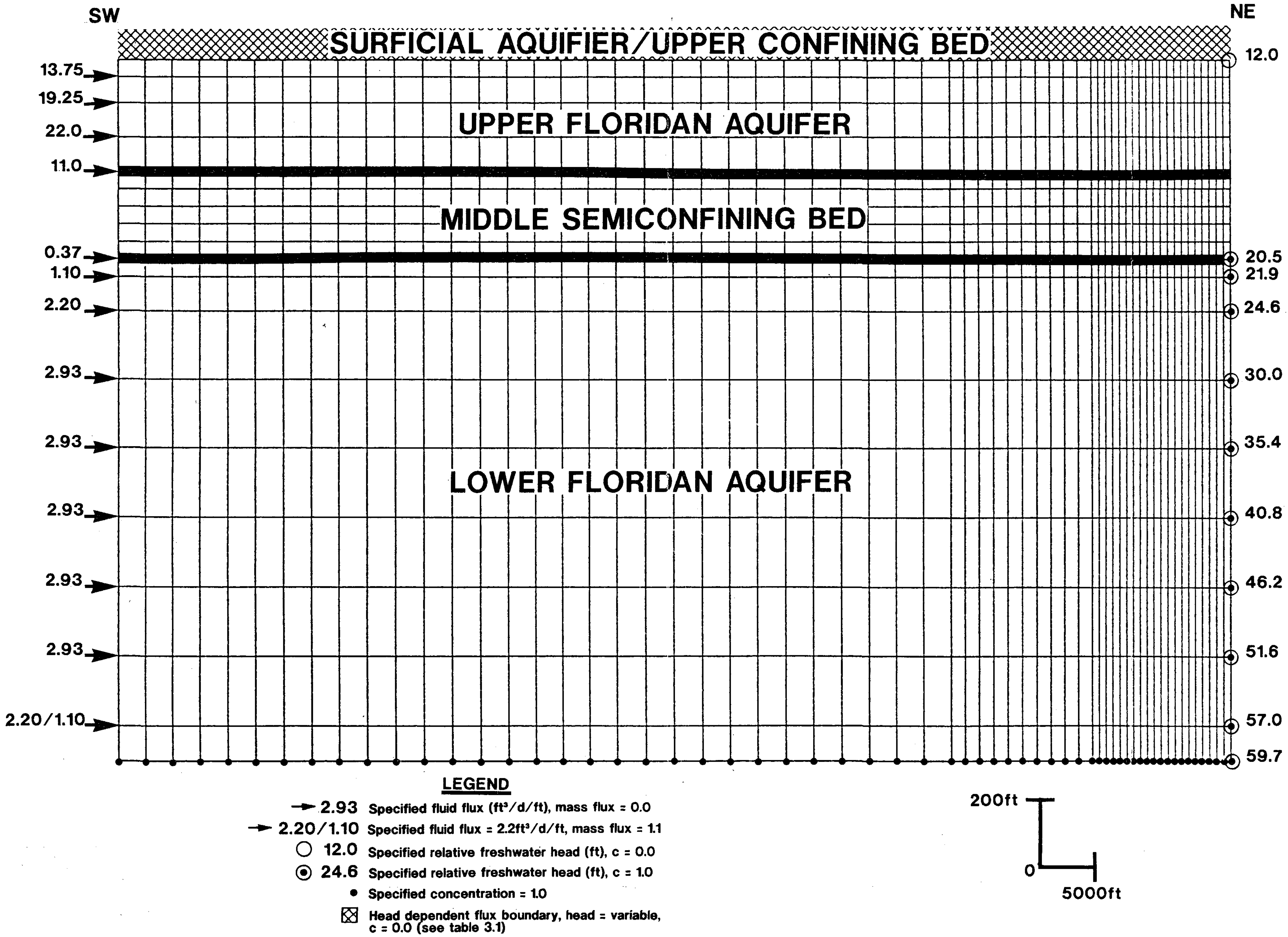

Figure 3.2. Finite-element grid and boundary conditions for the cross-sectional model.

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The thicknesses of the Upper Floridan, Lower Floridan, and middle semi-confining unit were derived from maps of unit thicknesses and depths presented by Miller (1986). Uniform thicknesses of 325 ft, 250 ft, and 1450 ft were specified for the Upper Floridan, middle semi-confining unit, and Lower Floridan, respectively. Uniform thicknesses were used for three reasons: 1) the vertical finite element grid resolution, which varies from 50 ft to 200 ft, could accommodate only major changes in thickness, 2) the actual changes in thickness along the cross-section were fairly small, and 3) changes in transmissivity resulting from thickness change would be small compared to uncertainty in hydraulic conductivity variation.

Boundary conditions are either assigned or are implicit to all nodes which surround the perimeter of the model. No-flow boundaries and zero concentration gradient boundaries are implicit in SWICHA. If a perimeter boundary is not assigned, these two boundary conditions are assumed. Figure 3.2 shows the boundary conditions used in this model.

The bottom of the model is the base of the Lower Floridan. Because the Lower Floridan overlays a low permeability zone, the flow boundary condition associated with bottom of the model is a no-flow boundary. The no-flow boundary is implicit in SWICHA and it is therefore not assigned in the data set. This boundary seems most appropriate due to the contrast in permeability between the Floridan and underlying beds as well as the uncertainties and constraining effect of either a specified head or leaky boundary condition. For transport, a relative concentration of 1.0 is assigned along the entire model base. A relative concentration of 1.0 is equivalent to a 19,000 mg/l actual chloride concentration, which corresponds to a 1.025 specific gravity of solute. This boundary assumes that high chloride water equivalent to seawater concentrations will exist at a depth of greater than 2000 ft. Because hydraulic heads in the Upper Floridan are generally less than 50 ft across the model area, the Ghyben-Herzberg principle supports the contention that high chloride water should exist at depths of 2000 ft or less across the model area. Virtually no field data exist in this area, however, to support or contradict this boundary condition. The combination of a no-flow boundary and a specified concentration boundary has the net effect of inducing chloride movement into the model area from below only due to the concentration gradient across this boundary.

The southwest boundary was assigned a specified flux boundary condition in the aquifers. The flux magnitudes were based on fluxes derived from the GeoTrans (1991c) modeling study. Because a single layer of nodes represented each aquifer in the GeoTrans (1991c) study and 6 and 11 nodes represent the Upper and Lower Floridan aquifers in the current study, the net aquifer flux from the previous study had to be distributed to specific nodes in the current study. It was assumed that the flux was evenly distributed within each aquifer. This assumption was evaluated during the sensitivity analysis. All flow entering from the southwest, with the exception of the lower corner, was assumed to be freshwater. In this area (see Figure 3.2) a relative concentration of 0.5 was combined with the fluid flux of 2.2 $ft^3/d/ft$ to give a mass flux of 1.1 $ft^3/d/ft$. This boundary was necessary for numerical stability to prevent two nodes of high concentration contrast (1.0 on the model base and 0.0 on the model side) from being adjacent to one another. Therefore the 0.5 concentration was selected to provide a more gradual change in concentration. Because flow in the middle semi-confining unit was assumed to be vertical, this area was not assigned a boundary condition along the southwest side.

The upper boundary condition was considered to be a head dependent flux condition. This allows flow into or out of the Upper Floridan aquifer from/to the overlying surficial aquifer based upon the head difference between the two units. A leakance term (vertical hydraulic conductivity/upper confining bed thickness) controls the degree of connection between the Upper Floridan and the surficial aquifer. A hydraulic head representative of the surficial aquifer is included in each head dependent flux boundary condition. The leakance term was computed using a uniform vertical hydraulic conductivity of 0.0028 ft/d and a variable upper confining bed thickness ranging from 20 to 65 feet. The value of vertical hydraulic conductivity is that which SJRWMD is reportedly using in a recharge area mapping project. The head in the surficial aquifer was derived from a topographic map and interpolation of hydraulic heads of surface water bodies. These range from 32.4 ft to 122 ft. Details regarding individual head dependent flux boundaries are given in Table 3.1.

The northeast boundary is represented by three different boundary conditions. The uppermost part of the Upper Floridan aquifer is represented by a single specified head node set at 12 ft. This node represents an exit point for flow into the St. Johns River. Its magnitude is based upon observed data. This boundary was necessary to provide an exit for flow along the cross-section, given problems with divergent flow along the stream tube represented by the cross-section. More discussion on the divergent flow problem is given in Section 3.3.3. The remainder of the Upper Floridan aquifer is represented as a no-flow boundary on the northeast edge of the model. This corresponds to a vertical flow line into the St. Johns River. The potentiometric surface map shown in Figure 2.8 supports specification of this boundary condition because of the localized potentiometric low at the St. Johns River. The Lower Floridan aquifer along the northeast boundary is represented by a specified head boundary condition. Because chloride concentrations are assumed to be equivalent to saltwater along this boundary, the relative freshwater heads which are assigned decrease linearly with depth. The relative freshwater heads were further adjusted to induce a 1 ft in head per 500 ft vertical distance upward gradient. This was done to include some upward flow toward the St. Johns River immediately beneath the river, rather than effectively isolating the Lower Floridan. The choice of 1 ft to 500 ft was arbitrary, but falls within the range of what would be expected beneath the river. Concentrations along this boundary are specified at 1.0, based on concentrations in a nearby well presented by Tibbals (1990) where chloride concentration reaches 9000 mg/L at approximately 440 ft. Data points show a sharp front which increases from 4000 to 9000 mg/L over about 20 feet of depth. Extrapolation of this data indicates seawater concentrations would be

Table 3.1. Hydraulic heads and confining bed thicknesses used in the numerical model to represent the upper confining bed.

Column*	Hydraulic head (ft)	Confining bed thickness (ft)
1	122.0	65.0
2	119.0	64.0
3	110.0	61.3
4	101.0	58.1
5	77.7	54.5
6	43.5	50.9
7	35.0	47.3
8	35.0	43.7
9	35.0	40.1
10	32.4	37.1
11	39.6	34.1
12	49.8	31.2
13	42.7	28.2
14	40.0	25.2
15	38.3	22.2
16	36.1	20.0
17	35.0	20.0
18	35.0	20.0
19	36.3	20.0
20	39.6	20.0
21	39.3	20.0
22	38.6	20.0
23	37.8	20.0
24	37.1	20.0
25	38.0	20.0
26	39.2	20.0
27	44.4	20.0
28	50.0	20.0
29	50.0	20.0
30	50.0	20.0
31	50.0	21.7
32	50.0	25.9
33	50.0	30.1
34	50.0	34.3
35	50.0	38.5
36	47.9	42.3
37	45.0	46.0
38	45.0	49.6
39	43.9	53.2
40	40.7	56.8
41	37.6	60.0
42	26.0	60.0

Table 3.1. Hydraulic heads and confining bed thicknesses used in the numerical model to represent the upper confining bed (continued).

Column*	Hydraulic head (ft)	Confining bed thickness (ft)
43	34.4	60.0
44	32.8	60.0
45	31.3	60.0
46	30.0	60.0
47	30.0	60.0
48	26.4	60.0
49	21.8	60.0
50	17.3	60.0
51	12.7	60.0
52	8.18	60.0
53	4.61	60.0
54	3.30	60.0
55	2.00	59.7
56	1.83	58.9
57	1.67	58.1
58	1.50	57.3
59	1.33	56.6
60	1.17	55.8

*Columns correspond to the element columns shown in Figure 3.2. Column number proceeds sequentially form left to right across the section.

attained at only slightly greater depth. The Ghyben-Herzberg principle also indicates that the saltwater interface should exist at 480 ft in this area.

3.3.2 Parameters

The hydrogeological parameters used in the model are presented in Table 3.2. The hydraulic conductivities used for the aquifers were derived by trial and error to best fit values for heads in the Upper Floridan and Lower Floridan aquifers as presented in GeoTrans (1991c). The values were higher than those based on transmissivities used in the regional flow model presented in the GeoTrans report. This is attributed to the flow divergence along the cross-section which is described in the following section. The conductivity of the middle semi-confining layer between the Upper and Lower Floridan units and the overlying upper confining bed is based on leakances given in GeoTrans (1991c). The horizontal to vertical hydraulic conductivity ratio (anisotropy ratio) for the Upper Floridan was 10:1. The anisotropy ratio for the Lower Floridan was set to 50:1. The anisotropies account for stratification within the aquifers.

Dispersivity values of α_L = 120 ft and α_T = 30 feet were used in the Upper and Lower Floridan aquifers. Smaller dispersivities of α_L = 60 ft and α_T = 20 ft were used in the middle semi-confining unit where vertical flow would dominate and shorter travel distances would be prevalent.

In the transient simulations, an effective porosity of 0.1 was used. Porosity is not considered in the steady-state simulations because it influences only the rate of chloride migration. The 0.1 value was selected based on the mid-range of values for dolomite and limestone (Freeze and Cherry, 1979). Velocities are linearly and inversely related to porosity: a porosity of 0.2 would reduce the velocity to one-half the value derived from using a value of 0.1.

Specific storage is also only required for transient simulations because it influences only the rate of change in hydraulic head. A value of 1×10^{-5}/ft was used and is based upon published values of

Table 3.2. Hydraulic parameters used in the cross-sectional model.

Parameter	Upper Floridan Aquifer	Semi Confining Bed	Lower Floridan Aquifer
Horizontal hydraulic conductivity (ft/d)	650	0.05	85
Vertical hydraulic conductivity (ft/d)	65	0.05	1.7
Longitudinal dispersivity (ft)	120	60	120
Transverse dispersivity (ft)	30	20	30
Porosity (transient)	0.1	0.1	0.1
Specific storage (ft^{-1}) (transient)	1E-5	1E-5	1E-5

specific storage for carbonate aquifers. This parameter is the least influential of all because the hydraulic heads attain steady state much more rapidly than do the concentrations.

3.3.3 Model Calibration

Extensive history matching or model calibration was not a part of this study. This was due to three major factors. First, the purpose of the cross-sectional model was to conceptualize or understand the dynamics of variable density flow in the Wekiva River basin. It was intended to provide a preview and resolution of some of the problems that would be encountered in the three-dimensional modeling. This does not involve extensive model calibration. Secondly, the data necessary to calibrate this cross-section are too sparse. Hydraulic head data do exist in the Upper Floridan, but head and concentration data in the Lower Floridan are virtually non-existent. Finally, some of the assumptions inherent in the cross-sectional analysis were not uniquely satisfied. The major assumption that was not satisfied was that of two-dimensional flow along a cross-section.

Although the choice of section location was probably optimal for the study area, it did not account for flow divergence from southwest to northeast along the section. Careful inspection of the potentiometric contours in Figure 2.8 reveals that a streamtube originating at the southwest end of the section expands toward the northeast. This is caused by the influence on the flow system of the St. Johns River, Alexander Springs, Blue Springs, and possibly Ponce de Leon Springs. The flow patterns result in a flow divergence, or flow out of the cross-section along its sides. Higher transmissivities or linearly increasing transmissivity along the cross-section, or an exit node along the section could partially circumvent this problem, but the two-dimensional assumption will never be completely satisfied in this area. Nevertheless, the steps which were taken (exit node at St. Johns River, higher transmissivity) provided a reasonable match of modeled results to observed data.

Velocity vectors for the model are given in Figure 3.3. Flow generally follows the classic saltwater wedge flow system, with some variation due to the middle semi-confining bed and hydraulic conductivity contrast between the Upper and Lower Floridan aquifers. As expected, the magnitude of velocity in the Upper Floridan is higher than in the Lower Floridan. The chloride distribution for the model is shown in Figure 3.4. It appears that the rapid flushing the Upper Floridan aquifer prevents saltwater intrusion into the Upper Floridan. Chloride contours in the Upper Floridan compare well with field data. Comparison of Figure 3.4 with Figures 2.4 through 2.7 indicates that chloride distribution trends in the model are similar to those interpreted from regional field data.

3.4 STEADY STATE SENSITIVITY SIMULATIONS

The model presented in the previous sections was systematically changed to evaluate the effect of uncertainty in aquifer parameters and conceptualization. This process, known as sensitivity analysis, was an essential part of this study in understanding the hydrologic controls on the flow system, identifying data weaknesses, and in preparing for the three-dimensional modeling. The sensitivity analysis consists of a series of simulations in which a parameter or boundary condition is independently varied and the change to the hydrologic system is assessed. A fairly qualitative sensitivity analysis is used because the focus of this study is on understanding the dynamics of the flow system and not in assessing the adequacy of the calibration. As such, general observations regarding system response are made rather than a statistical evaluation of the results of the perturbation. Sensitivity of three main categories were evaluated: boundary conditions, hydrologic parameters, and level of grid discretization. A summary of the sensitivity simulations made with the cross-sectional model is given in Table 3.3.

3.4.1 Boundary Conditions

Two simulations were made to evaluate the boundary condition on the northeast side of the model. The first simulation involved

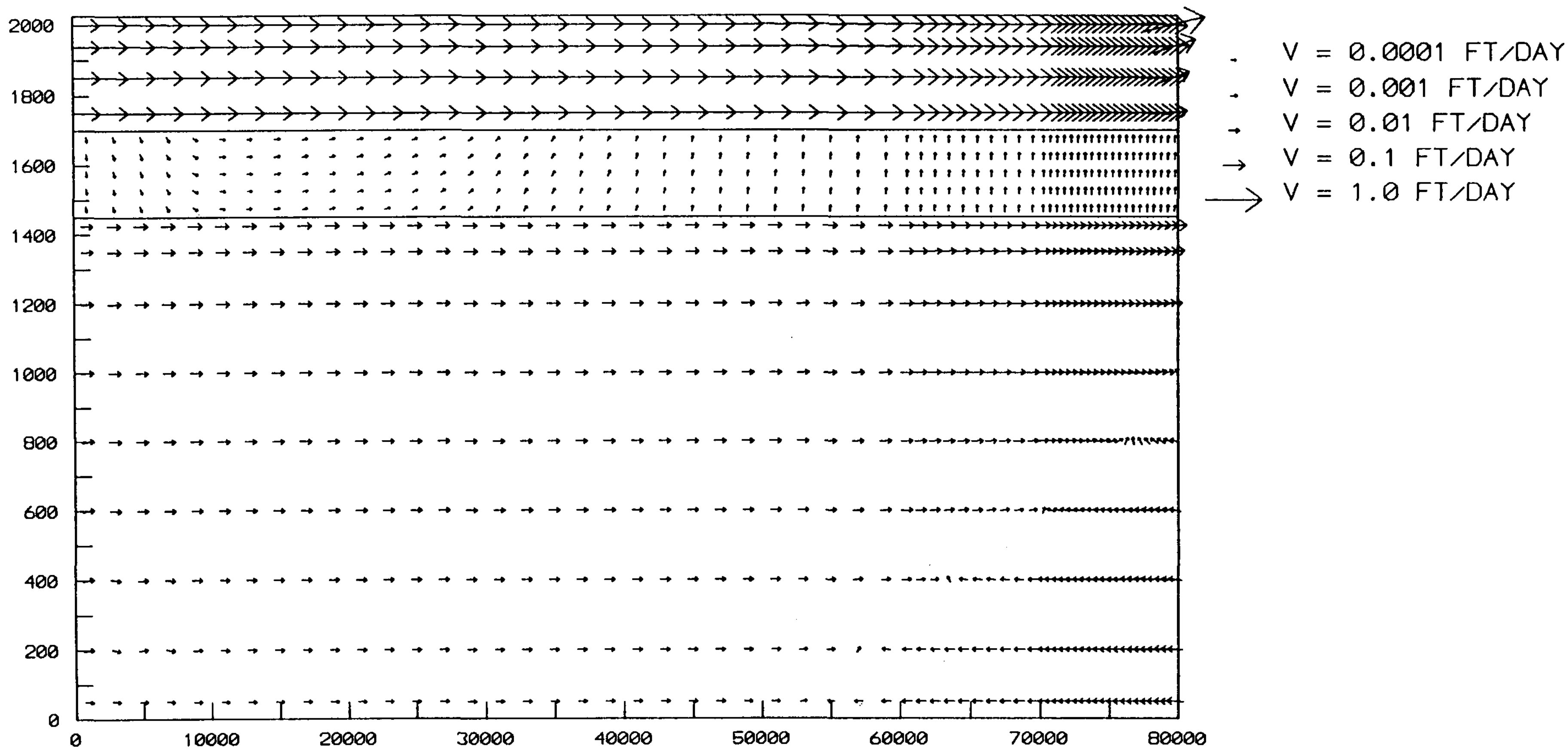

Figure 3.3. Plot of velocity vectors for the cross-sectional model. Numbers on left side and bottom of plot indicate distances in feet.

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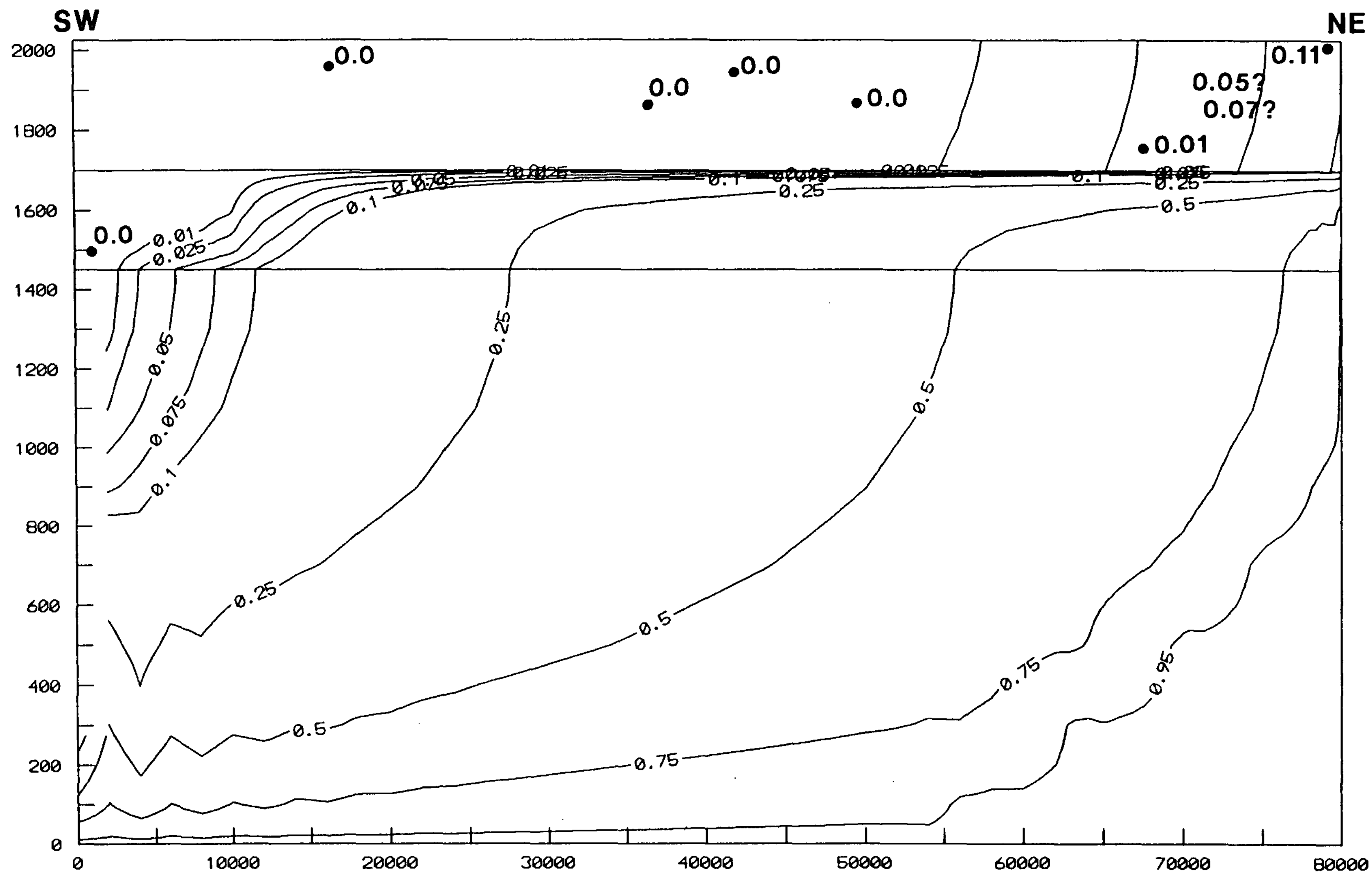

Figure 3.4. Relative chloride concentrations (1.0 = 19,000 mg/L) for the cross-sectional model. Observed concentrations are shown in relative locations.

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Table 3.3. Summary of steady-state sensitivity runs made with the cross-sectional model.

Sensitivity Run	Factor Varied	Result	Figure No.
Base	--	--	3.4
1	No flow on right boundary	Little change in 0.5 isochlor, less Cl^- in LF, dense saltwater lower in UF	3.5
2	Static head on right boundary	Uncontaminated water in UF moves northeast, dense saltwater in LF moves southwest	3.6
3	Kv of Hawthorn = 0.5 x base	0.01 isochlor moves 2 miles southwest in UF	3.7
4	Kv of Hawthorn = 2.0 x base	0.01 isochlor moves 2 miles northeast in UF	3.8
5	Kv of Semi-confining bed = 0.5 x base	Little change in UF 0.01 isochlor position, 0.025 and 0.05 move northeast	3.9
6	Kv of Semi-confining bed = 2.0 x base	0.01 isochlor moves northeast, higher isochlors southwest	3.10
7	Kh/Kv of Upper Floridan = 50:1	1/2 to 1 mile northeast movement of isochlors in UF	3.11
8	Kh/Kv of Lower Floridan = 10:1	Small northeast movement of isochlors in UF, southwest movement in LF	3.12
9	Kh/Kv of Lower Floridan = 200:1	Small northeast movement of isochlors in UF	3.13

Table 3.3. Summary of steady-state sensitivity runs made with the cross-sectional model (continued).

Sensitivity Run	Factor Varied	Result	Figure No.
10	High conductivity zone in Lower Floridan	Large northeast movement of isochlors in UF, large downward northeast movement of isochlors in LF	3.14
11	α_L and α_T in aquifers = 2.0 x base	Large northeast movement of isochlors in UF	3.15
12	α_L and α_T in aquifers = 0.5 x base	Large southwest movement of isochlors in UF	3.16
13	α_T in aquifers = 0.4 x base	Large northeast movement of isochlors in UF	3.17
14	α_L and α_T in middle semi-confining unit same as aquifers	Small southwest movement of isochlors in UF	3.18
15	Refined grid spacing	Very minor change	3.20
16	Coarse grid spacing	Very minor change	3.22

eliminating the specified head boundary condition in the Lower Floridan. This results in a no-flow boundary along the entire northeast boundary of the model. All flow along the cross-section in the Lower Floridan is diverted upward into the St. Johns River. The conceptual model is thus changed to one where the St. Johns River completely influences flow in the Lower Floridan, and there is no flow continuing on the northeast. The effect of this change is fairly limited in the Upper Floridan aquifer and in much of the Lower Floridan (Figure 3.5). Very little change is noted in the 0.01 to 0.5 concentration contours. Considerably less of a wedge of 0.5 chloride concentration is noted because there is primarily dispersive flux into the system. This scenario is useful in understanding the cross-sectional model, but has little bearing on the three-dimensional model because that model will extend beyond the St. Johns River.

The 500:1 upward hydraulic gradient on the northeastern boundary was independently eliminated from the model in the second sensitivity simulation. The gradient was originally input to account for some upward movement of water in the Lower Floridan toward the St. Johns River. Using the static head conceptualization assumes less influence of the St. Johns River on the Lower Floridan than in the original model. The effect of this change (Figure 3.6) is a minor lowering of concentration in the Upper Floridan and a flatter wedge in the Lower Floridan. This results from less salt being swept upward by the hydraulic gradient. From these results and available data, it is impossible to ascertain whether the 500:1 upward gradient is warranted. However, it does seem likely that the St. Johns River should have some influence in the Lower Floridan. Like the first scenario, this uncertainty is somewhat specific to the cross-sectional analysis because the St. Johns River will generally not be a boundary to the three-dimensional model.

3.4.2 Parameters

A series of simulations was performed to evaluate the sensitivity of the system to variations in hydrologic parameters. Changes to vertical hydraulic conductivities, anisotropy ratios, and

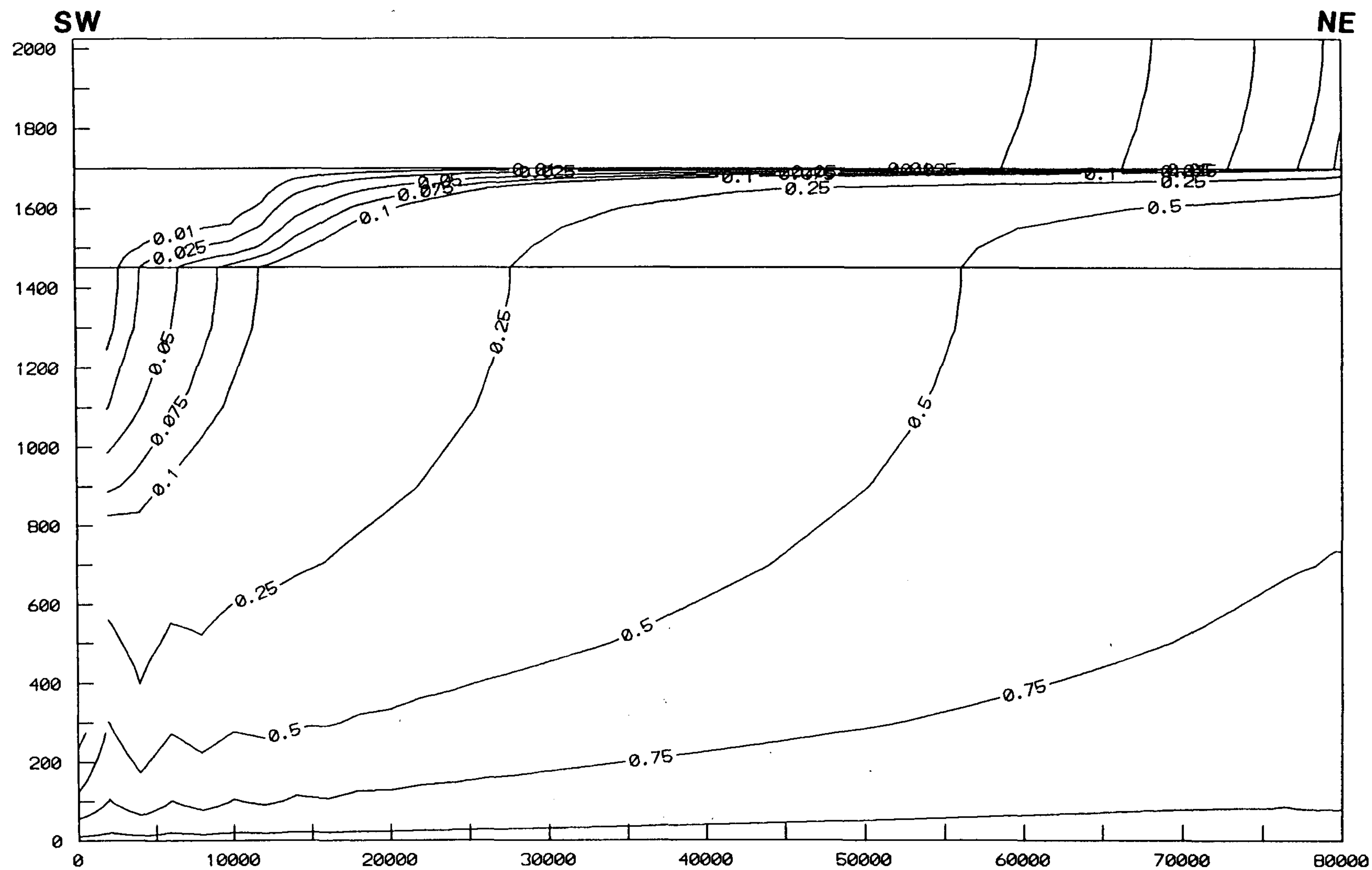

Figure 3.5. Relative chloride concentrations (1.0 = 19,000 mg/L) for a change to a no-flow boundary condition in the Lower Floridan aquifer beneath the St. Johns River.

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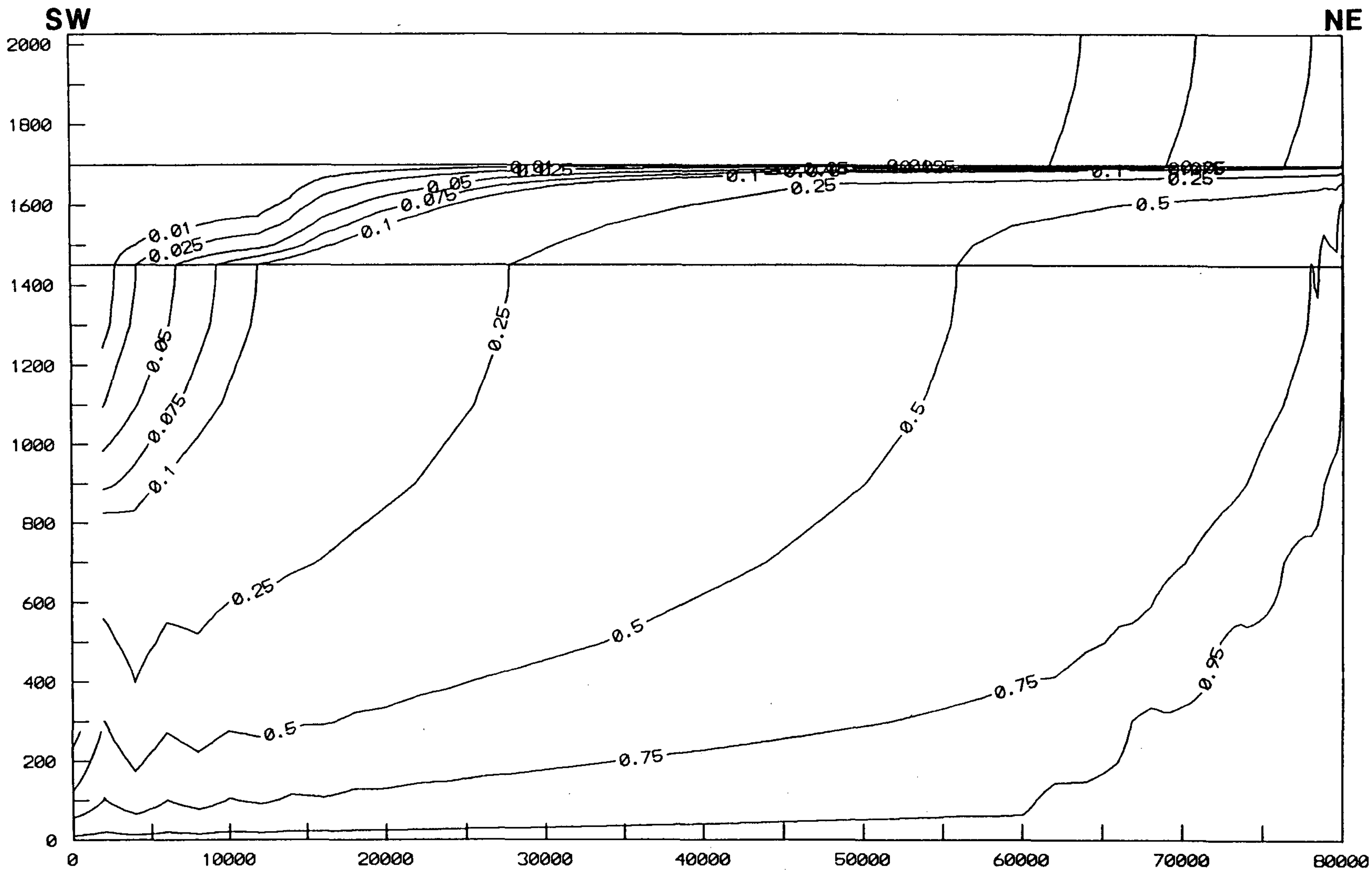

Figure 3.6. Relative chloride concentrations (1.0 = 19,000 mg/L) for a static hydraulic head boundary condition in the Lower Floridan aquifer beneath the St. Johns River.

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dispersivities were evaluated as a part of this analysis. Values of horizontal hydraulic conductivities were not changed because they were derived from calibration of the model and were consistent with flux boundary conditions assigned in the model.

The sensitivity of the model to change in the hydraulic conductivity of the upper confining bed and associated leakage from the surficial aquifer was examined by halving and doubling the conductivities. Halving the hydraulic conductivities results in less downward leakage and a significant (2 mile) southwest movement of the 0.01 to 0.05 concentration contours in the Upper Floridan (Figure 3.7). Some southwest movement is also noted in the 0.75 and 0.95 concentration contours in the Lower Floridan. As shown in Figure 3.8, doubling the hydraulic conductivity of the upper confining bed has the opposite effect. Greater leakage into the system pushes the 0.01 to 0.05 concentration contours to the northeast. The hydraulic conductivity of the upper confining bed appears to be very influential in governing the amount of saltwater intrusion. This influence is magnified by uncertainty in the homogeneity of this bed.

The influence of the vertical hydraulic conductivity of the middle semi-confining unit on chloride concentrations was also examined in the sensitivity analysis. Halving the hydraulic conductivity caused a very slight northeast movement of chloride contours in the Upper Floridan as shown in Figure 3.9. This results from less upward movement of salty water from below. Little change was noted in the Lower Floridan isochlors. Doubling the hydraulic conductivity of the middle semi-confining unit caused slightly higher concentrations in the Upper Floridan (Figure 3.10). The 0.1 chloride concentration contour occurs where the 0.075 contour previously occurred. This results from more upward movement of salty water from below. Again, little change is noted in the Lower Floridan. Changes of this magnitude in middle semi-confining unit hydraulic conductivity appears to have only a limited effect on the flow system.

The ratio of horizontal to vertical hydraulic conductivities in the Upper Floridan was changed from 10:1 to 50:1 in sensitivity run 7.

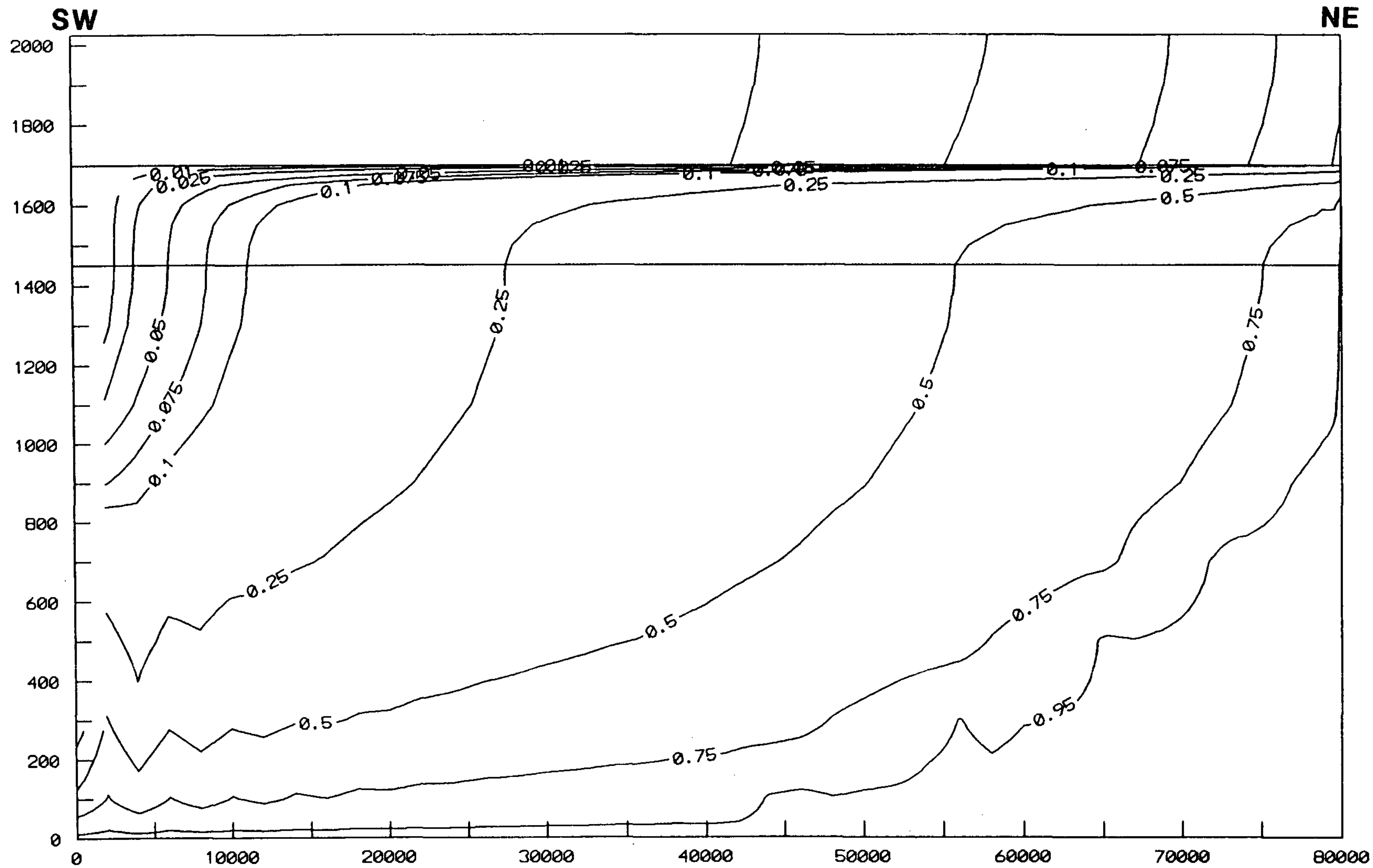

Figure 3.7. Relative chloride concentrations (1.0 = 19,000 mg/L) for a halving of the vertical hydraulic conductivity of the upper confining bed.

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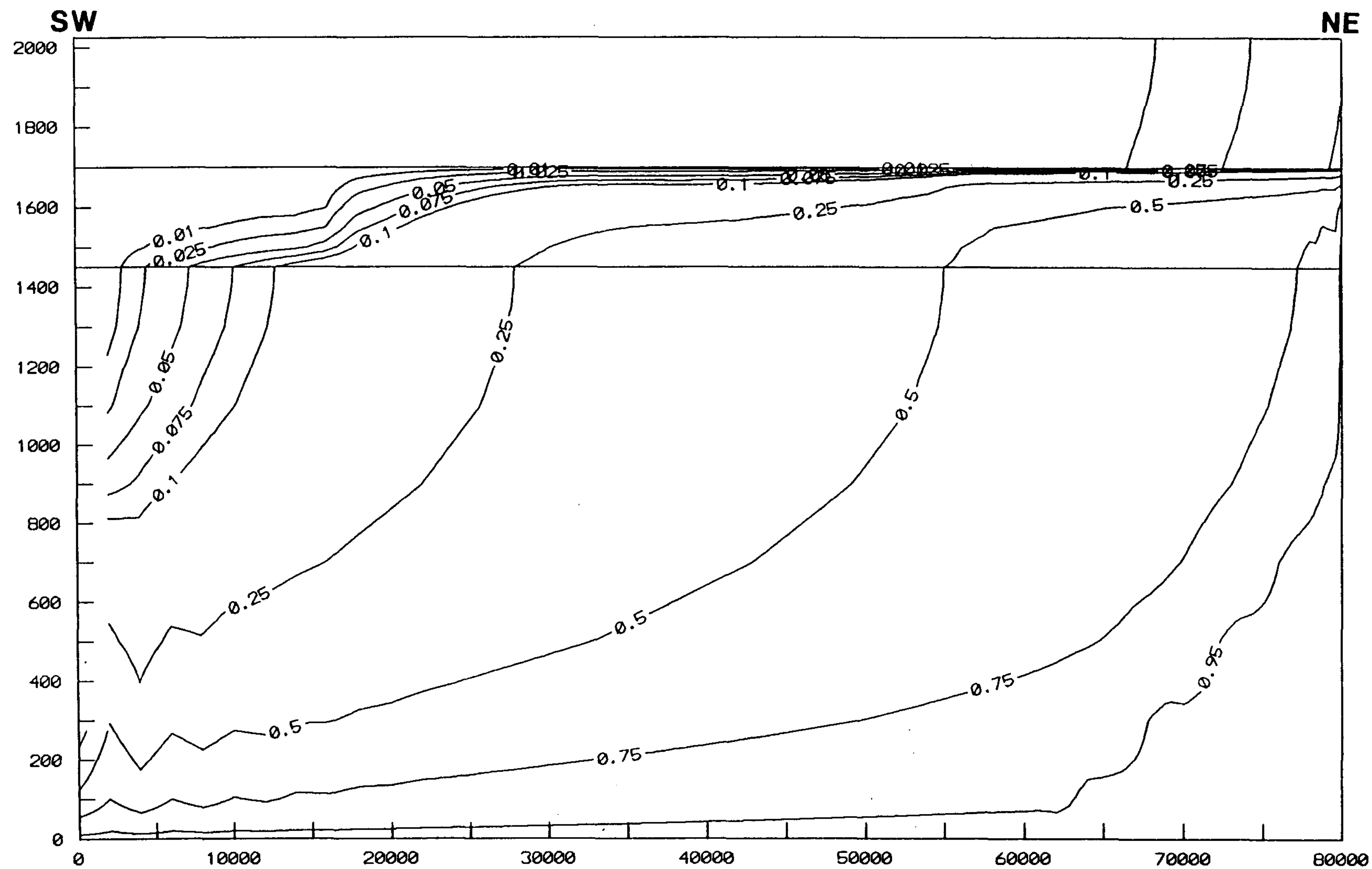

Figure 3.8. Relative chloride concentrations (1.0 = 19,000 mg/L) for a doubling of the vertical hydraulic conductivity of the upper confining bed.

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P 7602-003/OA/11

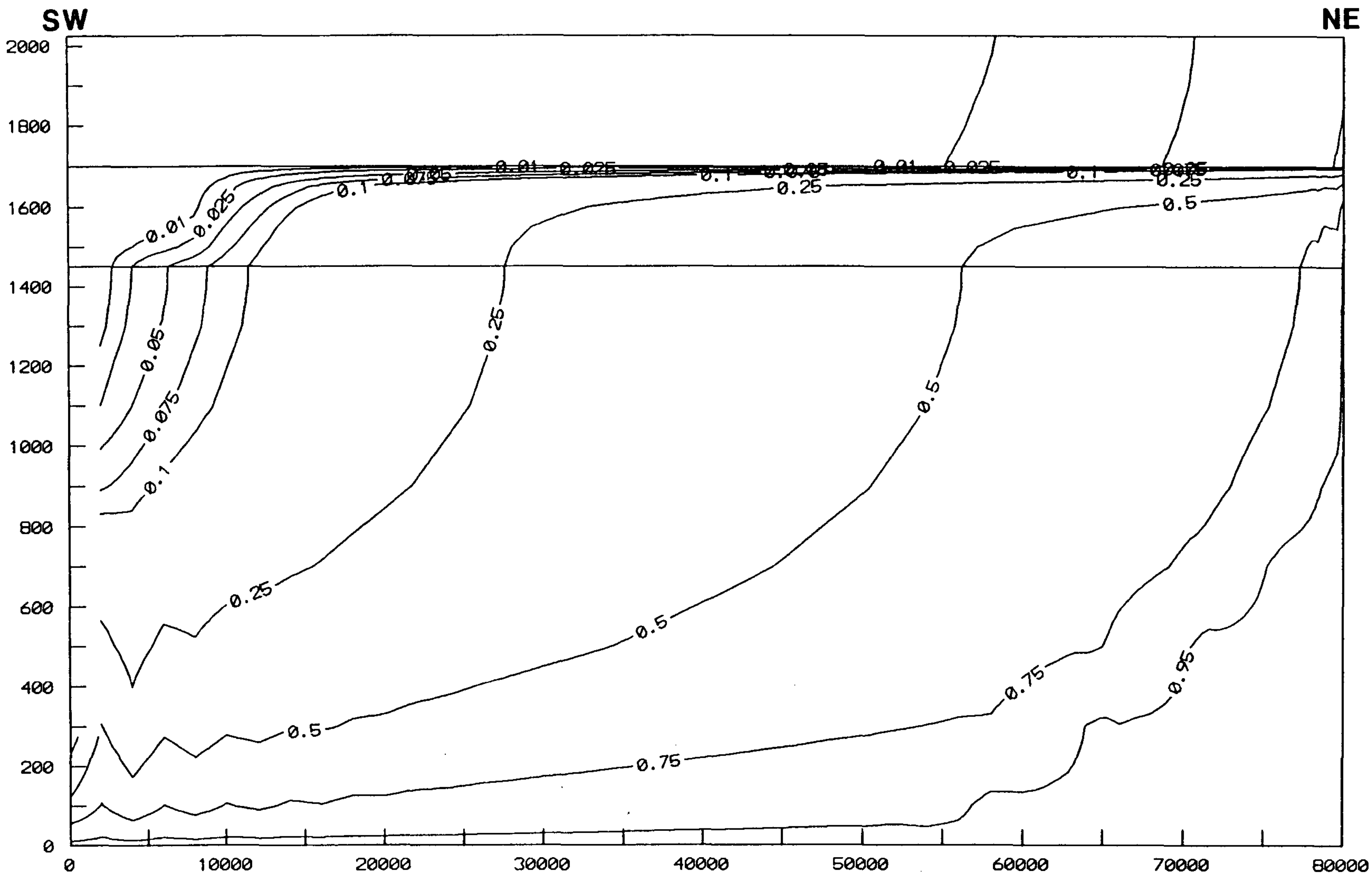

Figure 3.9. Relative chloride concentrations (1.0 = 19,000 mg/L) for a halving of the vertical hydraulic conductivity of the semi-confining bed separating the Upper and Lower Floridan aquifers.

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P 7602-003/OA/13

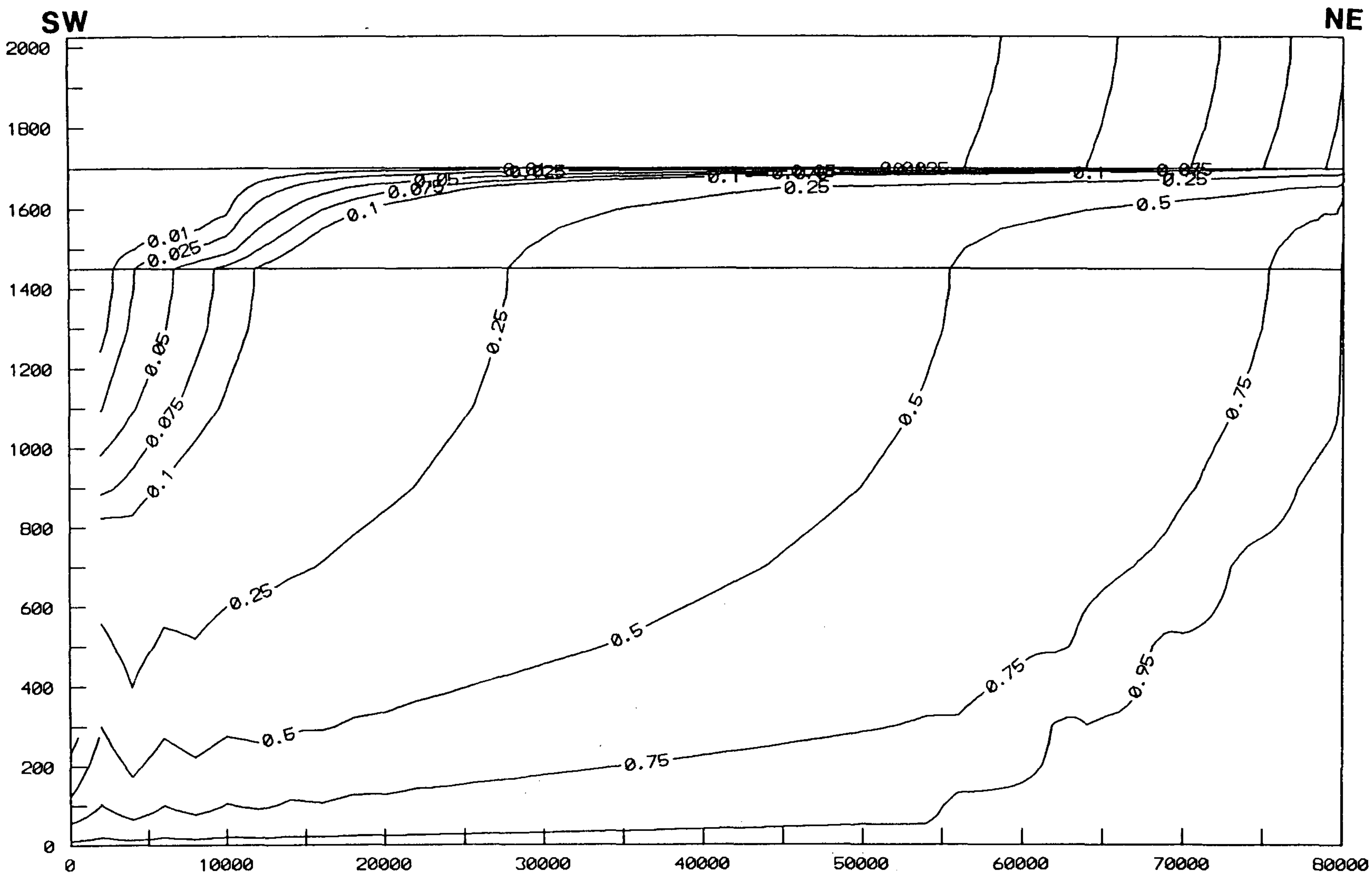

Figure 3.10. Relative chloride concentrations (1.0 = 19,000 mg/L) for a doubling of the vertical hydraulic conductivity of the semi-confining bed separating the Upper and Lower Floridan aquifers.

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As shown in Figure 3.11, a 3000 ft to 4000 ft northeast movement of the 0.01 to 0.05 chloride concentration contours occurs in the Upper Floridan while very little effect is noted in the Lower Floridan. The movement results from a greater flow within the Upper Floridan due to less leakage to below.

Anisotropy within the Lower Floridan was assessed in sensitivity runs 8 and 9. In run 8, the horizontal to vertical ratio of hydraulic conductivity was reduced from 50:1 to 10:1. This caused limited northeast movement of isochlors in the Upper Floridan and limited southwest movement of isochlors in the Lower Floridan (Figure 3.12). Note the oscillations that occur near the southwest boundary for this simulation. These oscillations are a direct result of the anisotropy ratio reduction: it is generally easier to solve a problem of this nature if it has a high anisotropy ratio. The oscillation can be circumvented using finer elements near the southwest boundary. The anisotropy ratio was raised to 200:1 in run 9 (Figure 3.13). This resulted in a more stable solution with only limited movement of isochlors in both aquifers. Comparison of Figures 3.12 and 3.13 indicate that the steady-state simulations are relatively insensitive to changes in anisotropy ratio in the Lower Floridan.

Heterogeneity or hydraulic conductivity zonation is likely in both aquifers. Sensitivity run 10 was made to assess the effect of a hypothetical regional high hydraulic conductivity zone. A zone with hydraulic conductivities ten times greater than the bulk of the Lower Floridan was included in the upper 350 ft of the Lower Floridan. For consistency, the bulk transmissivity of the Lower Floridan remained the same as in the original model and fluxes on the southwest side were adjusted to reflect the zonation change. As shown in Figure 3.14, this change has a marked effect on the flow system. Concentration contours are pushed toward the northeast in the upper part of the Lower Floridan. The magnitude of this movement is approximately 5 miles for the 0.1 contour. Northeasterly movement of chloride contours is also noted in the lower part of the Lower Floridan and, to a limited extent, in the Upper Floridan. Regional

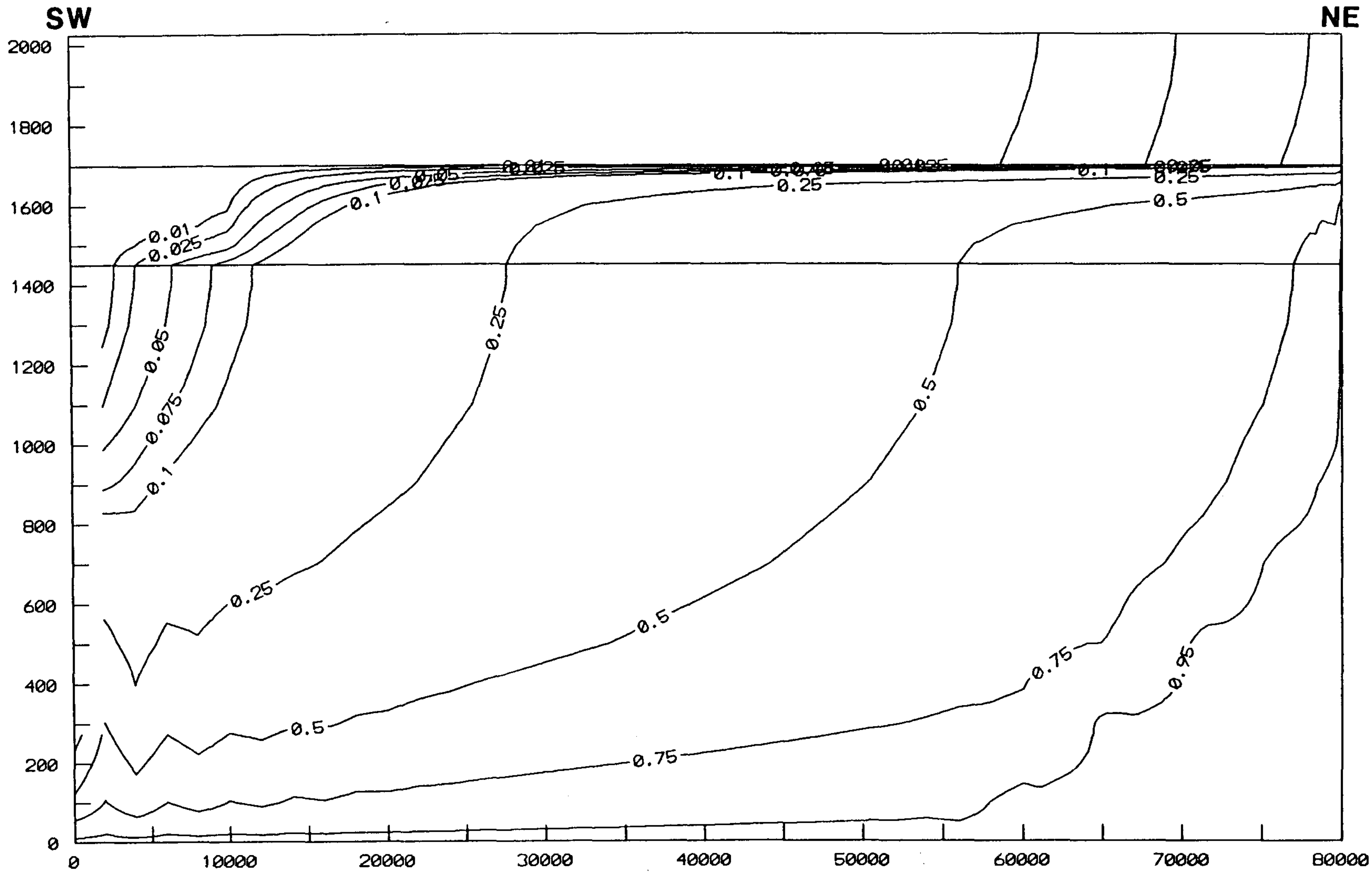

Figure 3.11. Relative chloride concentrations (1.0 = 19,000 mg/L) for a 50:1 horizontal to vertical hydraulic conductivity ratio in the Upper Floridan aquifer.

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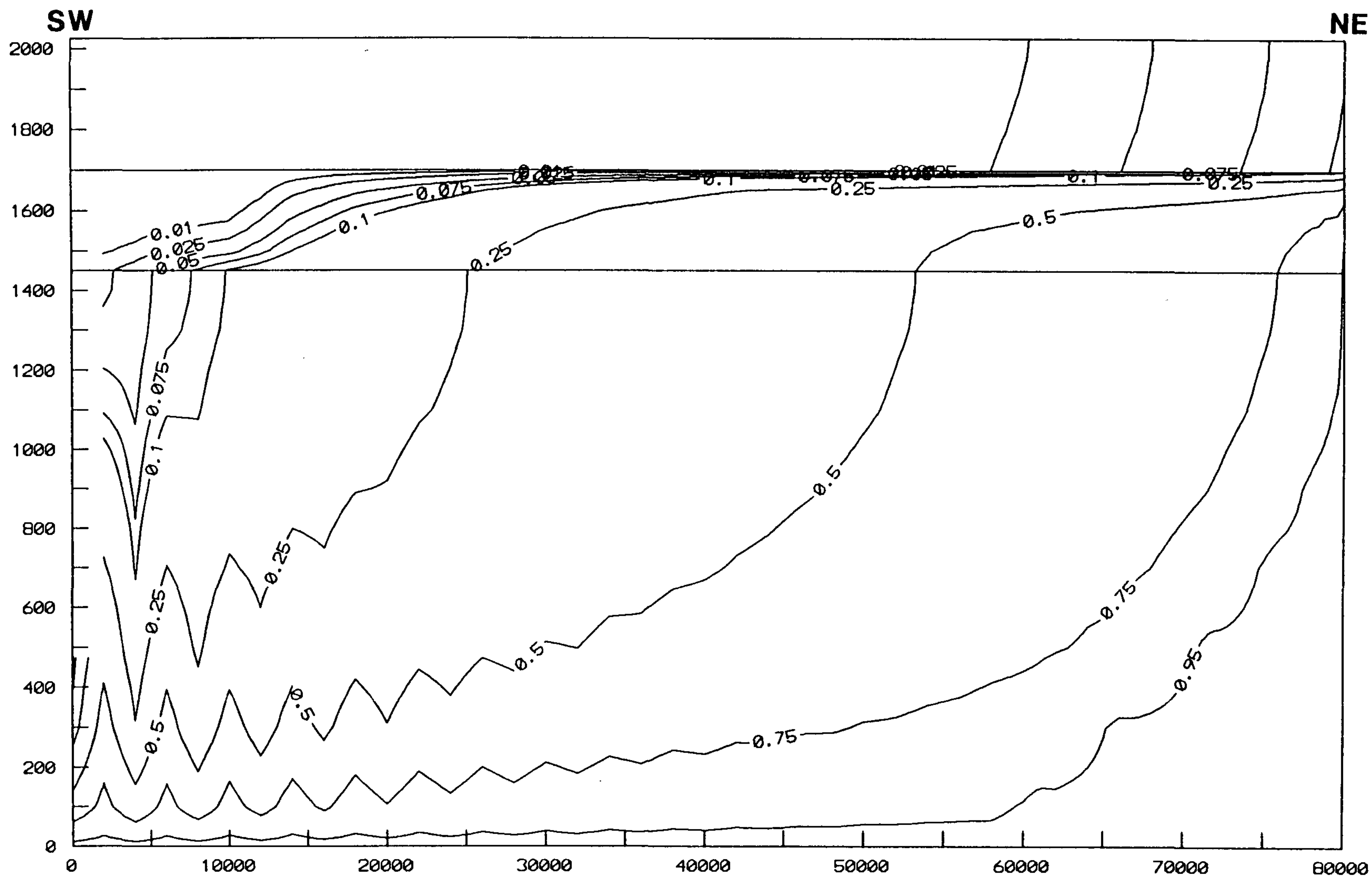

Figure 3.12. Relative chloride concentrations (1.0 = 19,000 mg/L) for a 10:1 horizontal to vertical hydraulic conductivity ratio in the Lower Floridan aquifer.

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P 7602-003 /OA/16

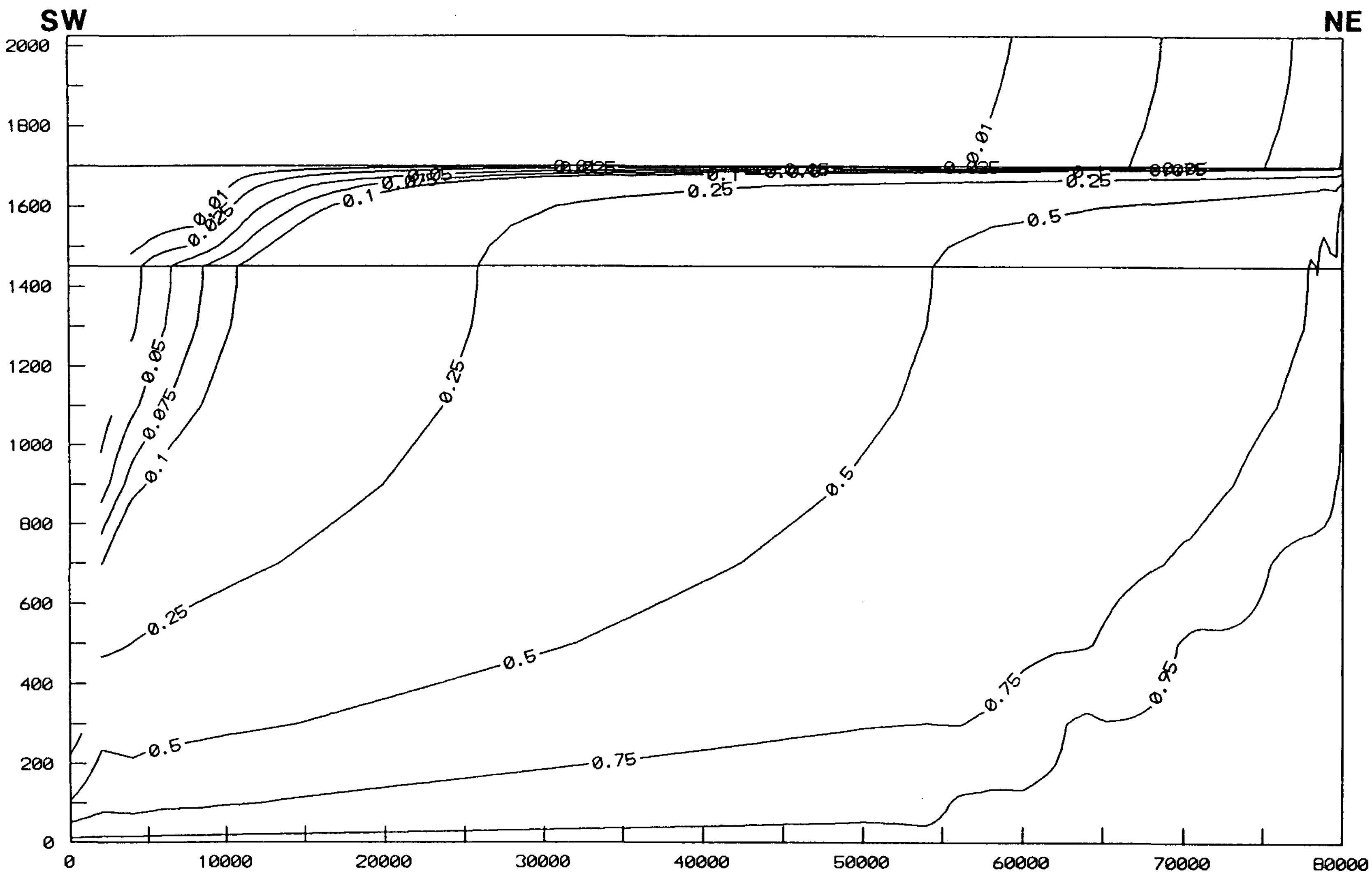

Figure 3.13. Relative chloride concentrations (1.0 = 19,000 mg/L) for a 200:1 horizontal to vertical hydraulic conductivity rate in the Upper Floridan aquifer.

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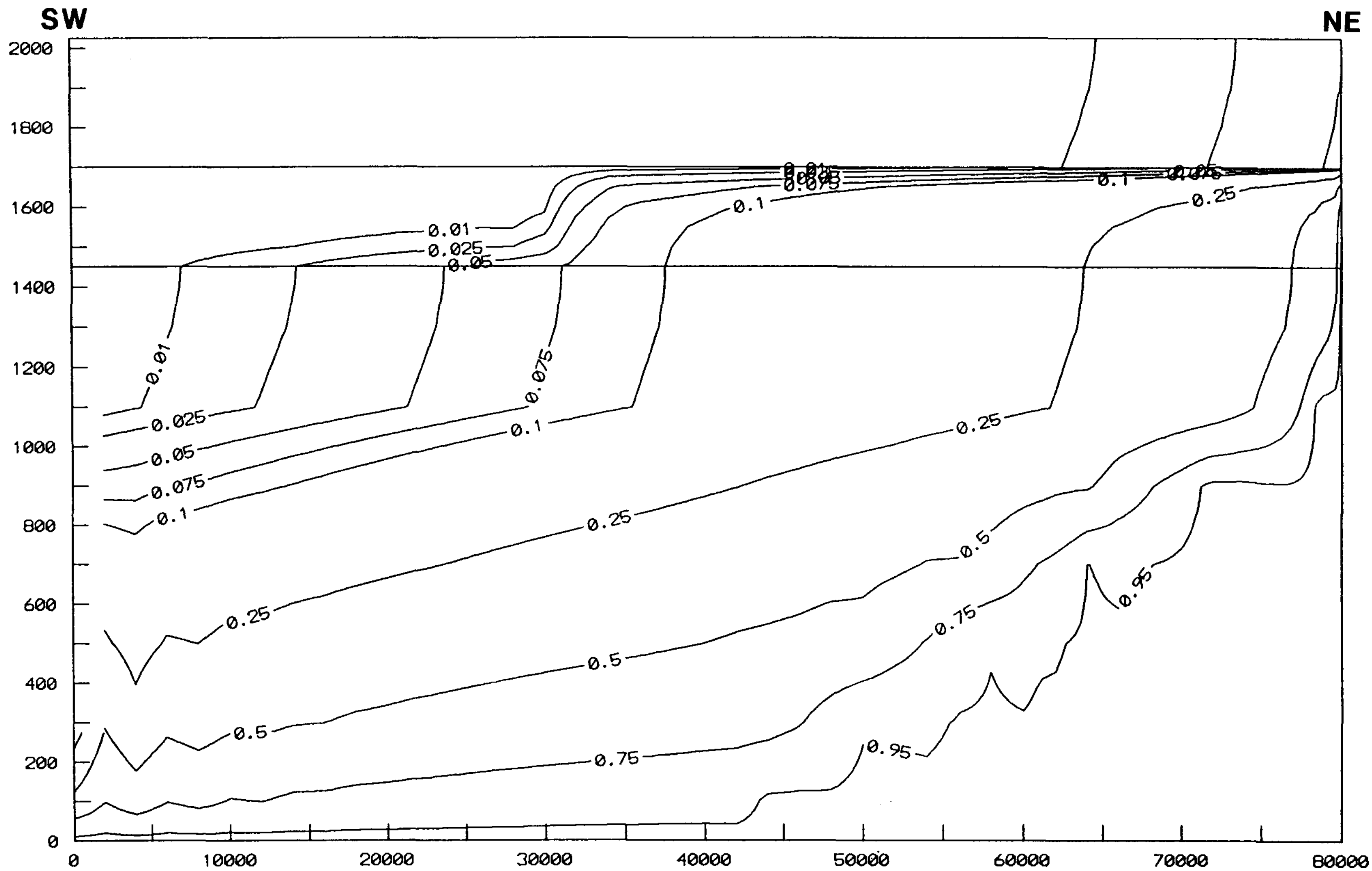

Figure 3.14. Relative chloride concentrations (1.0 = 19,000 mg/L) for a high conductivity zone in the upper portion of the Lower Floridan aquifer.

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zonation within aquifers appears to be an important consideration for this flow system. Although zonation is difficult to document and quantify, both the cross-sectional and three dimensional model will have the capability of incorporating zonation data as it becomes available.

Also examined in the sensitivity analysis was the influence of dispersivities on the system. In run 11 the longitudinal and transverse dispersivities were set to double that of the original model (α_L = 240 ft and α_T = 60 feet). This caused Lower Floridan isochlors to move southwesterly and upward but caused the Upper Floridan isochlors to move to the northeast (Figure 3.15). Halving the dispersivities to α_L = 60 ft and α_T = 15 ft had the opposite effect, causing the Lower Floridan isochlors to move northeast and the Upper Floridan isochlors to move southwest (Figure 3.16). Halving the dispersivities also caused the wedge shape of the chloride contours to flatten in both aquifers. A small amount of instability is also noted on the northeastern side of the model. Comparing Figures 3.15 and 3.16 indicate that the model is fairly sensitive to changes of this magnitude in dispersivity.

Shown in Figure 3.17 are the results of a simulation (run 13) where transverse dispersivity (α_T) was reduced by a factor of 2.5 in the Upper and Lower Floridan aquifers. This resulted in a 10:1 ratio of α_L to α_T. Isochlors of 0.5 or lower move toward the northeast in the Lower Floridan, while the isochlors in the Upper Floridan spread out and become less steep. The modeling is again fairly sensitive to this type of change.

In sensitivity run 14, the dispersivities in the middle semi-confining layer were raised to the values used for the aquifers. As shown in Figure 3.18, this resulted in almost no change in the Lower Floridan but a 2000 ft shift to the southwest of isochlors in the Upper Floridan. Because of the small travel distance in the middle semi-confining unit, it seems unlikely that dispersivity in this unit should be as high as in the aquifers. Nevertheless, the change had only a limited effect on simulation results.

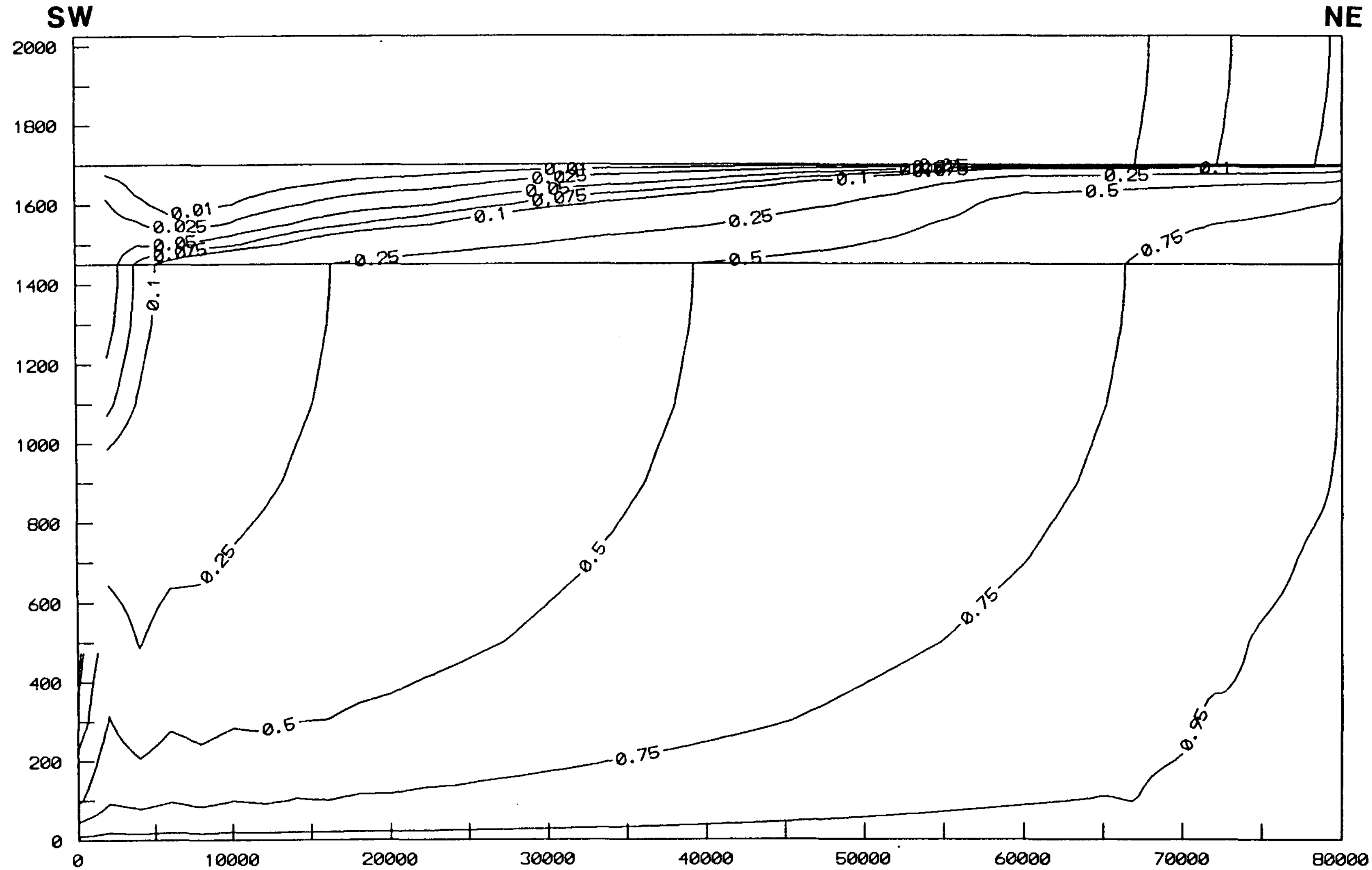

Figure 3.15. Relative chloride concentrations (1.0 = 19,000 mg/L) for a doubling of longitudinal and transverse dispersivities in the aquifers.

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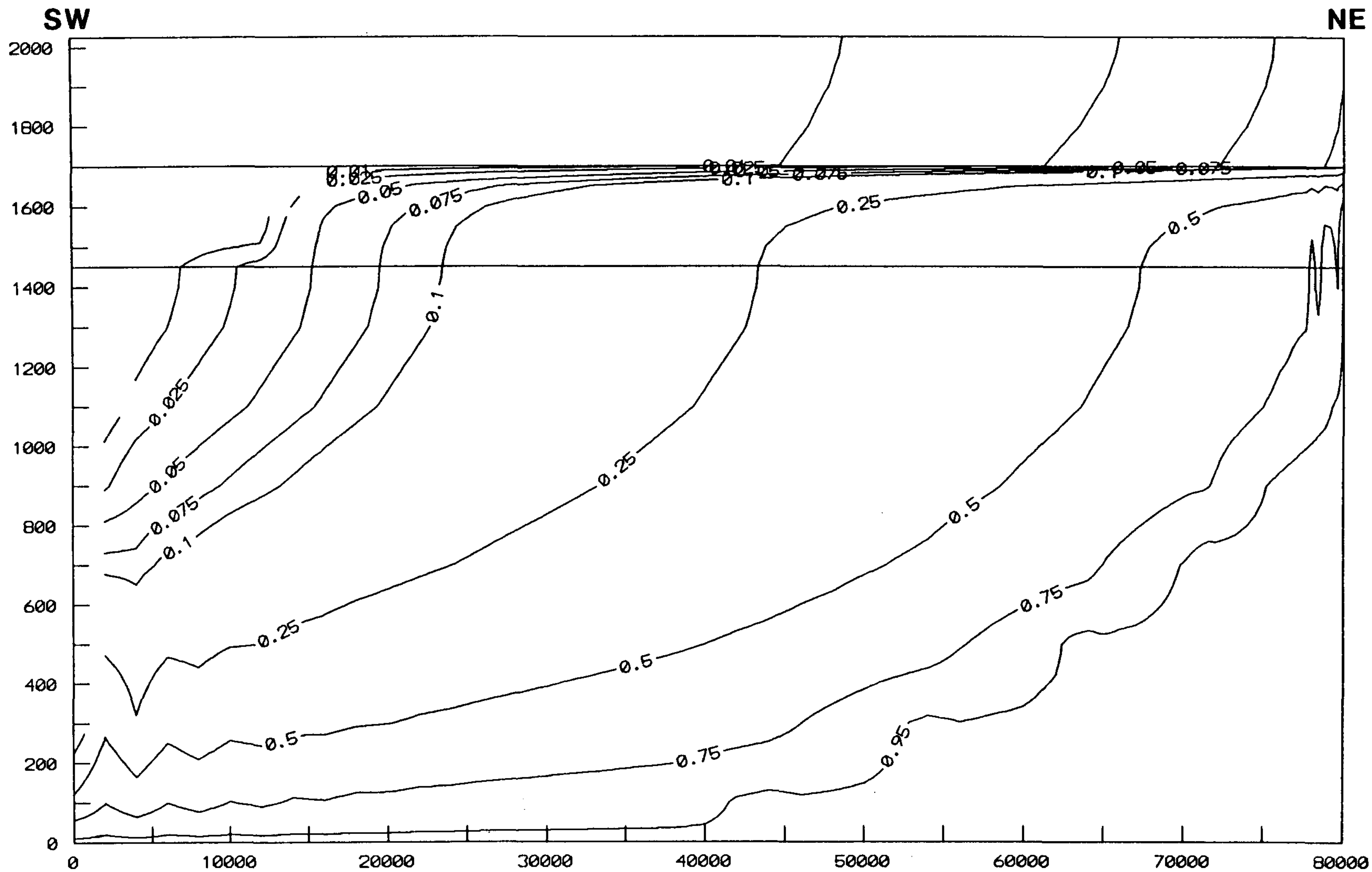

Figure 3.16. Relative chloride concentrations (1.0 = 19,000 mg/L) for a halving of longitudinal and transverse dispersivities in the aquifers.

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GROUNDWATER SPECIALISTS
P7602-003 /OA/20

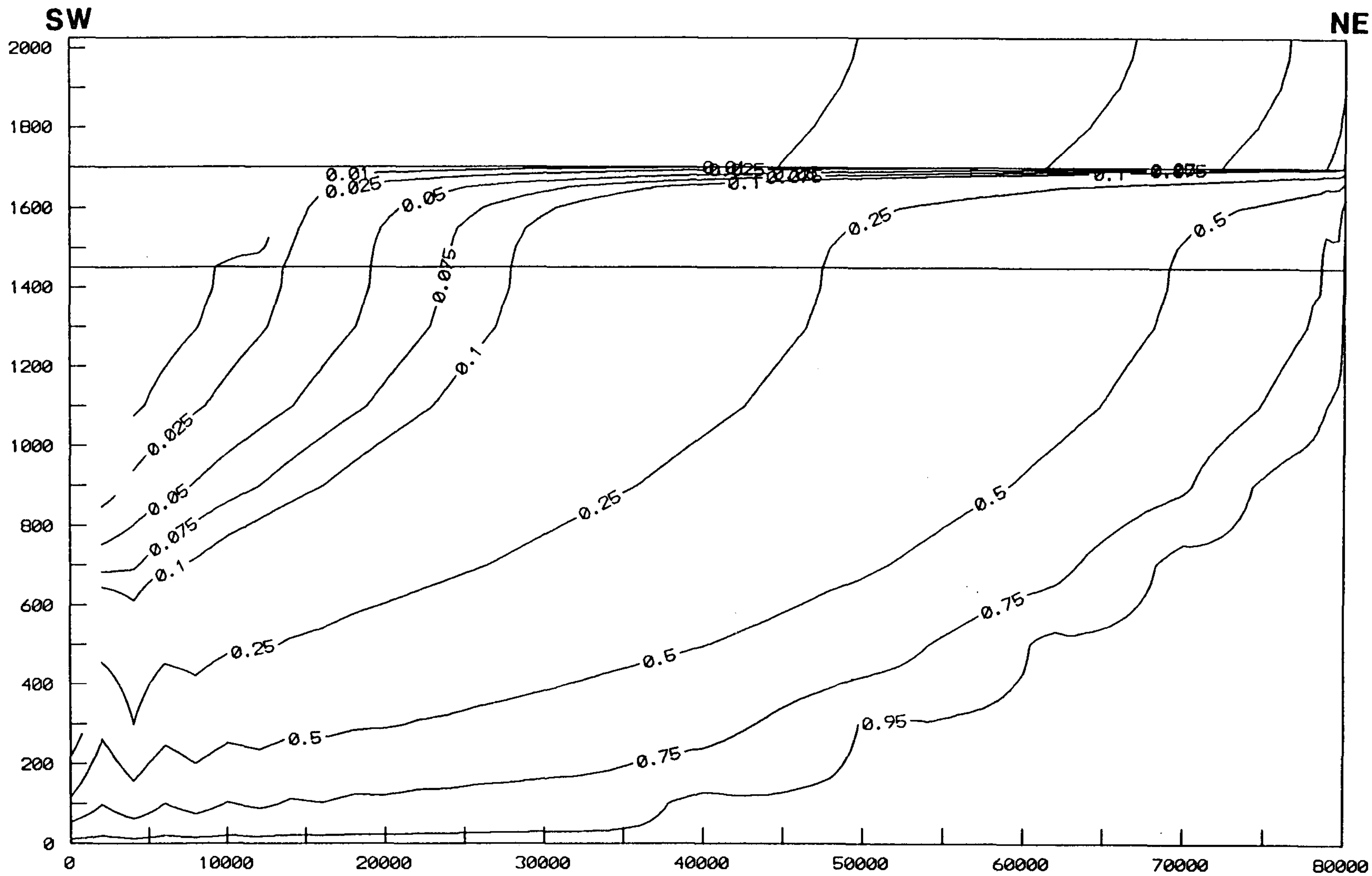

Figure 3.17. Relative chloride concentrations (1.0 = 19,000 mg/L) for a 2.5 fold reduction in transverse dispersivity in the aquifers.

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P7602-003/OA/21

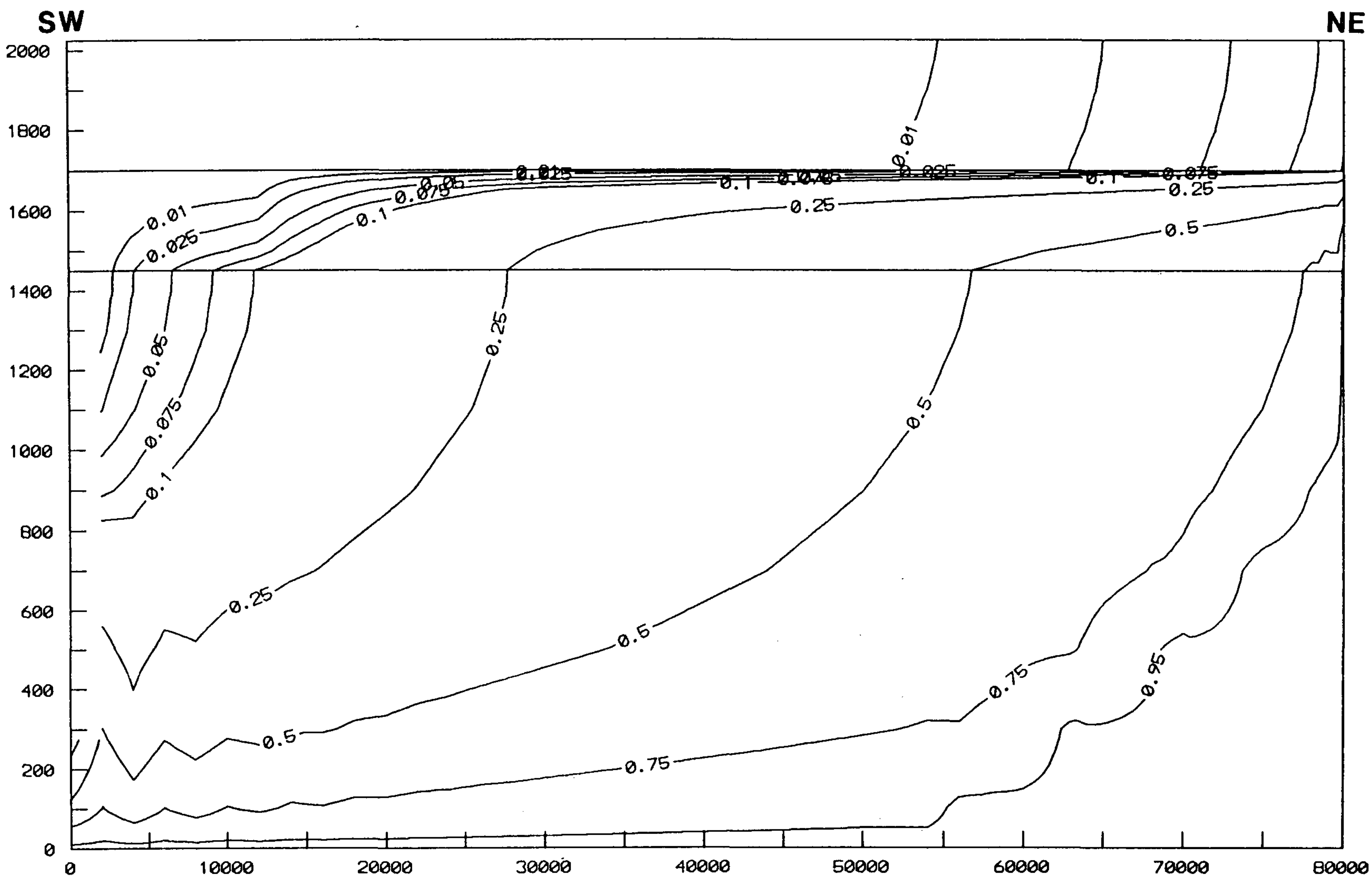

Figure 3.18. Relative chloride concentrations (1.0 = 19,000 mg/L) for change to α_L = 120 ft, α_T = 30 ft in the semi-confining bed separating the Upper and Lower Floridan aquifers.

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3.4.3 Discretization

The influence of grid discretization was also examined in the sensitivity analysis. Figure 3.2 depicts the medium grid used for the previously mentioned runs. The model was divided into 61 nodal columns and 19 nodal rows with column spacing ranging from 500 to 2000 ft and row spacing from 50 to 200 ft. A sensitivity run using original model parameters was performed using a finer grid spacing depicted in Figure 3.19. The grid had 101 nodal columns and 27 nodal rows with horizontal spacing ranging from 500 to 1000 ft and vertical spacing from 50 to 100 ft. Comparing results from the fine grid simulation (Figure 3.20) with that of the medium mesh simulation (Figure 3.4) shows a relatively small variation in isochlors. Also examined was a coarse mesh simulation using a number of nodes designed for a three-dimensional simulation. The coarse grid (Figure 3.21) is divided into 41 nodal columns and 14 nodal rows with horizontal spacing ranging from 500 to 3000 ft and vertical spacing ranging from 50 to 400 ft. Note that horizontal spacings at both ends are 500 ft. Comparing the coarse grid simulation (Figure 3.22) with the fine grid simulation (Figure 3.20) shows the results to be similar. It appears from this analysis that a well designed coarse mesh, similar to the one presented here, will be suitable for the three-dimensional analysis.

3.5 TRANSIENT SENSITIVITY ANALYSIS

The original model and three of the sensitivity analyses were also run as transient analyses using the steady-state results as initial conditions (Table 3.4). The purpose of this exercise was to assess the influence of hydrologic parameters and boundary conditions on flow and transport to the Upper Floridan production zone. The coarse grid, which typifies the spacing to be used in the three-dimensional analysis, was used for the transient sensitivity analysis. The production zone was represented by a nodal flux of 10 $ft^3/d/ft$ located 31000 ft from the northeastern boundary, 50 ft above the middle semi-confining unit. Chloride distributions after 51 years of pumping are presented in Figure 3.23. Comparing these concentrations

Table 3.4. Summary of transient sensitivity runs made with the cross-sectional model.

Sensitivity Run	Factor Varied	Result	Figure No.
16	Base	--	3.22
17	10 ft^3/d/ft stress in Upper Floridan	Southwest movement of isochlors in UF	3.23
18	10 ft^3/d/ft stress in Upper Floridan, 10:1 Kh/Kv ratio in Lower Floridan	Southwest movement of isochlors in UF (not as great as in run 15)	3.24
19	10 ft^3/d/ft stress in Upper Floridan, no flow boundary in Lower Floridan	Northwest movement of 0.1 and greater isochlors in UF, southwest movement in LF	3.25

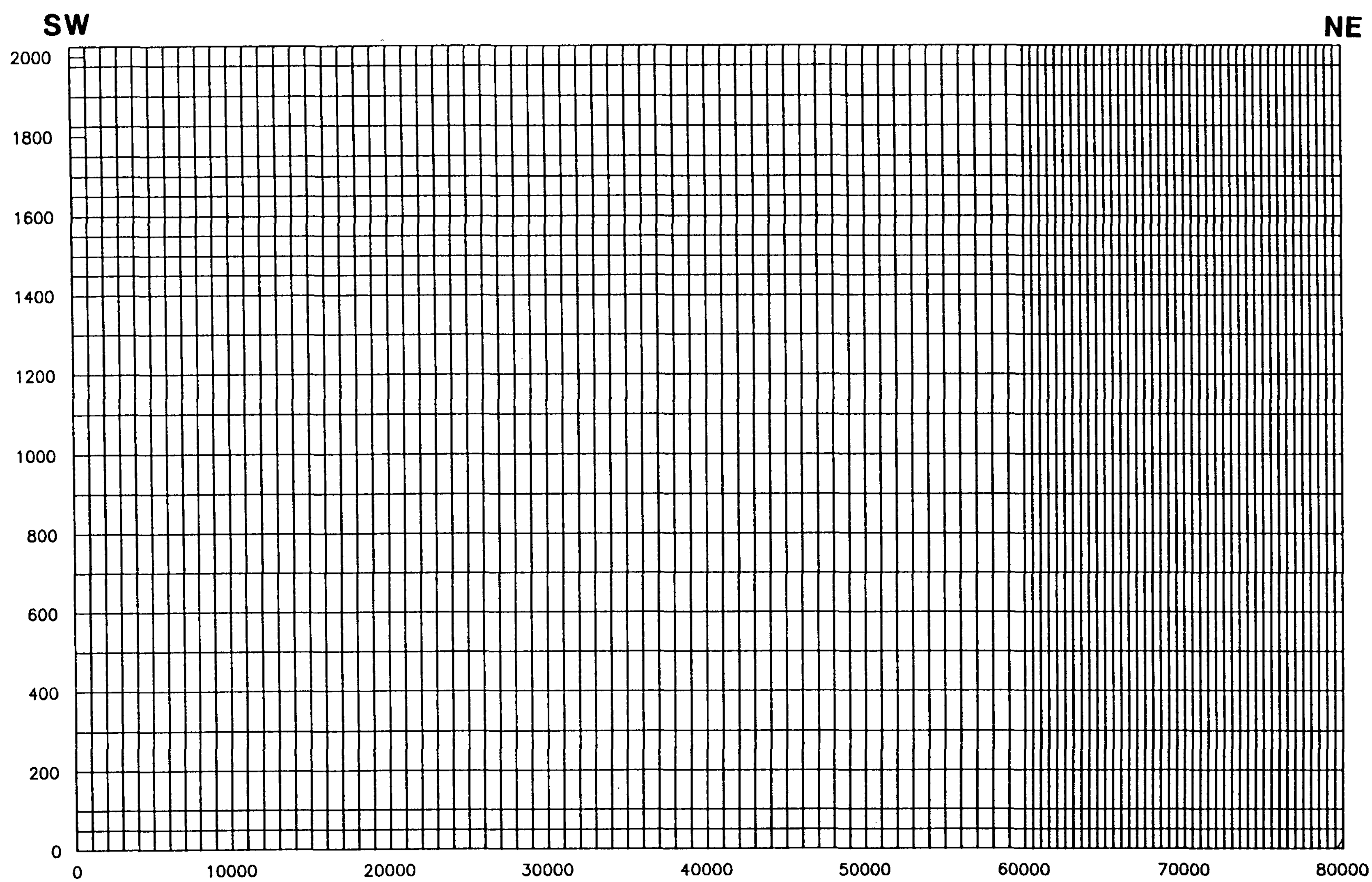

Figure 3.19. Finite-element grid spacing for the fine gridded model.

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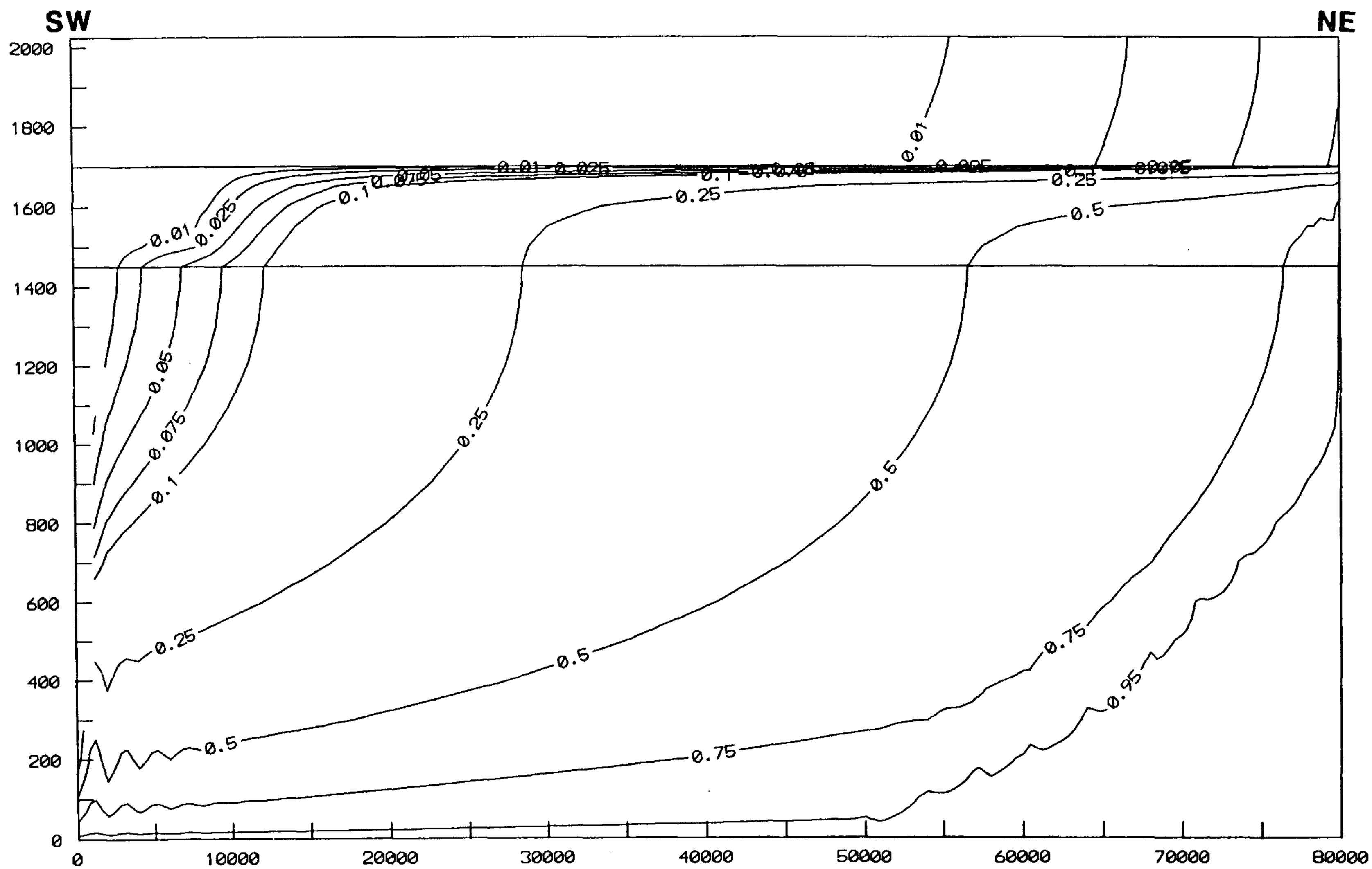

Figure 3.20. Relative chloride concentrations (1.0 = 19,000 mg/L) for the cross-sectional model using the fine grid.

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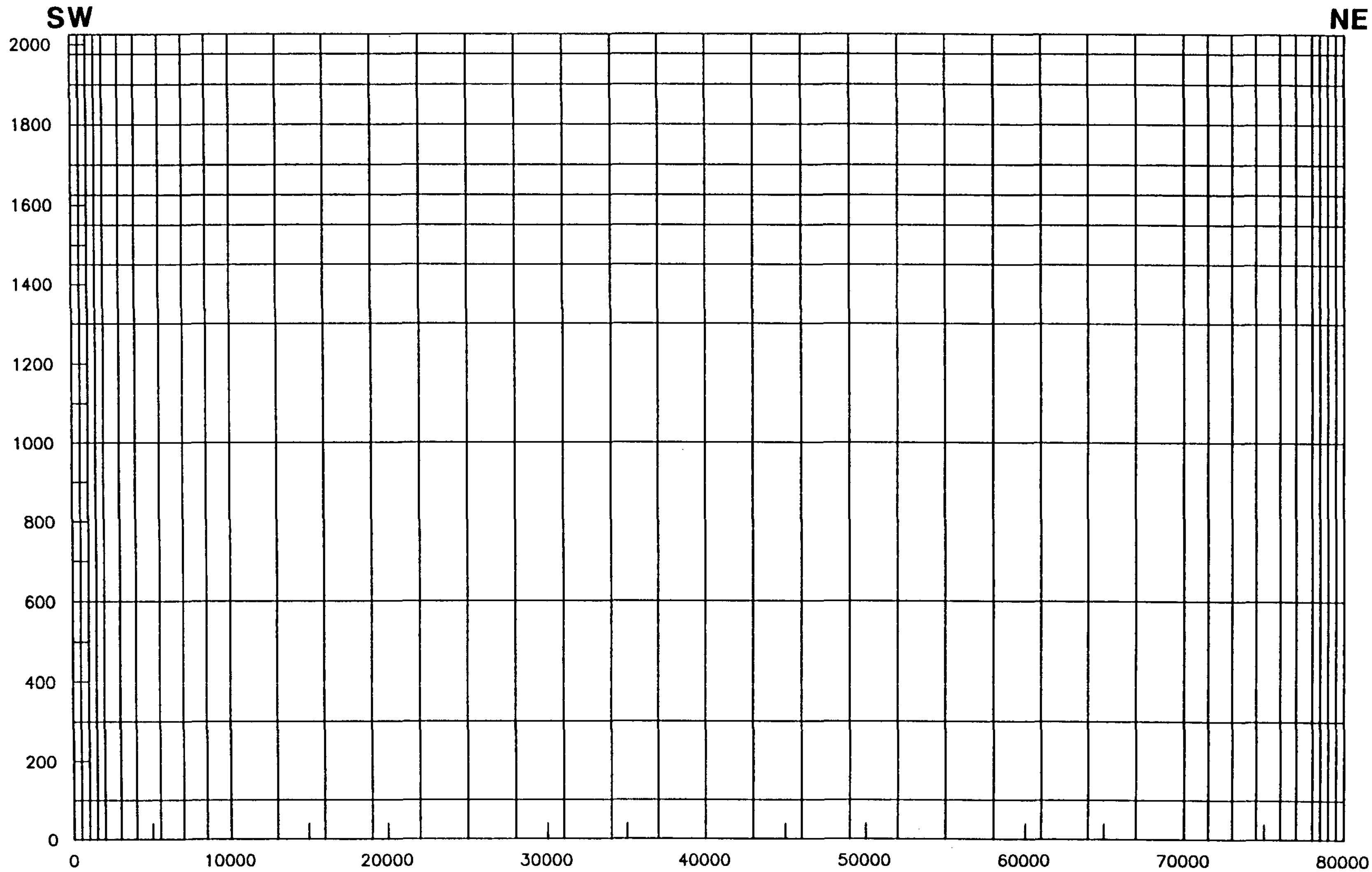

Figure 3.21. Finite-element grid spacing for the coarse gridded model.

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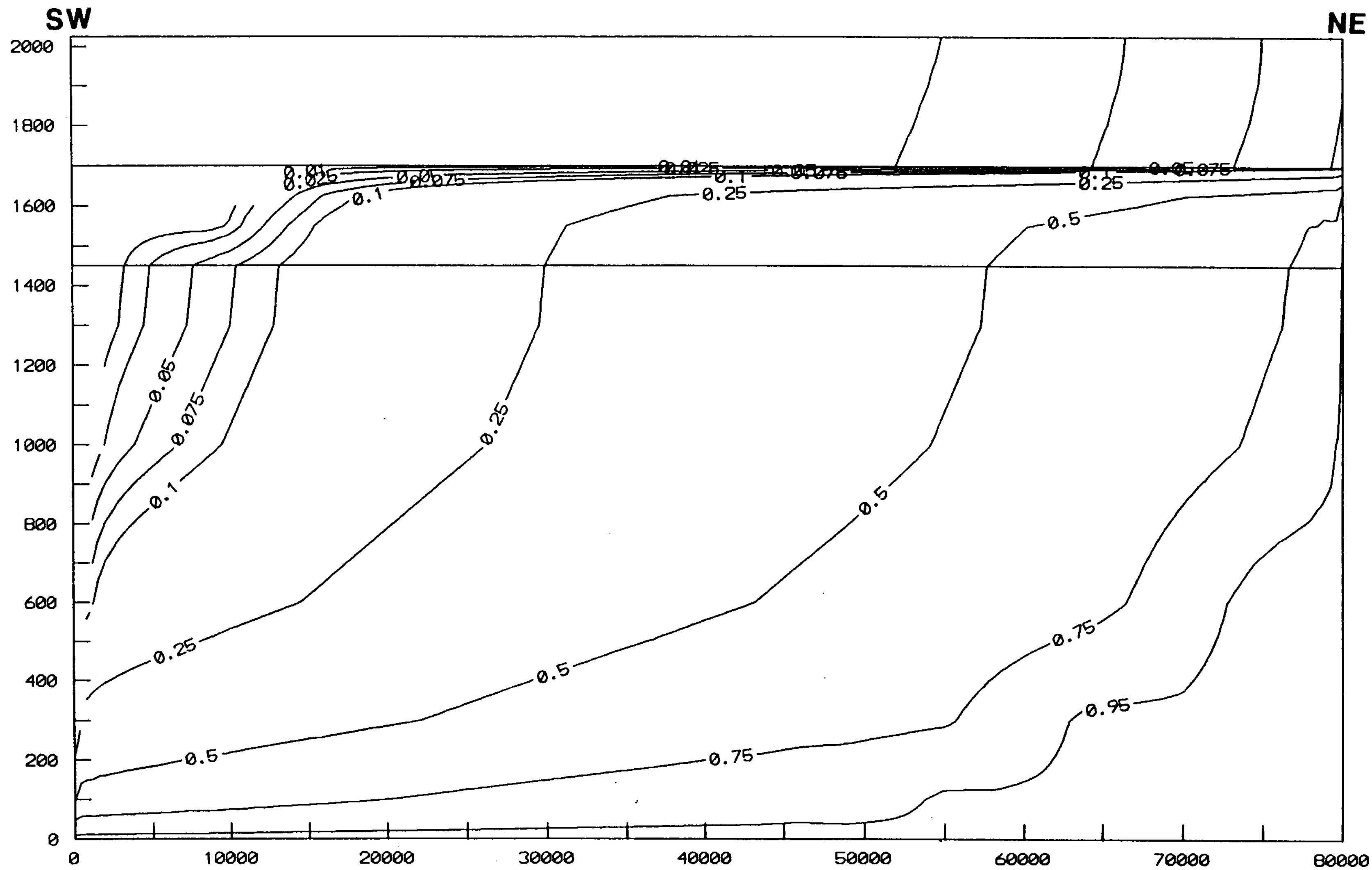

Figure 3.22. Relative chloride concentrations (1.0 = 19,000 mg/L) for the cross-sectional model using the coarse grid.

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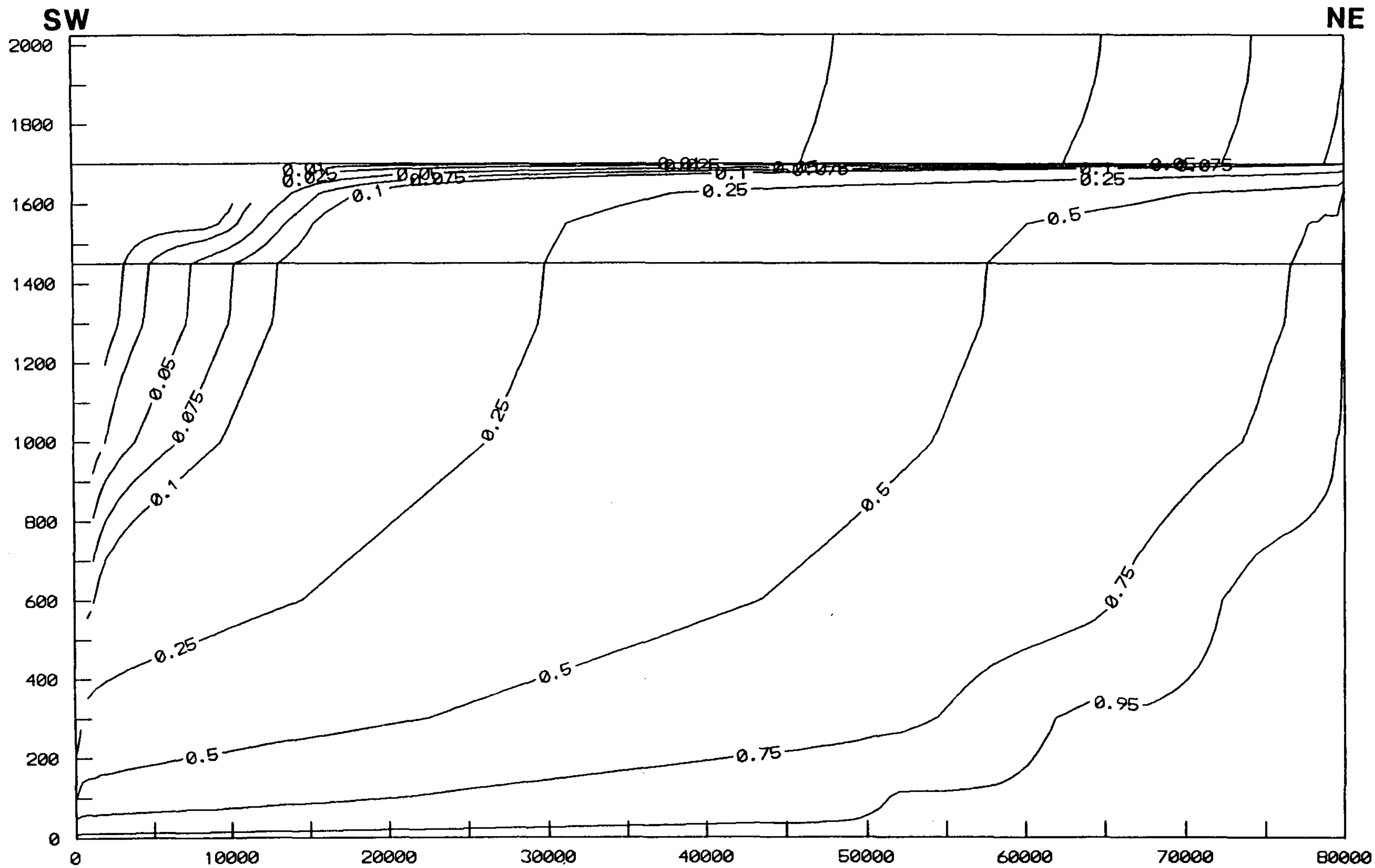

Figure 3.23. Relative chloride concentrations (1.0 = 19,000 mg/L) after 51 years for a transient simulation involving a stress of 10 ft^3/d/ft in the Upper Floridan aquifer.

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to those of Figure 3.22 show a 5000 ft southwesterly movement of the 0.01 concentration contour in the Upper Floridan aquifer. Movement of other contours is less in the Upper Floridan, with no perceptible change in the Lower Floridan. The model appears to be capable of simulating a transient stress scenario using the coarse grid.

A transient simulation of the same stress was also made with the 10:1 ratio of horizontal to vertical hydraulic conductivity. Comparing the results of this simulation (shown in Figure 3.24) to the steady-state equivalent shown in Figure 3.12 shows southwesterly movement of isochlors in both the Upper and Lower Floridan aquifers. Of greater interest, however, is that the numerical instability present in the steady state medium grid results has vanished in the transient coarse grid results. This is the result of two things: grid refinement in the area of instability and the transient nature of the simulation. The stability of the results also supports the viability of a well designed coarse mesh for the three dimensional analysis.

The final transient simulation assessed the transient effect of stressing the aquifer combined with a no-flow boundary along the northeastern side of the model in the Lower Floridan. The results of this simulation after the 51 years of pumping are shown in Figure 3.25. These results may be compared to those of Figure 3.5, which is the steady state equivalent. Very little change is noted between the two simulations.

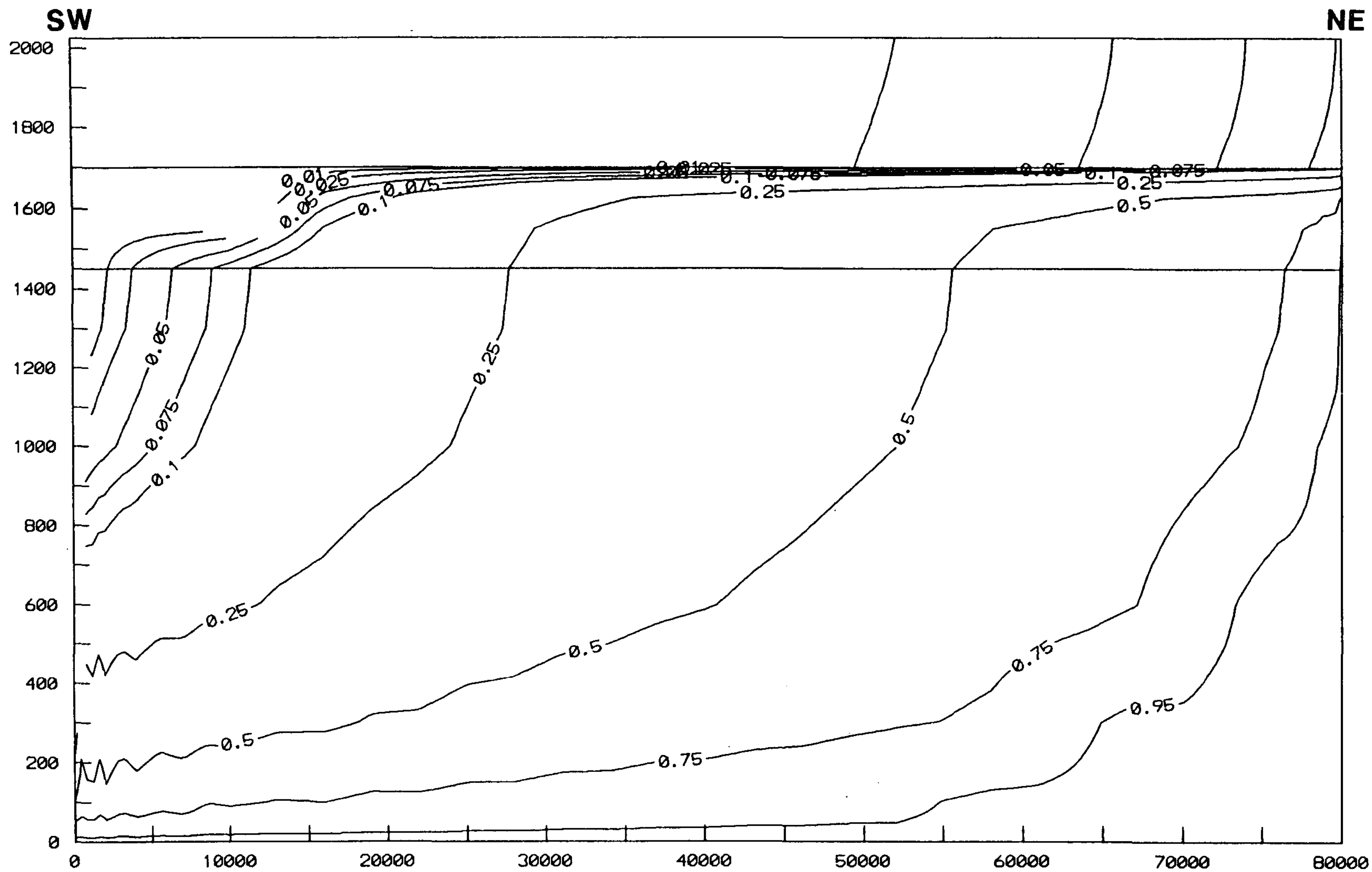

Figure 3.24. Relative chloride concentrations (1.0 = 19,000 mg/L) after 51 years for a simulation with a 10:1 horizontal to vertical hydraulic conductivity ratio in the Lower Floridan aquifer and a stress of 10 $ft^3/d/ft$ in the Upper Floridan aquifer.

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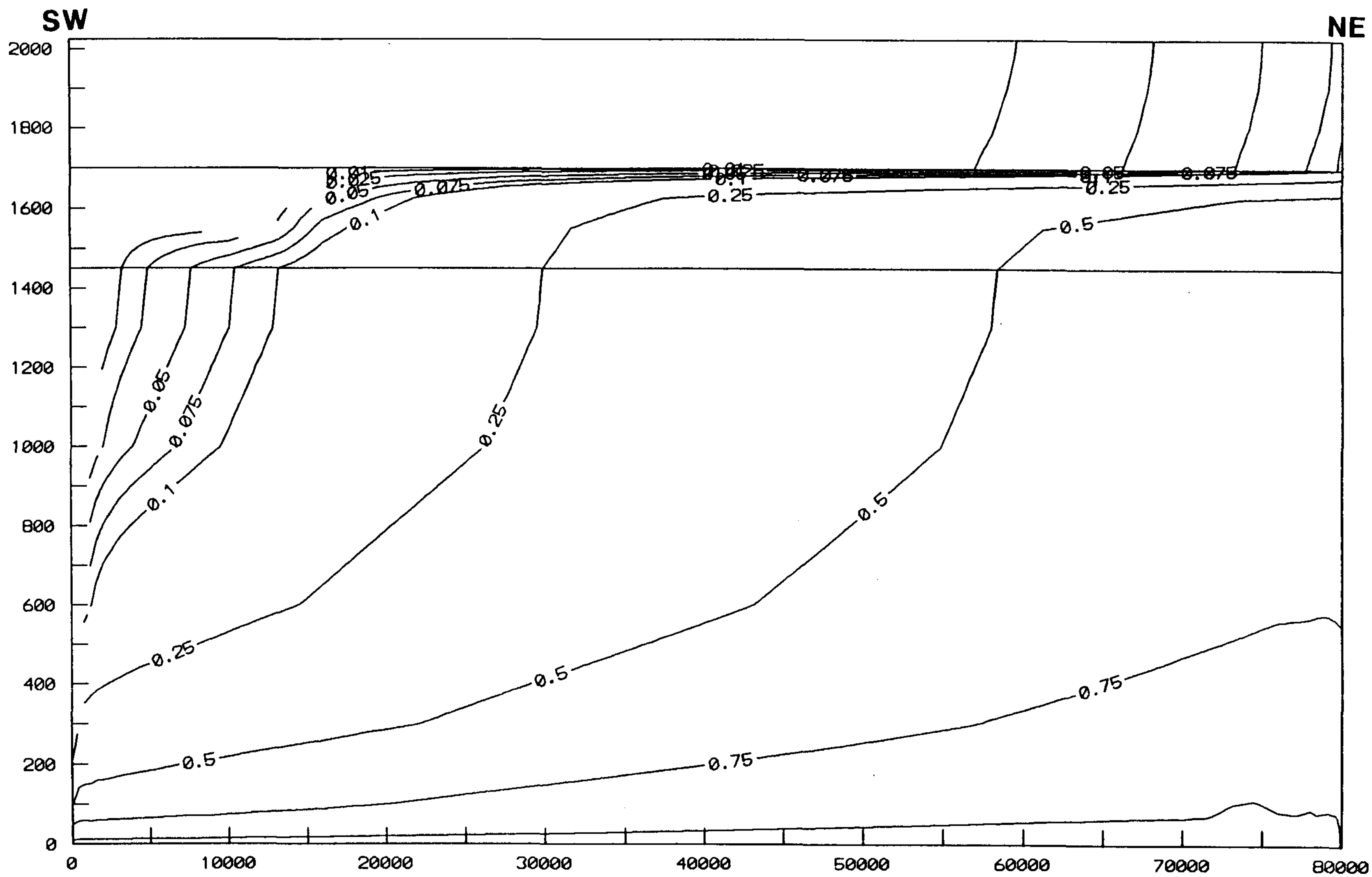

Figure 3.25. Relative chloride concentrations (1.0 = 19,000 mg/L) after 51 years for a simulation with a no-flow boundary in the Lower Floridan aquifer and a stress of 10 $ft^3/d/ft$ in the Upper Floridan aquifer.

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4 EXTENSION TO THREE DIMENSIONAL MODEL

A major objective of the two-dimensional cross-sectional model was to preview and resolve problems that will be encountered when developing the three-dimensional transport model in the next phase of this study. Specific difficulties include: (1) defining transport boundary conditions; (2) horizontal and vertical grid spacing; (3) sensitivity of results to parameter uncertainty; and, (4) calibration of an inherently transient system to a steady-state condition. The cross-sectional model has contributed insight to these problems and resolved some critical issues, such as level of discretization.

The transport boundary conditions will be handled in a similar fashion as they were in the cross-sectional model. The proposed model area is shown in Figure 4.1. The conceptual model that uses a saltwater concentration (19,000 mg/L) at the base of the Lower Floridan provides a reasonable representation of interpolated and estimated chloride concentrations in the Lower Floridan and the Upper Floridan. Other flow boundaries will be derived from the regional groundwater flow model. Concentrations associated with the boundaries will generally be representative of freshwater. The concentration boundary in the Upper Floridan to the northeast will be more difficult and will have to be determined from the data. In the Lower Floridan, it will be assigned a saltwater concentration of 19,000 mg/L. The surficial aquifer will be treated similarly as it was in the cross-sectional simulations. The head dependent flux boundary provides a reasonable representation of recharge to the Upper Floridan aquifer.

The proposed model area is extremely large for a solute transport model. Using a Peclet criteria of 2.0 with α_L = 120 ft would result in a 440 node by 354 node areal grid, without even considering the vertical dimension. The vertical dimension will require a minimum of 10 nodes to accurately define the wedge in the Floridan aquifer system and to evaluate the potential for and transient behavior of an upconing event. This level of areal discretization is clearly impractical and will not be attempted.

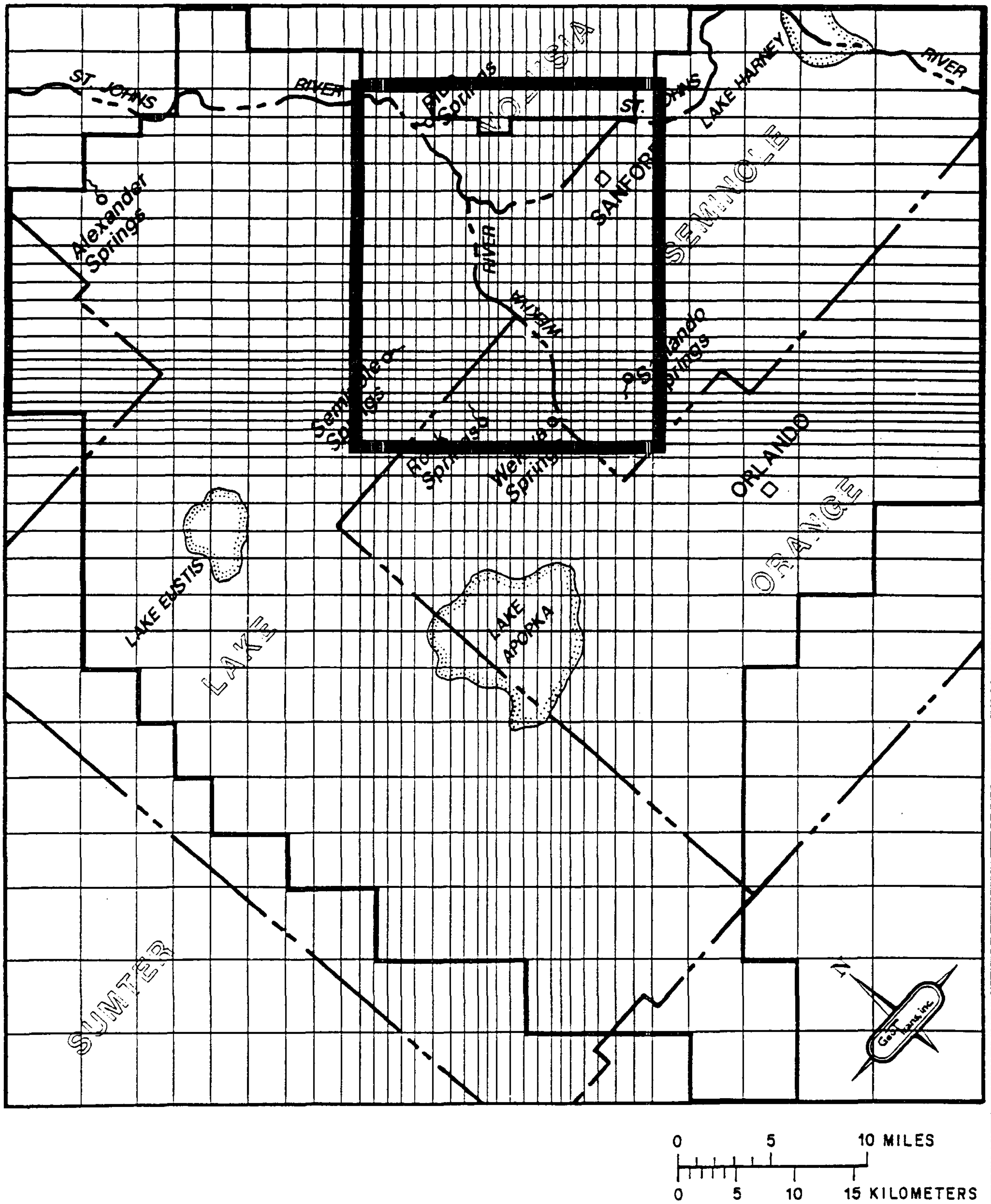

Figure 4.1. Location and areal extent of three-dimensional transport model.

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Instead, the three-dimensional representation of the coarse grid tested as a part of the sensitivity analysis will be used. The coarse grid provided reasonable answers in cross-section and could readily be extended to three dimensions. Note that upstream weighting, a means of stabilizing the numerical solution of the transport equation, was not used. Upstream weighting could be used if necessary, but prototype simulations will not incorporate it. Upstream weighting has the net effect of increasing the input dispersivities. The actual dispersivity used in the solution will not be readily apparent to the user. Therefore, 41 columns, 14 layers, and 30 slices will be used for the three-dimensional model. The 17,220 nodes used by this model is consistent with reasonable computation power and execution times for these types of problems.

The sensitivity of results to parameter uncertainty was tested thoroughly with the cross-sectional model. Accurate characterization of the surficial system will be necessary because the competence of the upper confining bed is so influential. Characterization of the middle semi-confining bed is less important for the steady state current conditions, but could be important for transient predictive simulations.

Calibration to a steady-state may not be as problematic as first envisioned because it appears that the concentrations can be handled via boundary conditions, rather than an initial condition. Secondly, the concentrations are most likely changing so slowly that a quasi-steady-state can be assumed.

The three-dimensional model will include most of the major springs in the Wekiva River basin: Rock, Wekiva, Sanlando, Palm Starbuck, Seminole, Messant, and Blue Springs. The model will include features of both the regional flow model and the cross-sectional transport model. A steady state calibration to heads and concentrations will be performed. Predictive transient simulations and sensitivity analysis will be conducted.

5 CONCLUSIONS AND RECOMMENDATIONS

This report presents the results of the second phase of a three-phase study of the Wekiva River basin. The overall objective of the study is to provide the St. Johns River Water Management District with a tool to aid in the establishment of minimum groundwater levels within the basin to protect the quality of its water resources. The objective of Phase II was to develop a two-dimensional cross-sectional model through the study area. This model incorporates the complexity of variable density groundwater flow and is capable of modeling saltwater transport. The two-dimensional model was used to preview and resolve problems which could be encountered during the third phase of this study, which involves development of a three-dimensional flow and transport model.

Development of the cross-sectional model involved interpretation of an experimentation with various boundary conditions. It appears from the analysis that the assumptions inherent in a two-dimensional analysis cannot be uniquely satisfied in this area. This is due to the curvilinear flow paths which invalidate the assumption of two-dimensional flow along a flow line. Despite the difficulties this posed, the location of the cross-section was in the best area possible and the model provided useful insight into the dynamics of the flow system.

It appears that the competence of the upper confining bed exerts significant control on flow and solute transport in the system. This is because the flushing which pushes saltwater out or prevents intrusion is derived from leakage through the upper confining bed as well as lateral influx. The competence of the middle semi-confining bed appears to be less influential for the steady state simulations, but could play an important role in the transient predictive simulations. Regional zonation within aquifers also controls the configuration of the saltwater wedge in the system. Hydraulic conductivity data from deep wells could help characterize stratigraphic variation that influences saltwater intrusion. Some parameters, such as dispersivity and longitudinal to transverse dispersivity ratios have a significant effect on the system, but are difficult to quantify in the field.

The model provided insight into the grid spacing required for numerical stability. Experimentation with three grids, a fine, medium, and coarse grid, indicated that a 17000 node (approximately) grid should be capable of modeling the three-dimensional area under consideration. Grid design must take into account areas of expected changes to high concentration.

A significant deficiency in the data base is water level and chloride data in the Lower Floridan aquifer. A series of deep monitoring wells, placed in areas of anticipated future buildout or stress, would be useful for characterizing the system as well as providing a warning system for future intrusion. Indirect methods of locating the saltwater interface, such as geophysical techniques, would also be beneficial to understanding the system and to future modeling.

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APPENDIX A

SWICHA INPUT DATA SET FOR BASE CASE

```
   1                                                                    CARD 1
CROSS SECTION A-A'  -  WEKIVA - MEDIUM GRID BASE CASE  -  STEADY-STATE     CARD 2
 2318 1080    1    2    4    8    0    0    2  180    0    1    0    0    1  200CARD 3
 0.100E 03 0.000E 00 1.414E 00 0.100E 05 0.100E 01 0.100E-01 0.500E-02 0.100E 01CARD 4
     0.000     0.000                                                        CARD 5
    1    1   -1    1    1    0    3    0    1    1                          CARD 6
    0    0    0    1    0    0    0    0    0    0    1    1    0           CARD 7A
    4    4    4    4    4    4    4    4    4    3    3    3    3    3    2    2
    1    1    4    4    4    4    4    4    4    4    4    3    3    3    3    3
    2    2    1    1    4    4    4    4    4    4    4    4    4    3    3    3
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0.000E 00 1.000E 00                                                             CARD 11
0.000E 00 1.000E 00                                                             CARD 11
0.000E 00 1.000E 00                                                             CARD 11
0.000E 00 1.000E 00                                                             CARD 11
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  78000.0   78500.0   79000.0   79500.0   80000.0
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   1400.0    1450.0    1500.0    1550.0    1600.0    1650.0    1700.0    1800.0
   1900.0    1975.0    2025.0
   0.0000  100.0000                                                             CARD 14C
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  82   26    0    0                                                             CARD 18A
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9	1	0	1.100		
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APPENDIX B

DOCUMENTATION OF MONOTONICALLY DECREASING UNDER-RELAXATION FACTOR

Appendix B

The sequential solution of the coupled systems of fluid flow and solute transport equations for density dependent salt water intrusion problems is hampered by the non-convergent nature of the Picard iteration scheme. This tendency toward non-convergence is associated with the behavior of the vertical velocity term, V_z

$$V_z = -K_z \left[\frac{\partial h}{\partial z} + \eta c \right] \qquad \text{(B-1)}$$

where

	K_z	=	the vertical hydraulic conductivity
	h	=	the equivalent freshwater head
	η	=	the density coupling factor
and	c	=	the concentration.

In areas of the flow system where vertical flow is dominant, a non-convergent iterative cycle may ensue. For example, downward flow increases freshwater flow into an unstable section thus decreasing the concentration used in the subsequent flow simulation. The decrease of concentration in the transport simulation changes the flow direction to upward. This in turn increases the concentration in the following transport solution, etc. For direct steady state simulations a non-convergent (chaotic) solution can result. The automatic under-relaxation factor used in SWICHA, developed by Cooley (1983) for unsaturated flow analysis, decreases the under-relaxation factor when divergent behavior is noted and increases it when convergent behavior is noted. If the problem being solved has a tendency to have convergence problems, the increasing of the under-relaxation term returns the equations to a non-convergent path. Except for problems where horizontal flow dominates the system or where the system is redefined to accentuate the horizontal flow dominance, direct steady state solutions may not be achievable. The standard method for circumventing this problem is to run a transient solution to equilibrium. The transient solution techniques has the same non-convergent (flip-flopping) tendencies, except by limiting the time step size the changes in concentration after each iteration is limited and the oscillatory behavior can be kept to a minimum. Unfortunately, the utility of the transient method is a function of the complexity of the system and how small a time step is needed to avoid non-convergence. If the system is complex and has two or more areas where reversal of the vertical flow component becomes important, the transient method may entail using 20000 or more time steps to reach equilibrium. For some problems, a single simulation on a 386-PC may take weeks to complete.

To circumvent this problem a version of SWICHA was developed that allowed for an adjustable under-relaxation factor. Unlike the Cooley method, the under-relaxation factor is only allowed to adjust in one direction (decreasing) and applied only to the solute equation. Every time and error terms grows the under-relaxation factor decreases. The concentration at a given node or iteration is defined as:

$$c_i = Wc_i + (1 - W)\ c_{i-1} \qquad \text{(B-2)}$$

This allows the stable portion of the system to approach its equilibrium during the early iterations then adjust as smaller and smaller changes of concentration over each iteration allow the oscillations to dampen out. The weighting factor, W, begins at 1.0 and slowly decreases each iteration where the error term increases. This becomes similar to using small time steps after the stable sections of the system approach equilibrium. The major requirement for this technique is that the weighting factor decreases at a slow enough rate and that enough iterations are used. The under-relaxation factor used in this program are defined as follows:

$$W_j = \frac{W_{j-1}}{2^{1/a}} \qquad \text{(B-3)}$$

Trial runs suggest that a range of "a" from 8-12 and number of iterations ranging from 100-400 will suffice. The larger "a" is associated with the larger number of nonlinear iterations. In general, a = 10 and 200 iterations will suffice, but it has been noted that for problems with high Peclet numbers 400 iterations and a = 12 should be used.

The solution technique was tested using a cross-sectional model. Figure B-1 depicts a contour plot of the solution using the transient solution techniques. Figure B-2 shows the same physical system simulated using the monotonically decreasing under-relaxation factor. Little difference is seen between the two schemes. Figure B-3 depicts a transient solution using the time steps used in the original solution but using initial conditions from the direct steady-state run. Note the little change between Figure B-2 and B-3.

REFERENCE

Cooley, R.L., 1983. Some new procedures for numerical solution of variably saturated flow problems. Water Resources Research, 19(5): 1271-1285.

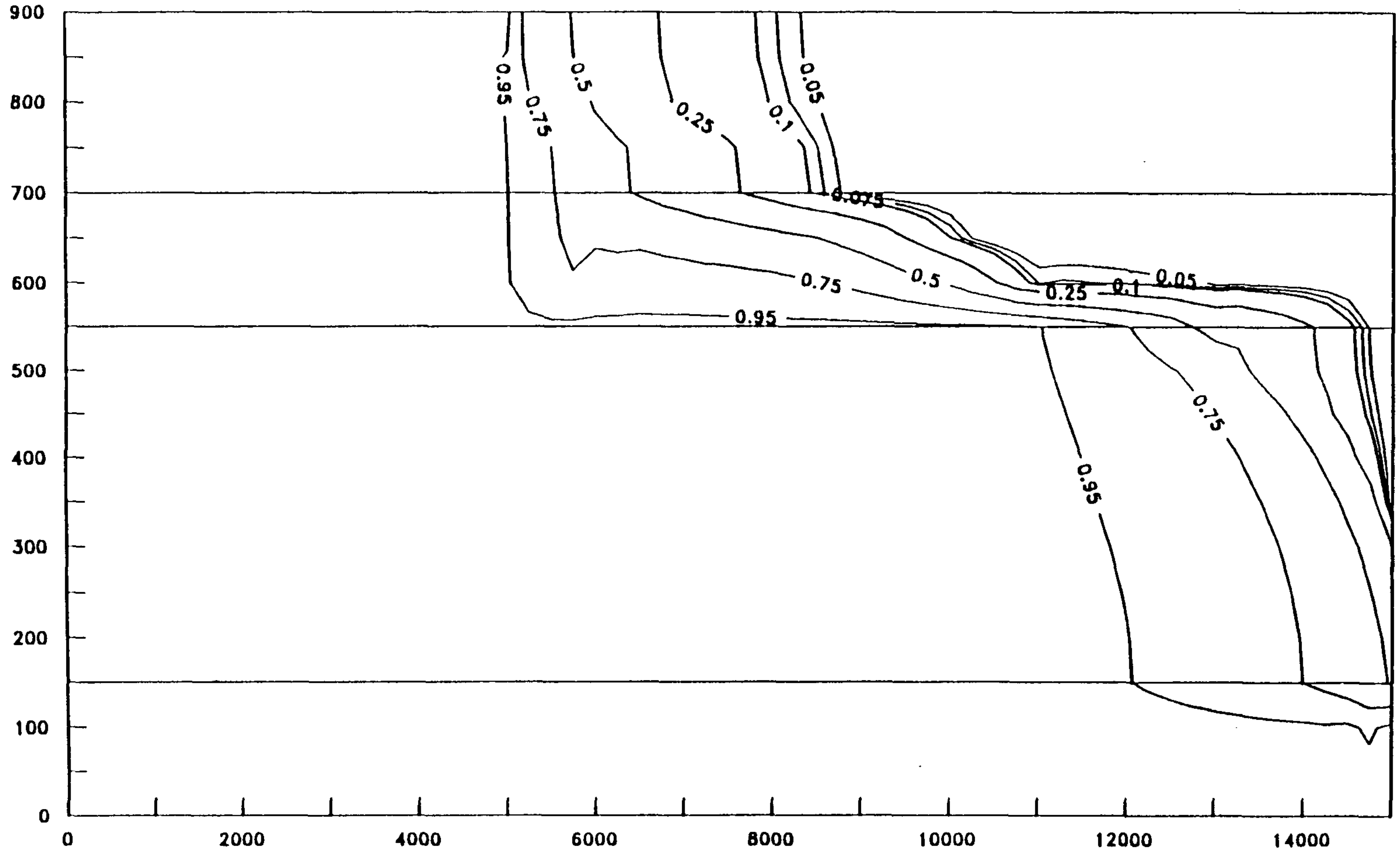

Figure B.1. Simulation results for cross-sectional model using transient approach.

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P7552-002/OA/53

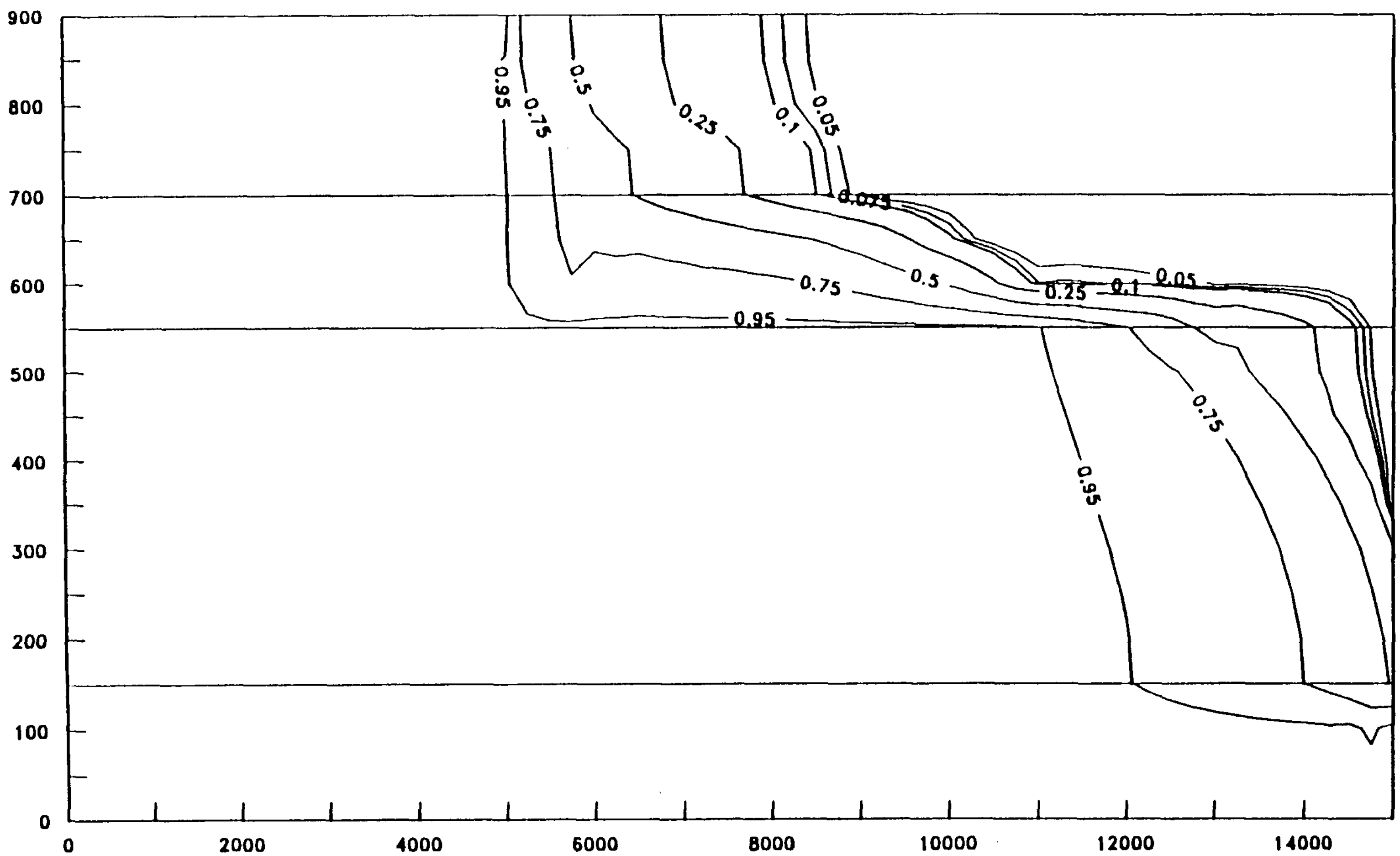

Figure B.2. Simulation results for cross-sectional model using monitonically decreasing under-relaxation factor.

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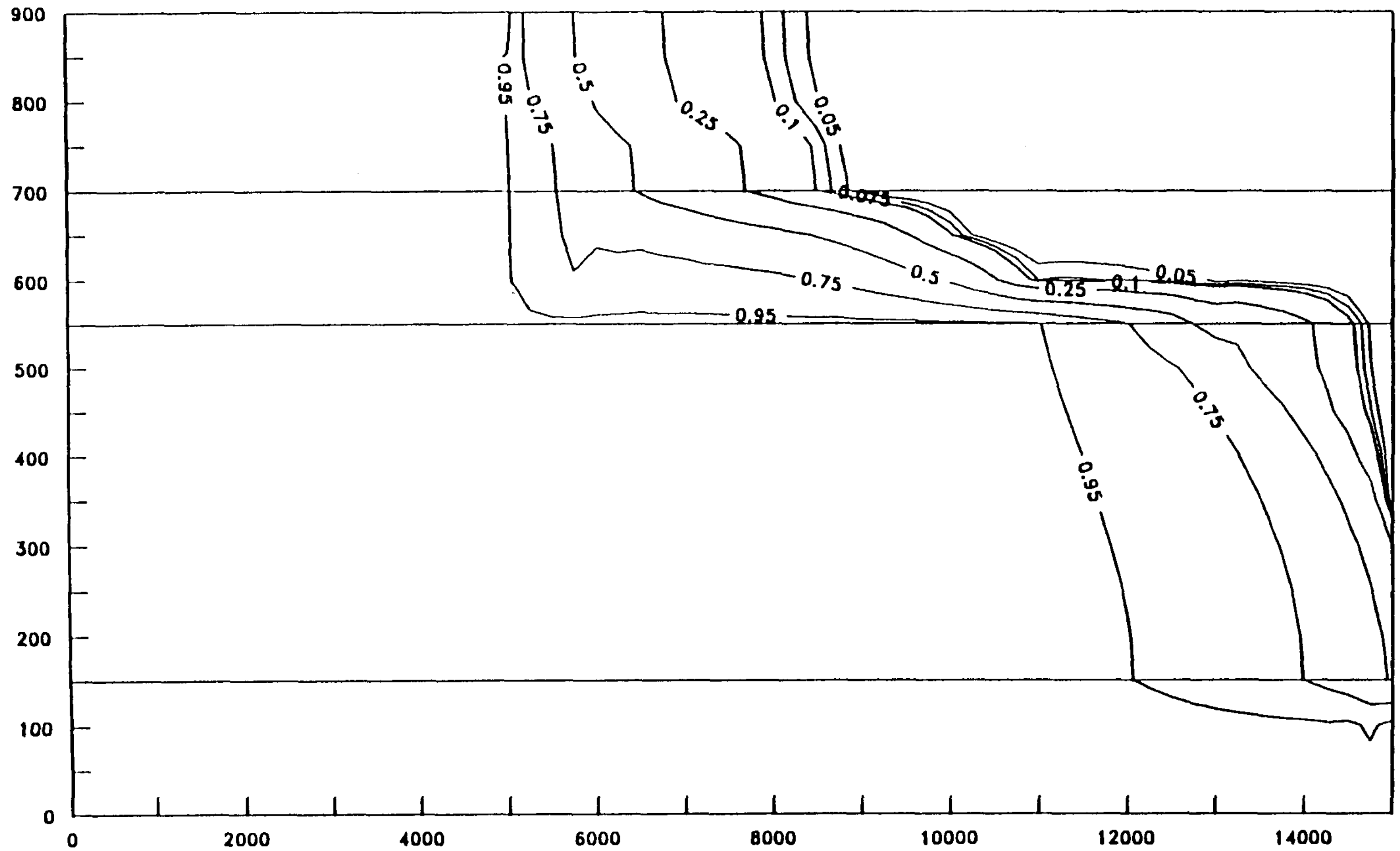

Figure B.3. Simulations results for cross-sectional model using transient method and initial conditions from monotonically decreasing under-relaxation factor simulation.

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