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WEKIVA RIVER BASIN GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELING STUDY

Phase III: Three-Dimensional Density Dependent Groundwater Flow and Solute Transport Model Development

December 1991

Prepared for:
St. Johns River Water Management District
P.O. Box 1429
Palatka, Florida 32178-1429

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GeoTrans Project No. 7602-004

December 31, 1991

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WEKIVA RIVER BASIN GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELING STUDY

Executive Summary

GeoTrans, Inc. was contracted on August 1, 1990 to conduct a three phase study of the Wekiva River Basin. The overall objective of the study was 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 water resources. Specific objectives, as defined by the District, included 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.

Groundwater modeling formed the basis of the study and is the tool with which predictions of future system behavior are made. The project involved submittal of three reports dealing with three different model configurations that were used to answer various questions about the aquifer system. District staff have been trained in the use of the models and should be able to expand upon the study, if necessary. The project concluded on December 31, 1991 with the submittal of the Phase III final report and this executive summary.

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 was used in subsequent phases to determine boundary flows and boundary conditions for two- and three-dimensional flow and saltwater transport models of a smaller sub-regional area.

Development of the regional flow model involved a two-step calibration process. In the first calibration phase, model parameters were adjusted within reasonable ranges until the model reproduced the estimated steady-state predevelopment potentiometric surface of the Upper Floridan aquifer. Important features, notably the potentiometric trough along the lower Wekiva River, were reproduced. Simulated spring discharges were in excellent agreement with estimated values.

A second calibration phase of modeling was also conducted. This involved adding estimated annual average pumping stresses for 1988 to the predevelopment model and running a new steady-state simulation. Simulated drawdowns were compared to estimated values and further refinements to model parameters were made as necessary to give acceptable results. Simulated water levels were in overall good agreement with estimated levels. The fact that simulated results were less accurate than those predicted for predevelopment conditions reflects the added uncertainty associated with (a) having to estimate average groundwater withdrawals, and (b) using an arithmetic average of the May and September potentiometric surfaces to define an average potentiometric surface. It is believed that for the most part, simulated groundwater levels associated with pumping conditions in 1988 were consistent with the average groundwater levels defined based on the observed May and September potentiometric surfaces.

Simulated declines in spring discharges totaled 82.5 cfs over the model domain, a reduction of approximately 14 percent. Under-prediction of spring discharges at Rock, Wekiva, Sanlando, Palm, and Starbuck springs is believed to be due in part to the inability of the model to accurately account for capture by the springs of groundwater discharged to the surficial aquifer in the immediate vicinity of these springs. However, simulated spring discharges in the Wekiva River basin are within 85% of those observed or estimated discharges. Simulated discharges at springs outside of the basin were all within 70 percent of their observed or estimated rates.

The model developed in Phase I is believed to provide a reasonably accurate tool for simulating the impacts of groundwater withdrawals on groundwater levels and changes in spring discharges in the Wekiva River basin and thus to define boundary conditions of the Phase II and Phase III solute transport models.

A two-dimensional cross-sectional groundwater flow and saltwater transport model of a portion of the Wekiva River Basin was developed during Phase II of the study to assess mechanisms of saltwater intrusion. The model is a vertical cross-section running from southwest near Seminole Springs to northeast near the St. Johns River. 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 with the Phase II model. 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 was noted during the phase II study. This data gap is the location of the saltwater wedge with depth. 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. A concurrent project by the St. Johns River Water Management District helped to reduce the uncertainty of the saltwater location. This was a Time Domain Electromagnetic geophysical study designed to locate the saltwater interface in East Central Florida.

Phase III of the study involved developing and calibrating a three-dimensional density dependent groundwater flow and solute transport model of the smaller subregional area of the Wekiva River basin. The Phase I regional groundwater flow model formed the basis for the overall structure, boundary conditions, and initial conditions for the Phase III model. The understanding of aquifer system response gained as a part of Phase II was invaluable in setting up the Phase III model.

The model was calibrated to 1988 groundwater conditions using hydraulic head measurements, spring discharge rates, spring concentrations, maps of chloride concentration, and inferred concentrations from the TDEM data. A reasonable match was obtained with these parameters. Nine sensitivity simulations were conducted to assess the adequacy and important parameters in the model. Following model calibration and sensitivity analysis, the model was run to develop predictions of future groundwater levels and water quality resulting from a projected 2010 pumpage schedule. The model indicated that additional drawdown will occur in the southwestern part of the model area, and will cause movement of the saltwater front. Some rebound of water-levels is also predicted in another area with an accompanying reduction of chloride concentration in the Upper Floridan aquifer.

Several areas of data deficiency have been identified as a result of the modeling. The most obvious area of data deficiency is in the Lower Floridan aquifer system. Basic uncertainties regarding boundary conditions (location of base, location of saltwater interface, overall transmissivity, etc.) resulted in the need to make rather broad assumptions. Further boring data and monitor well data are needed to better quantify the dynamics of flow in the system. A series of deep monitor 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. A deep cluster well near a spring would provide a prototype of typical near spring behavior. Indirect methods of locating the saltwater interface, such as the time domain electromagnetic geophysical technique, are beneficial to understanding the system. Although TDEM data does not replace directly measured data, it does provide an economical means of filling data gaps.

A second area of uncertainty is in the hydraulic characteristics of the overlying Hawthorn confining bed. Aquifer testing particular to the competence of this bed are important from a research standpoint. The importance of data on the Hawthorn is apparent from the sensitivity of this and other models. It is underscored with the realization that most inflow to the Floridan System occurs through the Hawthorn.

A better system of organizing the data is necessary as more data become available. Some data deficiencies are related to access rather than actual availability. For example, the data base for current and projected water use is nearly unmanageable in its current format. Cross-referencing current and projected water use was a particularly difficult task. A more user friendly approach to access and analyze all types of data is needed. The St. Johns River Water Management District should consider inclusion of these data into a hydrologic Geographic Information System (GIS). The system should be accessible to and usable by District hydrologists.

Continued monitoring of wells is necessary to truly understand the transient dynamics of the system. A ten-year or more history of chloride and water levels is useful for model verification as well as simple trend extrapolation. The importance of adequate data management system is particularly important as the transient data base evolves.

The flow and transport model should continuously be updated, recalibrated, and verified as additional data become available. The models should be used as tools to assist in water management decisions. Due to current uncertainties in the models, they should not be used as the sole basis for a water management decision. Because less assumptions are made in the flow model, it is likely that it is a more accurate predictive tool than the transport model.

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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 third and final phase of a 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. Emphasis is on the Floridan aquifer system.

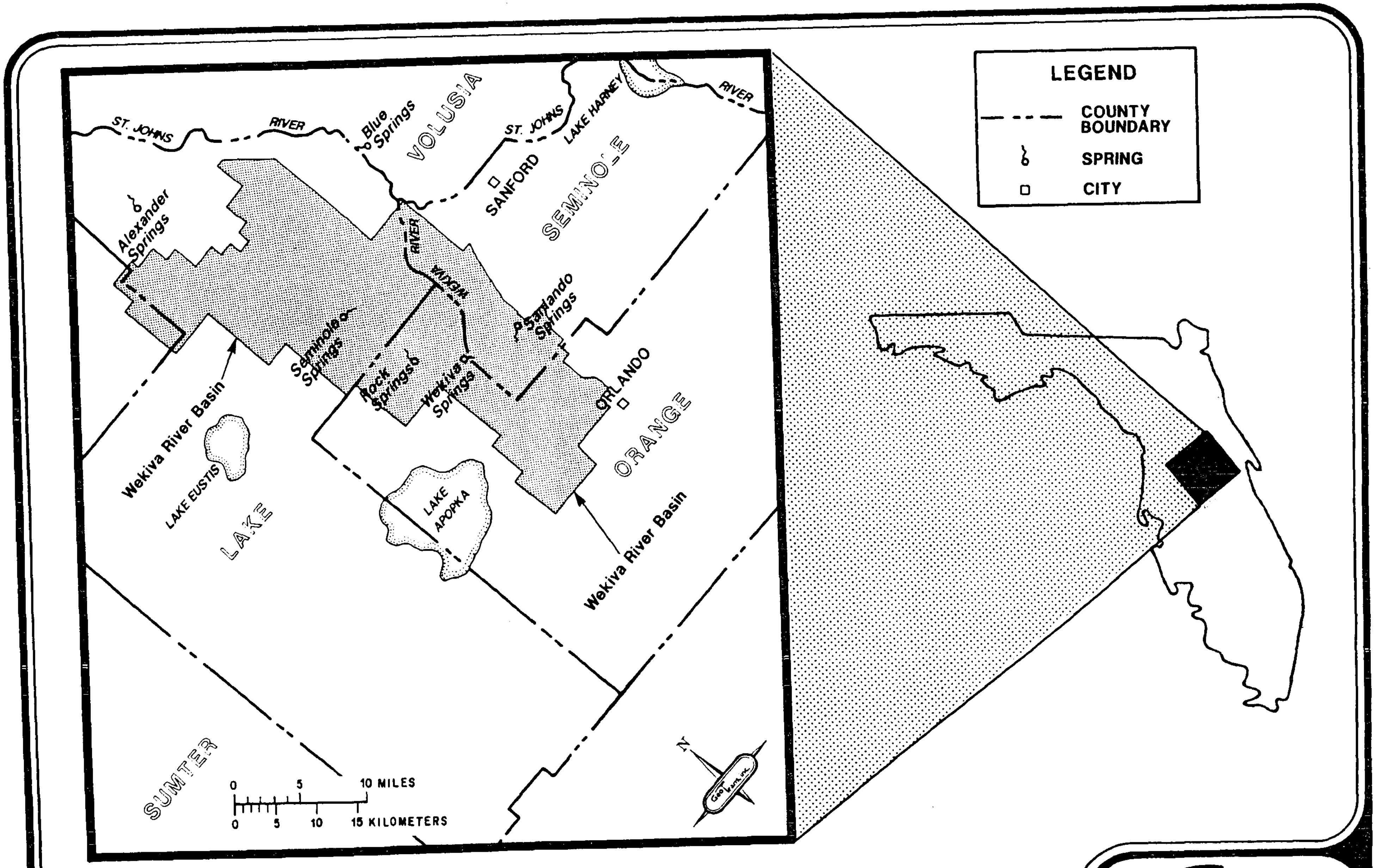

Figure 1.1. Location of study area.

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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:

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- The flow magnitudes of various springs within the project area;
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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 was used to determine boundary flows and boundary conditions for two- and three-dimensional flow and saltwater transport models of a smaller sub-regional area. The final report for Phase I was submitted in May, 1991 (GeoTrans, 1991a).

The second phase of the study involved developing a two-dimensional cross-sectional model through the study area. This model incorporated the additional complexity of variable density groundwater flow and is capable of modeling saltwater transport. The cross-sectional model was used to conceptualize the dynamics of flow and solute transport in the project area. Sensitivity analysis and transient simulations were performed with the model to test hypotheses regarding boundary conditions and uncertainty in aquifer parameters. The main objective of Phase II was to develop an understanding of the system with a relatively simple two-dimensional model before proceeding to the more complex three-dimensional modeling of Phase III. The final report for Phase II was completed in June, 1991 (GeoTrans, 1991b).

Phase III involves the development and calibration of a three-dimensional, density dependent groundwater flow and solute transport model of a smaller subregional area of the Wekiva River basin. Sensitivity analysis is also performed with this model prior to conducting predictive simulations of system response to future groundwater use. Specific tasks associated with Phase III include:

- Provide the District with a progress report describing the approach to the problem and status of conversion of the finite-difference based flow model to the finite-element based solute transport model.
- Incorporate recently collected time-domain electromagnetic (TDEM) data into the conceptual model of the aquifer system under consideration.
- Construct and calibrate the three-dimensional model of density dependent groundwater flow and solute transport. Use the finite-element code SWICHA. Evaluate and discuss the advantages of incorporating natural limitations on maximum discharge/recharge rates between the surficial and Floridan aquifers.
- Perform predictive simulations to assess drawdown and saline water movement as a result of current and projected water use conditions.
- Provide a two-day reporting and training session at District headquarters.
- Provide a draft report, final report, and executive summary on the results of the project.

A progress report was submitted to the District on September 9, 1991. A draft report on Phase III was submitted on November 18, 1991. The draft incorporated the progress report and included discussions on the second, third, and fourth tasks listed above. Following a two-week review period by the District, GeoTrans staff met with District staff to discuss the report and to provide training on model use. This report includes revisions to the draft, as agreed upon at the meeting and represents the final report for Phase III. An executive summary which describes the entire project is submitted as a separate document.

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 Group that act as the overlying confining unit for the limestones of the Floridan aquifer system. The Hawthorn Group 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 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.

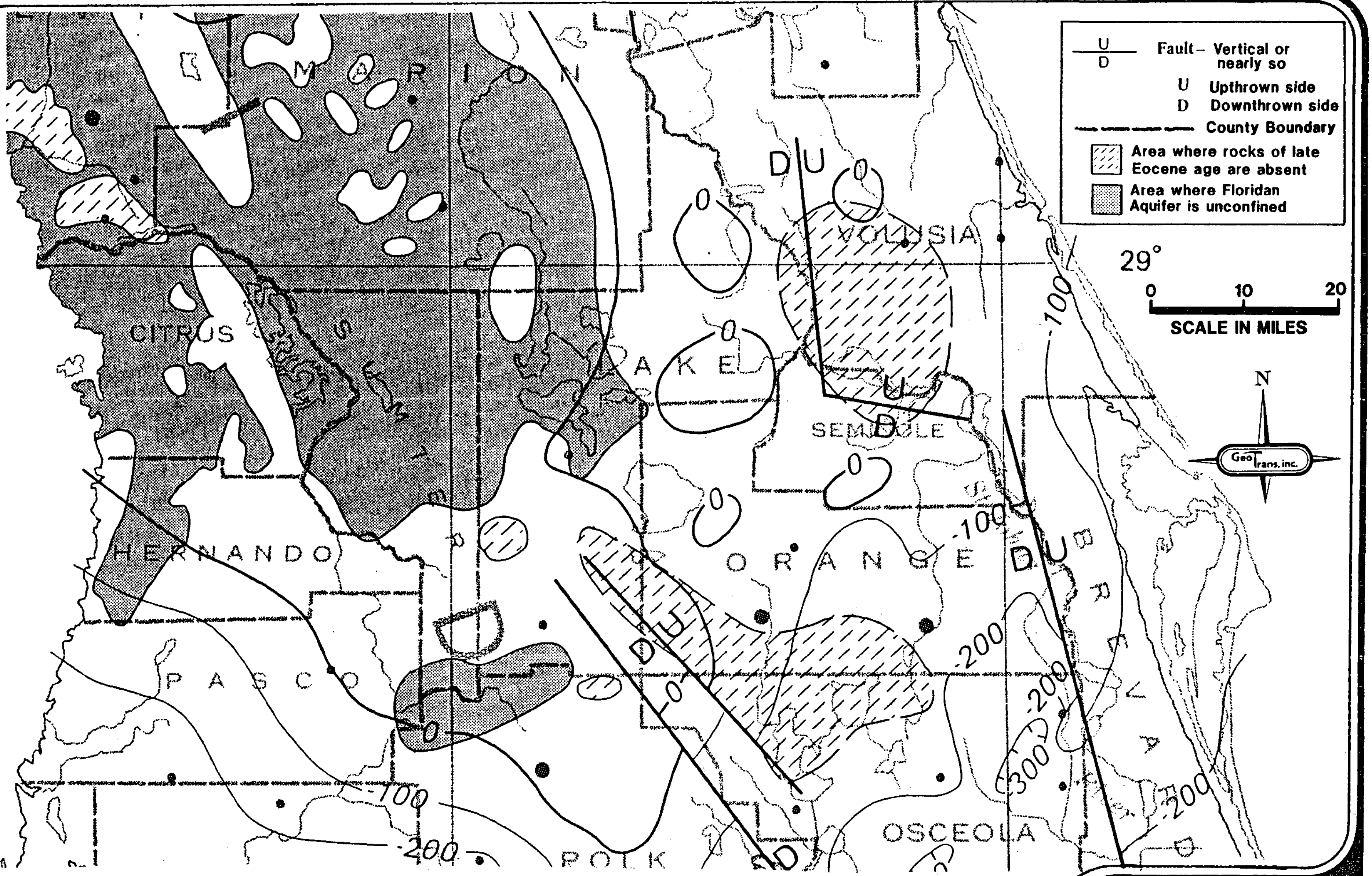

Figure 2.1. Altitude of the top of the Floridan aquifer relative to mean sea level, in feet (from Miller, 1986).

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 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

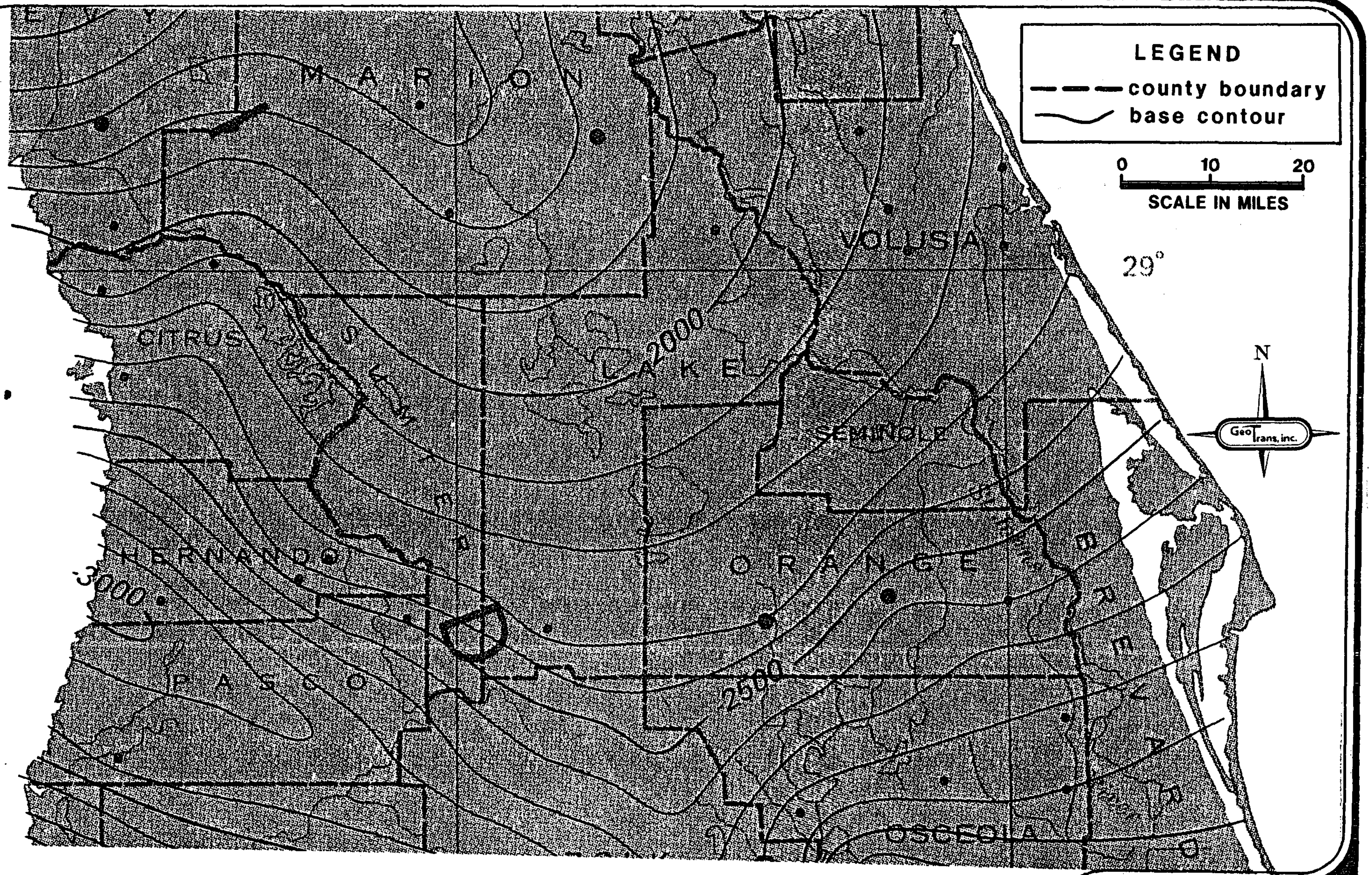

Figure 2.2. Altitude of the base of the Floridan aquifer relative to mean sea level, in feet (from Miller, 1986).

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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). Based on the relatively little head differential between the upper and lower aquifers, typically less than 4-5 feet, it is believed that this unit provides only limited impedance to flow between them.

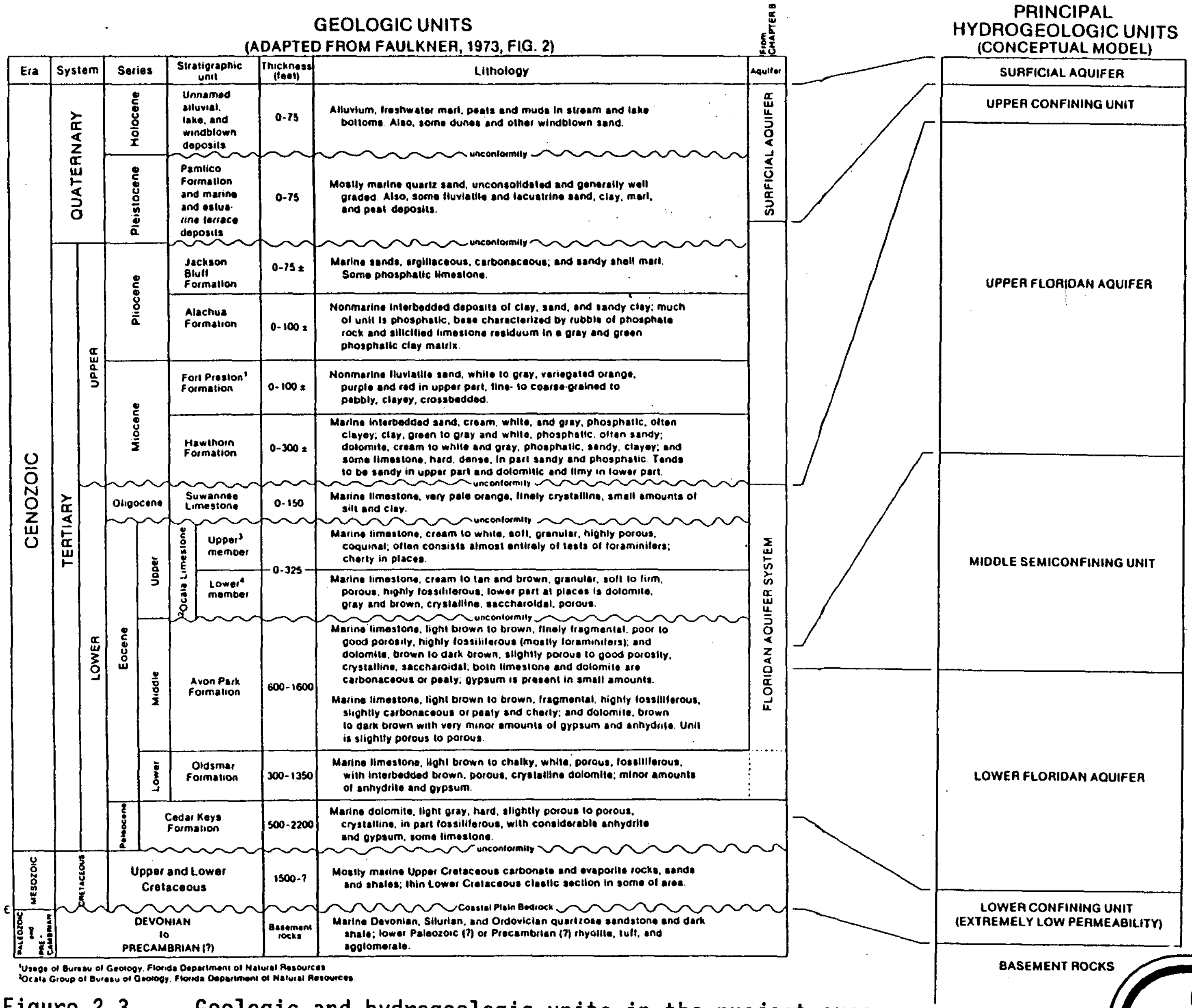
2.1.3 Aquifer Hydrology

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 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



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	
			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.	
								unconformity	
	TERTIARY	UPPER	Pliocene		Jackson Bluff Formation		0-75 ±	Marine sands, argillaceous, carbonaceous; and sandy shell marl. Some phosphatic limestone.	
					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.	
			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.	
					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	
		LOWER	Oligocene		Suwannee Limestone		0-150	Marine limestone, very pale orange, finely crystalline, small amounts of silt and clay.	FLORIDAN AQUIFER SYSTEM
								unconformity	
			Eocene	Upper	[2]Ocala Limestone	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.	
						Lower[4] member		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.	
								unconformity	
				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.	
				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.	
			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

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

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 numerical model 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 regional 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), Toth, et al (1989), Sprinkle (1982), Tibbals (1977), 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

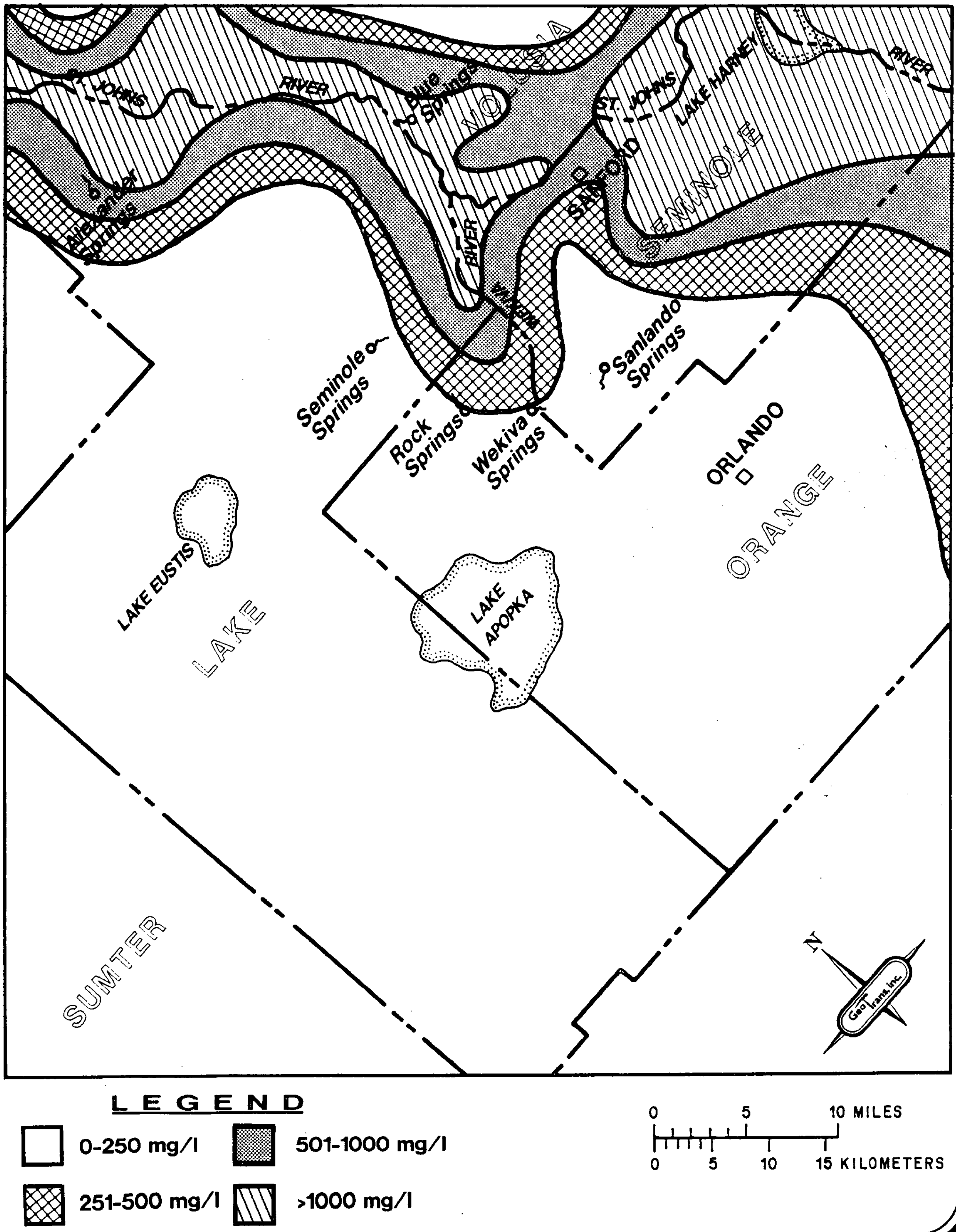


Figure 2.4. Total dissolved solids (mg/L) in the upper Floridan aquifer in the study area (adapted from Klein, 1975).

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(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 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 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 OF SUBREGIONAL STUDY AREA

The study area used for the three-dimensional flow and transport model is shown in Figure 2.8. Also shown in this figure are the Phase I (groundwater flow) and Phase II (cross-sectional flow and transport) model extents. The present study area is smaller than the Phase I study area in order to keep the number of computational nodes reasonable. Even though the Phase III model area is smaller, more nodes are used in the Phase III model because the transport model requires finer horizontal and vertical grid discretization for numerical stability and accuracy. This particular area was chosen because it is in the central part of the study area, contains many of the springs that are of interest, and has elevated chloride concentrations that are of concern.

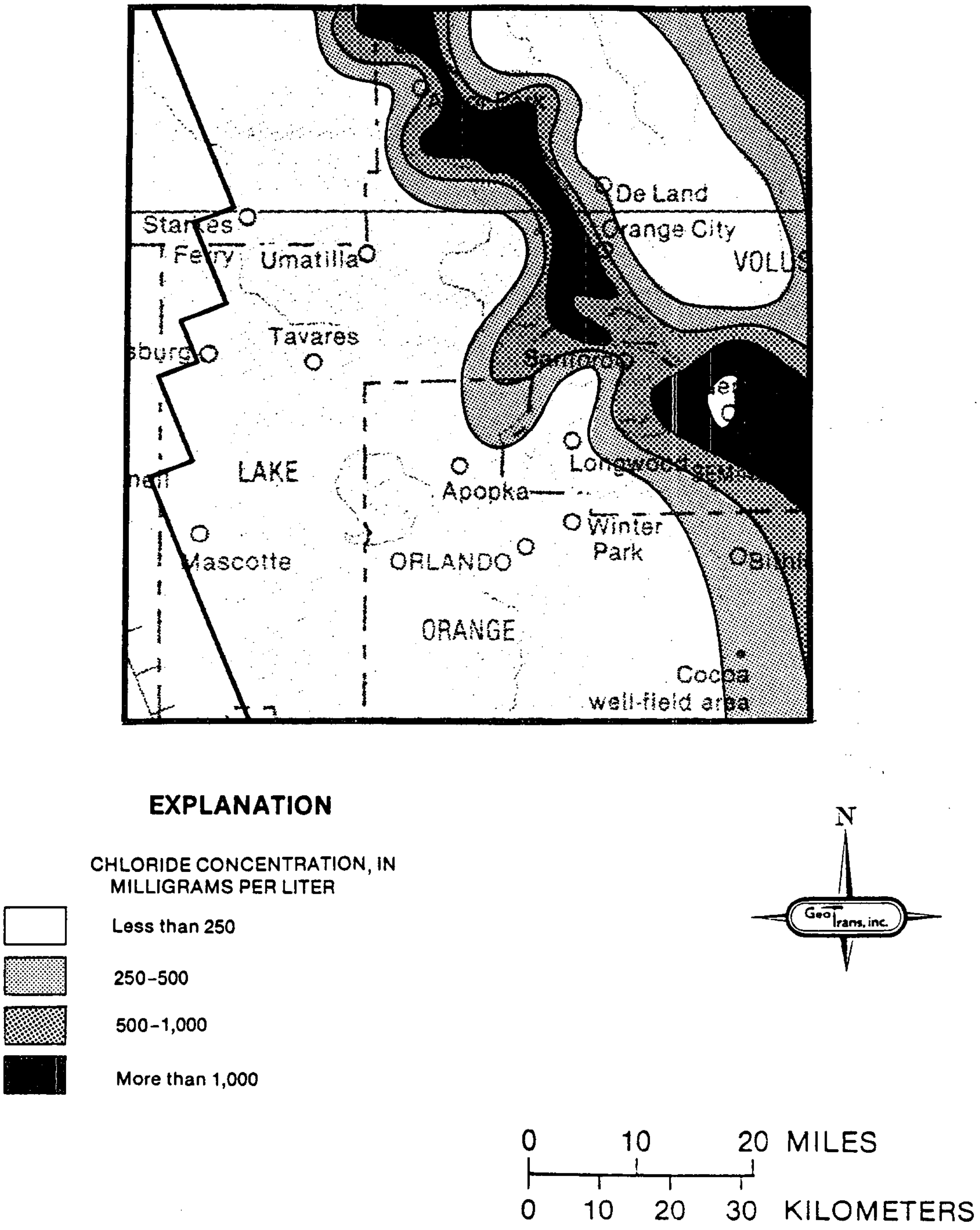

Figure 2.5. Chloride concentrations in the upper Floridan aquifer in the study area (adapted from Sprinkle, 1982).

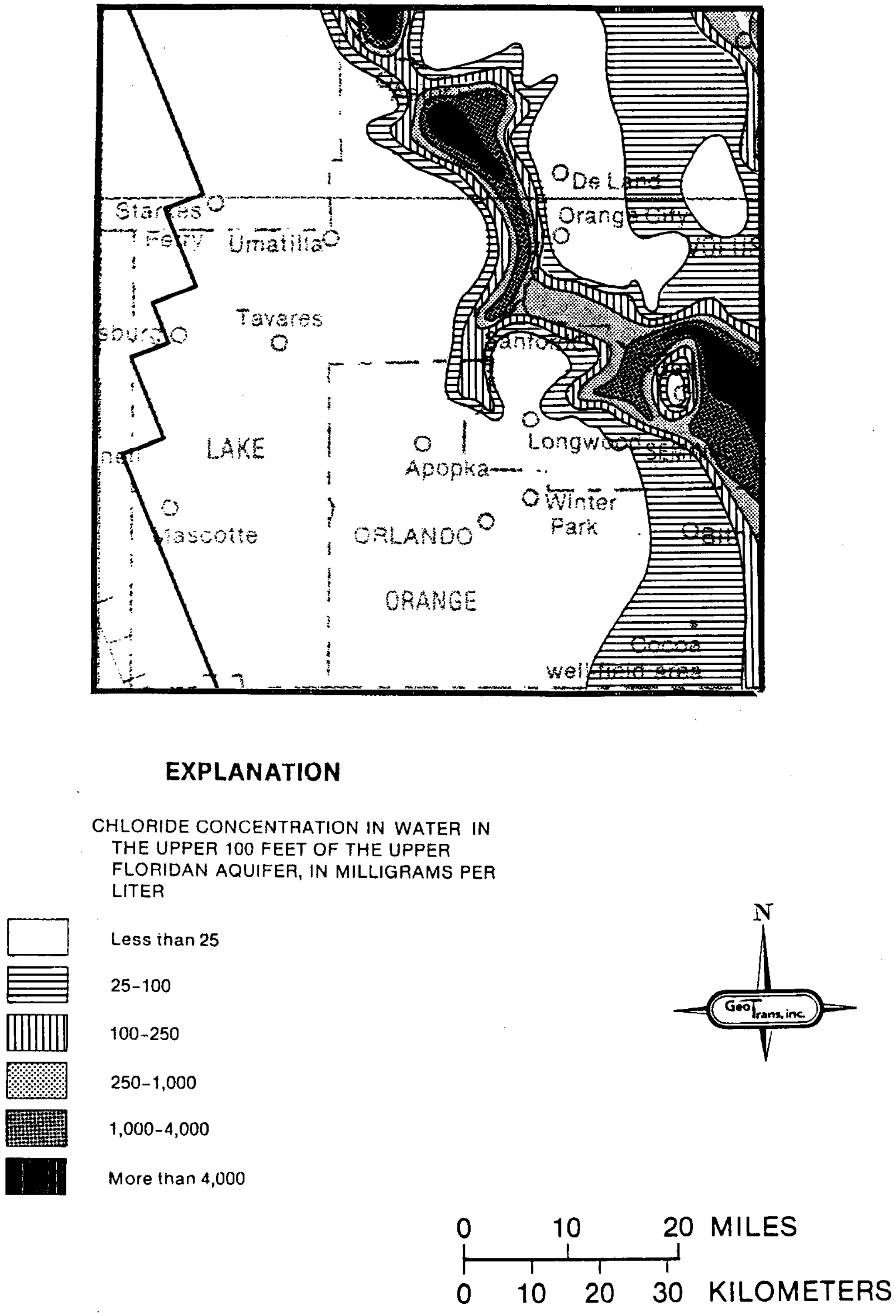

Figure 2.6. Chloride concentrations in the upper 100 ft of the upper Floridan aquifer in the study area (adapted from Tibbals, 1990).

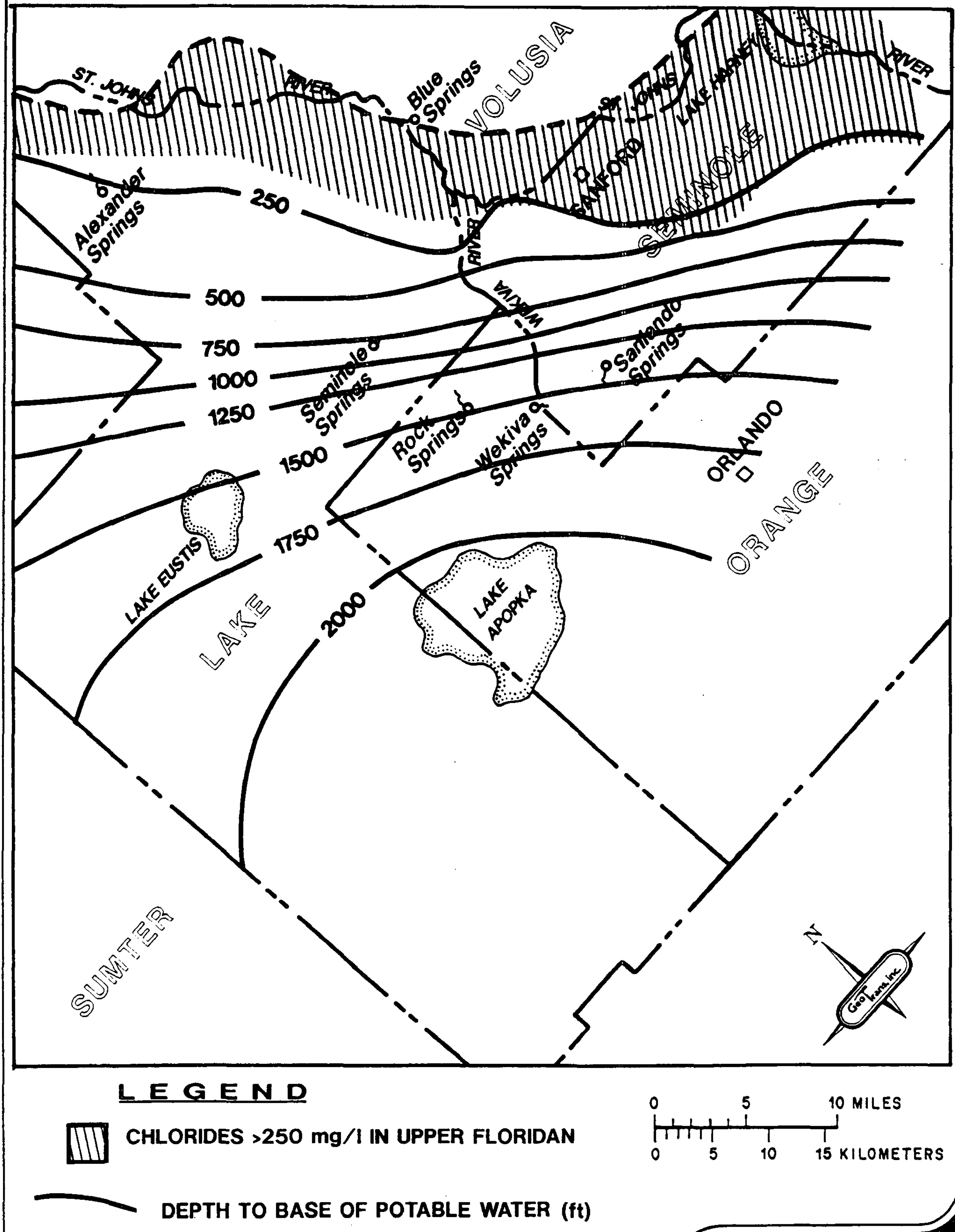

Figure 2.7. Depth to base of potable water in the Floridan aquifer system (adapted from Klein, 1975).

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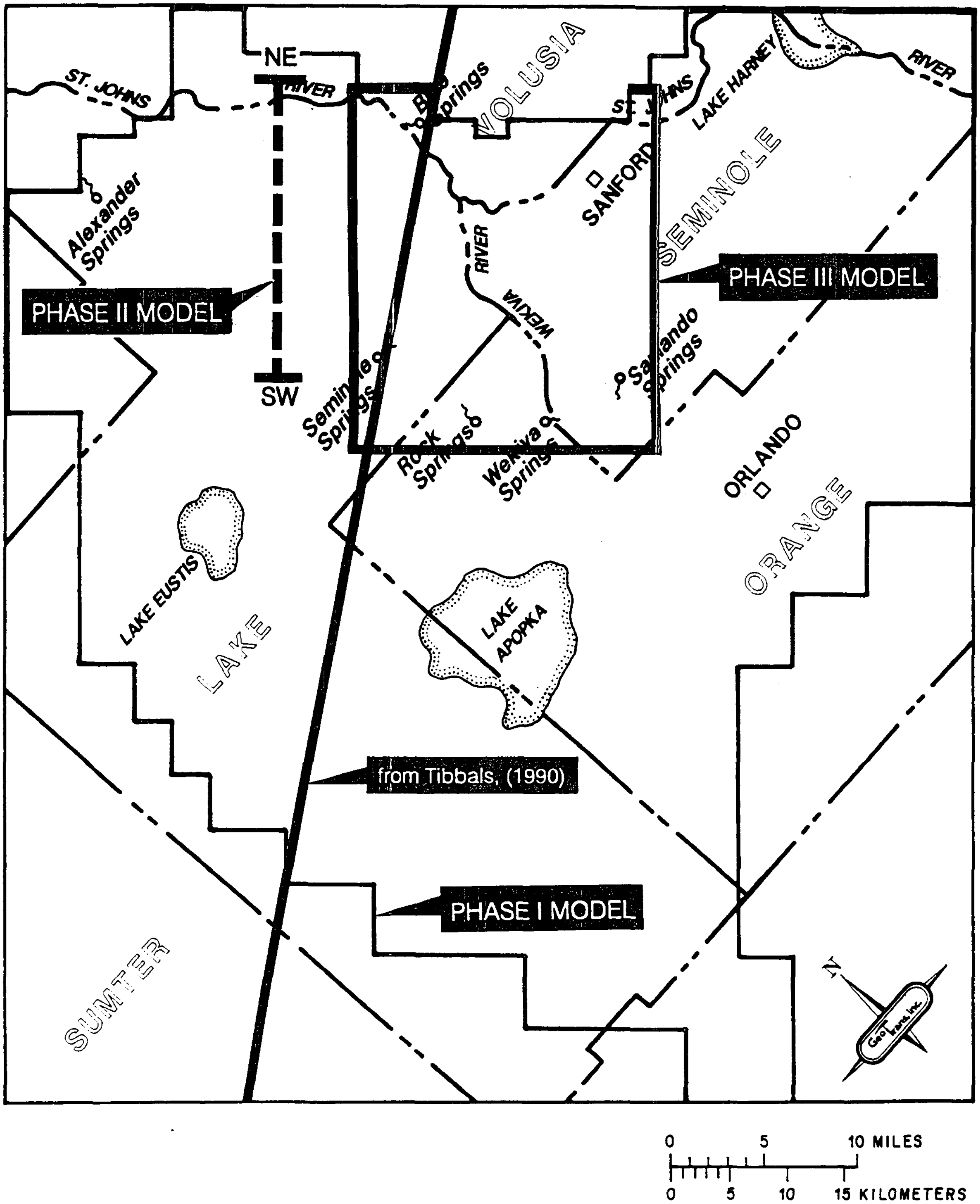

Figure 2.8. Location of the present model area relative to the Phase I and Phase II models. Also shown is the location of a cross-section presented in Tibbals (1990).

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Tibbals (1990) presents a cross-section which runs through the central portion of the model area. This section, reproduced as Figure 2.9, shows concentrations along the St. Johns River being elevated as a result of upward discharge from the Lower Floridan. Tibbals (1990) conceptualizes a wedge of saltwater of concentration greater than 10,000 mg/L east of the St. Johns River in the upper part of the Lower Floridan and with the toe in the lower part of the Lower Floridan approximately beneath Seminole Springs.

Several wells exist in the study area that have chloride data available (Figure 2.10). Most of the data are near the St. Johns River with a major concentration of data points in the area east of the Wekiva River and southwest of the St. Johns River. Although the data base appears to be extensive, there is only limited data to quantify chloride distribution in the Lower Floridan.

2.2.1 Time Domain Electromagnetic Data

Concurrent with this study, Blackhawk Geosciences (1991) conducted a geophysical field investigation using the Time Domain Electromagnetic (TDEM) technique to locate the position of the saltwater interface. The TDEM investigation covered an area larger than the modeled area, however, specific data collection sites within the model area were chosen in part based on data needs for this study. A primary uncertainty in the three-dimensional model was the location and attributes of the boundary condition on the base of the model. The cross-sectional modeling conducted as Phase II of this study (GeoTrans, 1991b) indicated that the model was sensitive to quantifying the depth, type, and concentration of this boundary condition. The TDEM data locations are shown in Figure 2.11. The TDEM method requires assumption of a porosity to obtain the depth. Due to uncertainty in porosity, a range of depths to interface was obtained from the study.

The TDEM data answered a key question regarding placement and quantification of the lower boundary condition. In addition, it was used during the calibration as a guide to the reasonableness of the generated chloride concentrations.

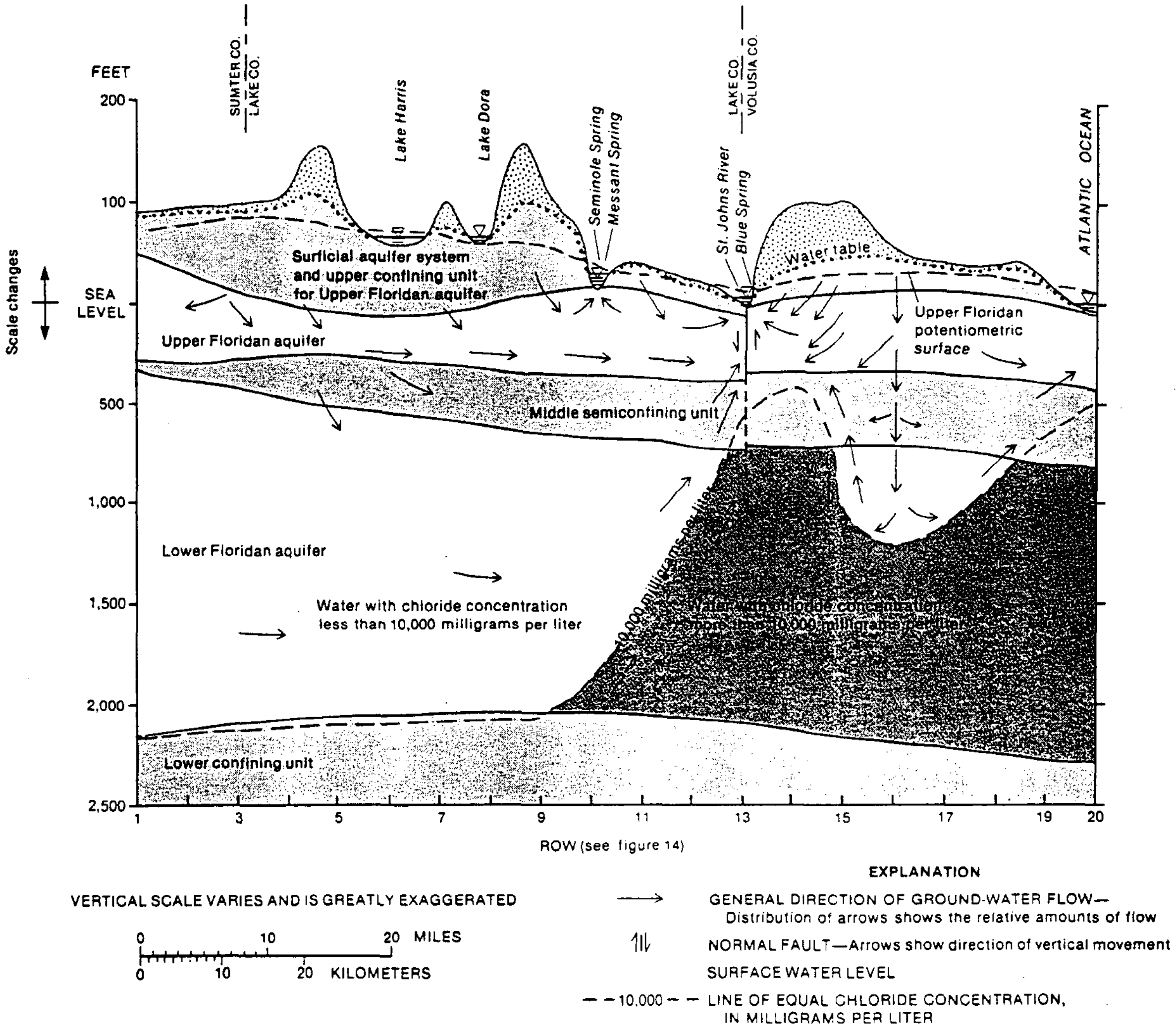

Figure 2.9. Regional cross-section through Blue Springs and Seminole Springs (adapted from Tibbals, 1990). Location of cross-section is shown in Figure 2.8.

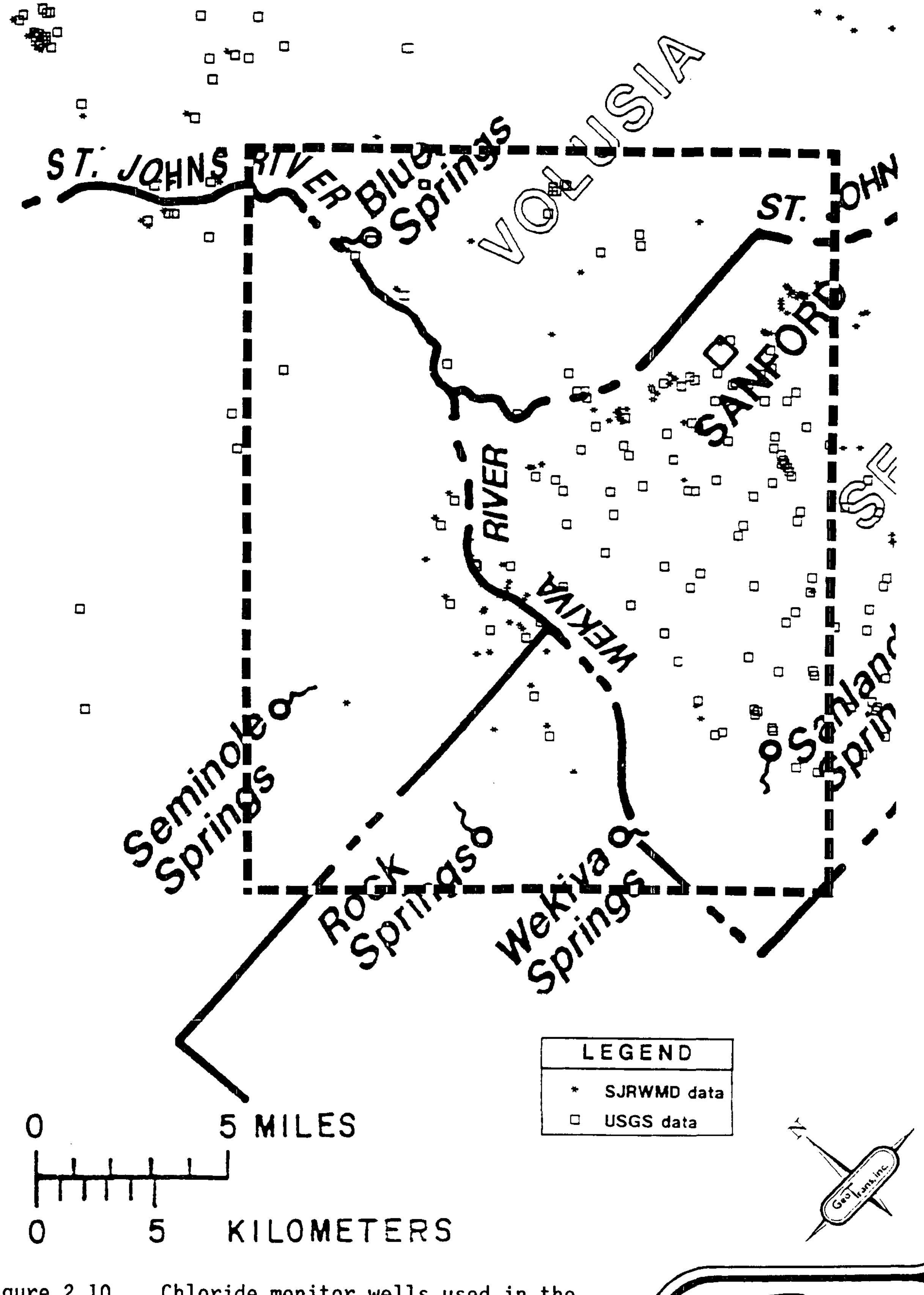

Figure 2.10. Chloride monitor wells used in the cross-sectional analysis.

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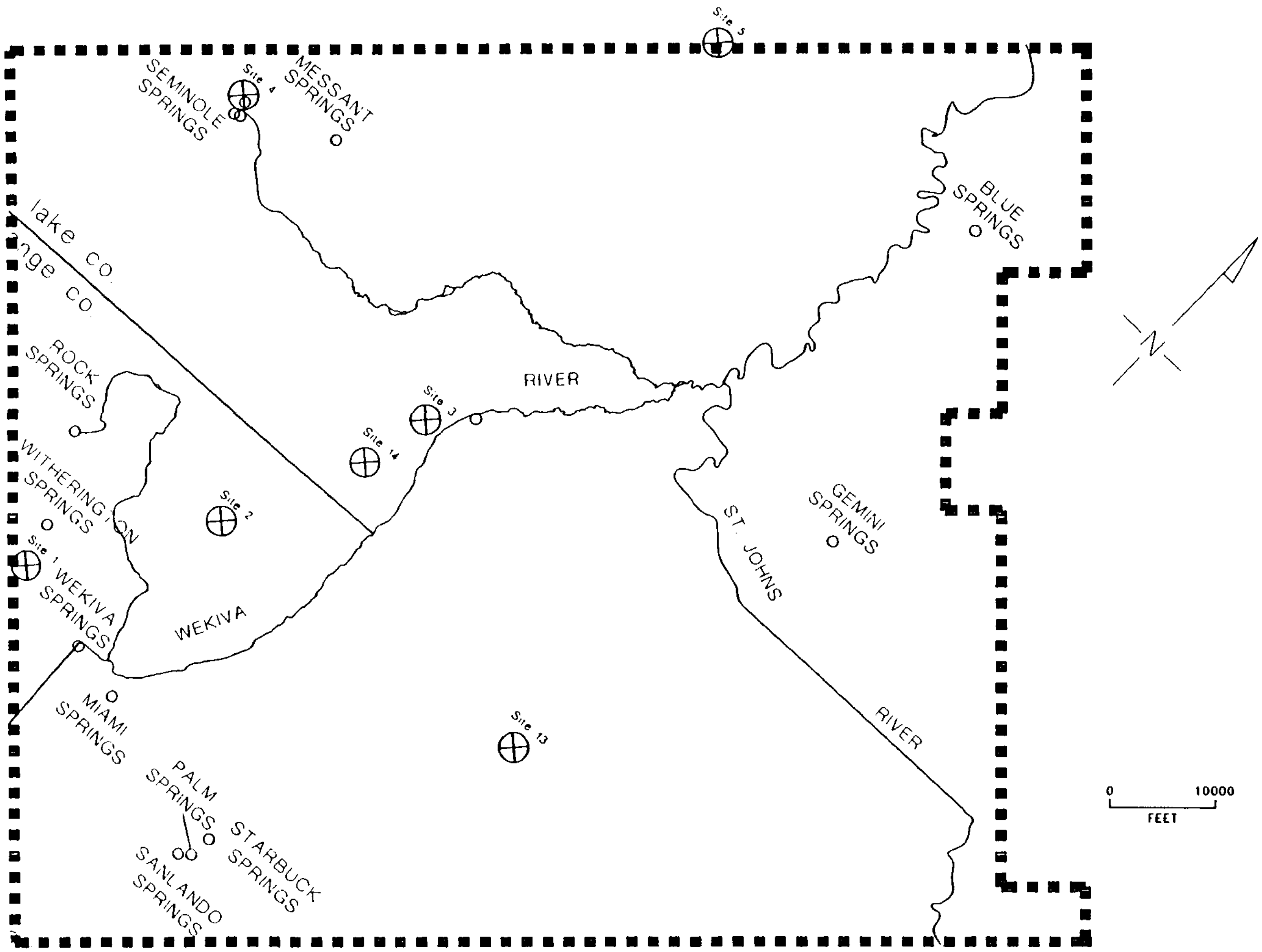

Figure 2.11. Location of the TDEM data collection sites.

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3 MODEL DEVELOPMENT

3.1 BACKGROUND

A number of investigators have developed groundwater flow models of the Floridan aquifer that encompass all or part of the current project area. These include Bush (1982), Tibbals (1981, 1990), CH2M Hill (1988), Jammal and Associates (1990), the HydroGeologic (1990). The work by Bush (1982) included the entire Floridan aquifer system using a grid spacing of 16 mi by 16 mi. Tibbals (1981) carried this analysis further by focusing on the east-central Florida area and a more refined grid spacing of 4 mi by 4 mi. His later work (Tibbals, 1990) utilized the same model and incorporated a transient analysis of the effects of the pumpage in 1978 on the Floridan aquifer. The models developed by CH2M Hill, Jammal and Associates, and HydroGeologic have all focused on sub-areas of the east-central Florida area and have typically used Tibbals' model as a starting point.

The groundwater flow model developed in Phase I of this study (GeoTrans, 1991a) also used Tibbals' model as a starting point to the analysis. That model used a variable grid spacing ranging from 0.5 mi by 0.5 mi to 4 mi by 6 mi. Grid spacing was variable to account for different accuracy requirements, variation in hydraulic gradients, and stresses on the system.

The Phase I model is used as a starting point to this analysis. Aquifer parameters, hydrostratigraphy, and boundary conditions are derived from the Phase I analysis. Additional complexity is built into the Phase III model by considering density dependent flow and a finer vertical and horizontal grid spacing.

3.2 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 1991c), benchmarked (Huyakorn et al., 1987), and field tested (Andersen et al., 1986, Andersen et al., 1988, and GeoTrans, 1991d) at three sites in Florida. SWICHA was also used to perform cross-sectional modeling as a part of Phase II of this study. 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 = fluid pressure
g = gravitational acceleration
ρ_o = freshwater density
Y = 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, 1991c).

3.3 CONCEPTUAL MODEL

The conceptual model for flow along a typical cross section paralleling a flow line in the Upper Floridan is shown in Figure 3.1. Groundwater flow in the study area (Figure 2.8) is generally southwest to northeast in the Upper Floridan aquifer with the St. Johns River providing a local discharge point for surficial aquifer flow, Upper Floridan aquifer flow, and to a lesser extent, Lower Floridan aquifer flow. Local variations in the flow direction reflecting the flow path of the St. Johns River are present. Flow directions in the Lower Floridan aquifer are less certain due to lack of data and differences in fluid density.

In classical saltwater intrusion studies, a saltwater interface with freshwater on the landward side and saltwater on the seaward side is formed near the coast. The interface is tilted and forms a wedge with saltwater present most landward at the base of the aquifer. The tilt of the interface results from the differences in density between the fresh water and the saltwater. The dynamics of saltwater intrusion is complicated by a

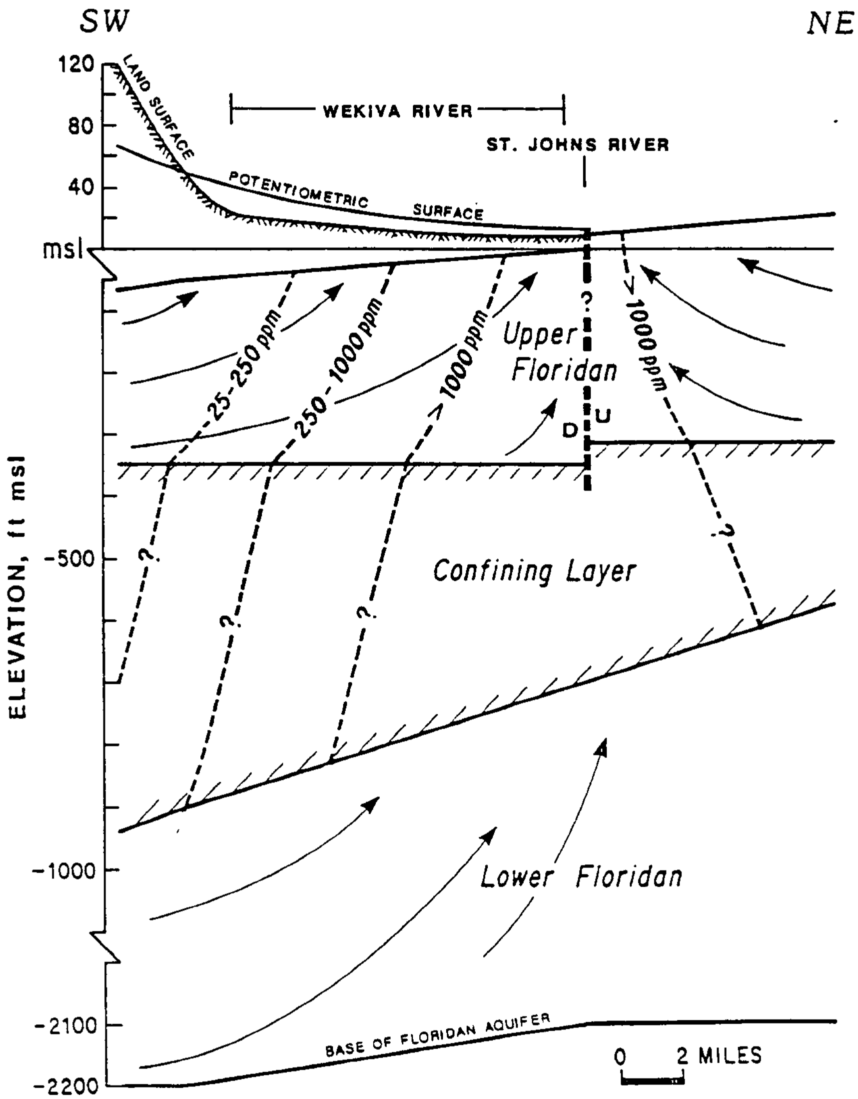

Figure 3.1. Conceptual model of the Floridan aquifer system in the study area.

transition zone that exists between the fresh and saltwater. It is further complicated by the fact that the interface is made up of flowing water. Generally, landward flowing saltwater mixes with seaward flowing fresh water, becomes less dense, rises and exits at the top of the wedge. The conceptual model for flow in the Lower Floridan aquifer follows this classical example. Flow of the fresher water in the Lower Floridan is generally toward the northeast, as it was in the Upper Floridan. Flow of the denser water in the Lower Floridan should follow an opposite trend (southwesterly) with a wedge formed within the model area.

In the Phase III study area, fresh water enters the Upper Floridan from the southwest and flows toward the northeast, mixing with residual saltwater. Local perturbations in the Upper Floridan flow field caused by discharge to the St. Johns and Wekiva Rivers generate a southeast flow of freshwater along the northwest boundary of the study area. In the Lower Floridan aquifer, relatively fresh water also enters the southwest portion of the study area, flowing northeast and upward atop a saltwater wedge. The rising water mixes with the saltier water along the wedge. Some of the water discharges through the semi-confining layer, with the remainder flowing northeasterly in the Lower Floridan.

The surficial aquifer system provides downward leakage over much of the study area. Recharged by precipitation, this water is usually low in dissolved chloride content. Much of the surficial aquifer system is covered by shallow lakes and wetlands in the study area. A postulated fault in the vicinity of the St. Johns River (see Figures 2.1 and 3.1) may provide an upward route for leakage into the St. Johns River and adjacent surficial system.

3.4 NUMERICAL MODEL CONFIGURATION

3.4.1 Boundary Conditions and Hydrogeological Unit Geometry

The conceptual model for density dependent saltwater flow in the area of Florida where the Wekiva River flows into the St. Johns River (Figure 2.8) is partially based on the MODFLOW flow model presented in GeoTrans (1991a). Relative locations of the two models are shown in Figure 3.2. Where appropriate, hydraulic head boundary conditions for the saltwater

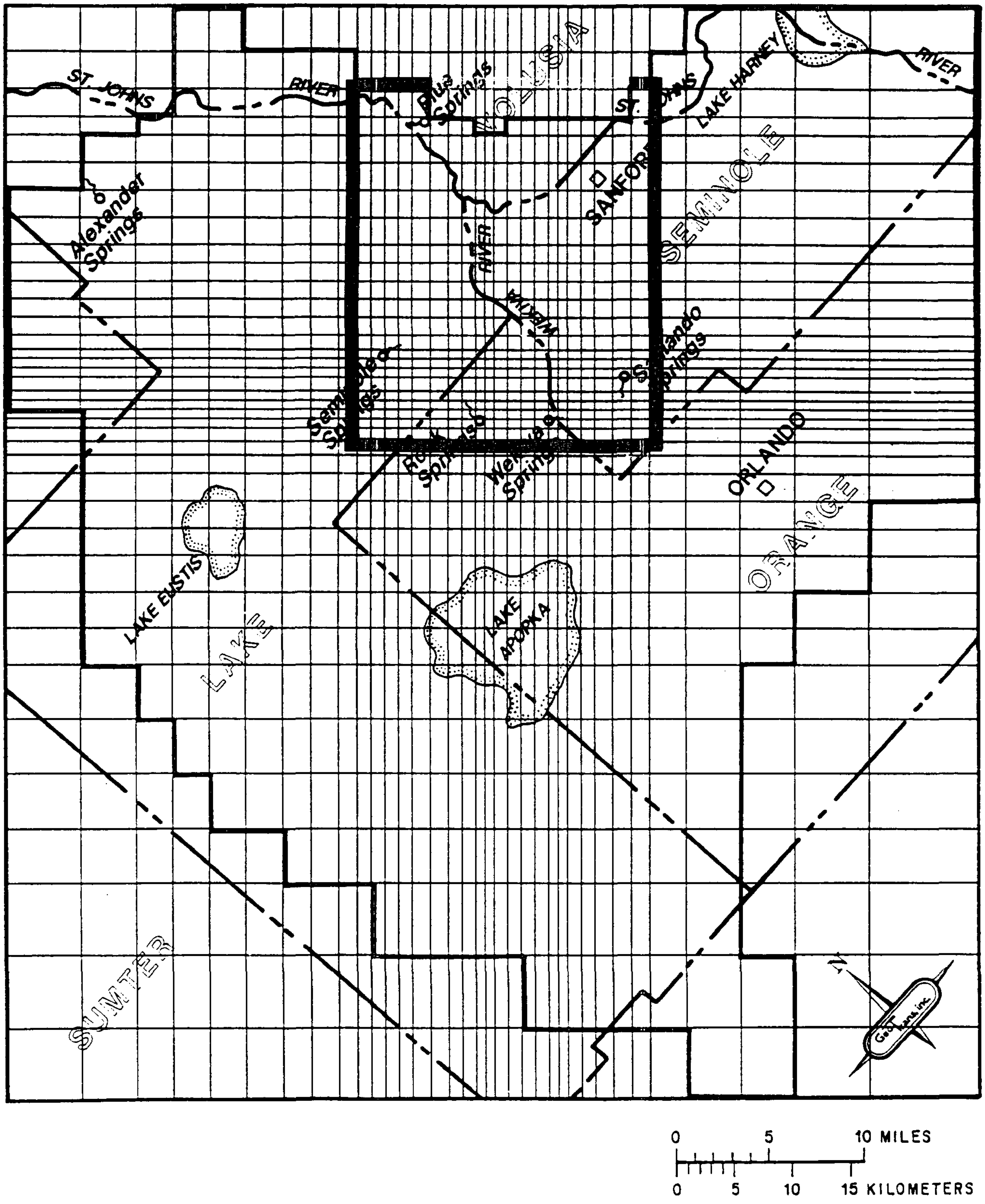

Figure 3.2. Location and coverage of the Phase III flow and transport model grid relative to the regional Phase I flow model grid.

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model are derived by interpolation from the block-centered results of regional MODFLOW runs (Figure 3.3 and 3.4). Additional information used in generating the flow boundary conditions was derived from the data provided by the SJRWMD as well as the studies of Miller (1986) and Tibbals (1990). The thicknesses of the Upper Floridan, Lower Floridan, and separating semi-confining layer were derived from maps of unit thicknesses and depths presented by Miller (1986). Due to the large degree of uncertainty involved with defining the spatial variability of hydraulic conductivities and unit thicknesses over the area of the model, all hydrogeologic units were considered to be of constant thickness and the variance of thickness embedded in transmissivity values derived from the MODFLOW study were reflected in the hydraulic conductivity values used in the saltwater model. Concentrations from wells and springs and as interpreted from the TDEM study were used to help assign the boundary conditions for the transport portion of the model.

Discretization of the saltwater model was based on several often conflicting interests, including maximizing the level of detail in the study area, generating a stable solution scheme, and running a problem within an acceptable time frame. Unfortunately, the latter interest, brevity of solution time, was the controlling factor. The steady-state runs took approximately 10-12 hours each on a Gateway 486-33 PC with 32 megabytes of RAM. On a 486-33 PC with only 8 megabytes of RAM, which necessitates the use of paging, the computation time increased to over 4 days. The 10-12 hour time frame, although long, is consistent with a problem which is as large and complex as this one. The discretization scheme used in the three-dimensional runs is depicted in Figures 3.5 through 3.7. The model consists of 24570 nodes and 21736 elements. In the areal plane, the finite-element model was discretized into a system of 45 by 39 nodal columns and rows. Figure 3.5 shows the relationship between the discretization schemes used in the MODFLOW model and the saltwater model. Note that the MODFLOW block edges always coincide with nodal rows and columns. This guarantees spatial consistency of material property distribution between the two models. Areal grid spacing varies between 660 ft and 2640 ft. The finest grid spacing is on the northeast and southwest boundaries of the study area. Phase II modeling indicated the need to have

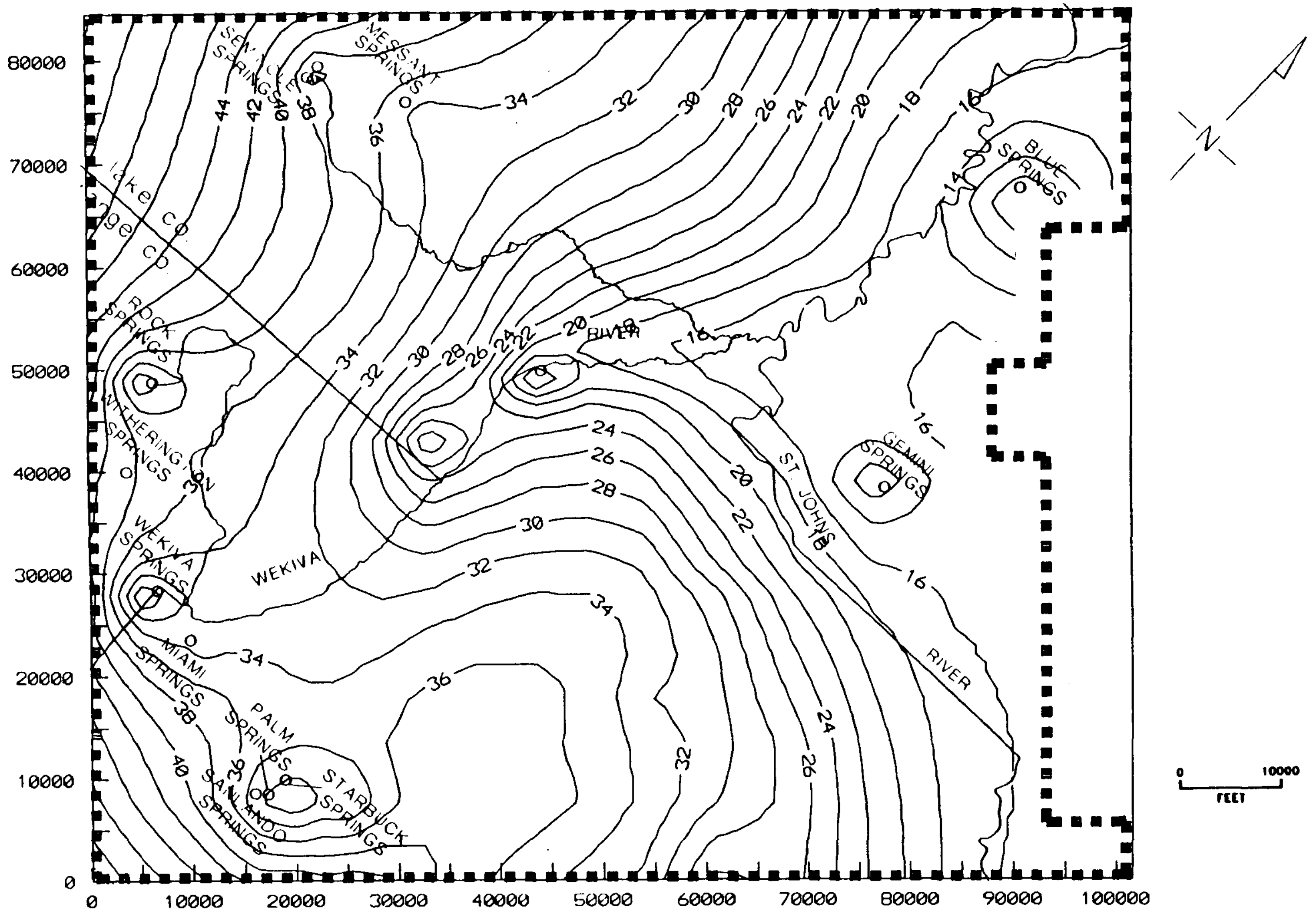

Figure 3.3. Potentiometric surface (ft, msl) in the Upper Floridan aquifer from the MODFLOW regional model of current (1988) conditions in the Phase III study area.

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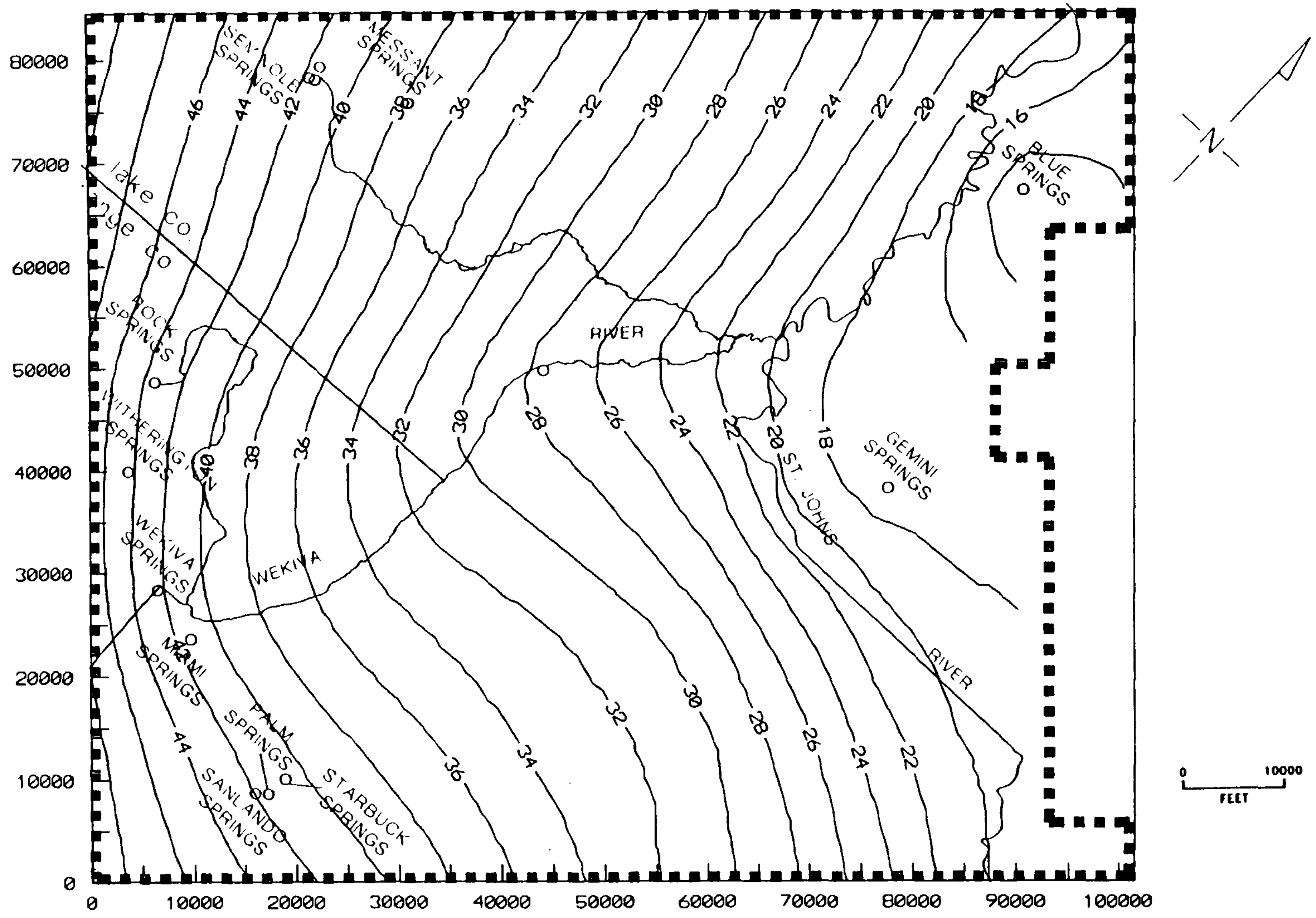

Figure 3.4. Potentiometric surface (ft, msl) in the Lower Floridan aquifer from the MODFLOW regional model of current (1988) conditions in the Phase III study area.

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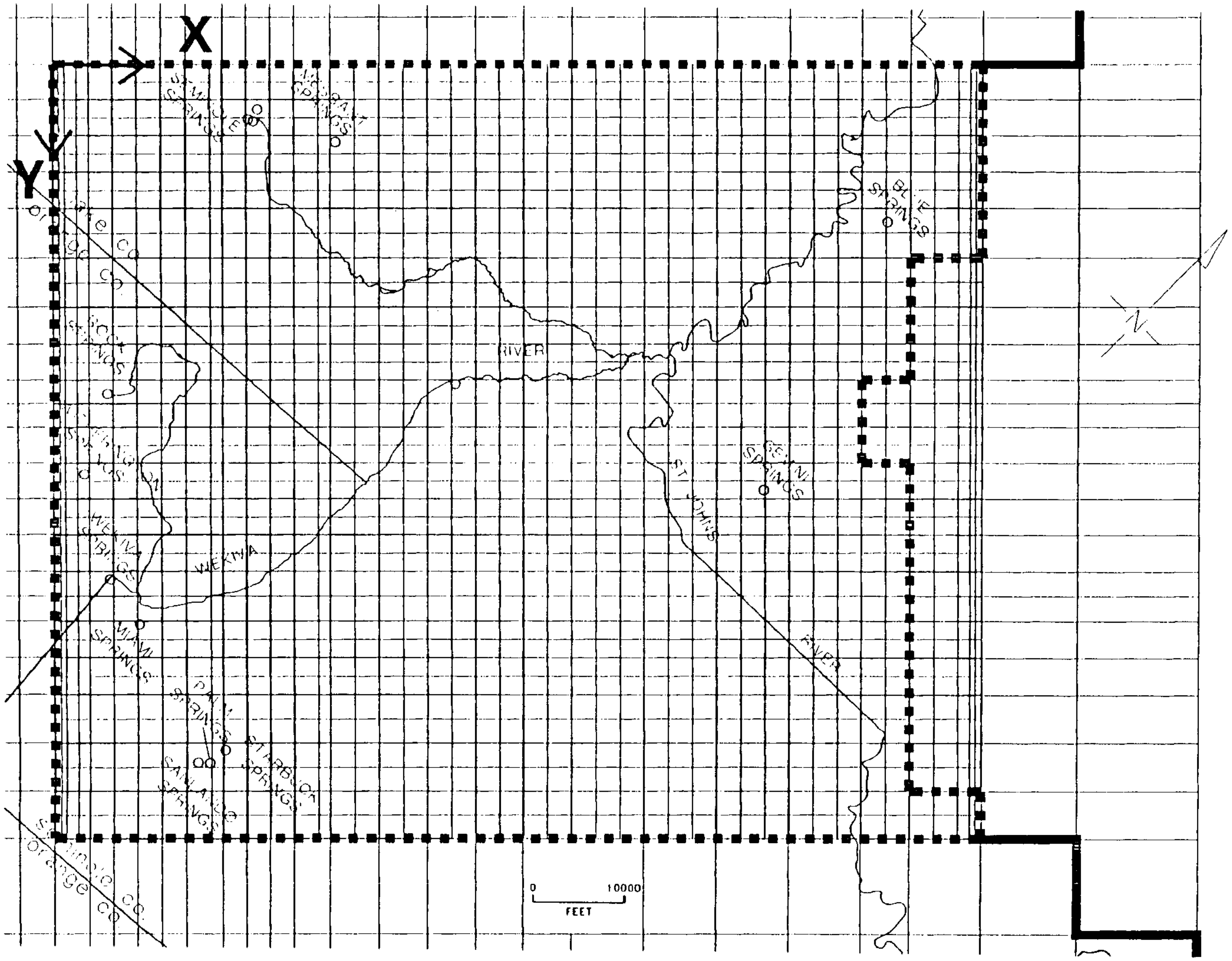

Figure 3.5. Areal discretization scheme used in the flow and transport model superimposed on a portion of the Phase I regional MODFLOW grid.

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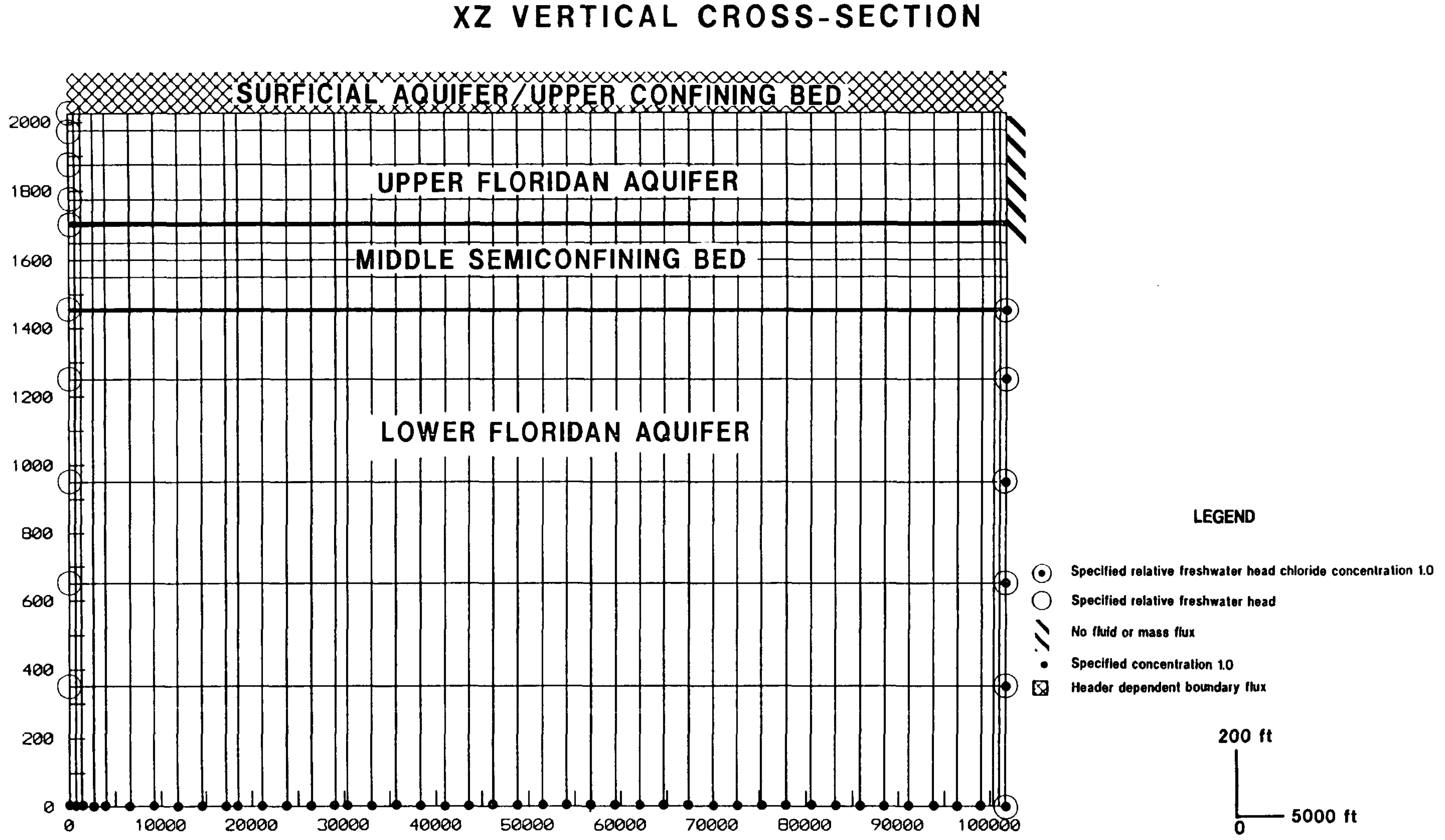

Figure 3.6. Vertical discretization scheme oriented along a slice in the flow and transport model.

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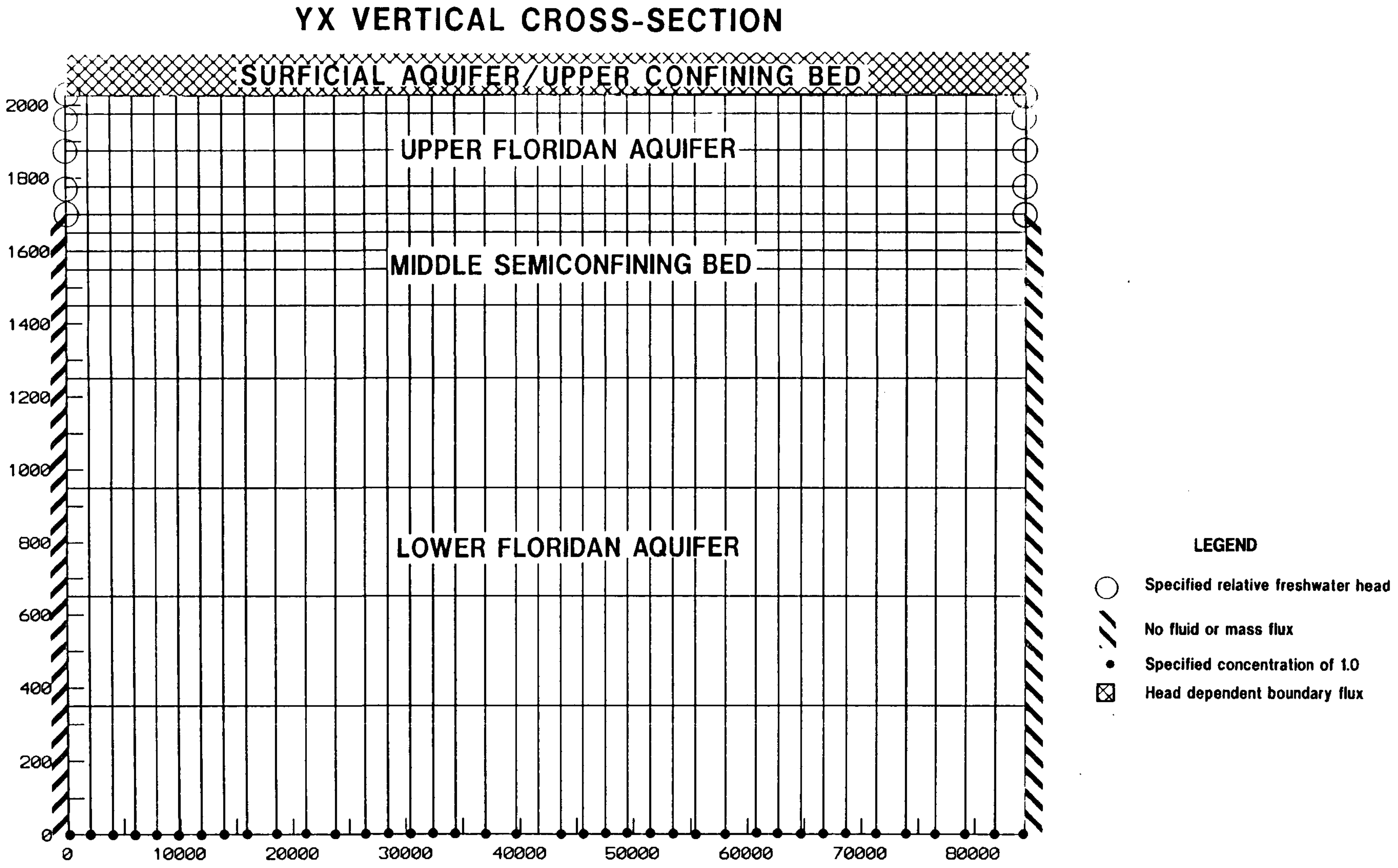

Figure 3.7. Vertical discretization scheme oriented perpendicular to a slice in the flow and transport model.

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fine spacing in these areas to avoid excessive smearing of the saltwater front. Nodal spacings along vertical slices (as defined by the slice successive over-relaxation solution scheme) are presented in Figure 3.6. Spacings along vertical planes oriented perpendicular to the slices are shown in Figure 3.7. Fourteen nodal layers are used to model the entire vertical sequence. The vertical grid spacing varies from 50 ft to 350 ft. The vertical discretization is fairly coarse, especially in the Lower Floridan aquifer. Since little detail exists on the three-dimensional spatial chloride distribution in the Lower Floridan, the bias associated with this coarse discretization cannot be evaluated. To allow for greater detail and generation of a less disperse front along the saltwater wedge while staying within the stability requirements of the finite-element solution scheme, the optimal vertical discretization for this type problem would be more in the neighborhood of 25 to 50 foot spacings, but the resultant computational effort would be prohibitive.

The bottom flow boundary condition of the model was specified as a no-flow boundary at a depth of 2025 ft. For transport, a concentration of 10,000 mg/L chloride was specified at the base of the model. This is generally supported by the limited available data which do not show chloride concentrations in excess of 10,000 mg/L. This boundary condition is also generally supported by Tibbals (1990) who shows a 10,000 mg/L isochlor in his conceptual diagrams of the flow system in this area. The presence of this concentration boundary condition is evaluated in the sensitivity analysis.

The lateral flow boundaries on all but the northeast boundary of the Upper Floridan aquifer were constant head nodes with values generated by interpolation of MODFLOW model results (see Figures 3.3 and 3.4). These boundaries were assigned constant concentrations of 0.0 mg/L for evaluation of solute transport. This assignment represents a good approximation for most of the model, but as can be discerned from Figures 2.4 through 2.6, there is some discrepancy for concentrations near the St. Johns River. In the case of the southeast boundary, the assignment of 0.0 mg/L chloride concentration is not critical because this is an exit condition and the model will generate its own concentration based on the concentration of the exiting fluid. The modeled concentration on the northwestern boundary near the St. Johns River will be slightly less than observed due to the boundary condition specification. Sensitivity analyses conducted later in the study indicated that this boundary had only a limited effect on the modeled results. This is because the predominant flow direction in this area is toward the river or parallel to the boundary. Because of the limited effect and location away from an area of predominant interest, simplification of this boundary to a concentration of 0.0 mg/L was deemed appropriate. Along the northeast boundary of the Upper Floridan aquifer, a no-flow boundary is placed along the lateral extent of the model. This is consistent with the boundary condition used in the MODFLOW model.

For the semi-confining layer separating the Upper and Lower Floridan aquifers, all lateral flow boundaries are no-flow boundary conditions. This is a reasonable assumption given the predominance of vertical flow in this unit. The transport boundary condition for the lateral boundaries of the semi-confining unit is no-mass flux.

In the Lower Floridan aquifer no-flow boundaries are imposed along the northwest and southeast boundaries of the model. Use of head values generated by the MODFLOW runs for the Lower Floridan aquifer for boundary conditions along the northwest and southeast sides of the model was not considered for several reasons. First, due to the paucity of data for the Lower Floridan aquifer, the MODFLOW runs were never calibrated for the Lower Floridan (GeoTrans, 1991a). Second, because of the high chloride levels and density dependent flow in the Lower Floridan aquifer, water levels would not necessarily be indicative of flow direction. For the purpose of this model, the general trend of Lower Floridan low-density fluid flow was considered to be to the northeast perpendicular to the general trend of the St. Johns River. High-density fluid flow was considered to be in the opposite direction (southwest). For the transport boundaries, the northwest and southeast sides of the Lower Floridan are considered no-flux boundaries. Constant heads interpolated from the MODFLOW model are used on the southwest lateral boundary for the Lower Floridan. A freshwater concentration of 0.0 mg/L is assigned in this location. This is based on a TDEM data site near this boundary which did not indicate a zone of high chloride concentration. The flow boundary conditions along the northeast boundary used in the MODFLOW simulations are not valid for solute transport. Upward movement of the water is a function of the salt wedge extending from this boundary. The nodes along this boundary are considered to be constant equivalent-freshwater heads with values based on potentiometric surfaces generated in the MODFLOW runs and an assumption of chloride levels above these nodes equal to 10000 mg/L in the Lower Floridan aquifer and semi-confining layer. The influence of potentially lower chloride levels in the semi-confining layer are assumed to be offset by chlorides in the Upper Floridan. Lower Floridan transport model boundary nodes along the northeast boundary are considered to be constant concentration nodes with values of 10000 mg/L. This includes all nodes along the uneven boundary in the northeast as shown in Figure 3.2. The 10,000 mg/L concentration is consistent with the basal concentration boundary and the conceptual cross-section given in Tibbals (1990).

A head dependent flux or leakance boundary condition was used to define the upper boundary of the flow model. These boundary nodes require specification of water levels above the confining unit, confining layer thicknesses, and vertical hydraulic conductivities. The head above the confining unit is representative of the surficial aquifer water table elevation. Water-table elevation and confining bed thickness vary areally in the model. The amount of flux from the surficial aquifer becomes a function of the difference between the specified surficial aquifer heads and computed heads at the top of the Upper Floridan aquifer. For consistency with the MODFLOW runs, SWICHA was modified to limit the downward leakage from the water table to a rate of 20 inches per year. Water levels in the surficial aquifer were generated from the spatial distributions used in MODFLOW runs and are presented in Figure 3.8. Recharacterization or improved resolution of water-table heads was not attempted in transferring to the finer gridded SWICHA model in order to maintain the tie-in with the MODFLOW model. Re-estimation of water-table heads could result in a more accurate model; however, it was decided that it was not justified due to parameter uncertainty and the need to recompute confining bed thicknesses in order to remain consistent with this methodology. Leakances taken from the MODFLOW model are presented in Figure 3.9. Influx water from the water table was considered to be fresh with a chloride concentration of 0.0 mg/L.

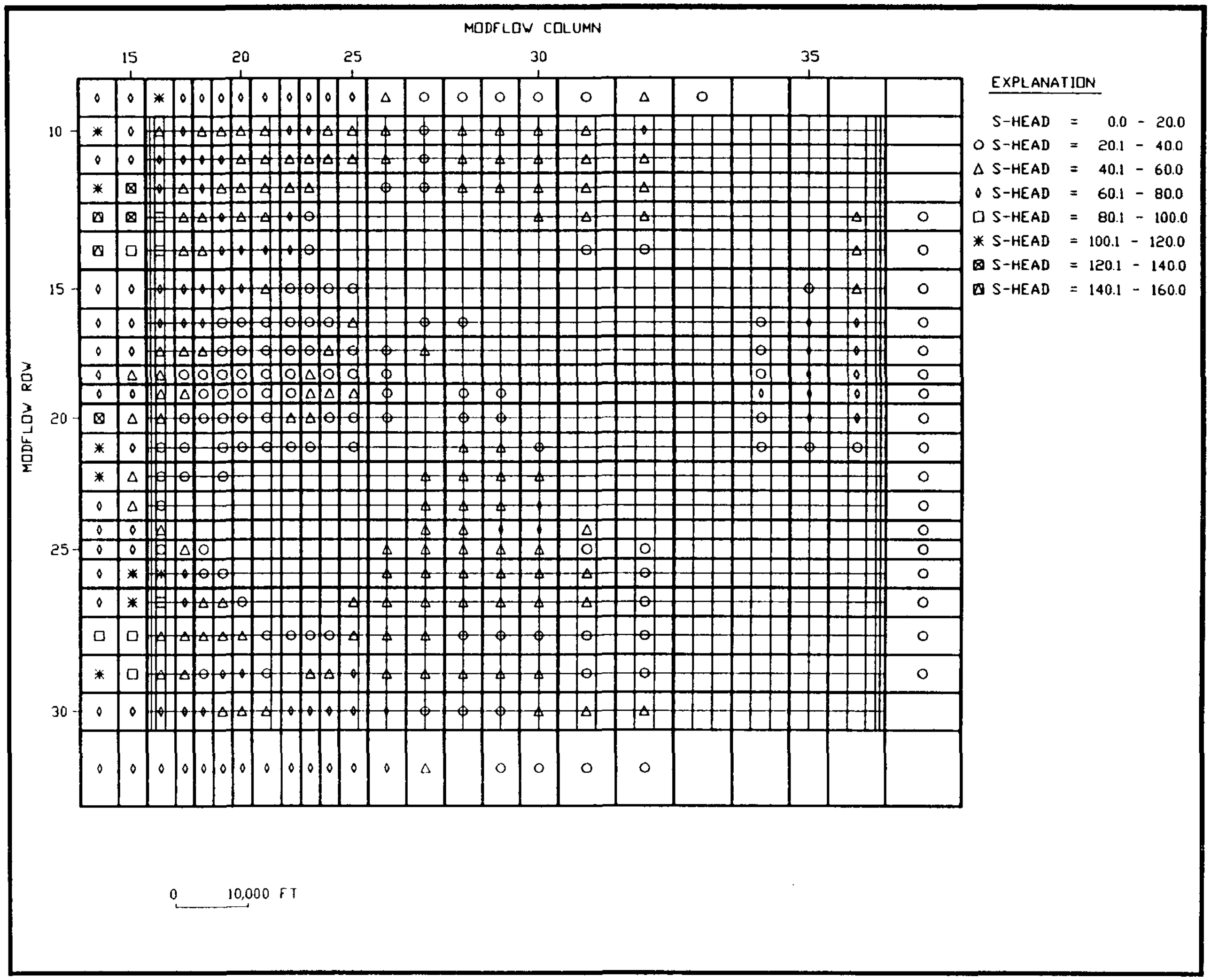

Figure 3.8. Areal distribution of surficial aquifer water levels in feet above msl for the MODFLOW and SWICHA models in the Phase III study area. The SWICHA grid is shown as a subgrid of the MODFLOW grid.

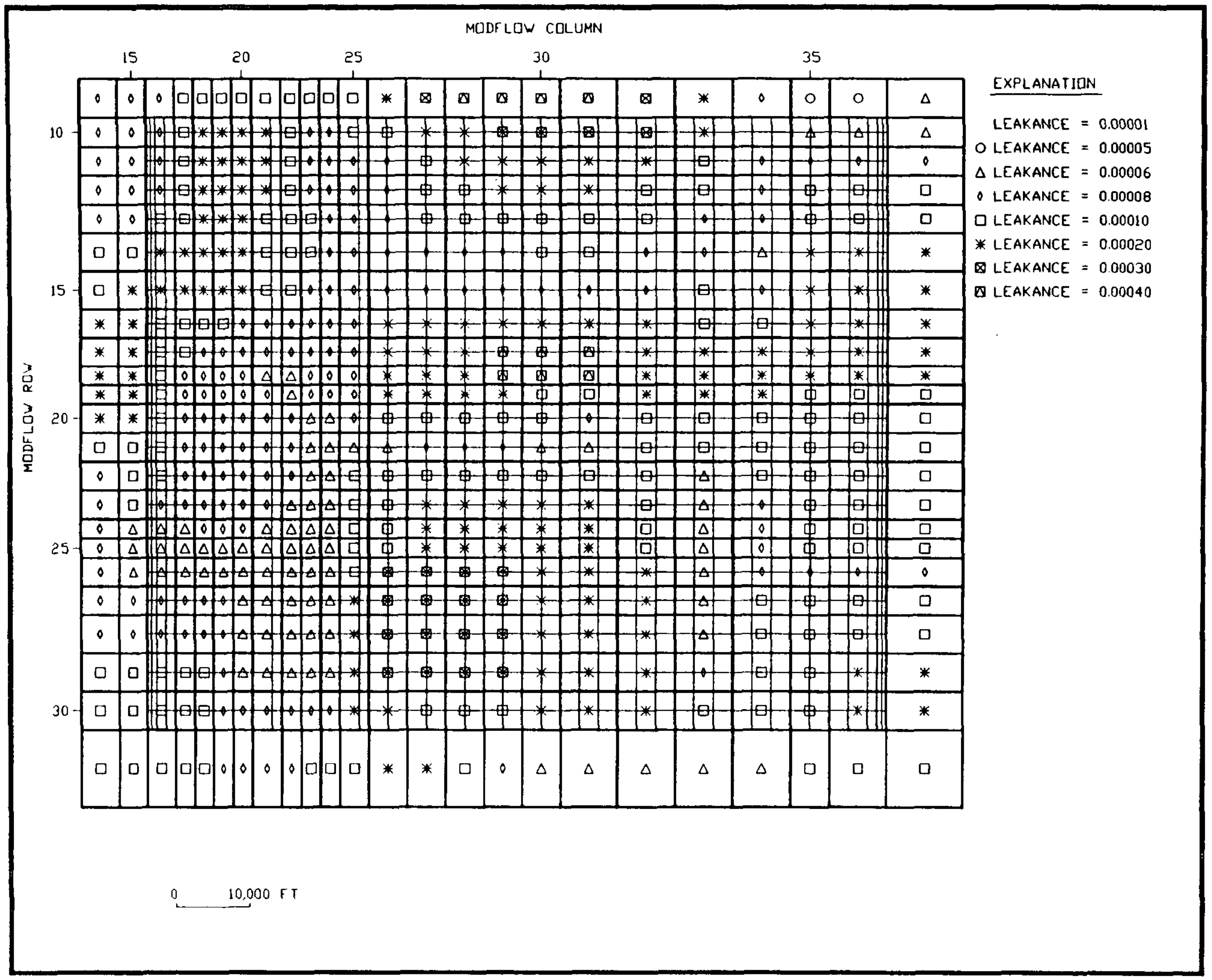

Figure 3.9. Areal distribution of confining layer leakances, in day^{-1} for the MODFLOW and SWICHA models in the Phase III study area. The SWICHA grid is shown as a subgrid of the MODFLOW grid.

Other boundary conditions utilized in the saltwater model are spring-type nodes and fluid-flux nodes representing wells. Well fluxes were taken from the MODFLOW simulations and applied to the column of nodes located nearest the actual pumping centers. Since open interval data was not available for most wells and since some nodes represent several wells, the fluxes were equally distributed along the column of nodes traversing the Upper Floridan aquifer. This is method is also consistent with the fact that a smaller interval may still represent the major transmissive zone of the aquifer. For consistency with the MODFLOW model, the fluxes to the springs were considered to be the same as those in the MODFLOW model. Spring conductances were generated for use in the transient simulations based on the MODFLOW spring flux and approximate distances from the top of the Upper Floridan to spring pool elevation.

3.4.2 Parameters

As much of the MODFLOW model calibration effort (Geotrans, 1991a) that was pertinent to the saltwater model was utilized in developing the base-case parameters for the saltwater model. Horizontal hydraulic conductivities used in the saltwater model were generated from MODFLOW model derived transmissivities by dividing the transmissivities by the assigned thicknesses of the units. For the Upper Floridan, elemental hydraulic conductivities were generated from the MODFLOW derived transmissivities presented in Figure 3.10 by dividing the transmissivities by the assumed thickness of the unit, 325 feet. Similarly, Lower Floridan hydraulic conductivities were generated by dividing the MODFLOW derived transmissivities presented in Figure 3.11 by the assumed Lower Floridan thickness of 1450 feet. Note that the translation of transmissivity between MODFLOW and SWICHA is most accurate in the freshwater portion of the aquifer. In the saltwater portion the flow paths between MODFLOW and SWICHA are somewhat different because density dependent flow is considered in SWICHA, but not in MODFLOW. A horizontal to vertical hydraulic conductivity anisotropy ratio of 10:1 was assumed for the Upper and Lower Floridan aquifers. This is consistent with the Phase II study and work by other researchers. The hydraulic conductivity used in the semi-confining layer for the saltwater model is based on the vertical leakances used in

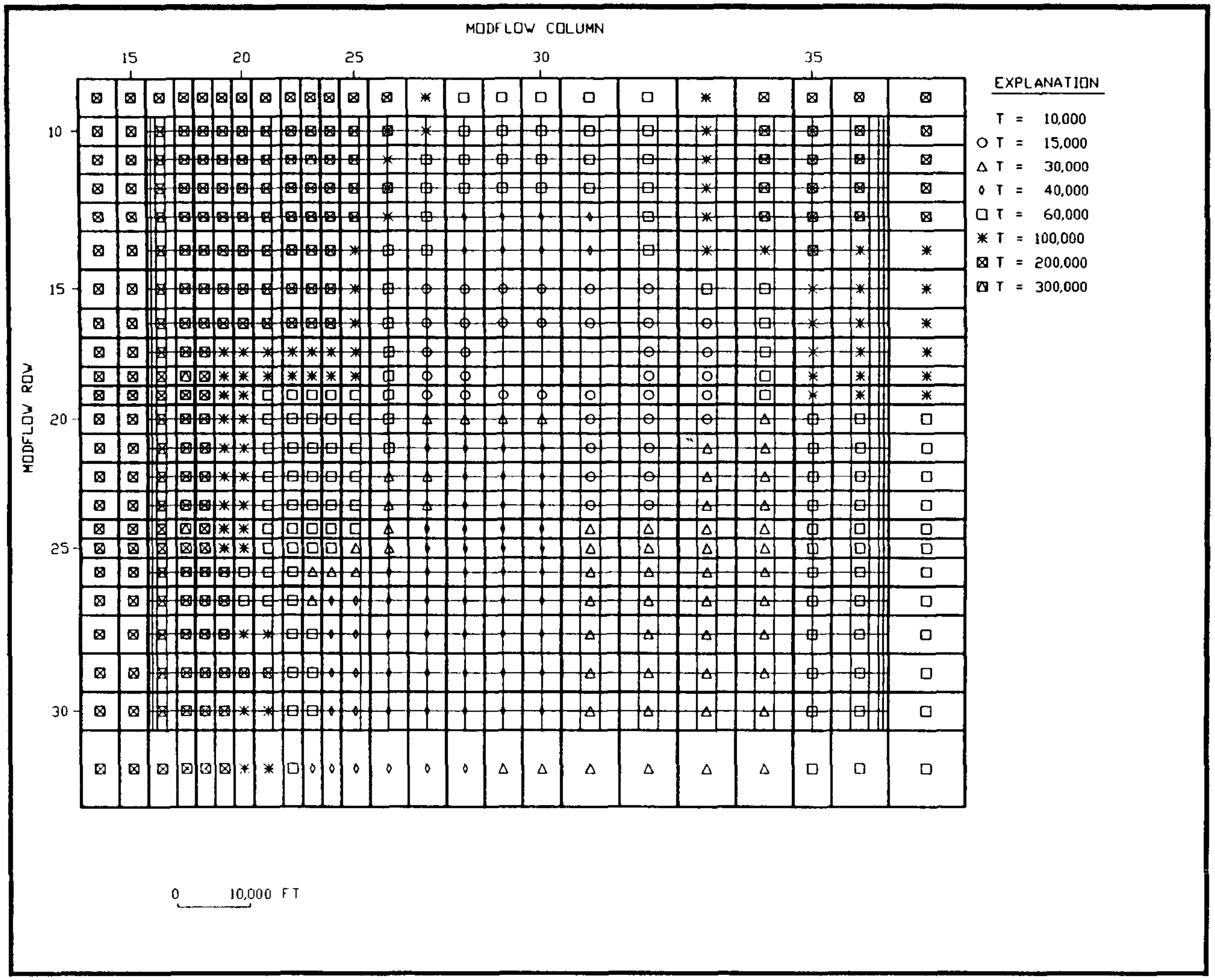

Figure 3.10. Areal distribution of Upper Floridan transmissivities in ft^2/day as utilized in the MODFLOW and SWICHA models in the Phase III study area. The SWICHA grid is shown as a subgrid of the MODFLOW grid.

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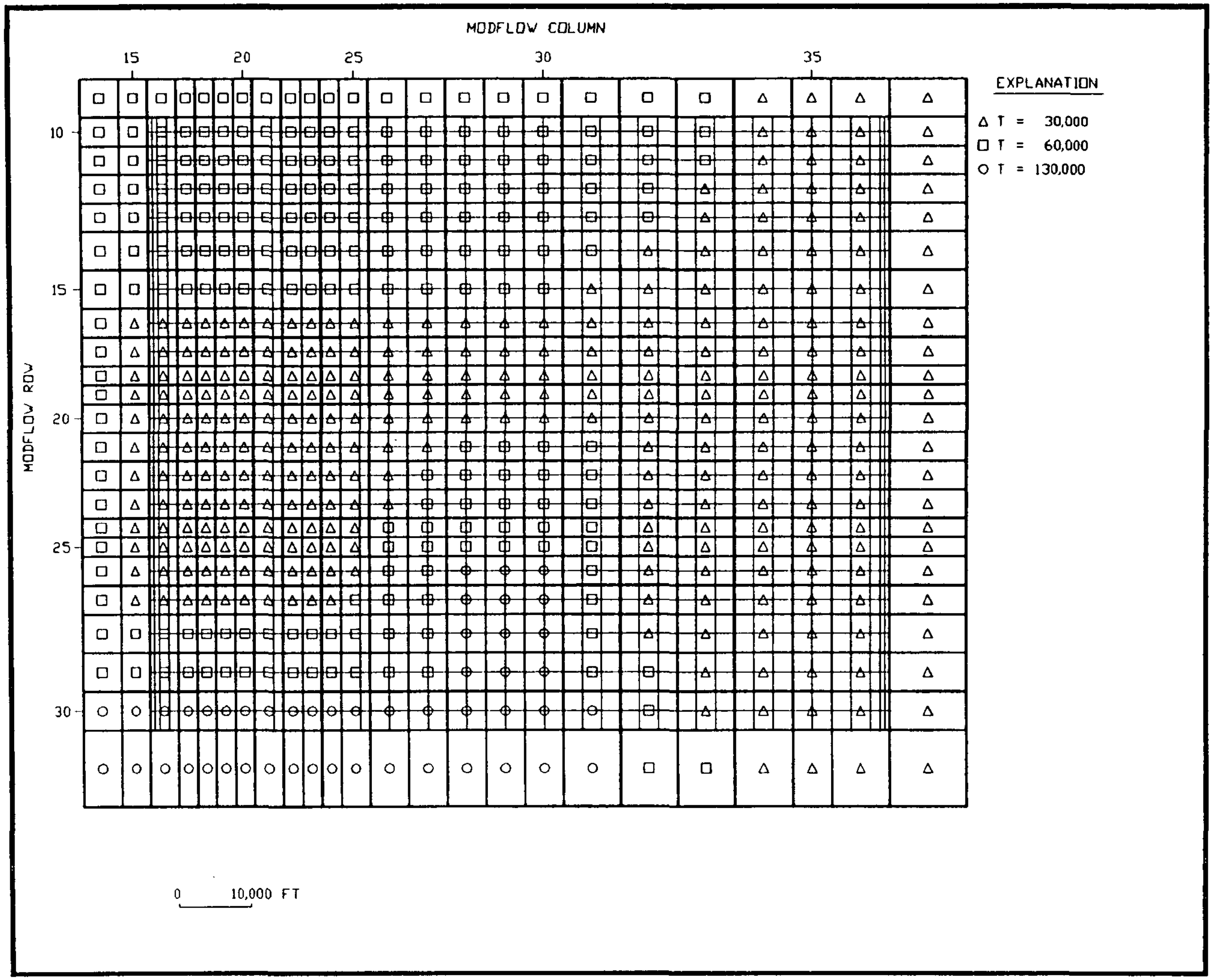

Figure 3.11. Areal distribution of Lower Floridan transmissivities in ft^2/day as utilized in the MODFLOW and SWICHA models in the Phase III study area. The SWICHA grid is shown as a subgrid of the MODFLOW grid.

the MODFLOW model. Values of hydraulic conductivity used in the saltwater model are 0.05 and 0.5 ft/d with a similar distribution of values as that of leakances of 0.0002 and 0.002 d^{-1} used in the MODFLOW model. The conductivity values were derived by multiplying the MODFLOW leakances by the thickness of the semi-confining layer, 250 feet.

Longitudinal and transverse dispersivities of 120 ft and 30 ft, respectively, were used in the model. This is consistent with values used in the Phase II cross-sectional model. Due to the instability caused by low dispersivities in the three-dimensional model, SWICHA's upstream weighting option was needed to attain results for this model. This has the net effect of introducing additional artificial dispersion which may smear or spread out concentration fronts.

3.4.3 Model Calibration

Calibration of the groundwater flow portion of the model was based on matching the results of the MODFLOW model. Since data needed to calibrate the Lower Floridan is not available, consideration was only given to matching flow results in the Upper Floridan. When comparing the results of MODFLOW and SWICHA simulations, several details must be considered. First, MODFLOW heads represent depth averaged values while SWICHA generated values vary over the vertical extent of the aquifer. Second, due to the finer discretization pattern applied to the saltwater model, a more detailed pattern of head variability will appear at well and spring nodes. Finally, hydraulic head plots of SWICHA simulations represent equivalent freshwater heads that account for chloride concentrations while the hydraulic head plots from MODFLOW do not account for chloride concentrations. Upper Floridan chloride levels are low enough that there is little difference between heads and equivalent freshwater heads, but care should be taken in comparing results near areas of higher saltwater concentrations. Lusczynski (1961) discusses differences between head, relative freshwater head, and environmental head. In general, the relative freshwater head plots presented in this report are valid for determining flow directions along a plane of the same elevation. Environmental heads should be used to determine flow directions in vertical cross-sections.

Since most of the flow parameters were taken from the calibrated MODFLOW model, a close match of Upper Floridan water levels generated by the two models was considered to be an appropriate starting point for refined calibration. Parameters were then changed slightly to achieve a closer match. A good comparison exists between the MODFLOW Upper Floridan results (Figure 3.3) and the saltwater model simulation results for a depth 150 ft below the top of the Upper Floridan aquifer (Figure 3.12). This model is referred to as the base case simulation.

The major difference in the two models occurs in the areas near springs, where the combined influence of the finer grid scheme and the vertical resistance in the saltwater model generates larger drawdowns around the springs. This result is expected, but its acceptability is dependent on the effect on the head differences around the springs. The appropriateness of the model would dictate that the heads in the Upper Floridan must be greater than the pool elevation to indicate discharge at the spring. The area around three of the springs was shown to be incapable of producing as much water as produced in the MODFLOW model. To improve the model, consideration was given to the properties of calcitic and dolomitic rocks in areas around springs. In general, these rocks will have a greater percentage of solution voids than areas away from the springs. This effect was approximated by doubling of the horizontal hydraulic conductivities in the elements immediately surrounding the spring nodes throughout the depth of Upper Floridan. Horizontal to vertical hydraulic conductivity ratios were also reduced to 1:1 in these elements. The conductivity changes produced appropriate heads in the spring areas and effective spring conductances were generated from the fluxes, head differences and nodal chloride levels. This model is referred to as the revised model.

The changes to the areas around the springs were required in part to make the SWICHA model more consistent with the MODFLOW model. The SWICHA grid resolution is finer in the vertical direction as well as the horizontal. This results in the SWICHA spring boundary condition being connected to only the uppermost node of the Upper Floridan aquifer. In MODFLOW, the spring boundary condition is by definition connected to the middle of the Upper Floridan aquifer.

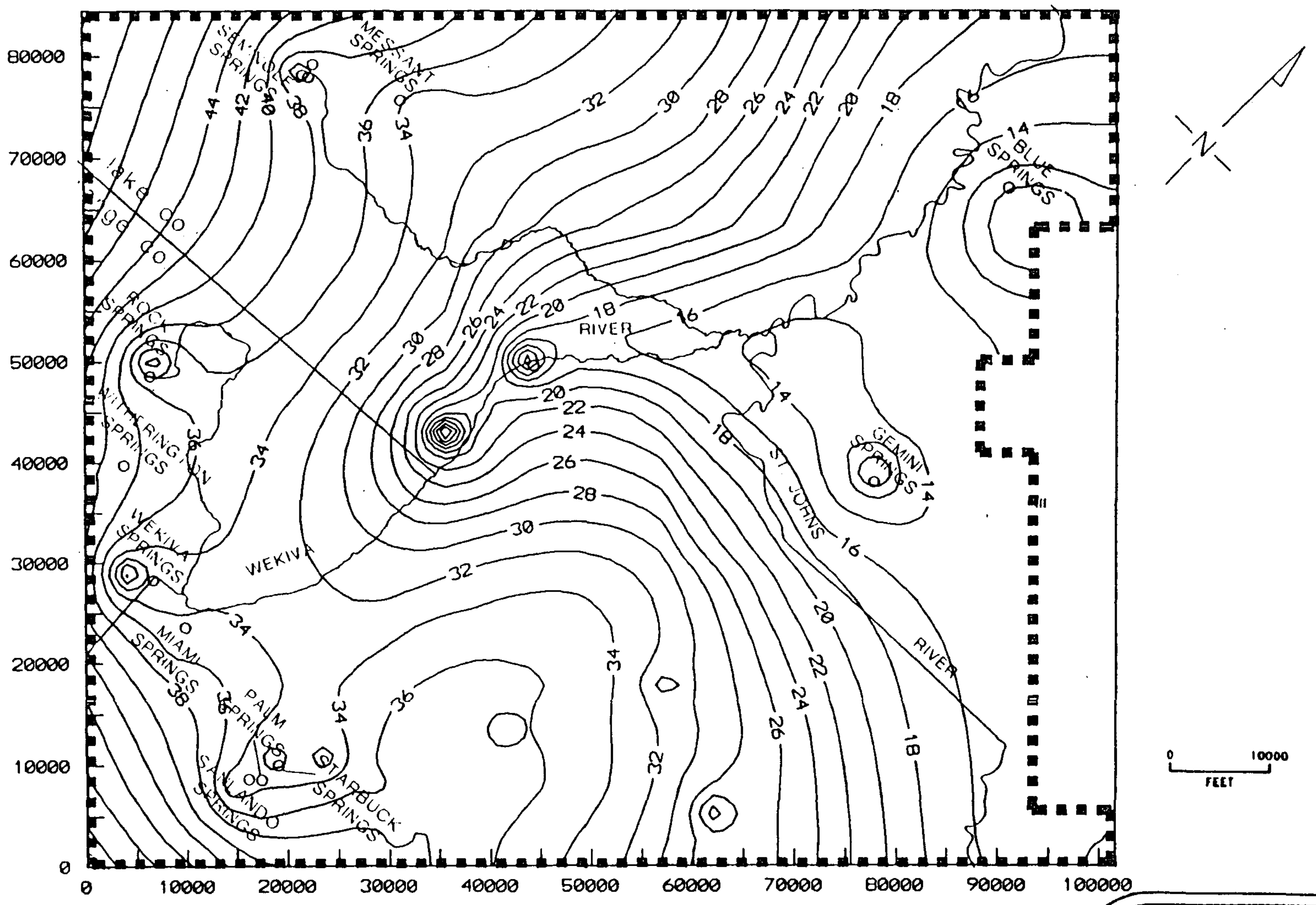

Figure 3.12. Simulated potentiometric surface (ft, msl) in the Upper Floridan aquifer for the base case simulation for current (1988) conditions.

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Increasing the connectiveness of the spring to the Upper Floridan in the SWICHA model has a similar effect as having the spring connected to the middle portion of the Upper Floridan.

A comparison of the revised model Upper Floridan potentiometric surface (Figure 3.13) with the base case model results (Figure 3.12) highlights the head changes in the areas adjacent to the springs. Equivalent fresh-water head contour plots for the base case and revised runs (Figures 3.14 and 3.15 respectively) show the lack of influence of the Upper Floridan high conductivity zones on the Lower Floridan flow system. Comparing Lower Floridan potentiometric surfaces (Figures 3.14 and 3.15) with the MODFLOW results (Figure 3.4) shows similar flow trends in areas of both models where the flow is not influenced by chloride levels. The influence of the high conductivity zones on the flow systems surrounding Rock Springs and Island Spring can be seen by comparing southwest to northeast cross-sections for the base case (Figure 3.16) and revised (Figure 3.17) models.

Due to the lack of chloride level data over much of the area and lack of vertical distribution data over areas with chloride data, calibration of the transport model presented a little more difficulty than calibration of the flow model. Calibration was performed by: (1) comparing modeled chloride concentrations with general trends presented in Figures 2.4 through 2.6; (2) comparing modeled chloride concentrations with localized measurements reported by Tibbals (1977) and Toth (1989); (3) comparing generated spring discharge chloride levels with data provided by SJRWMD; and (4) comparing modeled results to well data and TDEM data. Simulated Upper Floridan chloride levels for the initial and revised base cases are presented in Figures 3.18 and 3.19 respectively. Simulated chloride level trends follow the river similarly to trends depicted in Figures 2.4 through 2.6. Differences in trends occur in the northern and eastern corners of the model and slightly higher chloride levels are seen 4-6 miles north of Wekiva Springs along the Wekiva River. A better approximation of the chloride distribution for the northern corner could be generated by additional data gathering in the area. Further analysis of the sensitivity of the system to chloride levels along this boundary is presented in the sensitivity analysis section. Differences in the trends in the eastern

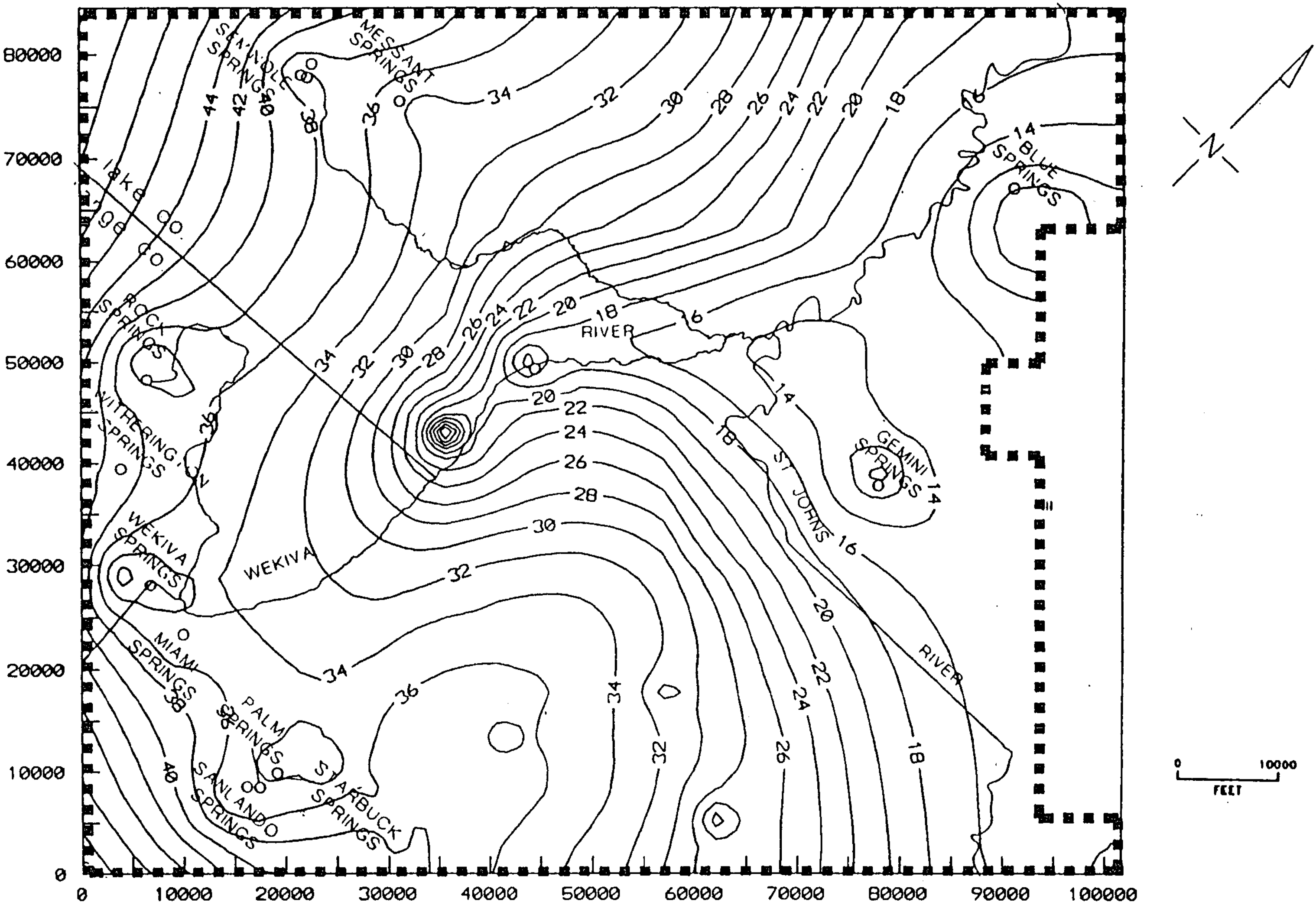

Figure 3.13. Simulated potentiometric surface (ft, msl) in the Upper Floridan aquifer for the revised simulation for current (1988) conditions.

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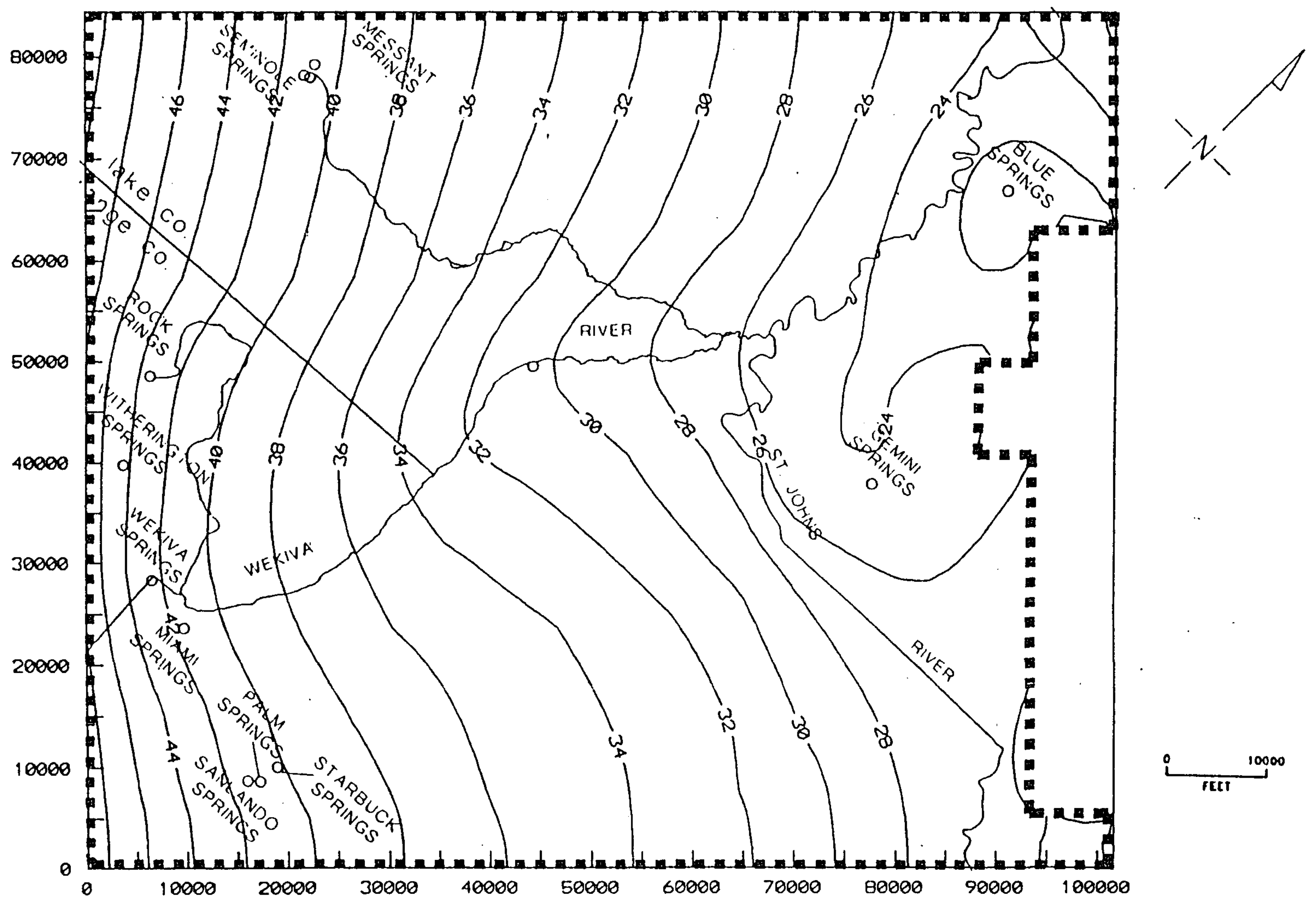

Figure 3.14. Simulated potentiometric surface (ft, msl) in the Lower Floridan aquifer for the base case simulation for current (1988) conditions.

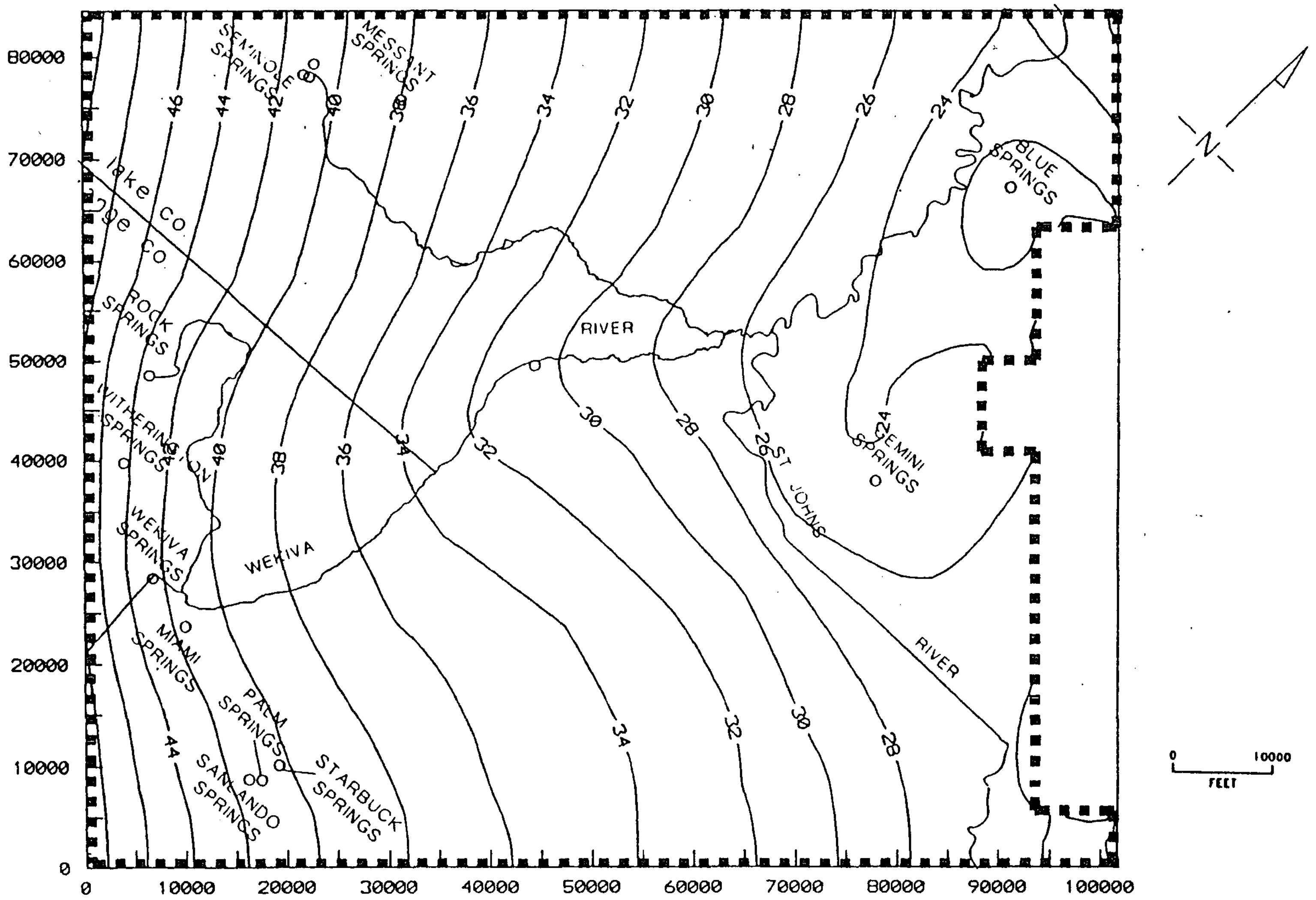

Figure 3.15. Simulated potentiometric surface (ft, msl) in the Lower Floridan aquifer for the revised simulation for current (1988) conditions.

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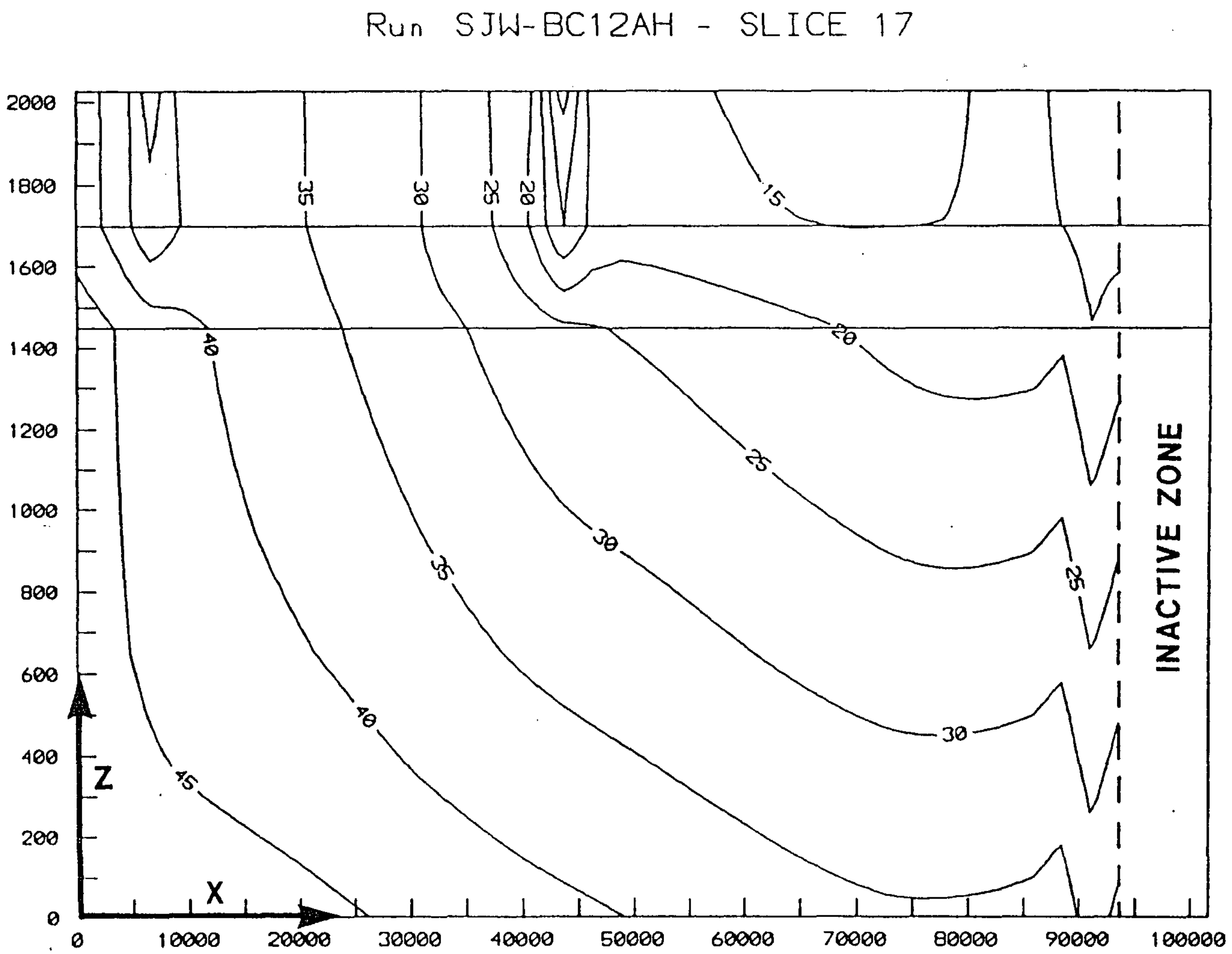

Figure 3.16. Simulated head distribution (ft, msl) in a vertical cross-section running southwest to northeast in the study area for the base case simulation for current (1988) conditions.

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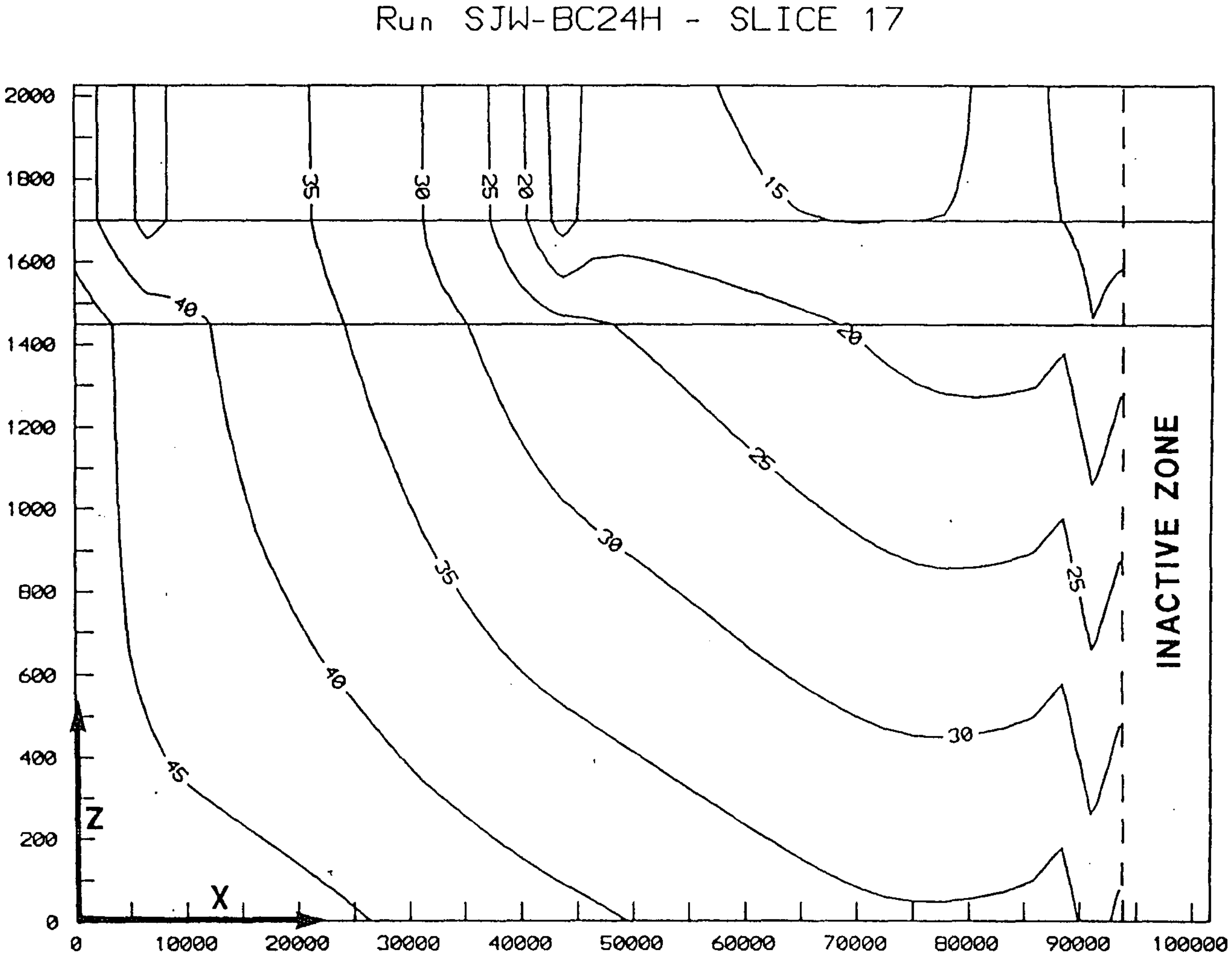

Figure 3.17. Simulated head distribution (ft, msl) in a vertical cross-section running southwest to northeast in the study area for the revised simulation for current (1988) conditions.

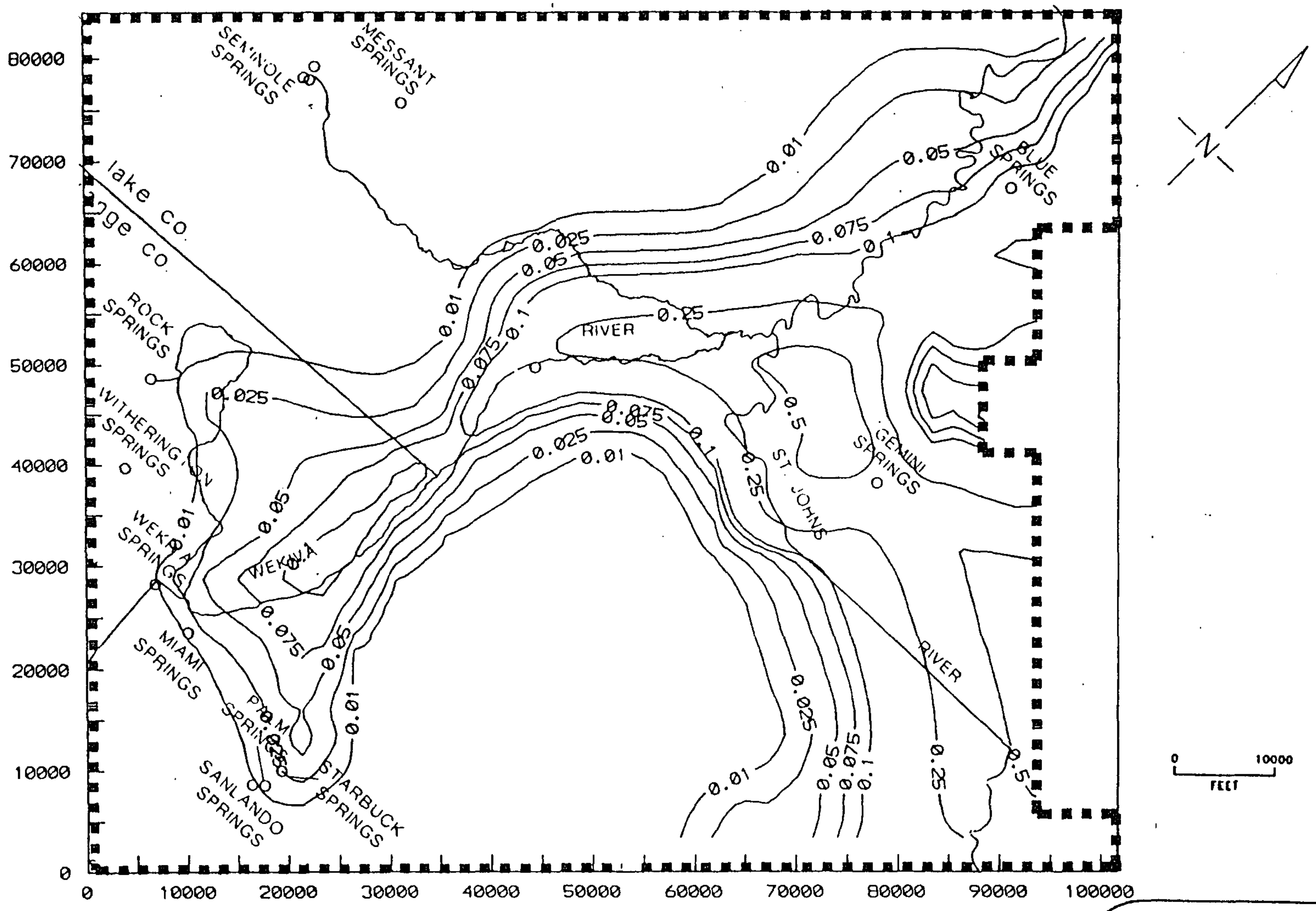

Figure 3.18. Simulated chloride concentrations (1.0 = 10000 mg/l) in Upper Floridan aquifer for the base case simulation for current (1988) conditions.

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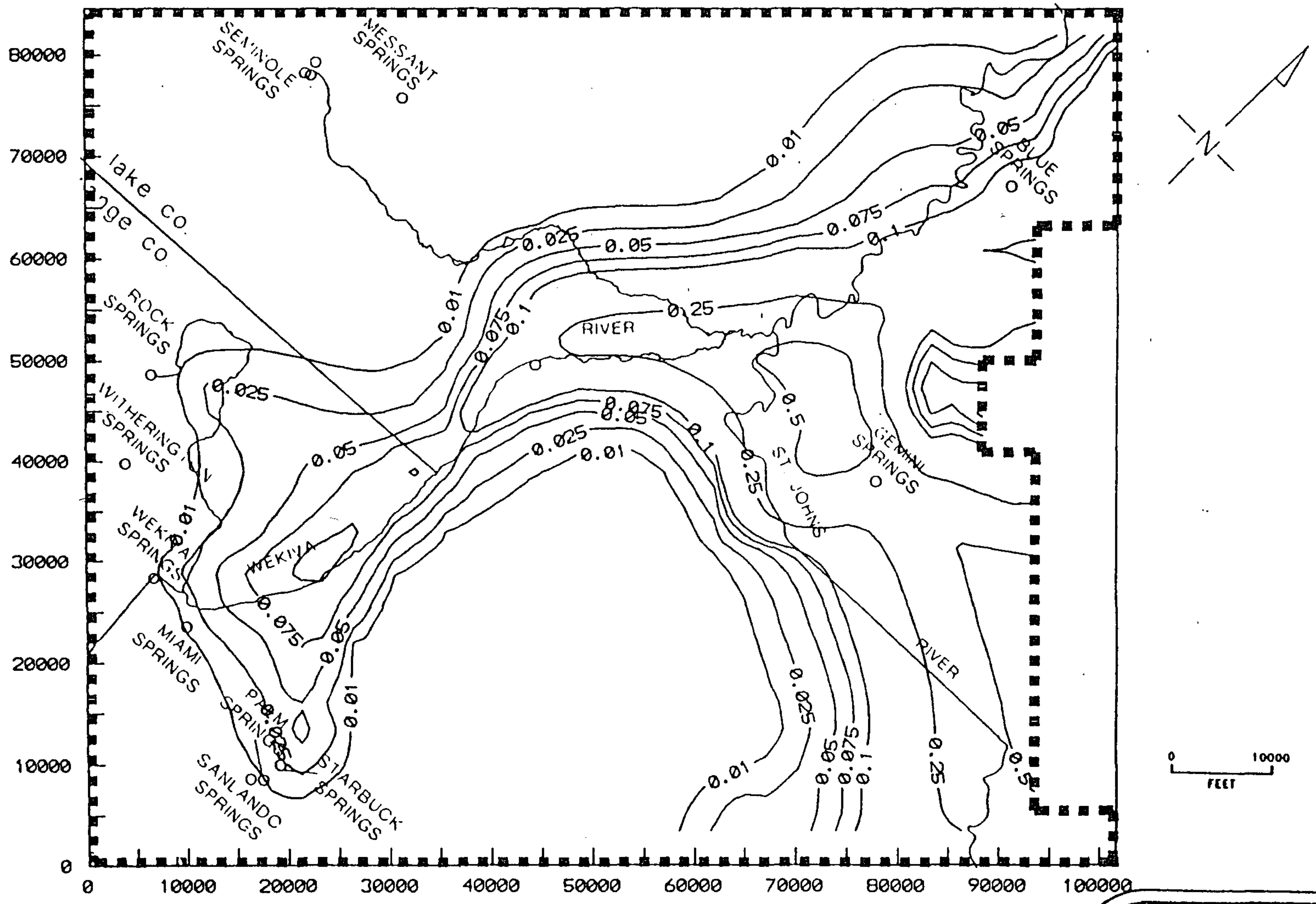

Figure 3.19. Simulated chloride concentrations (1.0 = 10000 mg/l) in Upper Floridan aquifer for the revised simulation for current (1988) conditions.

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corner of the model are due to the assumed no-flow boundary. The slightly elevated concentration levels along the Wekiva River are likely to be a function of the localized flow system. More specific data on the local hydrogeology in this area would help improve the model approximation in this area.

Comparison of simulated chloride concentrations to more localized data by Tibbals (1977) for 1973-74 and Toth (1989) for 1986 is also fairly good. The simulated values are slightly higher along the Wekiva River, as was noted previously, but the shape and extent of the saltwater "plume" is generally matched. The model does show some diversion of saltwater toward Rock Springs which was not noted by Tibbals (1977) or Toth (1989). This is probably a modeling inaccuracy resulting from the transport parameters that were specified or the groundwater flow calibration.

Comparison of simulated spring chloride levels with data provided by the SJRWMD (Table 3.1) show similar trends. The higher simulated value at Blue Springs (1900 mg/L vs 526 mg/L) is most likely a function of the nearby no-flow boundary. The no-flow boundary causes excessive lowering of Upper Floridan heads and therefore a greater upconing effect in this area.

Comparison of modeled nodal chloride concentrations with the TDEM data show a generally good match (Table 3.2). Note that a range in possible TDEM results is given due to uncertainty in porosity. Figure 3.20 shows the revised model chloride levels 500 ft below the top of the Lower Floridan aquifer. Since contours on a similar plot for the base case are virtually the same, the plot is not presented herein. The small influence of the high conductivity zones on the chloride levels surrounding Rock Springs and Island Spring can be seen by comparing southwest to northeast cross-sections for the initial (Figure 3.21) and revised (Figure 3.22) base case models.

3.5 STEADY STATE SENSITIVITY ANALYSIS

The following steady-state sensitivity runs were generated using the base case as the starting point or comparison simulation. The results presented below may therefore be compared to Figure 3.12 for hydraulic heads and Figure 3.18 for chloride concentrations. Nine sensitivity simulations were conducted; their purpose and general results are shown in

Table 3.1. Comparison of concentrations at spring nodes in the saltwater model.

			Concentration (mg/L)	
Spring	Global Nodal No.	Fluid Flux ft^3/d	SJRWMD Data	Revised Simulation
Seminole	2058	2.867E6	7.0	8.5
Messant	3358	1.325E6	10.0	16.7
Blue	6860	3.086E6	526.0	1900.0
Rock	10164	4.3031E6	9.0	19.4
Island	10374	4.701E5	ND	1639.0
Witherington	13272	3.323E5	ND	0.0
Gemini	13706	5.325E5	ND	4123.0
Wekiva	16450	4.9241E6	12.0	13.0
Miami	17108	3.764E5	2.0	111.4
Palm/Sanlando	21574	8.759E5	10.0	143.8
Starbuck	22126	2.154E6	13.0	22.8

Table 3.2. Comparison of calculated TDEM and modeled chloride concentrations at given depths in the aquifer for the data sites shown in Figure 2.11. The range in TDEM concentrations correspond to a porosity range of 0.35 (lowest concentration) to 0.25 (highest concentration).

		Chloride Concentration	
TDEM Site	Depth (ft)	TDEM (mg/L)	Simulation (mg/L)
1	>2000	>2000	9344
2	977	3874-4062	3653
3	247	1170-2140	2540
4	559	2690-4580	2259
5	1910	5540-9590	7423
13	1203	3260-5700	4472
14	927	2000-3540	5863

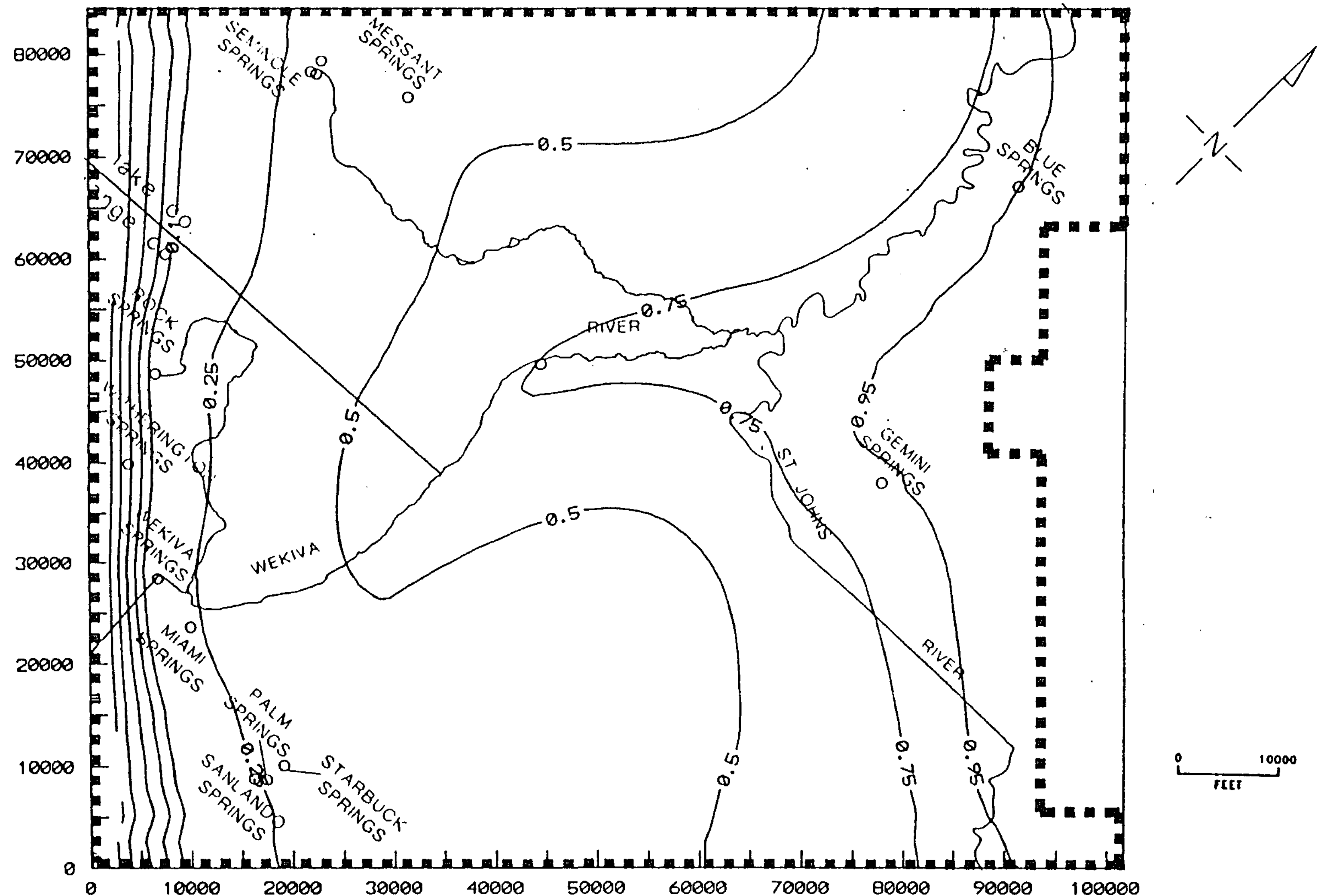

Figure 3.20. Simulated chloride concentrations (1.0 = 10000 mg/l) in Lower Floridan aquifer for the revised simulation for current (1988) conditions.

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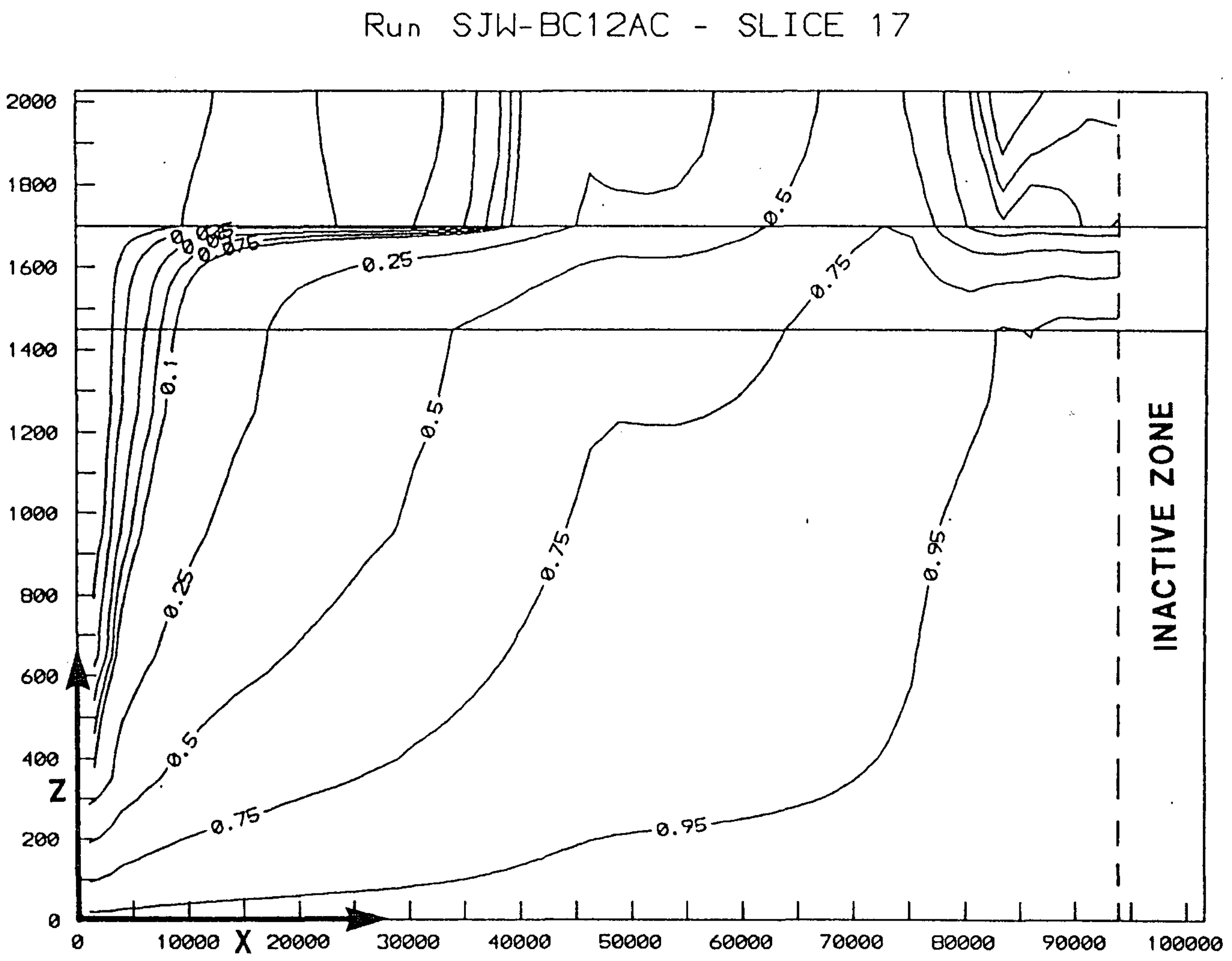

Figure 3.21. Simulated chloride concentrations (1.0 = 10000 mg/l) in a vertical cross-section running southwest to northeast in study area for the base case simulation for current (1988) conditions.

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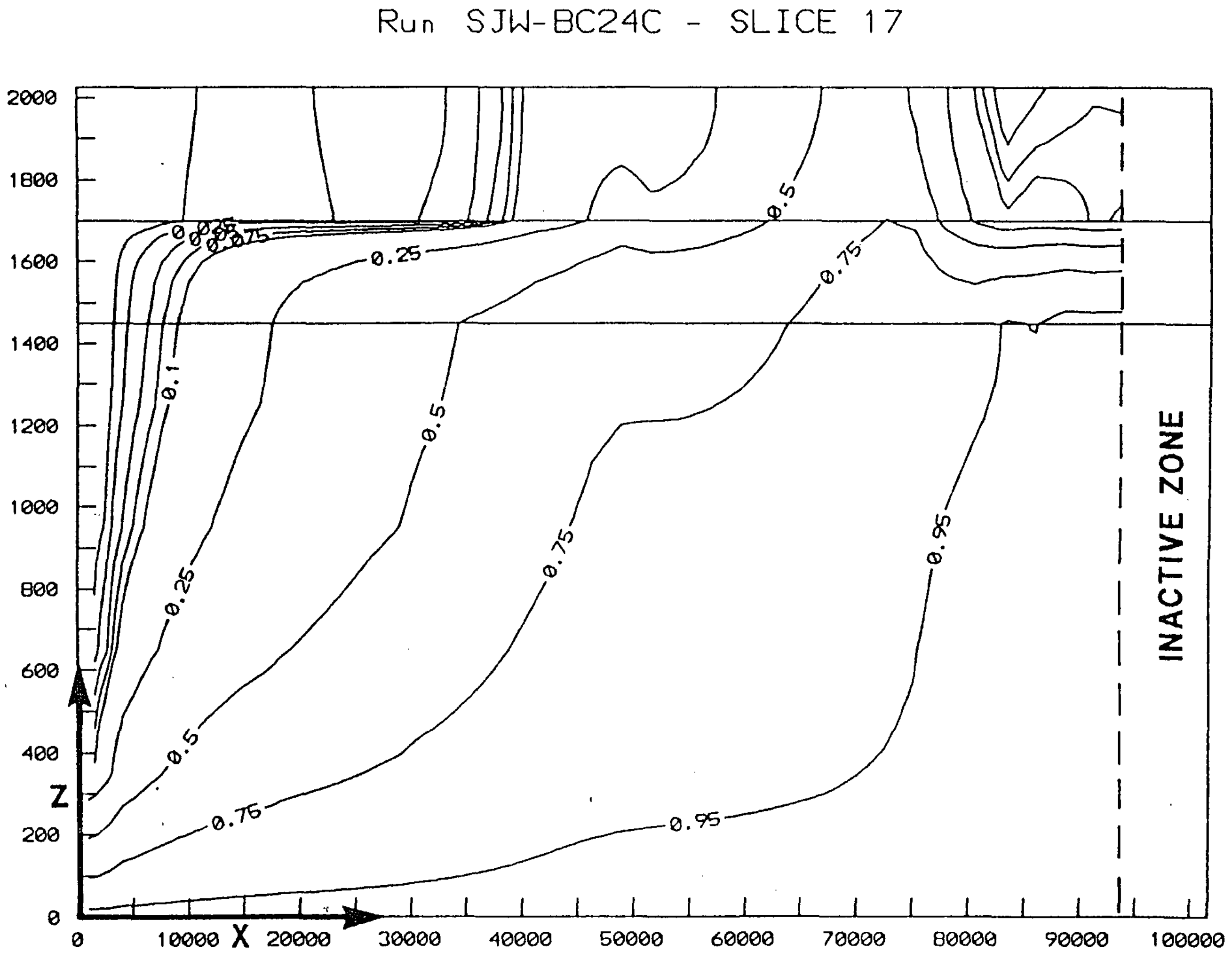

Figure 3.22. Simulated chloride concentrations (1.0 = 10000 mg/l) in a vertical cross-section running southwest to northeast in study area for the base case simulation for current (1988) conditions.

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Table 3.3. The simulations may be divided into two categories: 1) sensitivity to variations in boundary conditions, and 2) sensitivity to variations in hydrologic parameters.

3.5.1 Boundary Conditions

To examine the influence of the Lower Floridan boundary conditions, the bottom transport boundary condition was changed to a no-mass flux boundary condition and the northwest and southeast lateral boundary nodes were set to heads generated in the MODFLOW model and zero concentrations. This configuration simulates the Lower Floridan as having freshwater influx from three sides with no contribution of saltwater from the base. As can be seen by comparing the base case results presented in Figure 3.12 with this sensitivity run (Figure 3.23) the change of Lower Floridan boundary conditions had little effect on the generated Upper Floridan potentiometric surface. On the other hand, comparison of base case Upper Floridan chloride levels (Figure 3.18) with the sensitivity run (Figure 3.24) shows a marked reduction in Upper Floridan chloride levels. This simulation indicates that the base case conceptualization, which includes saltwater originating from below the Lower Floridan, is a probable explanation for the observed chloride concentrations in the Upper Floridan aquifer. Conceptualizing the system with freshwater boundary conditions in the Lower Floridan does not provide an acceptable match with chloride trends in the Upper Floridan.

To test the sensitivity of the system to the influence of saltwater overlying the northeast Lower Floridan boundary, the equivalent freshwater head boundary conditions were reduced to values based on minimal saltwater above the Lower Floridan. This results in a slight reduction in the Upper Floridan freshwater heads in the area where the Wekiva River and St. Johns River meet (see Figures 3.12 and 3.25). As can be seen by comparing Figures 3.18 and 3.26, Upper Floridan chloride concentrations along the St. Johns and Wekiva Rivers are also slightly reduced. This simulation indicates that the model is relatively insensitive to reduction of freshwater heads along the northeast boundary. The uncertainty associated with the assignment of reasonable values to this boundary can probably be neglected.

Table 3.3. Sensitivity simulations conducted with the SWICHA saltwater transport model.

	Change	Result
Boundary Conditions		
1	bottom Lower Floridan to no mass flux NW, SE, Lower Floridan to specified head	major change in Upper Floridan chloride concentrations
2	head condition above Lower Floridan NE reduced	slight reduction in Upper Floridan chloride concentrations along rivers
3	NW, SE Lower Floridan to specified head	minor effect
4	N corner Upper Floridan chloride concentrations interpreted from maps	major change in northern corner of model, no change in majority of model area
Parameters		
1	increase anisotropy of aquifers to 100:1	minor change except in vicinity of springs
2	double Hawthorn leakance	minor change for range tested
3	halve Hawthorn leakance	minor change for range tested
4	double semi-confining bed leakance	minor change for range tested
5	halve semi-confining bed leakance	minor change for range tested

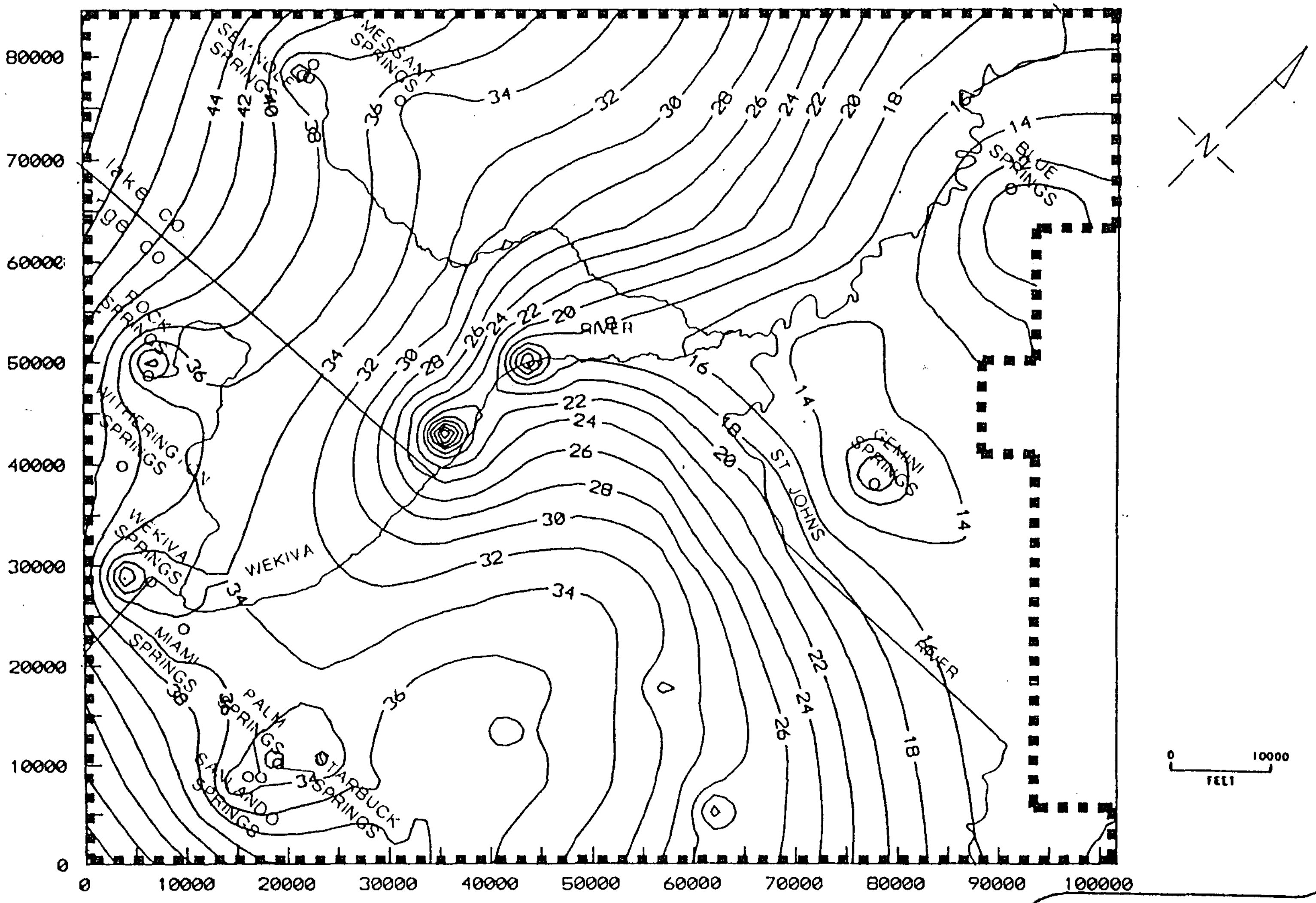

Figure 3.23. Relative fresh water heads (ft, msl) for a change in Lower Floridan lateral and bottom flow and transport boundary conditions for current (1988) conditions.

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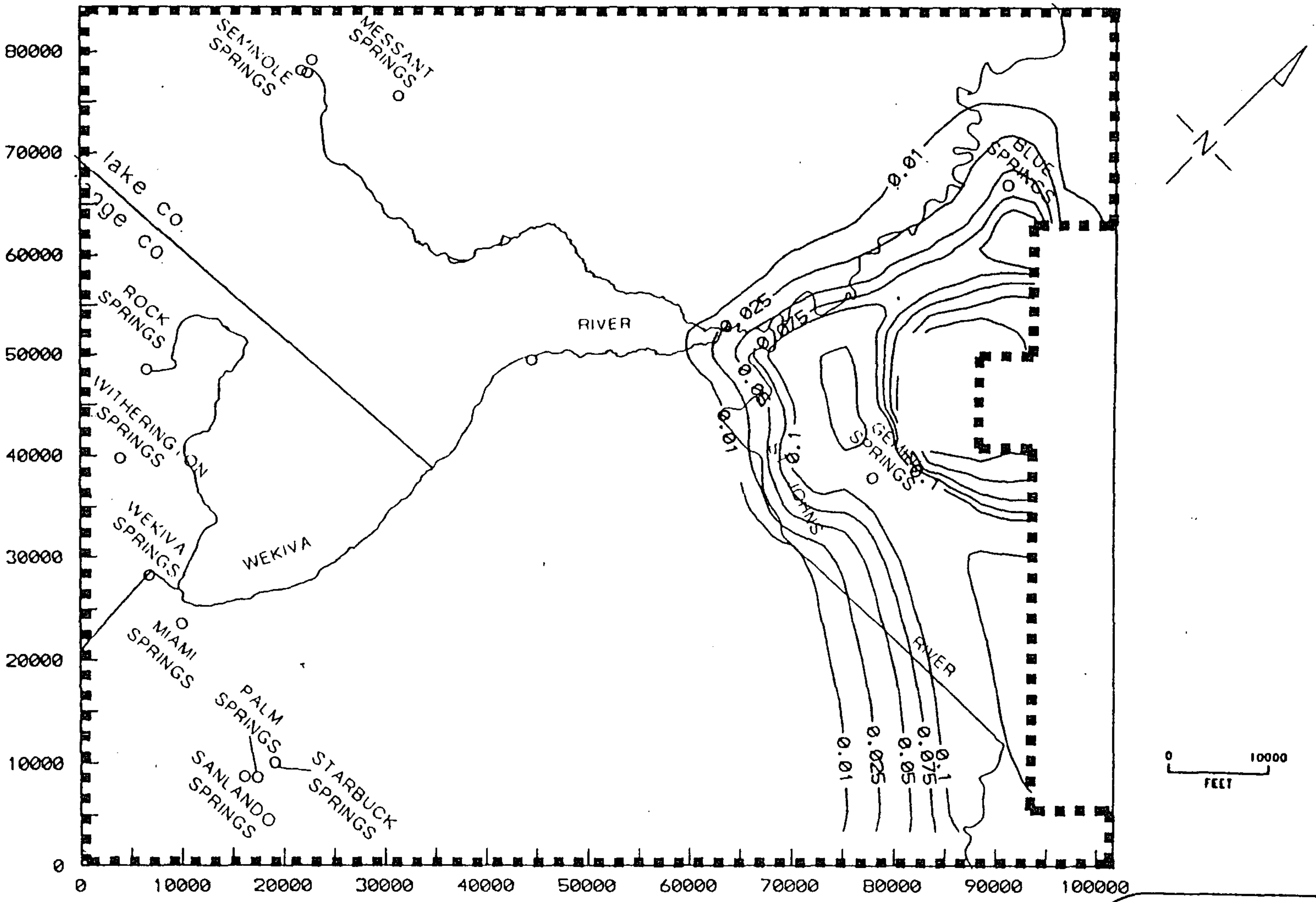

Figure 3.24. Relative chloride concentrations (1.0 = 10000 mg/l) for a change in Lower Floridan lateral and bottom flow and transport boundary conditions for current (1988) conditions.

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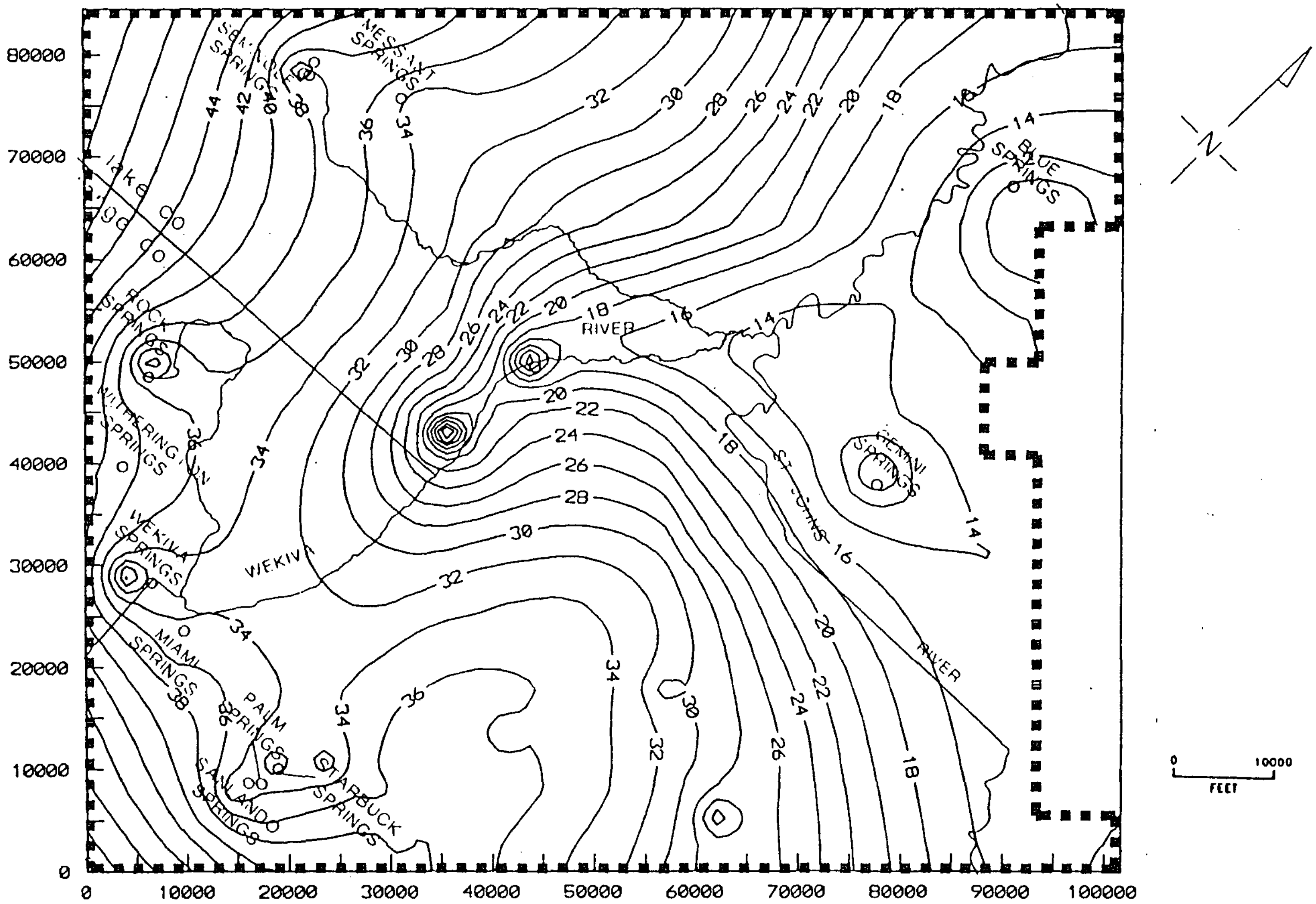

Figure 3.25. Relative fresh water heads (ft, msl) for a change in Lower Floridan fresh water head boundary conditions due to minimal saltwater in overlying units for current (1988) conditions.

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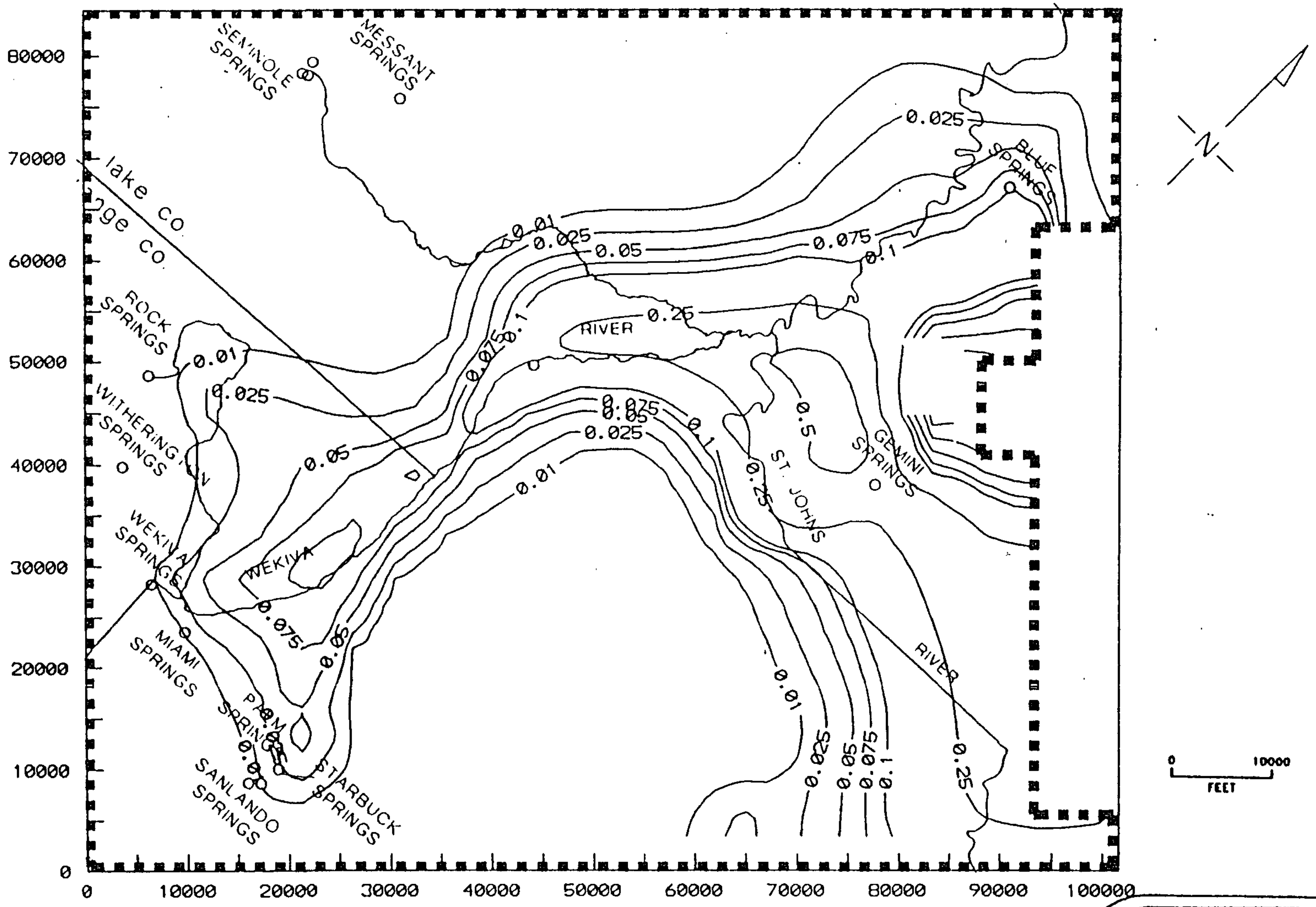

Figure 3.26. Relative chloride concentrations (1.0 = 10000 mg/l) for a change in Lower Floridan freshwater head boundary conditions due to minimal saltwater in overlying units for current (1988) conditions.

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The influence of changing the lateral no-flow boundary conditions on the northwest and southeast sides of the Lower Floridan aquifer to constant heads generated from MODFLOW was examined in the next sensitivity simulation. This was similar to the first sensitivity simulation, except the concentration at the base of the Lower Floridan was not altered. Comparing Figures 3.12 and 3.27 show that the Upper Floridan relative freshwater heads are changed very little. Comparison of Upper Floridan chloride concentration levels (Figures 3.18 and 3.28) show that the diffuse wedge has retreated from the lateral boundaries but the trends along the river remain similar. The ramifications of the simulation are that the no-flow boundary conditions chosen for the northwest and southeast sides of the model are an appropriate approximation, given the other alternatives. This probably results because these boundaries generally follow flow lines in the Lower Floridan aquifer.

The final boundary condition sensitive simulation examined the importance of more accurately defining the Upper Floridan chloride concentration boundary condition in the northern corner of the model. In the base case model these concentrations were set to 0.0 mg/L. In the sensitivity simulation, vertically averaged concentration values, generated by interpolating between contours taken from Figure 2.4, were applied at constant concentration boundary nodes. Negligible changes in the relative freshwater heads result, as can be discerned in comparing Figures 3.29 to 3.12. Upper Floridan chloride concentrations change considerably in the northern corner of the study area, but as can be seen by comparing Figures 3.18 and 3.30, changes are negligible over most of the study area. This indicates that the accuracy of the model in the central part of the study area was not compromised by simplifying the boundary condition in this area.

3.5.2 Parameters

Before describing the sensitivity analyses on the flow system parameters, it should be noted that these analyses generally included rerunning the MODFLOW model with the same parameter changes. Because the SWICHA boundary conditions do not correspond to hydrologic boundaries and

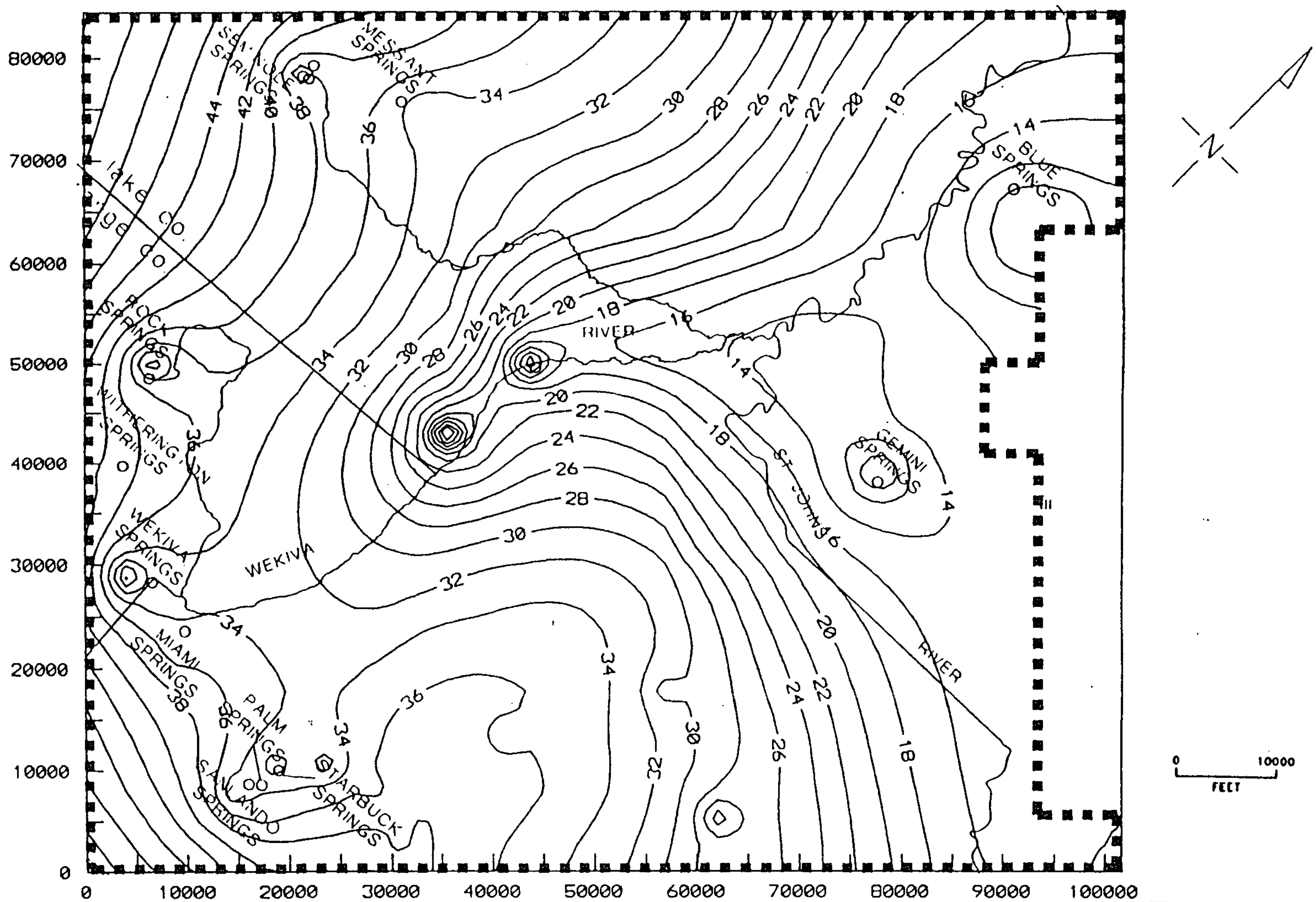

Figure 3.27. Relative fresh water heads (ft, msl) for a change in Lower Floridan lateral boundary conditions from no flux to specified head and concentration boundary conditions for current (1988) conditions.

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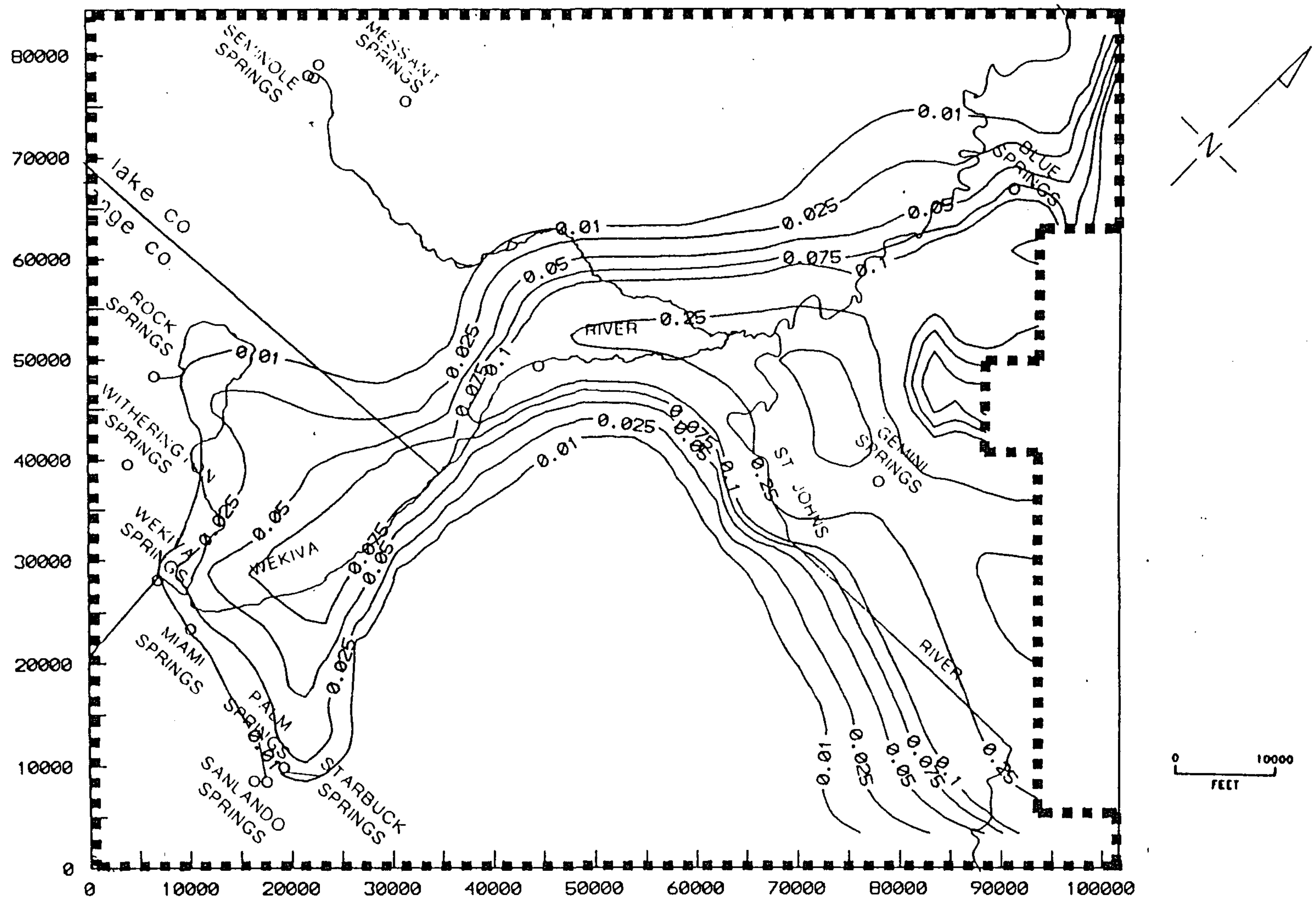

Figure 3.28. Relative chloride concentrations (1.0 = 10000 mg/l) for a change in Lower Floridan lateral boundary conditions from no flux to specified head and concentration boundary conditions.

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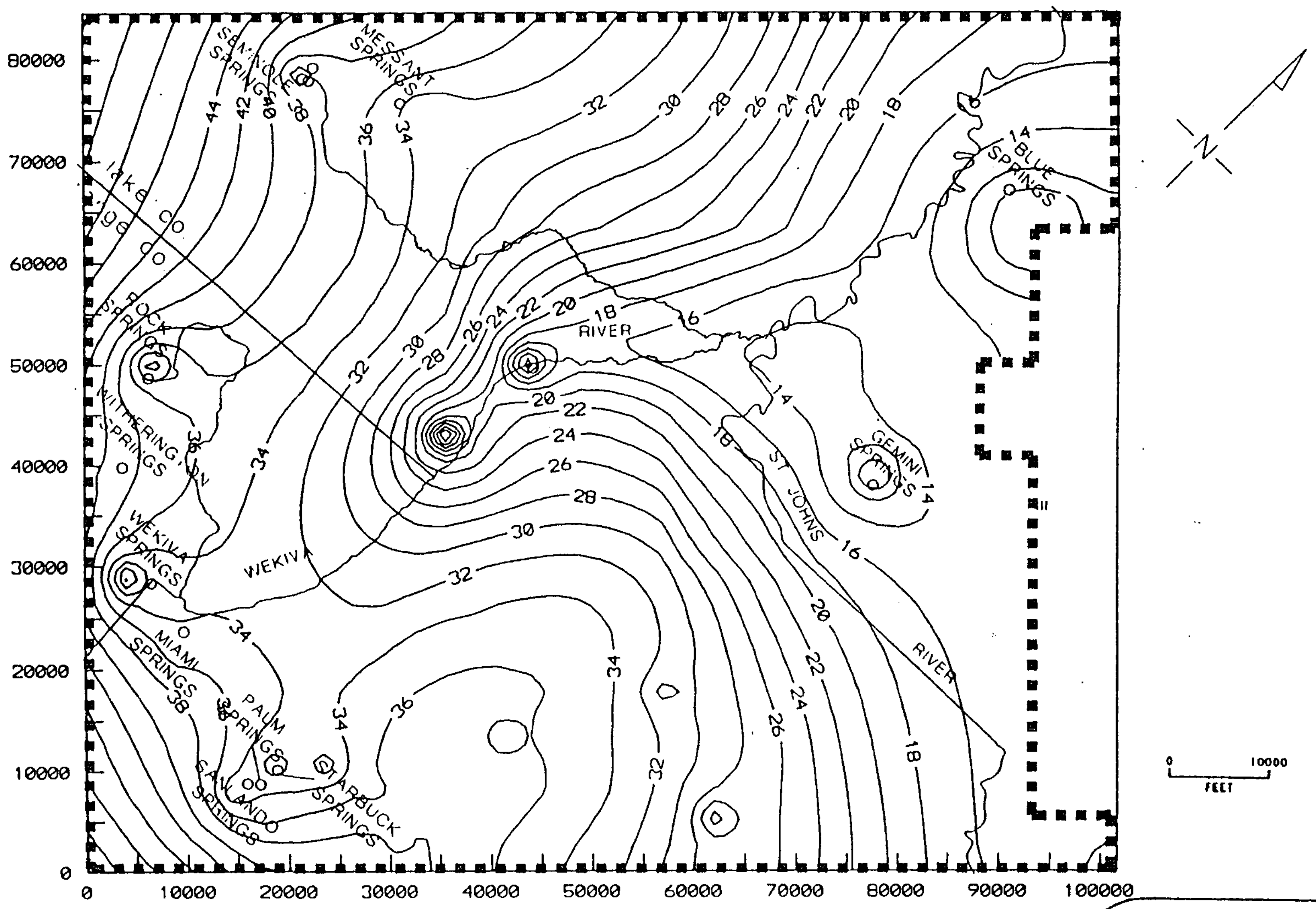

Figure 3.29. Relative freshwater heads (ft, msl) for a changing of Upper Floridan constant head and concentration nodes in the northern corner of the model based on contours in Figure 2.4. Current (1988) conditions are modeled.

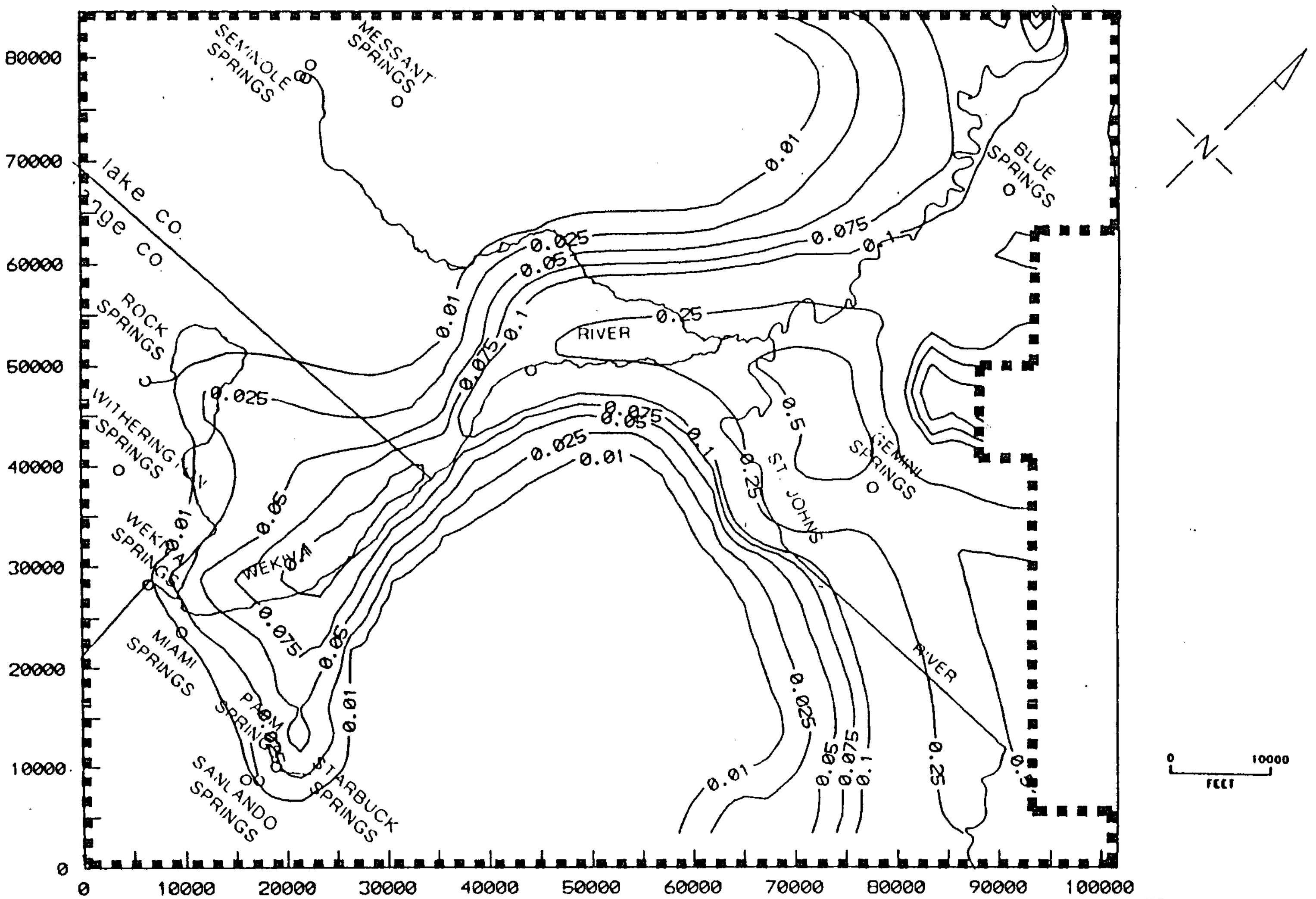

Figure 3.30. Relative chloride concentrations (1.0 = 10000 mg/l) for a changing of Upper Floridan constant head and concentration nodes in the northern corner of the model based on contours in Figure 2.4. Current (1988) conditions are modeled.

will change with a change to the overall flow system, it was necessary to re-run MODFLOW each time a parameter or stress was changed.

The sensitivity of the model to changes in the ratio of horizontal to vertical hydraulic conductivities in the aquifers was examined by increasing the ratio from 10:1 to 100:1. Comparing Figure 3.12 to Figure 3.31 shows that changes in the Upper Floridan potentiometric surface are negligible except in areas immediately adjacent to springs. Little change is seen in the Upper Floridan chloride distribution except along the Wekiva River just to the northeast of Wekiva Springs (see Figures 3.18 and 3.32). This indicates that the steady state chloride distribution is generally not affected by changes in the anisotropy ratio of the aquifers. The more pronounced effect near the springs is the result of induced flow in the direction (vertical) of the increase in hydraulic conductivity. Based on this observation, anisotropy changes would presumably have more of an effect in areas of new stresses in the transient scenarios.

The sensitivity of the model to changes in the Hawthorn leakance was examined by the doubling and halving the base case values. Doubling of the Hawthorn hydraulic conductivity generated a marked rise in the Upper Floridan potentiometric surface in the southwest portion of the model and a decline of the surface to the east and northeast (see Figures 3.12 and 3.33). This corresponds to an increase in head in recharge areas and a decrease in head in discharge areas. The increased connection of the surficial system to the Upper Floridan is the primary reason for this effect. A slight spreading of the salt water away from the rivers with slightly greater chloride levels under the rivers is also noted (see Figures 3.18 and 3.34). Halving the Hawthorn hydraulic conductivities tends to lower the potentiometric surface over most of the model except along the Wekiva River near the St. Johns River (see Figures 3.12 and 3.35). Upper Floridan chloride concentration levels change little except at the high concentration areas where they are slightly reduced and the low concentration area along the center of the northeast boundary where large increases are seen (see Figures 3.18 and 3.36). Although the hydraulic properties of the Hawthorn are an important aspect of the flow system, they do not appear to have a major effect over the range tested. It is likely

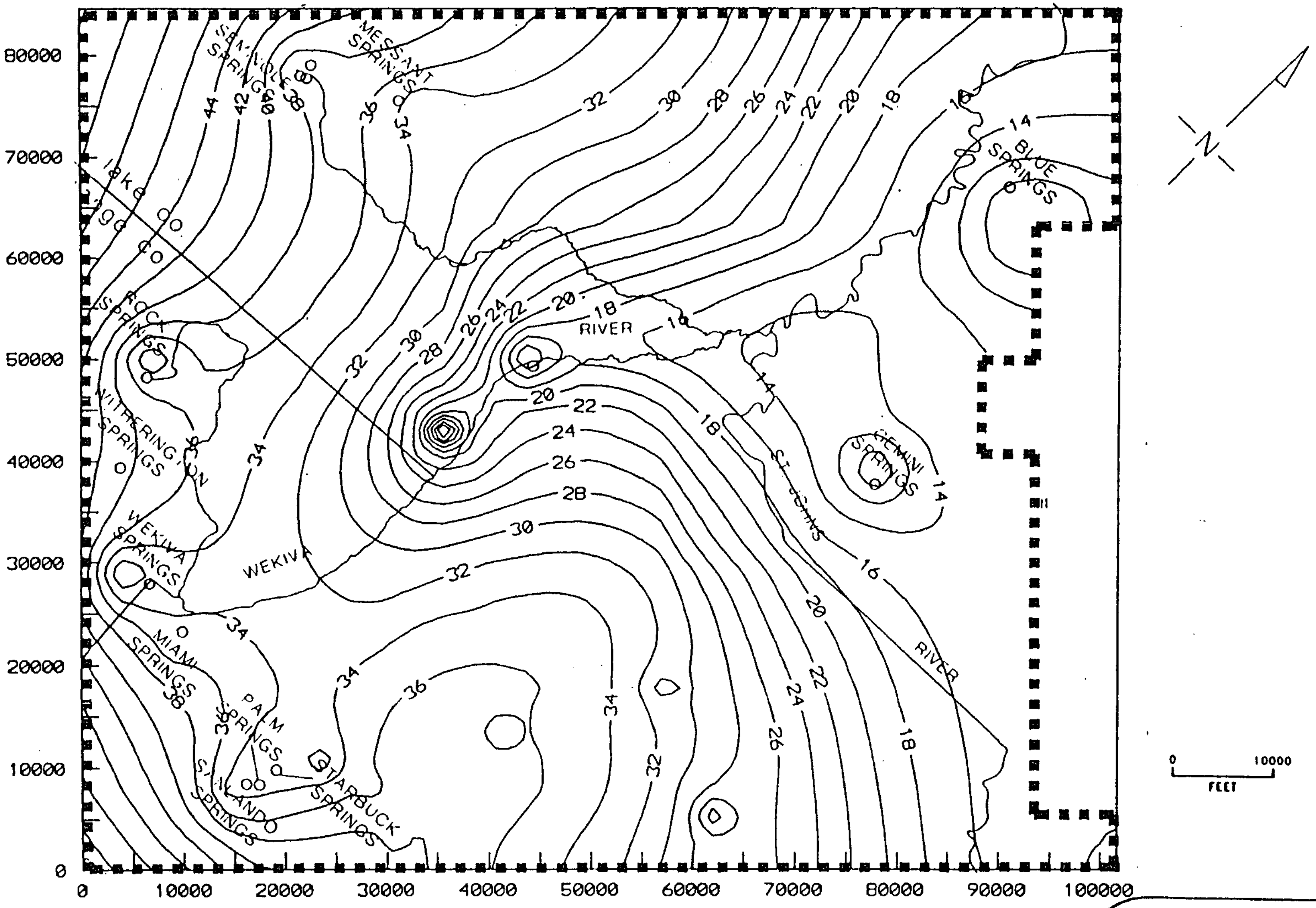

Figure 3.31. Relative fresh water heads (ft, msl) for a 100:1 ratio of horizontal to vertical hydraulic conductivities in the aquifers for current (1988) conditions.

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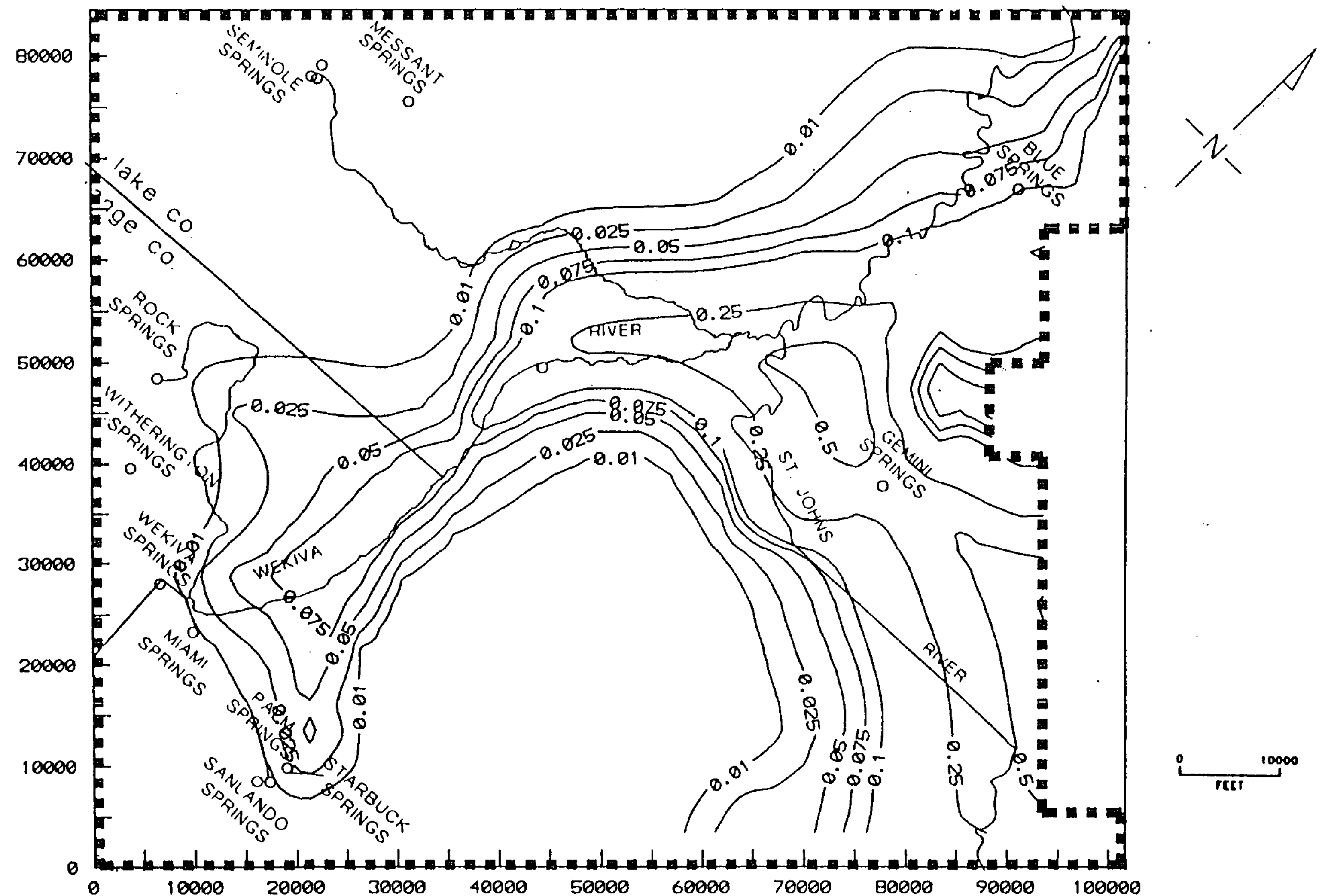

Figure 3.32. Relative chloride concentrations (1.0 = 10000 mg/l) for a 100:1 ratio of horizontal to vertical hydraulic conductivities in the aquifers for current (1988) conditions.

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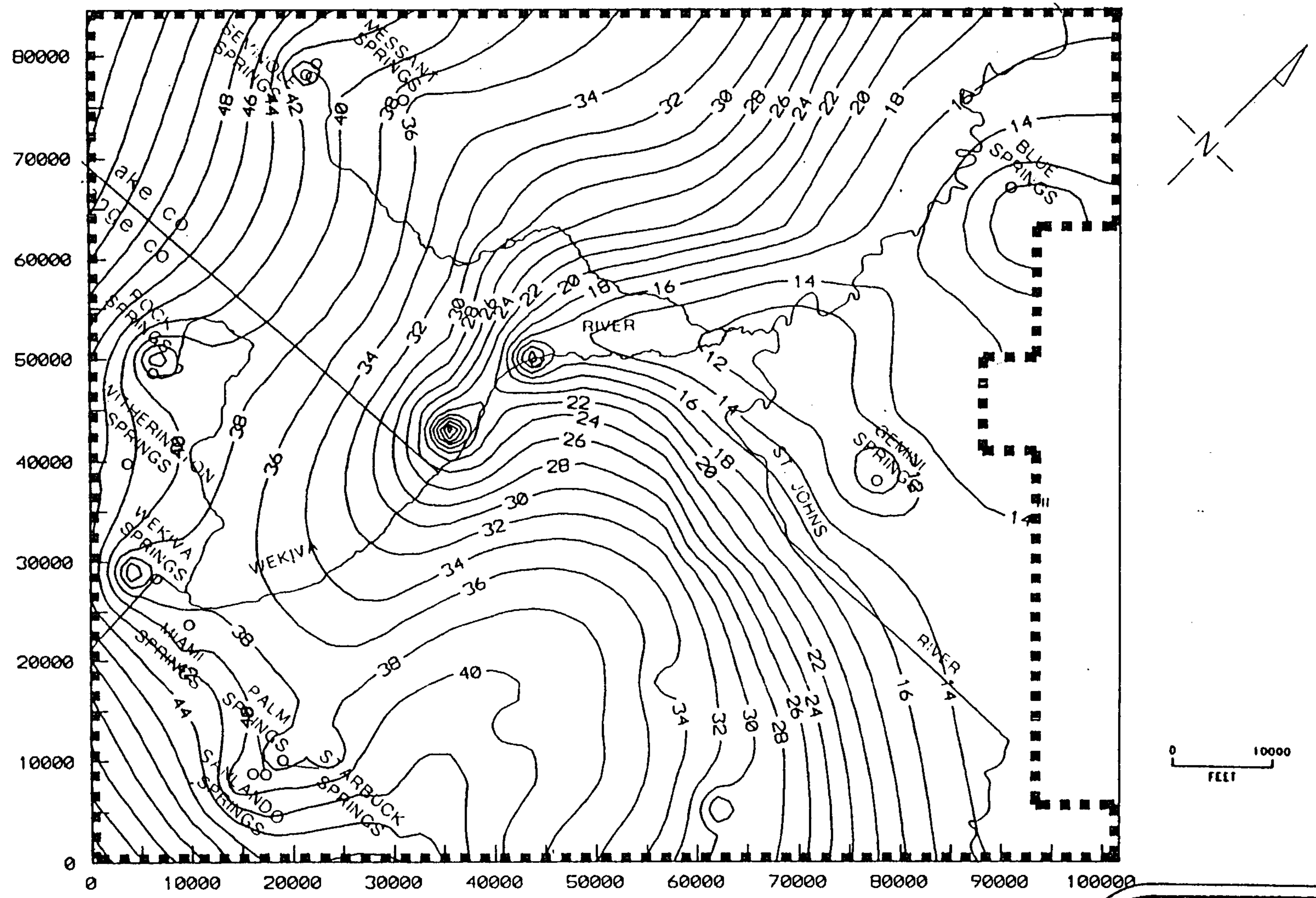

Figure 3.33. Relative fresh water heads (ft, msl) for a doubling of Hawthorn unit leakances for current (1988) conditions.

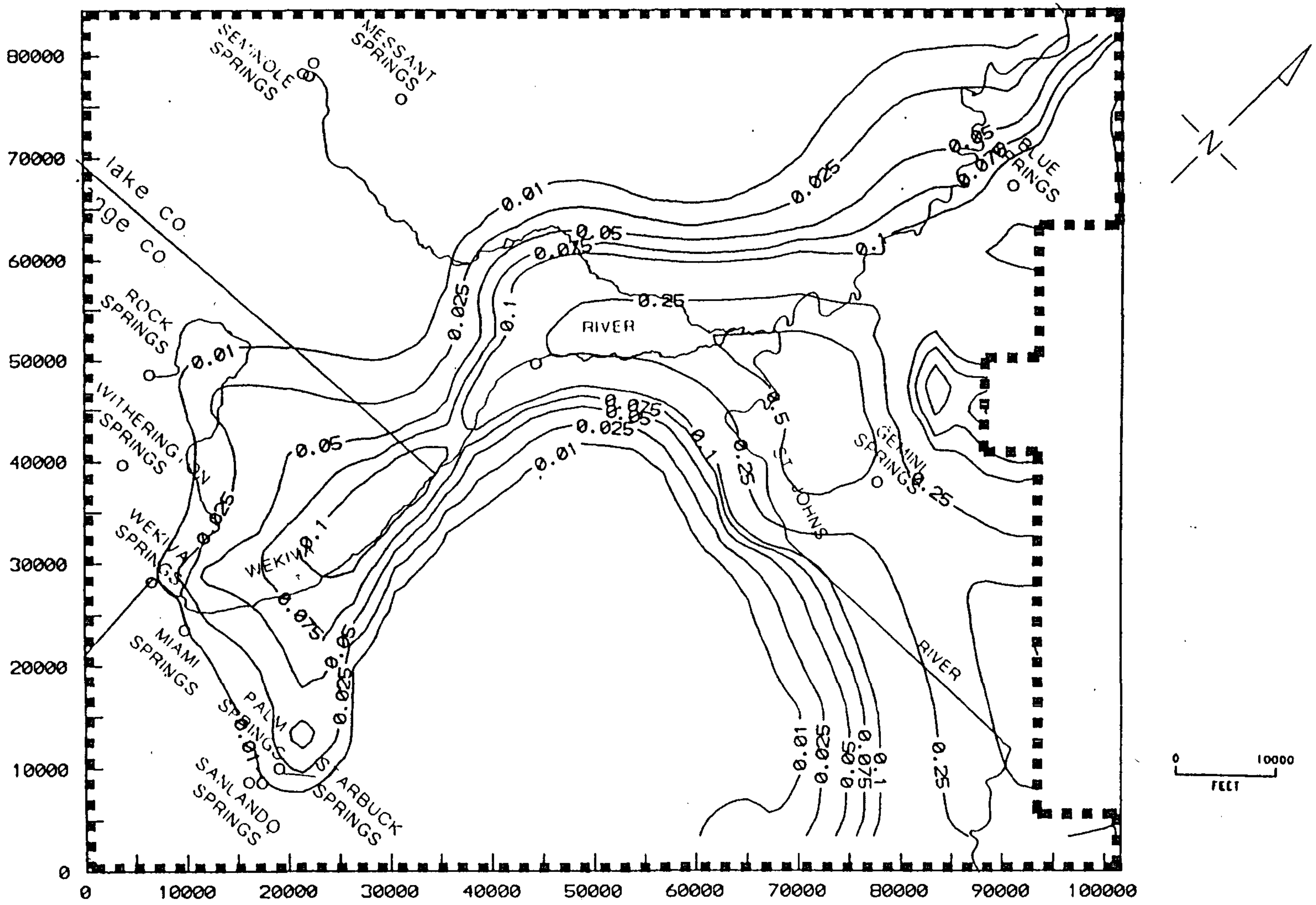

Figure 3.34. Relative chloride concentrations (1.0 = 10000 mg/l) for a doubling of Hawthorn unit leakances for current (1988) conditions.

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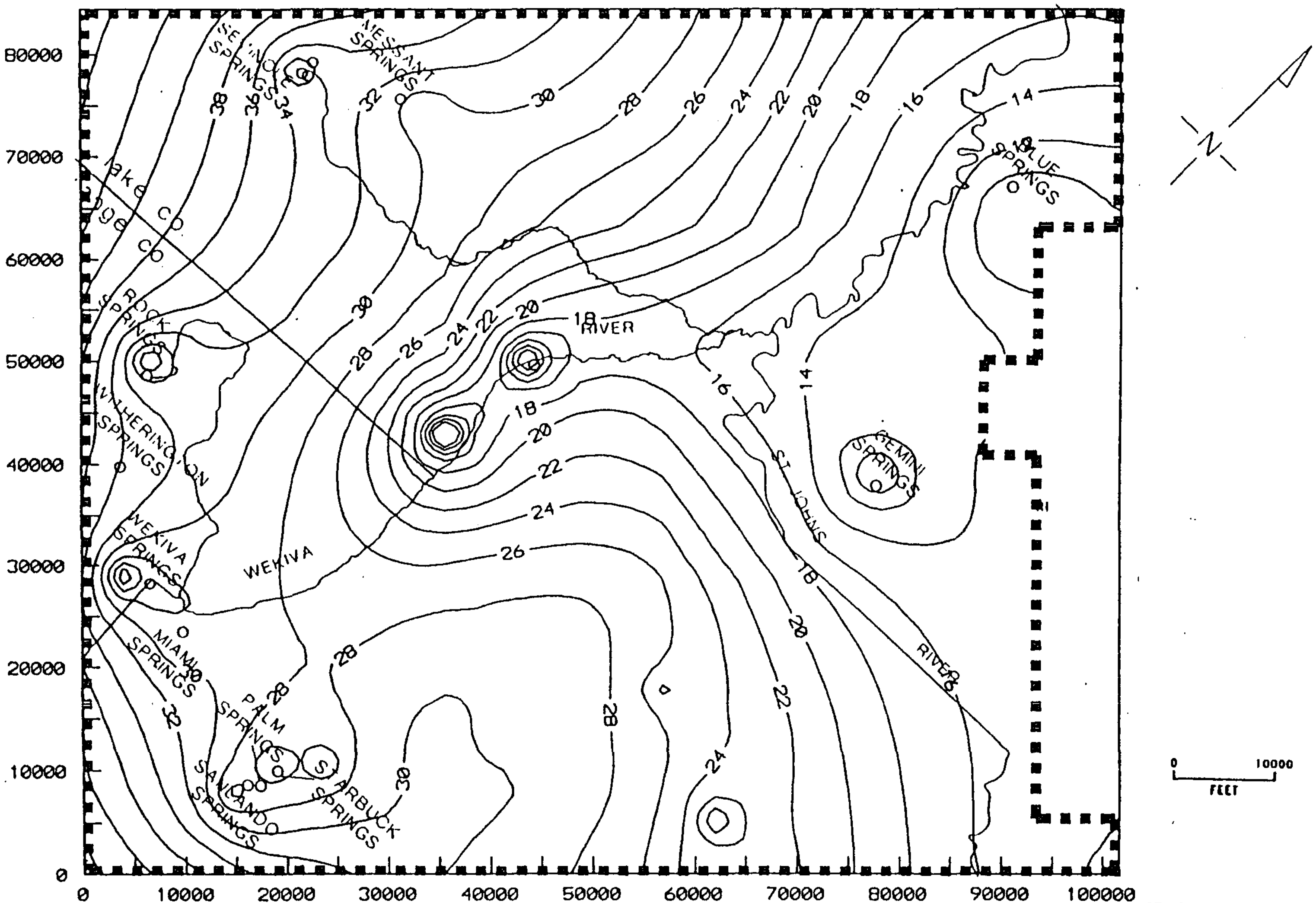

Figure 3.35. Relative fresh water heads (ft, msl) for a halving of Hawthorn unit leakance for current (1988) conditions.

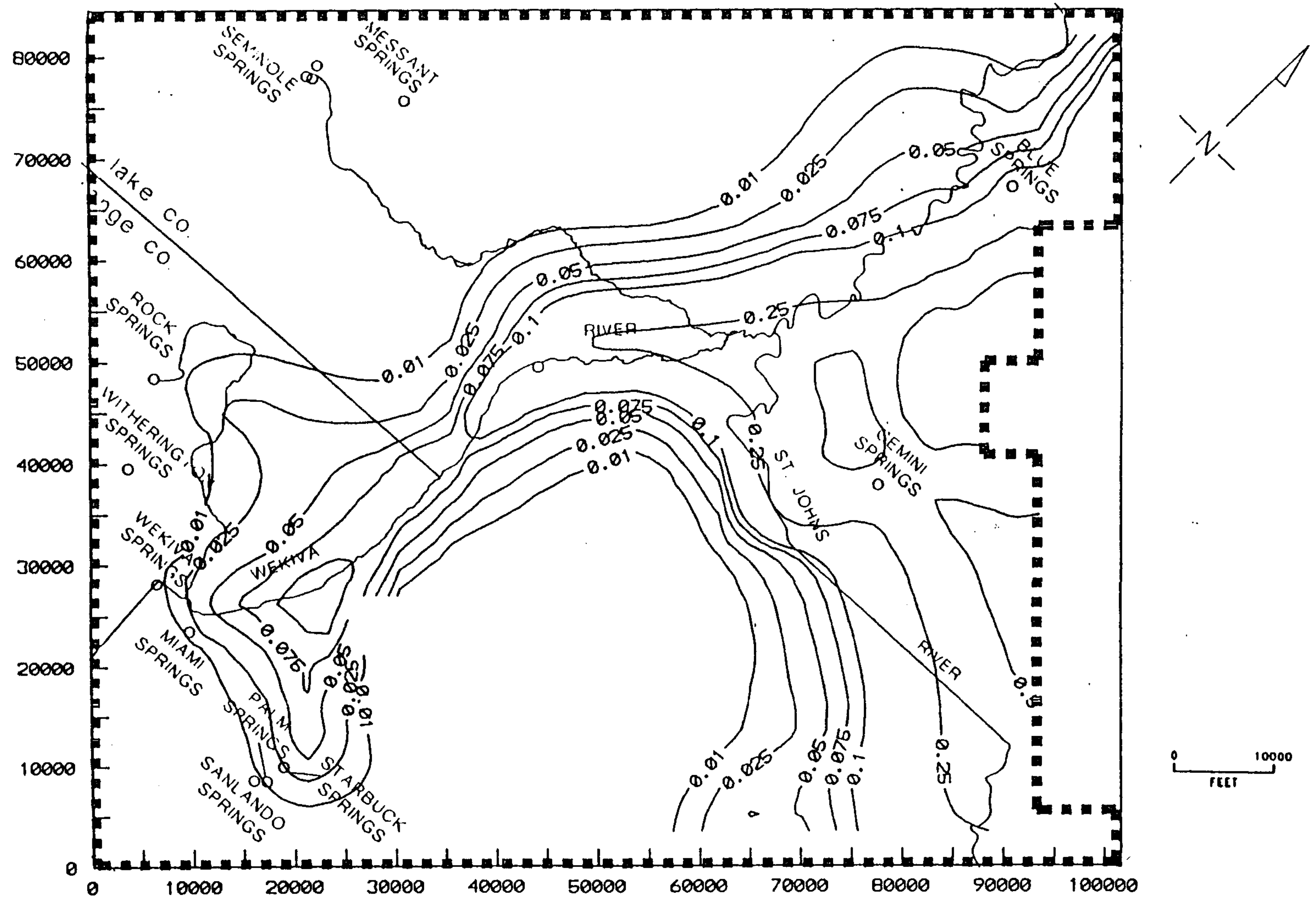

Figure 3.36. Relative chloride concentrations (1.0 = 10000 mg/l) for a halving of Hawthorn unit leakance for current (1988) conditions.

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that order of magnitude changes, which are more consistent with the level of uncertainty, would cause a much more marked effect.

Sensitivity of the system to changes in the semi-confining layer hydraulic conductivities was examined in the last two steady-state sensitivity runs by doubling and halving of the original values. Doubling of the conductivities generates very little change in the Upper Floridan potentiometric surface except along the rivers (see Figures 3.12 and 3.37). The relative freshwater head changes along the rivers are reflected in decreases in chloride levels under the rivers in the southwest portion of the study area and increases under the rivers in the northeast portion (see Figures 3.18 and 3.38). Halving of the semi-confining layer conductivities produces a slight decrease in the Upper Floridan potentiometric surface in the spring areas along the Wekiva River (see Figures 3.12 and 3.39). Comparing Figures 3.18 and 3.40, a decrease in Upper Floridan chloride concentration levels 4-6 miles to the northeast of Wekiva Springs is noted. Similar to the sensitivity simulations involving variations in the Hawthorn hydraulic conductivity, the model has only limited sensitivity to changes in the semi-confining bed hydraulic conductivity over the range tested. A more marked effect is probable if a large stress were imposed adjacent to the confining bed.

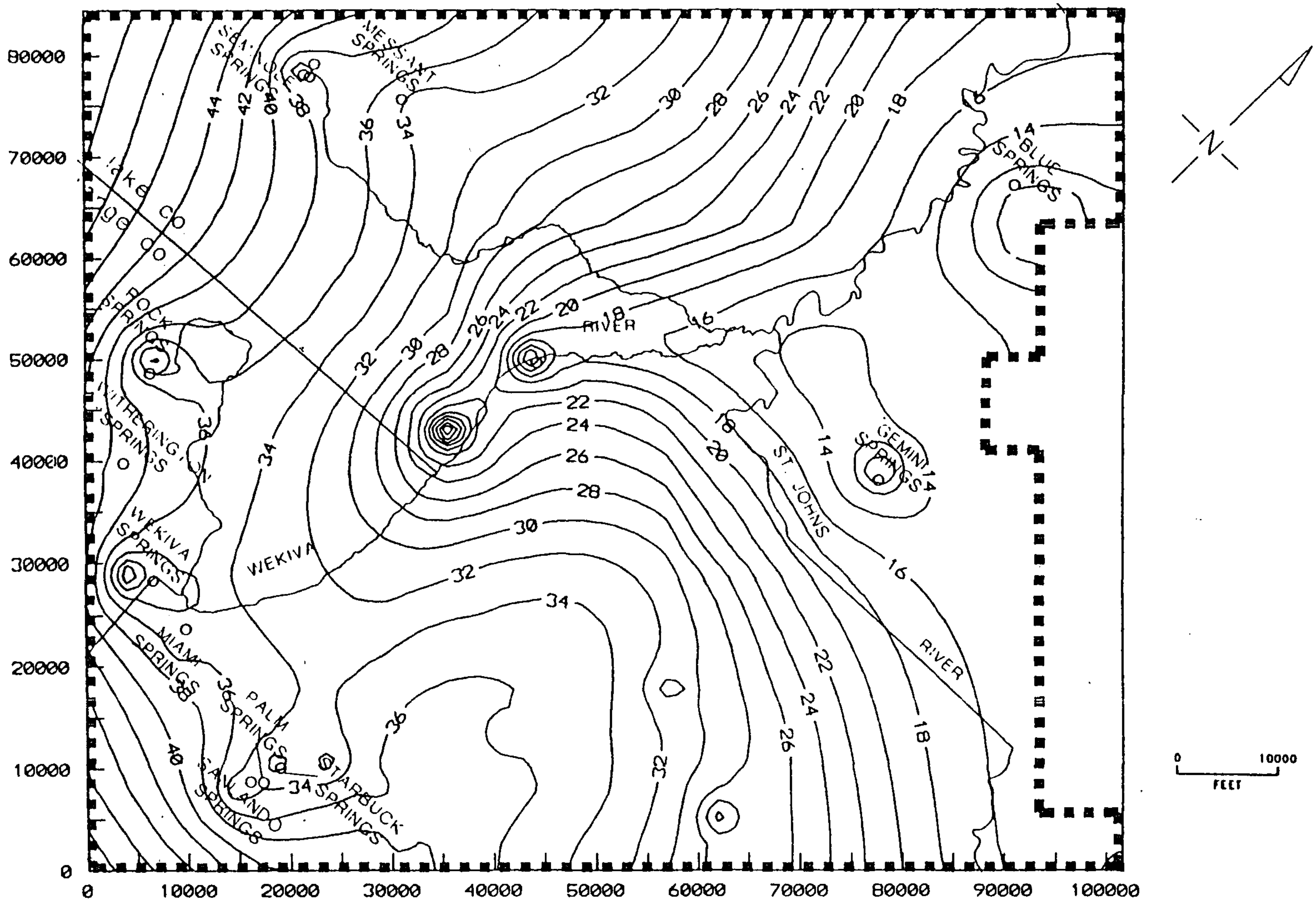

Figure 3.37. Relative fresh water heads (ft, msl) for a doubling of the semi-confining layer hydraulic conductivity for current (1988) conditions.

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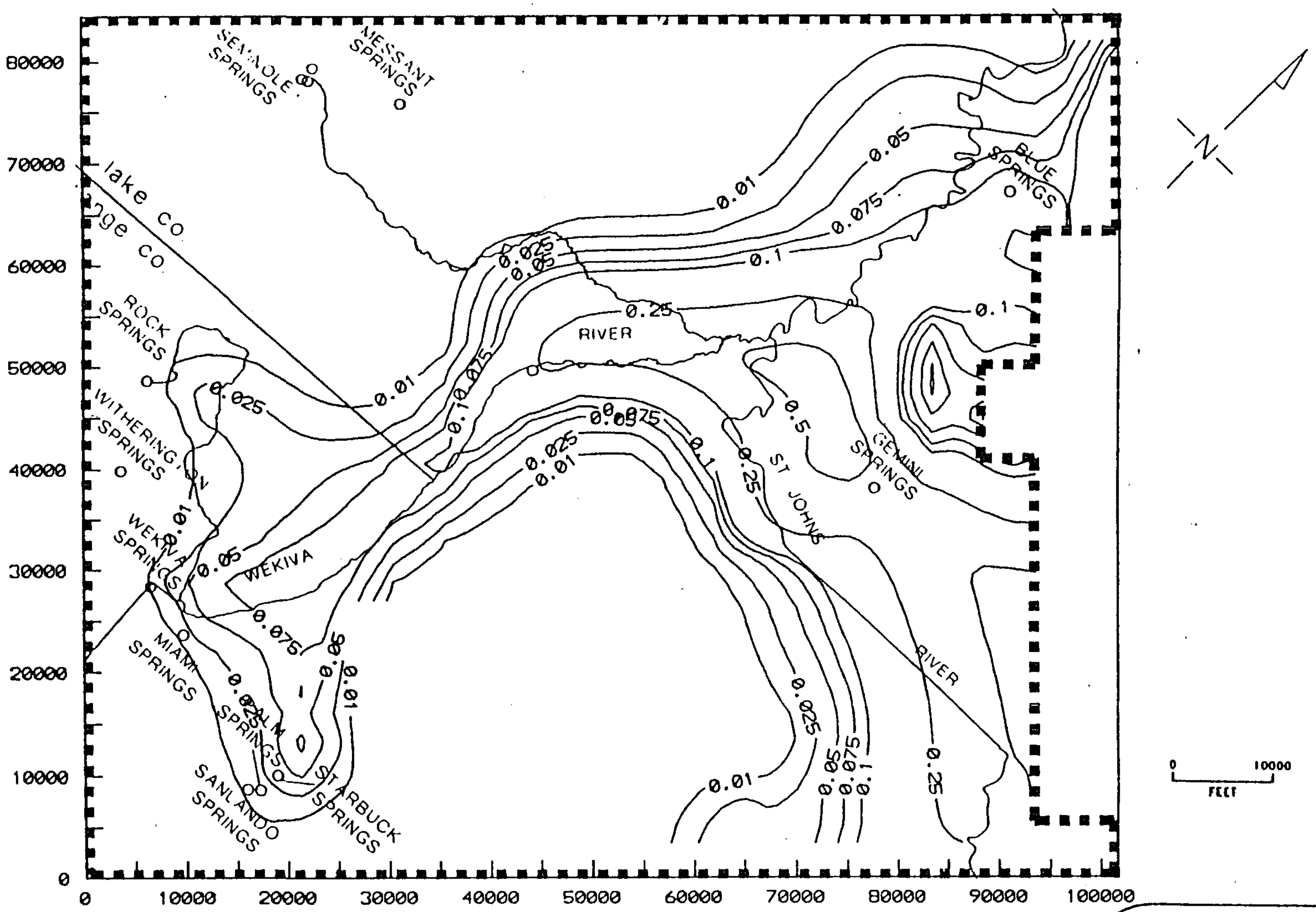

Figure 3.38. Relative chloride concentrations (1.0 = 10000 mg/l) for a doubling of the semi-confining layer hydraulic conductivity for current (1988) conditions.

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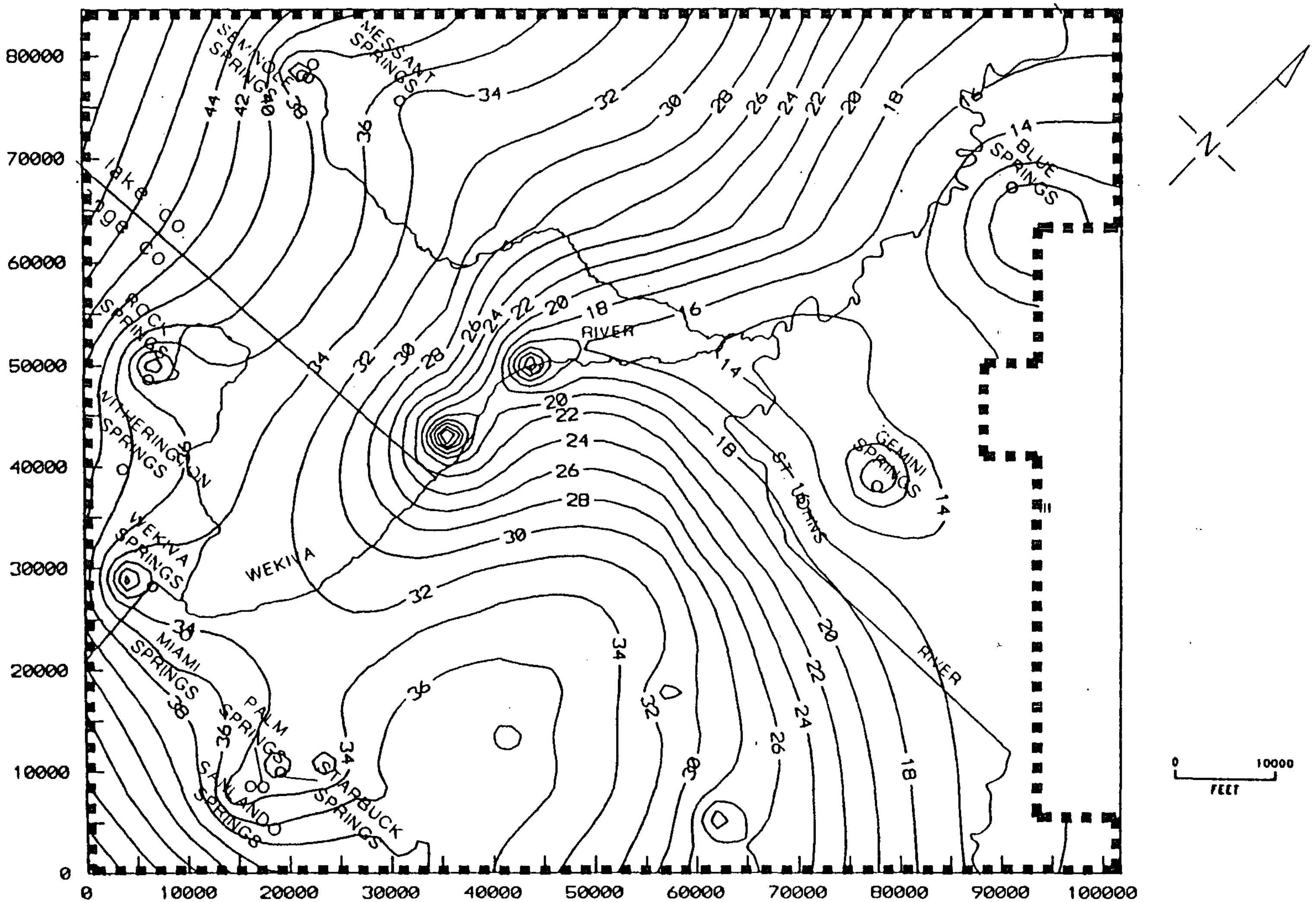

Figure 3.39. Relative fresh water heads (ft, msl) for a halving of the semi-confining layer hydraulic conductivity for current (1988) conditions.

GeoTrans, inc.
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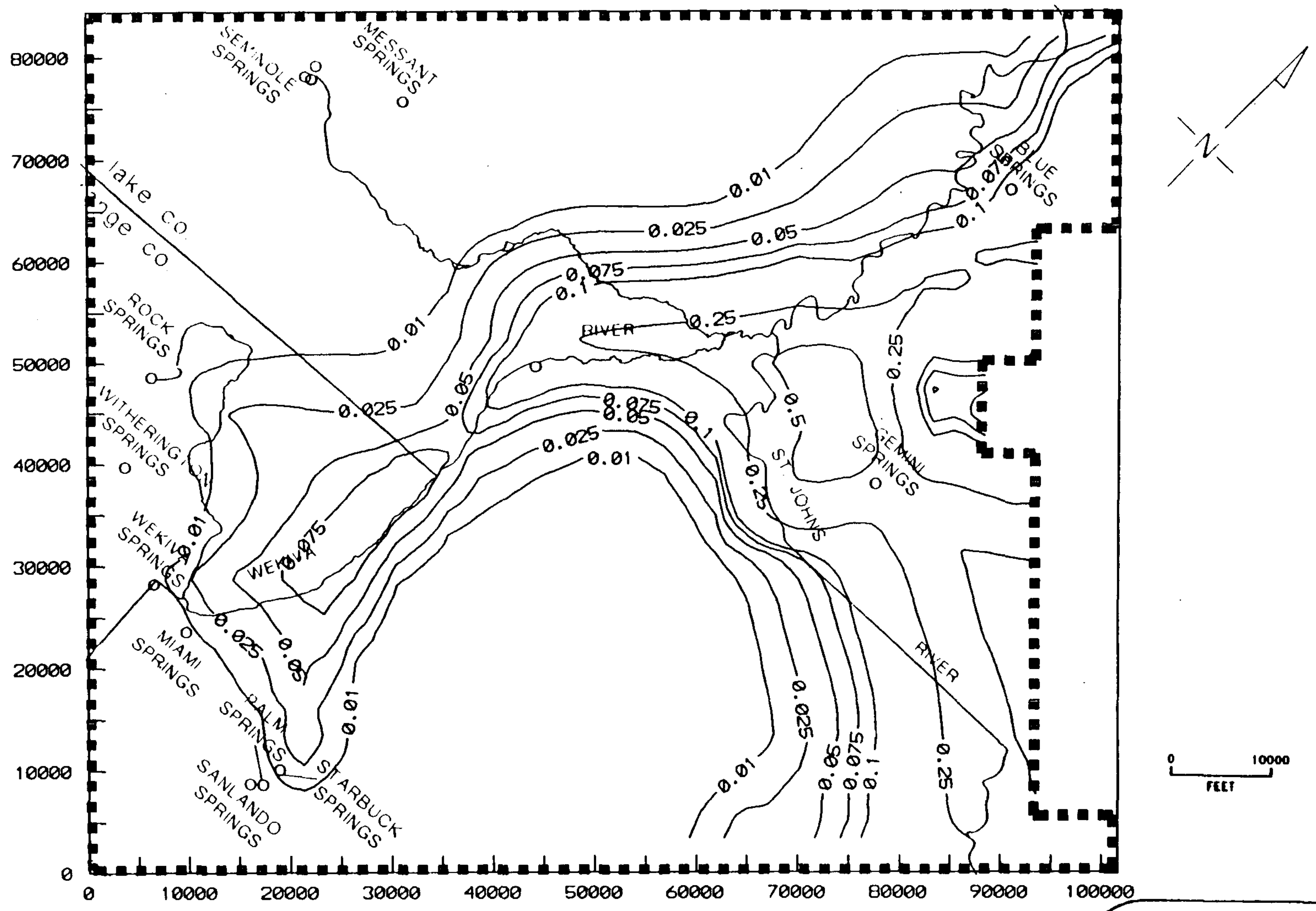

Figure 3.40. Relative chloride concentrations (1.0 = 10000 mg/l) for a halving of the semi-confining layer hydraulic conductivity for current (1988) conditions.

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4 SCENARIO SIMULATION

4.1 TRANSIENT ANALYSIS UNDER PROJECTED 2010 WATER USE CONDITIONS

The final part of the study was to use the model to predict the effect of a new pumpage stress on the movement of chloride concentrations over a 50 year time frame. Projected pumpage for the year 2010 was supplied by SJRWMD and converted to model input. The location of the pumping centers within the Phase III study area are shown in Figure 4.1. Initial chloride concentrations were derived from the revised model results.

Because the SWICHA head configuration results from regional changes in stress as well as those within the model area, it was necessary to run the MODFLOW model with the new regional stress in order to obtain boundary conditions for the more localized SWICHA model. Because the hydraulic heads reach a new equilibrium much faster than the chloride concentrations do upon imposition of a new stress, it was assumed that the hydraulic heads reach equilibrium instantaneously. This simplified the preparation of the transient model to running a single steady state MODFLOW to establish boundary conditions for the transient SWICHA model. A more rigorous approach would have been to generate new SWICHA boundary conditions for each time step by running MODFLOW in a transient manner. This procedure would have been excessively time consuming with very little increase in accuracy.

With boundary conditions thus established, the SWICHA model was run to made predictions over a 50 year time frame. Because the time frame over which pumpage increases to 2010 levels has no meaning in the model (steady state configurations are used), the reader may assume any time within the period 1990 to 2010 that the increase occurs. Since the change in pumpage is assumed to be instantaneous, it is probably reasonable to assume the year 2000 as the beginning of the transient simulation.

The regional hydraulic head configuration generated from the MODFLOW model for the new stress is shown in Figure 4.2. The change in head from current conditions for the regional area is shown in Figure 4.3. The hydraulic head configuration for the 2010 stress is shown in Figure 4.4 for the saltwater model. The change in head from current conditions for the Phase III study area is shown in Figure 4.5. The most marked drawdown effect results from an increase in stress in the southeastern part of the

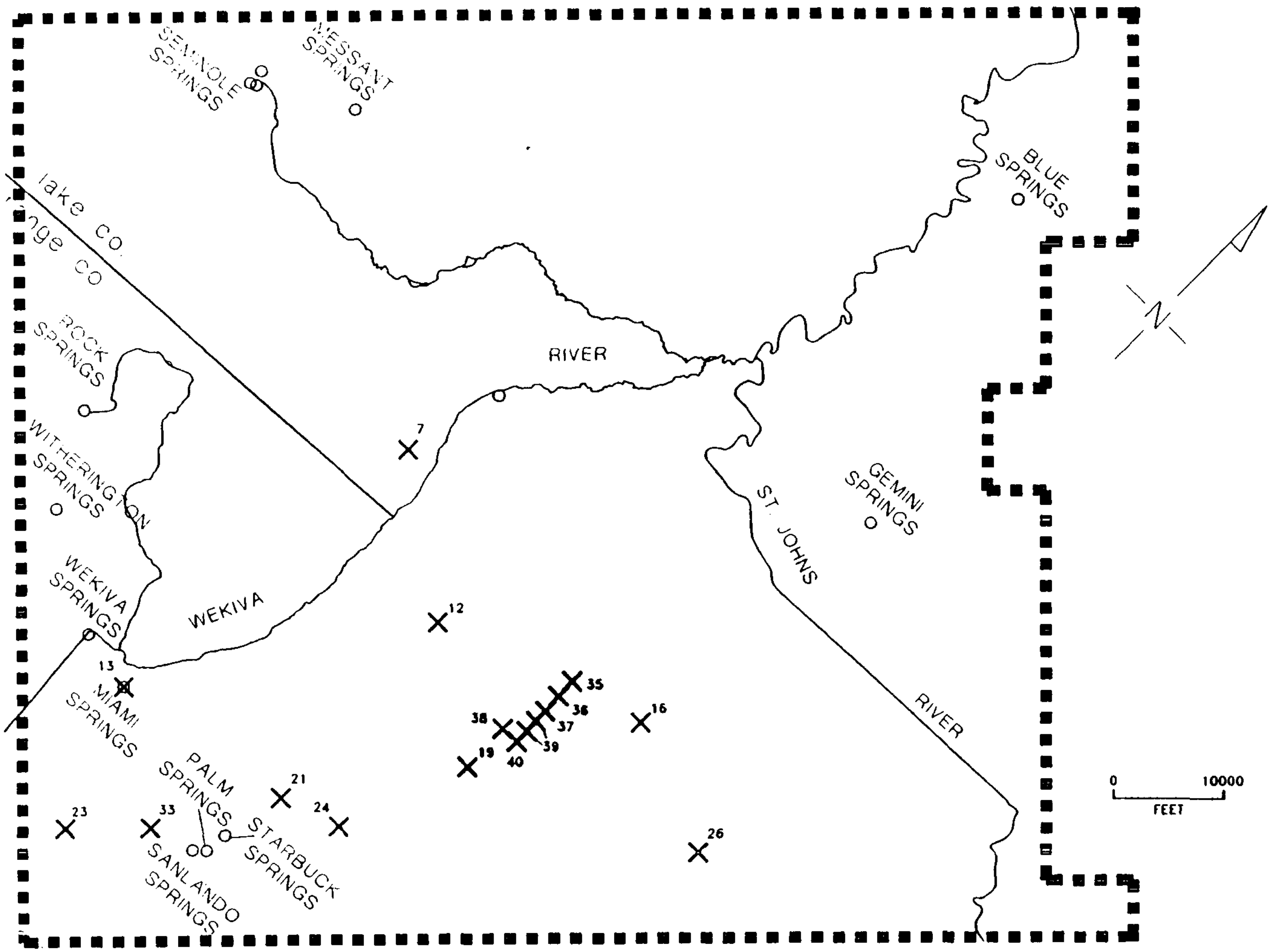

Figure 4.1. Location of pumping centers with withdrawals greater than 1 mgd. Numbers correspond to locations given in Table 4.2.

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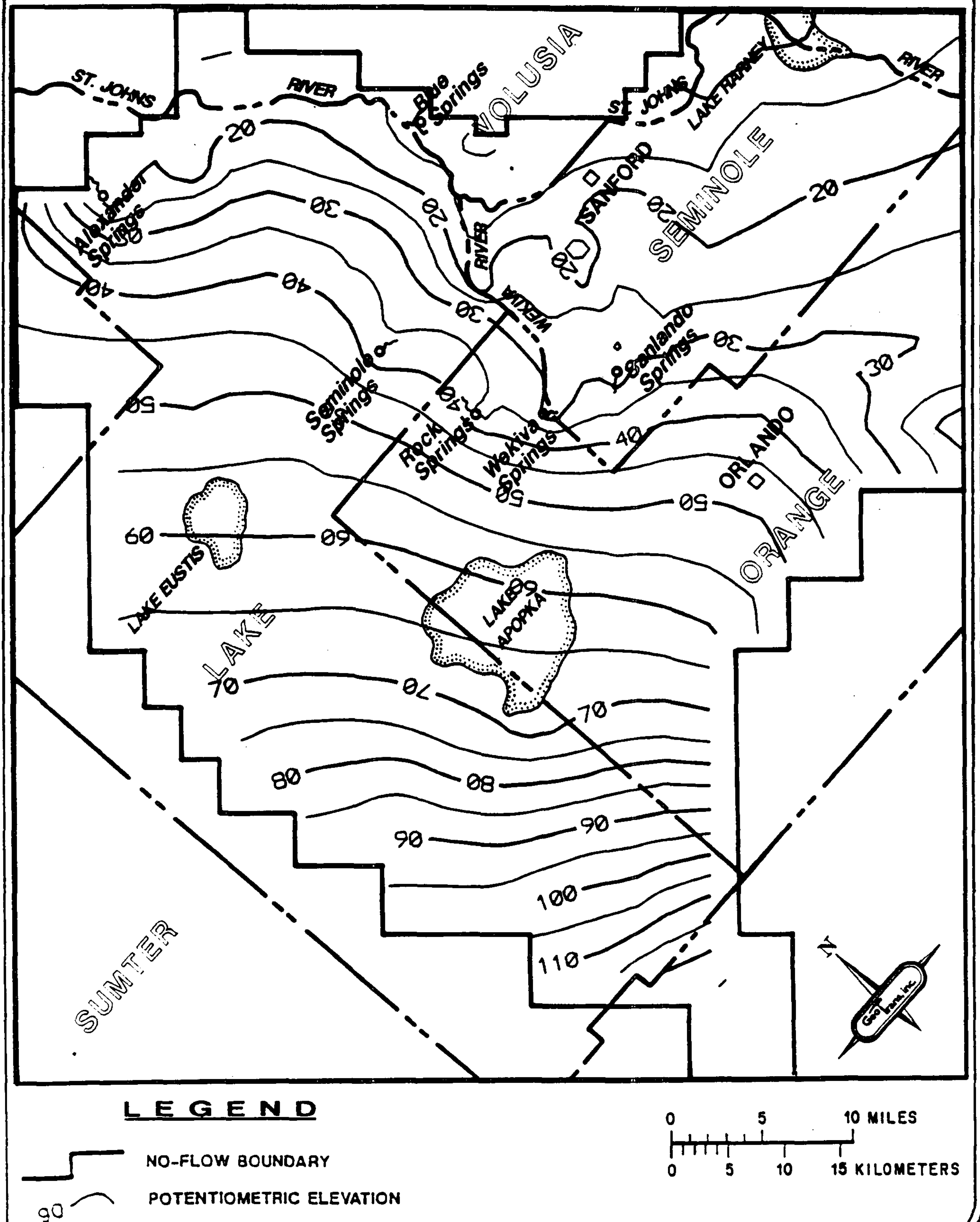

Figure 4.2. Regional potentiometric surface (ft, msl) of the Upper Floridan aquifer generated from the MODFLOW model for 2010 pumpage conditions.

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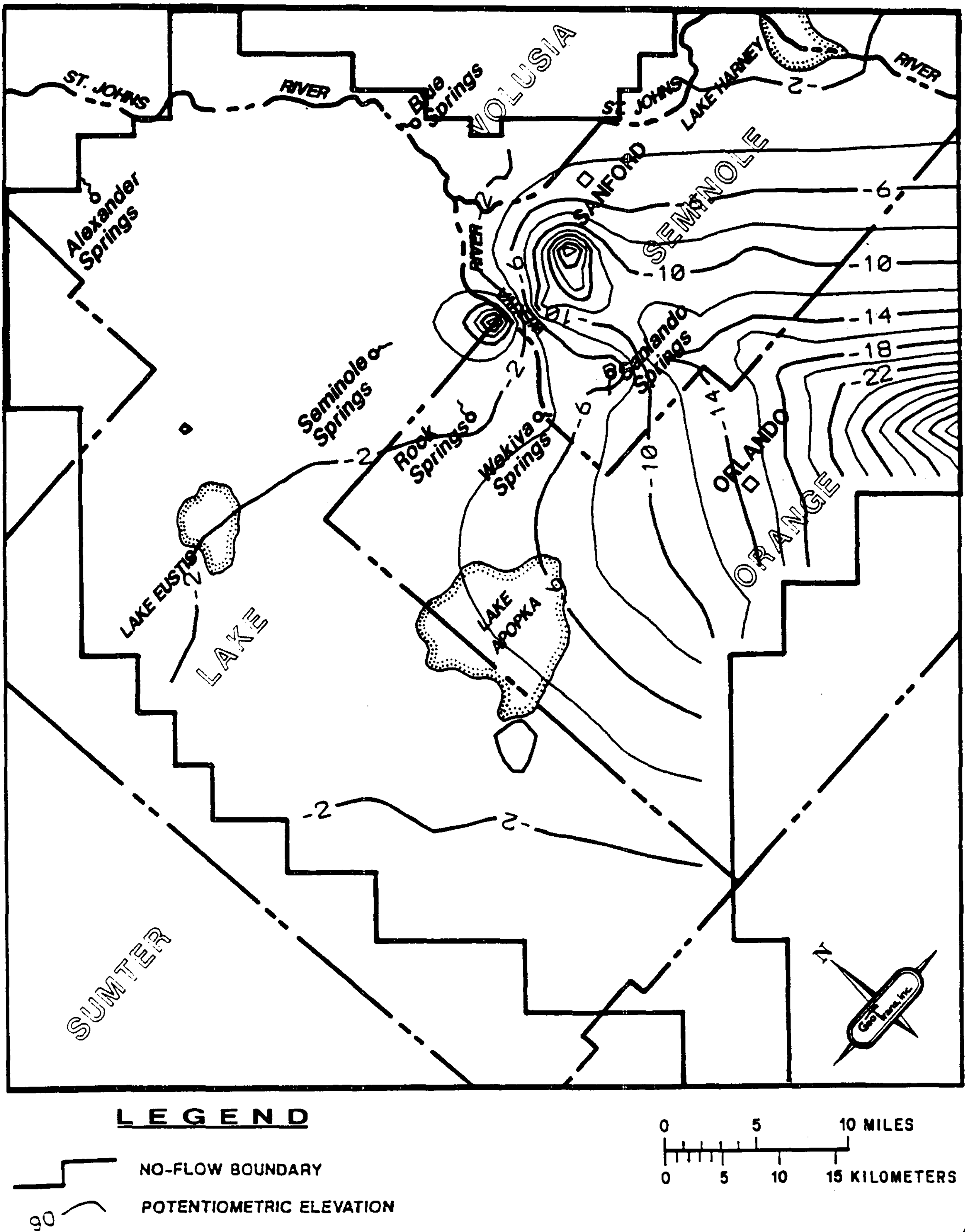

Figure 4.3. Regional change in potentiometric surface (ft) of the Upper Floridan aquifer generated from the MODFLOW model for 2010 pumpage conditions.

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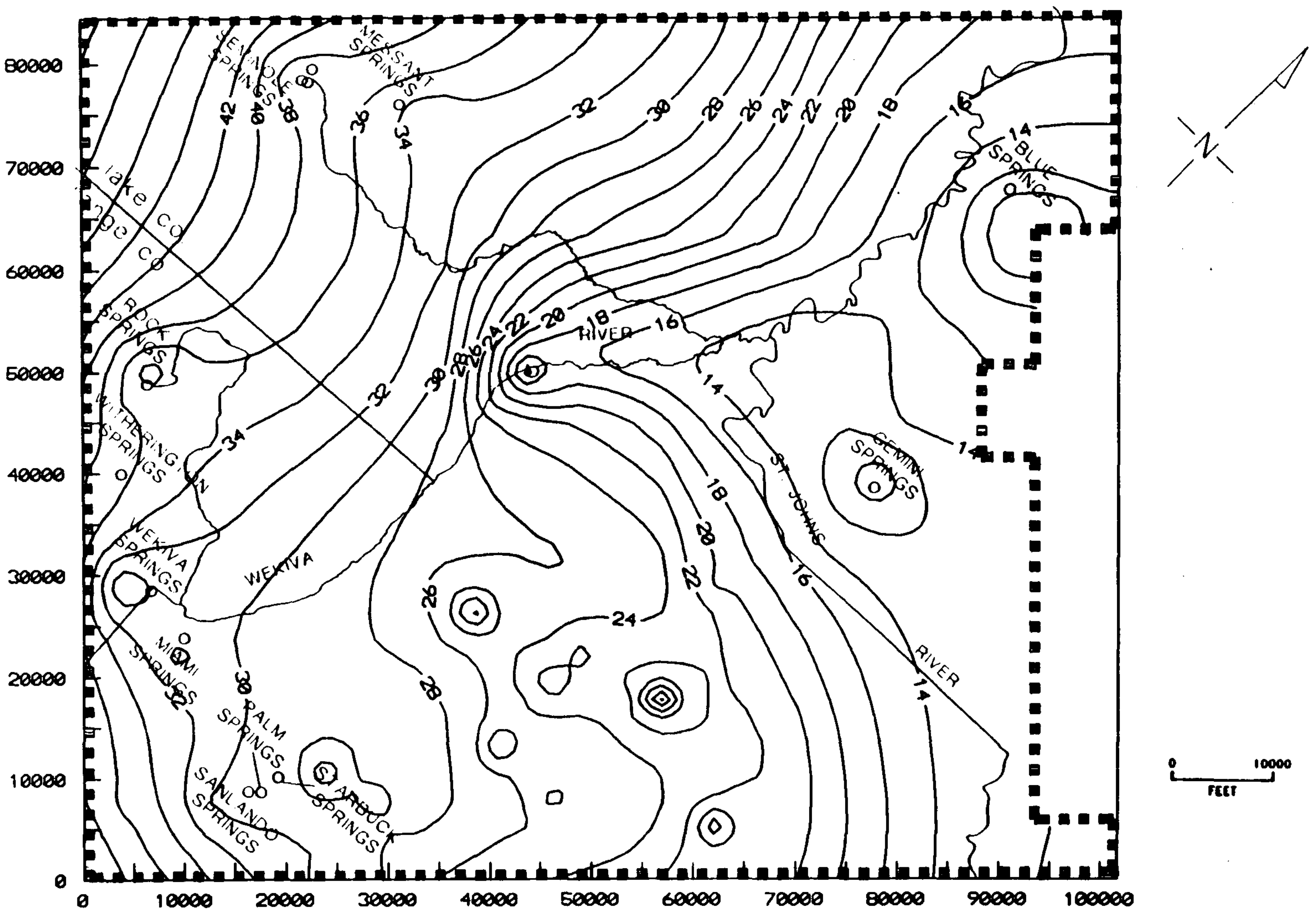

Figure 4.4. Potentiometric surface (ft, msl) of the Upper Floridan aquifer within the saltwater model study area for 2010 pumpage conditions.

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model area. An increase in head is noted near the Wekiva Falls resort where 2010 projected pumpage supplied by SJRWMD was 0.223 mgd. A general lowering of the Lower Floridan potentiometric surface can be seen by comparing Figure 4.6 to Figure 3.15.

Changes in chloride concentration over time can be seen by comparing transient Upper Floridan results plotted in Figures 4.7, 4.8, and 4.9 with the revised model results shown in Figure 3.19. Because response time is directly proportional to effective porosity, the times for Figures 4.7, 4.8 and 4.9 correspond to 5, 25, and 50 years, respectively, for an effective porosity of 0.1; 10, 50, and 100 years for an effective porosity of 0.20; and 15, 75, and 150 years for an effective porosity of 0.30.

As can be readily noticed, a major southwesterly extension of the saltwater in the Upper Floridan occurs along the southeast side of the study area. Some reduction in chloride concentration (750 mg/L isochlor) is present along the Wekiva River. Generally, chloride increases are noted in areas where heads have declined. The simulated time was too short for a new steady state equilibrium to be established for chloride transport.

Comparing Figure 4.10 with Figure 3.20, a similar trend can be seen in the Lower Floridan aquifer along the 5000 mg/L contour line. Transient changes in fluid fluxes and chloride concentrations at spring nodes at the end of the transient simulation are presented in Table 4.1. Fluid fluxes at some springs actually increased, while most decreased slightly. The highest increase was at Island Spring, which increased 4%. The highest decreases were at Palm/Sanlando Springs (63%) and Starbuck (59%). In general, the changing flow field had little effect on water quality at the springs, in fact, the general trend was towards lower chloride levels. This probably results from the wells drawing water of lower concentration from further upgradient into the area represented by the springs. The one exception was at Starbuck Springs where the chloride level increased by a factor of 12. This is in an area of significant drawdown that is near the saltwater interface.

Pumping rates at locations where the pumpage is greater than 1 mgd are given in Table 4.2. These locations were shown in Figure 4.1. The concentrations for these locations are given in Table 4.3. There is a general increase in concentration with time at most locations. A fairly significant decline in concentration takes place at location 7.

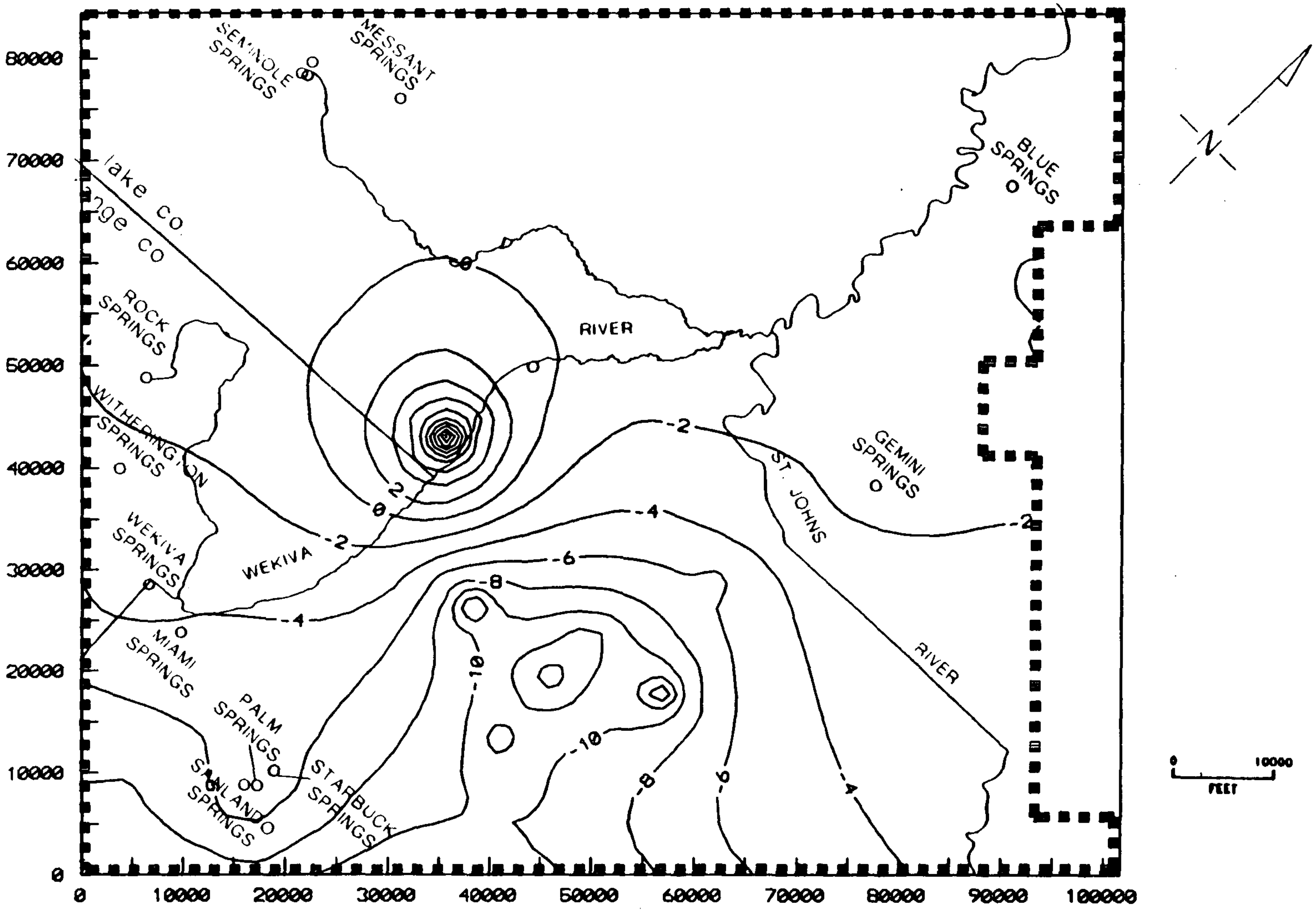

Figure 4.5. Change in potentiometric surface (ft, msl) of the Upper Floridan within the saltwater model study area for 2010 pumpage conditions.

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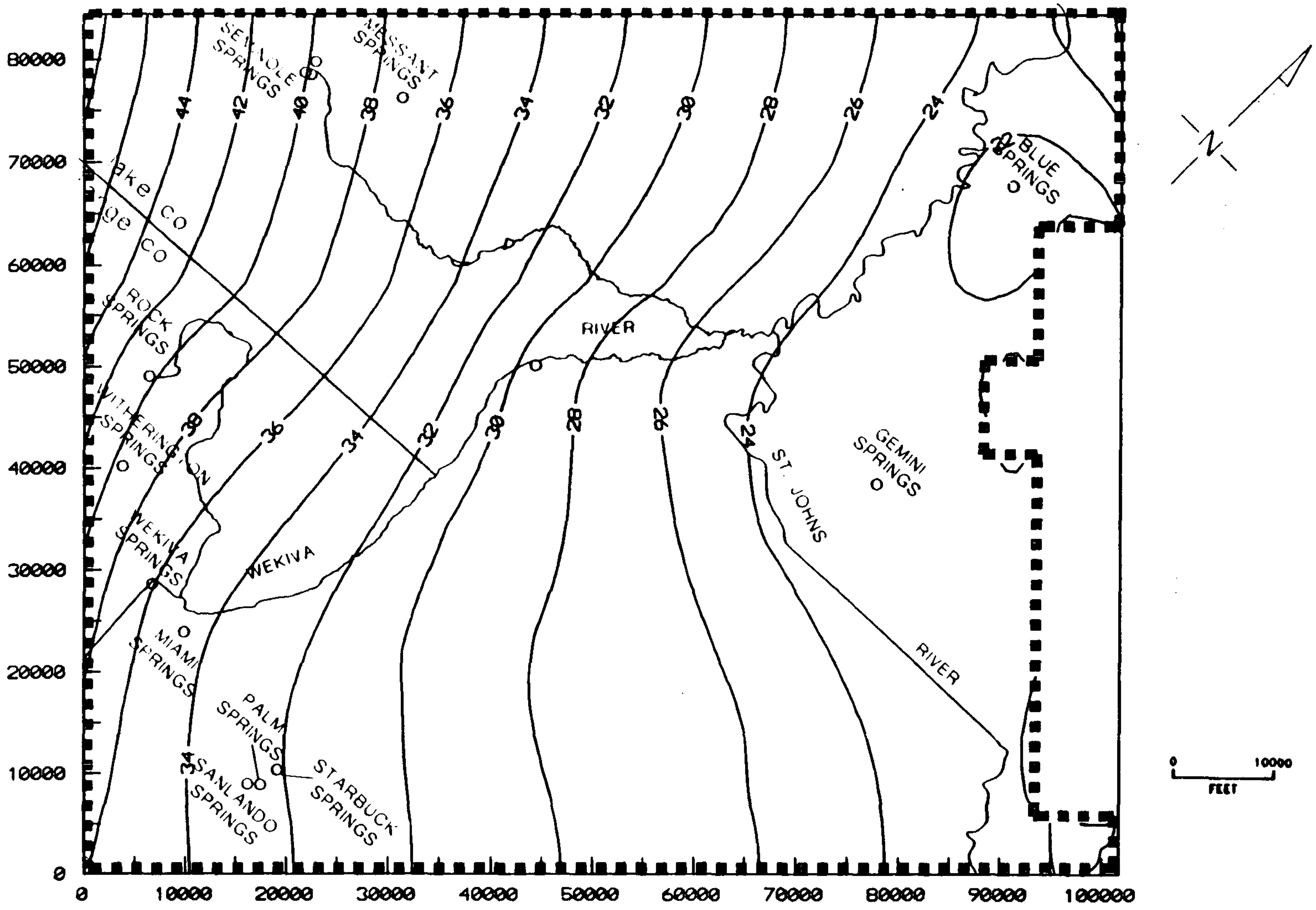

Figure 4.6. Potentiometric surface (ft, msl) of the Lower Floridan within the saltwater model study area for 2010 pumpage conditions.

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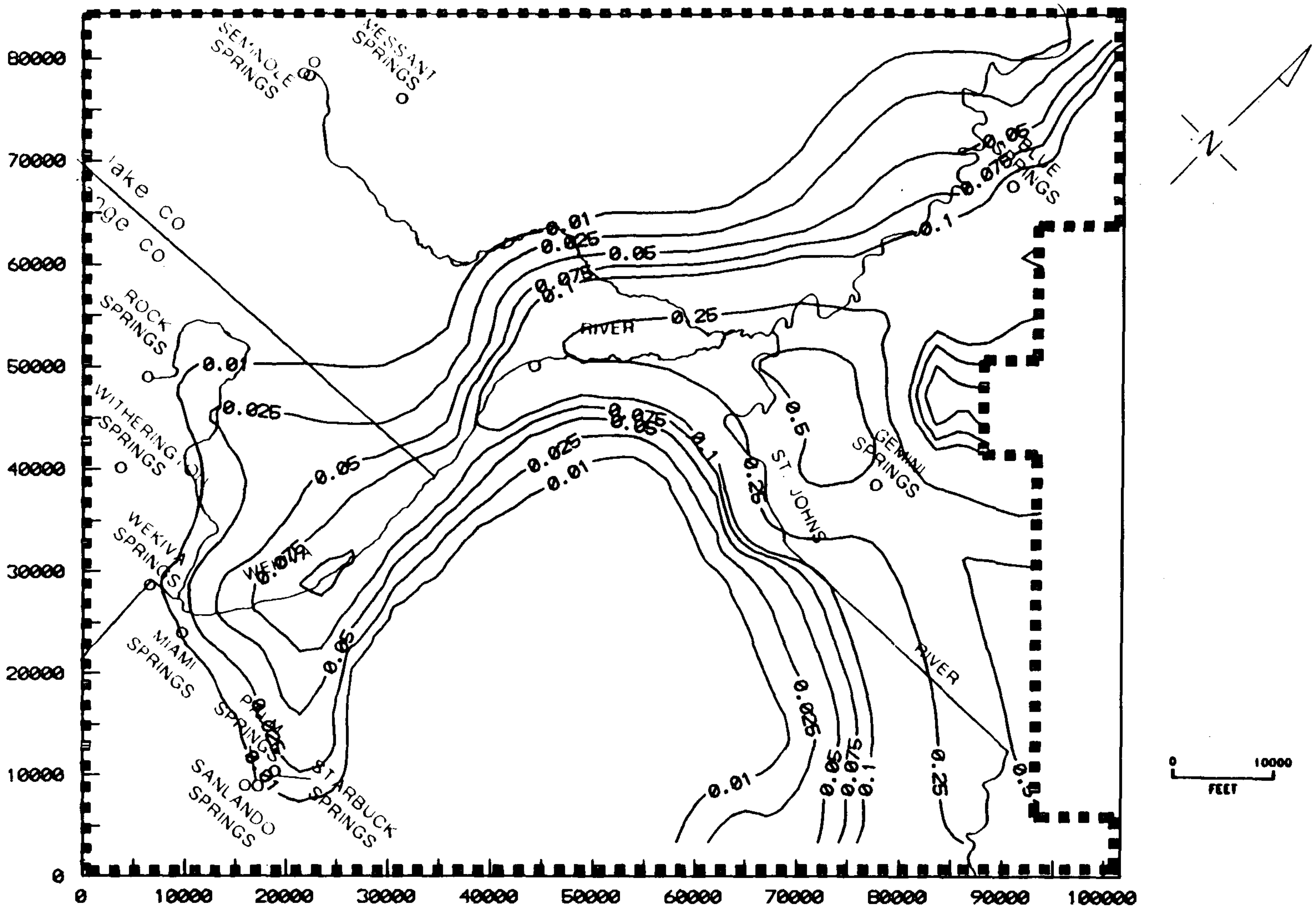

Figure 4.7. Simulated chloride levels (1.0 = 10,000 mg/L) in the Upper Floridan aquifer for well rates updated to the year 2010 withdrawal rates. Time frame corresponds to 5, 10, and 15 years for effective porosities of 0.1, 0.2, and 0.3, respectively.

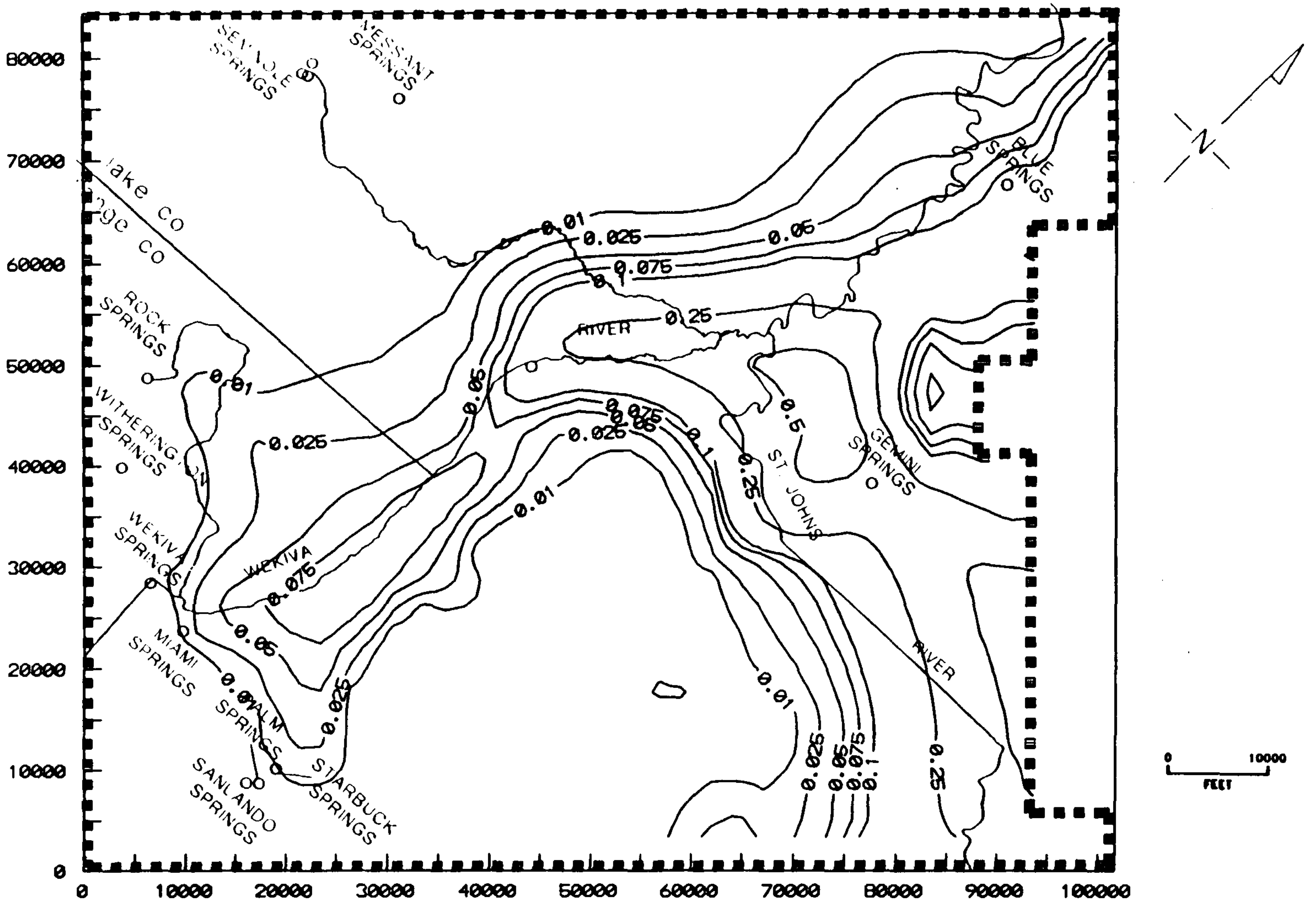

Figure 4.8. Simulated chloride levels (1.0 = 10,000 mg/L) in the Upper Floridan aquifer for well rates updated to the year 2010 withdrawal rates. Time frame corresponds to 25, 50, and 75 years for effective porosities of 0.1, 0.2, and 0.3, respectively.

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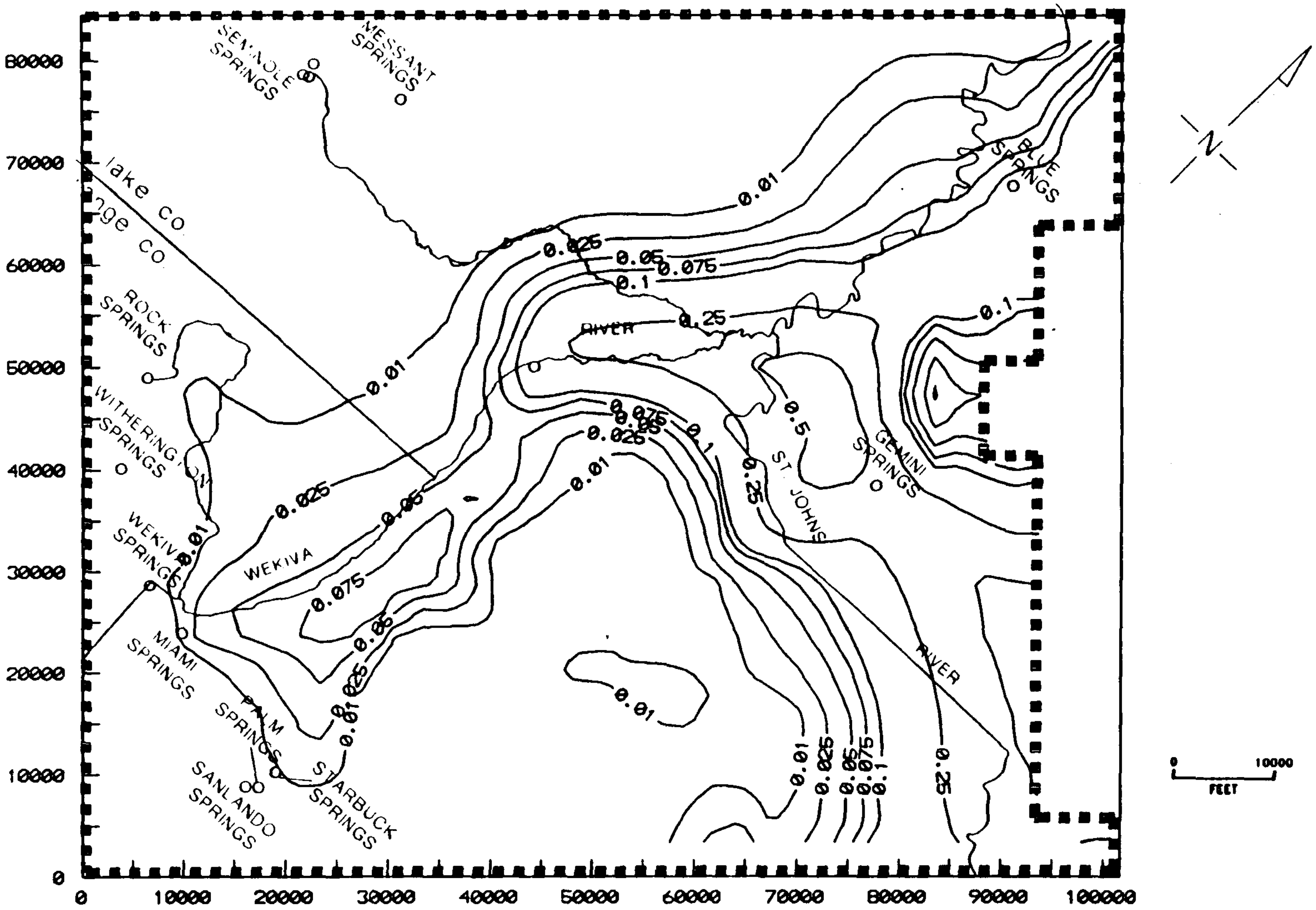

Figure 4.9. Simulated chloride levels (1.0 = 10,000 mg/L) in the Upper Floridan aquifer for well rates updated to the year 2010 withdrawal rates. Time frame corresponds to 50, 100, and 150 years for effective porosities of 0.1, 0.2, and 0.3, respectively.

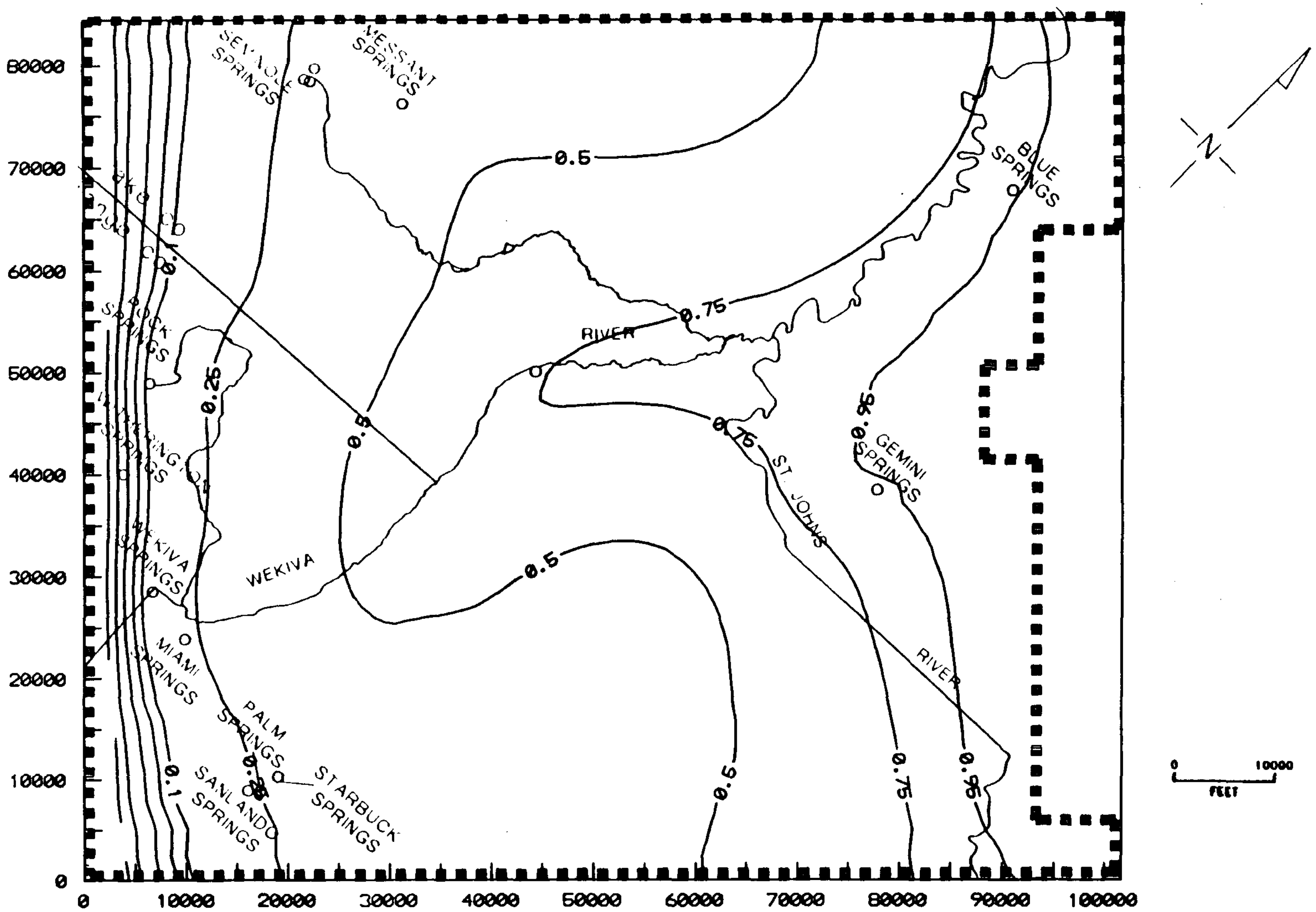

Figure 4.10. Simulated chloride levels (1.0 = 10,000 mg/L) in the Lower Floridan aquifer for well rates updated to the year 2010 withdrawal rates. Time frame corresponds to 50, 100, and 150 years for effective porosities of 0.1, 0.2, and 0.3, respectively.

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Table 4.1. Comparison of spring concentrations in the transient saltwater model at the end of the simulation for pumping at projected 2010 production levels.

		Fluid Flux ft^3/d		Concentration (mg/L)	
Spring	Global Nodal No.	Current Steady State Simulation	2010 Pumpage Simulation	Current Steady State Simulation	2010 Pumpage Simulation
Seminole	2058	2.867E6	2.646E6	8.5	5.1
Messant	3358	1.325E6	1.265E6	16.7	13.0
Blue	6860	3.086E6	3.053E6	1900.0	1792.0
Rock	10164	4.3031E6	3.587E6	19.4	14.1
Island	10374	4.701E5	4.885E5	1639.0	1113.0
Witherington	13272	3.323E5	2.688E5	0.0	0.0
Gemini	13706	5.325E5	4.583E5	4123.0	3963.0
Wekiva	16450	4.9241E6	4.136E6	13.0	8.5
Miami	17108	3.764E5	3.013E5	111.4	101.8
Palm/Sanlando	21574	8.759E5	3.225E5	143.8	65.8
Starbuck	22126	2.154E6	8.755E5	22.8	271.1

Table 4.2. Pumping rates (mgd) for locations having a withdrawal rate greater than 1 mgd. Locations of withdrawals are given in Figure 4.1.

Well Number	Withdrawal (mgd) 1988	Withdrawal (mgd) 2010
7	13.5	0.22
12	0.15	5.2
13	5.7	6.4
16	1.9	6.1
19	1.3	3.6
21	3.4	4.2
23	0.51	3.1
24	1.2	1.2
26	3.2	3.2
33	0.16	5.4
35	0	1.01
36	0	1.01
37	0	1.01
38	0	1.01
39	0	2.02
40	0	1.01

Table 4.3. Chloride concentrations (mg/L) at locations pumping greater than 1 mgd for the beginning and end of the transient simulation.

Well Number	Beginning		Ending	
	Well Top	Well Bottom	Well Top	Well Bottom
7	747.0	846.0	262.2	291.7
12	25.5	39.6	167.3	223.5
13	28.7	42.3	21.3	30.3
16	27.8	33.3	130.0	191.2
19	22.6	34.9	19.8	39.4
21	183.0	249.2	131.3	169.6
23	0.6	1.1	0.06	0.12
24	12.0	15.6	9.4	13.9
26	178.0	277.8	175.6	282.2
29	4.7	27.7	3.7	11.9
33	16.8	21.0	6.8	9.8
35	13.8	45.2	31.4	78.7
36	16.3	44.0	22.2	82.5
37	13.9	50.0	60.2	217.6
38	10.8	48.6	44.7	89.3
39	10.6	54.0	66.7	161.5
40	9.9	59.1	51.8	107.9

5 CONCLUSIONS

5.1 SUMMARY OF ASSUMPTIONS

Numerous assumptions must be made when applying a groundwater model. The number of assumptions is usually dependent upon the understanding of the hydrologic system and the complexity of the analysis. The understanding of the system is based upon the available data and previous site characterization. The understanding can be enhanced as a part of the modeling study by testing various hypotheses in a sensitivity analysis. The complexity of the analysis also affects the number of assumptions which must be made. An analysis of groundwater flow is generally simpler than a solute transport analysis and will therefore require less assumptions. In most cases, the assumptions that are a part of a groundwater flow study of the site will also be present when a solute transport model is applied to the same site.

For this study, assumptions must be made due to both uncertainty in understanding the system and the complexity of the analysis. Most of the assumptions that were a part of the Phase I groundwater flow model are also assumptions in this study. Additional assumptions are present due to the inclusion of solute transport and density dependent flow. The primary assumptions in the flow model were:

- Steady state conditions;
- Porous media or equivalent;
- Vertical flow gradients within aquifer units can be ignored;
- The surficial aquifer can be treated as a constant head condition;
- A no-flow boundary exists along the base of the Lower Floridan;
- The Wekiva River Basin is a closed system which can be represented by no-flow boundaries around its extent;
- Hydrologic properties can be averaged vertically within aquifer units.

The assumption of steady-state with regard to flow is also present in the transport model and is further extended to assuming steady state of chloride concentrations. Although historical data regarding chloride concentrations and hence saltwater interface movement is limited, it appears that there is no evidence of saltwater interface motion. Therefore, the assumption of a steady-state (or quasi steady-state) condition is probably justified.

The steady state assumption is consistent with placement of chloride boundary conditions on the lateral and lower extent of the model. It may have been reasonable to input existing chloride concentrations directly as an initial condition if a steady state condition were not assumed. This would be consistent with a hypothesis of relict saltwater slowly flushing from the system.

Boundary conditions in the transport model are for the most part taken from the flow model. It is therefore assumed that the flow model is an accurate representation of the hydrologic system. It is further assumed that the hydraulic heads which are non-density dependent and depth averaged in the flow model can be transferred directly into the transport model. Density dependence of hydraulic heads can probably be ignored in the Upper Floridan due to generally low concentrations. The uncertainty regarding hydraulic head in the Lower Floridan probably overwhelms any inaccuracy due to density effects. Depth averaging on the boundaries, which results in using the same head with depth across an entire unit, may introduce some inaccuracy, but vertical gradients are established in the interior of the model. Thus, there may be some boundary effects, but the interior of the model is accurate.

Perhaps the most significant uncertainty in this study is the location and dynamics of the lower boundary. This was also an issue in the flow model, however, location was less important than the flow dynamics. The lower boundary is important in the current model because it affects the magnitude and extent of saltwater contamination. It is assumed to be a diffusive boundary at a depth of 2025 ft. The assumption of location is not refuted by the data, however, the dynamics of the interface are not certain.

It is necessary to choose a constituent in saltwater to serve as the modeled tracer. Chloride is chosen as the tracer in this application. Therefore, it is assumed that chloride concentration is directly related to water density. Some error could be introduced by elevated sulfate concentrations in the central part of the model area, as an example.

The hydrologic properties of each unit are heterogeneous areally but are assumed to be homogeneous with depth. This assumption is made due to lack of data. Preferential flow paths or high conductivity layers are averaged with the present approach and could cause velocities and extent of intrusion to be underestimated.

A 1:10 vertical to horizontal anisotropy is assumed. This was done due to data uncertainty. Different rates were tested in the sensitivity analysis of this model and the previous cross-sectional model. The 1:10 ratio appears to be reasonable and is consistent with values used for the Floridan aquifer by other researchers.

5.2 MODEL ACCURACY

The relative accuracy of the flow and transport model has been assessed based on its ability to match:

- estimated or observed hydraulic heads.
- estimated or known spring discharges.
- reasonable rates of diffuse recharge.
- observed or estimated chloride concentrations.
- observed or estimated spring concentrations.

The first three factors are a direct function of the flow model and do not change appreciably in extending the analysis to include solute transport. Matching observed or estimated chloride concentrations is a difficult task due to (1) lack of data, (2) uncertainty in accuracy of data, and (3) natural variability of data. Matching observed or estimated spring discharges is not as difficult because concentrations are generally low and the spring discharge is restricted to the Upper Floridan, which is characterized fairly well.

Modeled chloride concentrations match observed trends in the Upper Floridan aquifer quite well. Attempts to match data on a point by point basis were generally unsuccessful. Given the difficulties enumerated above it seems appropriate to lend more credence toward trend matching than point-by-point data.

Only a steady-state calibration was achieved with this model. Historical data were insufficient both temporally and spatially to perform a steady state verification or a transient calibration. Because only limited historical data exist, it is difficult to comment on the accuracy of model predictions. The fact that current steady state conditions are matched does not ensure accurate predictive capability. However, a fair amount of certainty can be placed on the accuracy of the flow model because of the closed nature of the flow system and agreement with studies by others. Since advection is a major component of the system dynamics, a fair amount of certainty is also associated with the transport model.

5.3 RECOMMENDATIONS

Several areas of data deficiency have been identified as a result of the modeling. Recommendations regarding acquisition of additional data and the utility of the model are presented in this section.

The most obvious area of data deficiency is in the Lower Floridan aquifer system. Basic uncertainties regarding boundary conditions (location of base, location of saltwater interface, overall transmissivity, etc.) resulted in the need to make rather broad assumptions. Further boring data and monitor well data are needed to better quantify the dynamics of flow in the system. A series of deep monitor 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. A deep cluster well near a spring would provide a prototype of typical near spring behavior. Indirect methods of locating the saltwater interface, such as the time domain electromagnetic geophysical technique, are beneficial to understanding the system. Although TDEM data does not replace directly measured data, it does provide an economical means of filling data gaps.

A second area of uncertainty is in the hydraulic characteristics of the overlying Hawthorn confining bed. Aquifer testing particular to the competence of this bed are important from a research standpoint. The importance of data on the Hawthorn is apparent from the sensitivity of this and other models. It is underscored with the realization that most inflow occurs through the Hawthorn.

A better system of organizing the data is necessary as more data become available. Some data deficiencies are related to access rather than actual availability. For example, the data base for current and projected water use is nearly unmanageable in its current format. Cross-referencing current and projected water use was a particularly difficult task. A more user friendly approach to access and analyze all types of data is needed. The St. Johns River Water Management District should consider inclusion of these data into a hydrologic Geographic Information System (GIS). The system should be accessible to and usable by District hydrologists.

Continued monitoring of wells is necessary to truly understand the transient dynamics of the system. A ten-year or more history of chloride and water levels is useful for model verification as well as simple trend extrapolation. The importance of adequate data management system is particularly important as the transient data base evolves.

The flow and transport model should continuously be updated, recalibrated, and verified as additional data become available. The models should be used as tools to assist in water management decisions. Due to current uncertainties in the models, they should not be used as the sole basis for a water management decision. Because less assumptions are made in the flow model, it is likely that it is a more accurate predictive tool than the transport model. This is consistent with Mercer and Faust (1981) who state that solute transport modeling lags behind groundwater flow modeling in terms of predictive capability and validity.

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APPENDIX A

DOCUMENTATION OF MONOTONICALLY DECREASING UNDER-RELAXATION FACTOR

Appendix A

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

$$V_z = - K_z \left[\frac{\partial h}{\partial z} + \eta c \right] \tag{A-1}$$

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:

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

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:

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

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 A-1 depicts a contour plot of the solution using the transient solution techniques. Figure A-2 shows the same physical system simulated using the monotonically decreasing under-relaxation factor. Little difference is seen between the two schemes. Figure A-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 A-2 and A-3.

REFERENCE

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

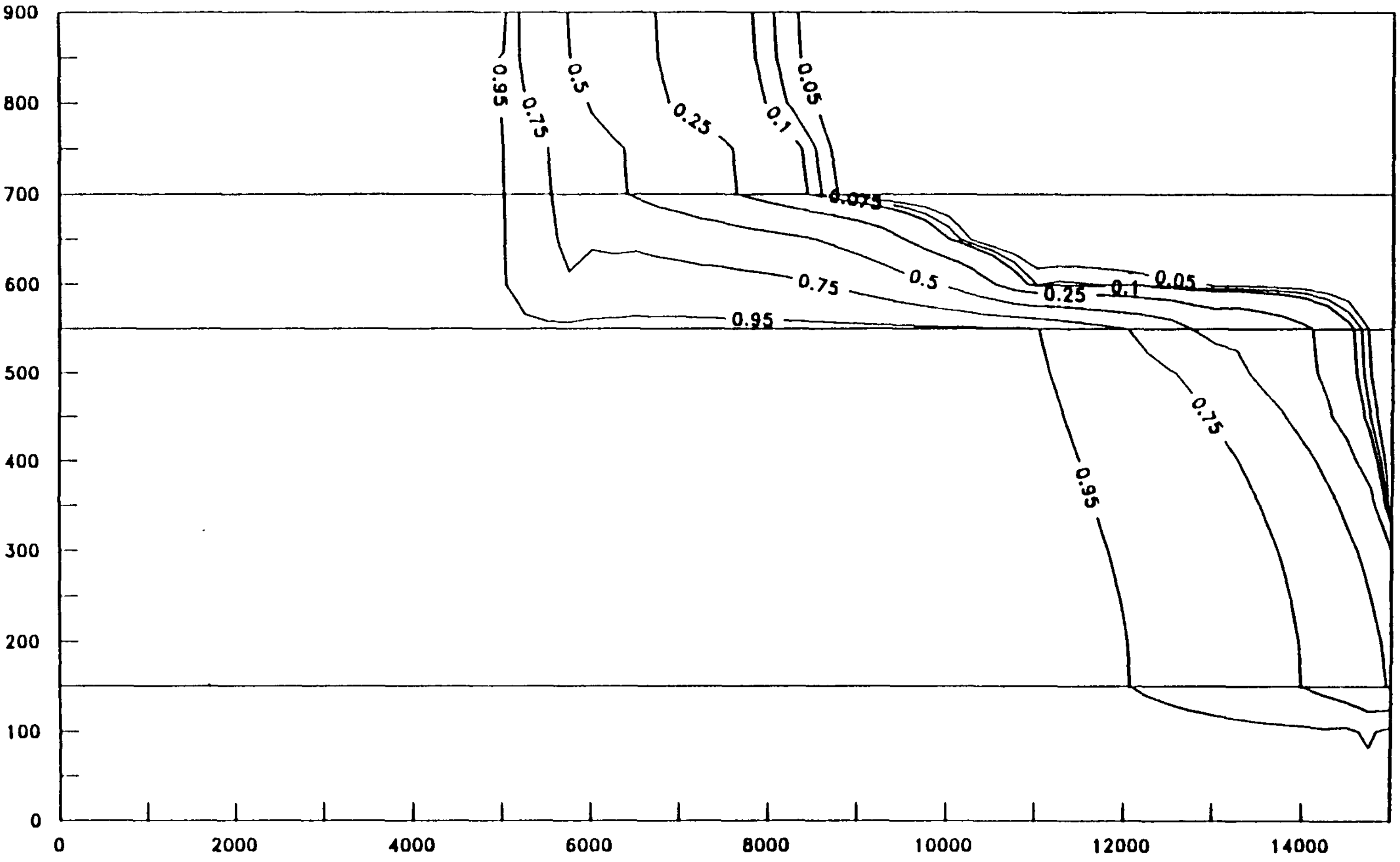

Figure A.1. Simulation results for cross-sectional model using transient approach.

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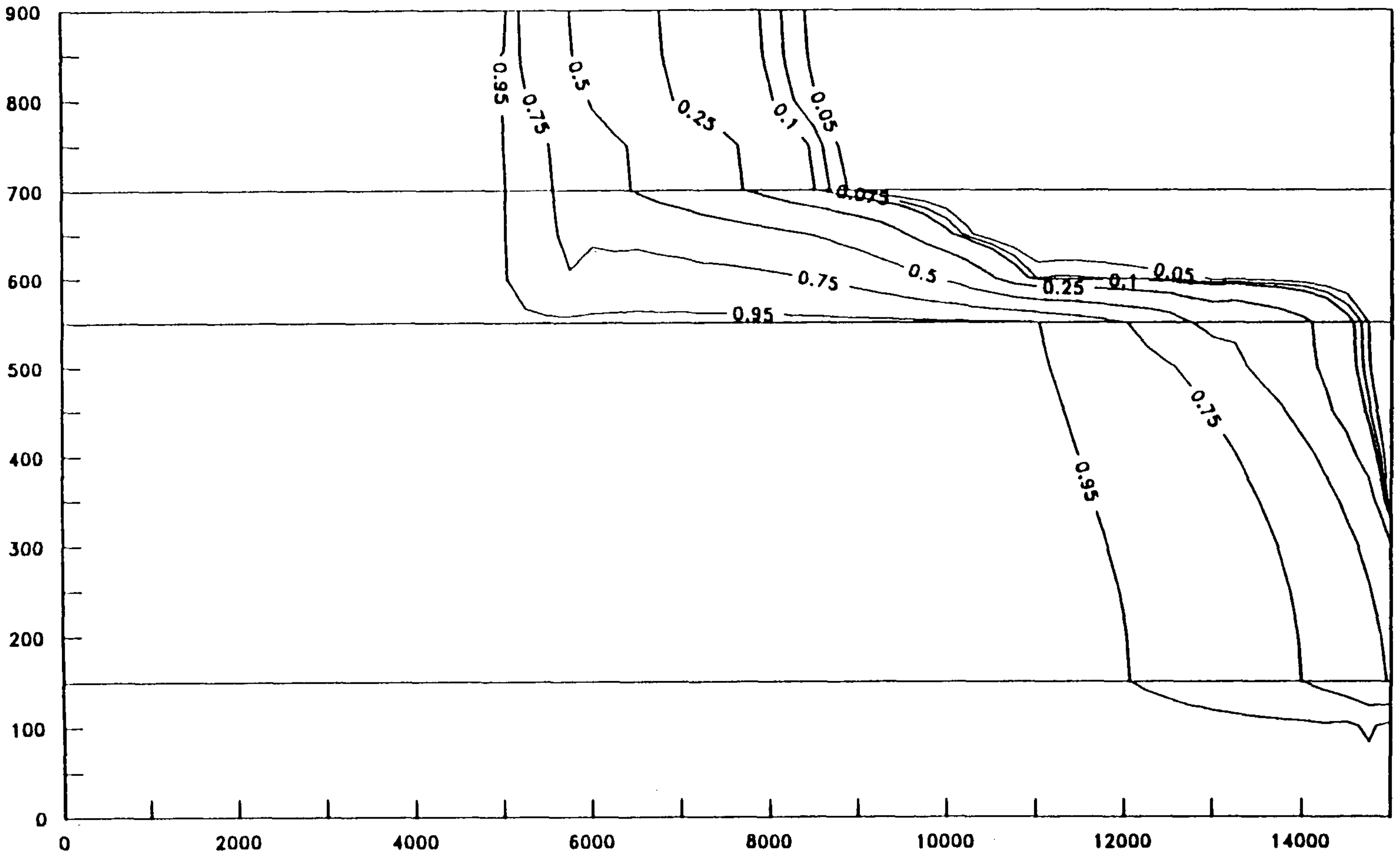

Figure A.2. Simulation results for cross-sectional model using monotonically decreasing under-relaxation factor.

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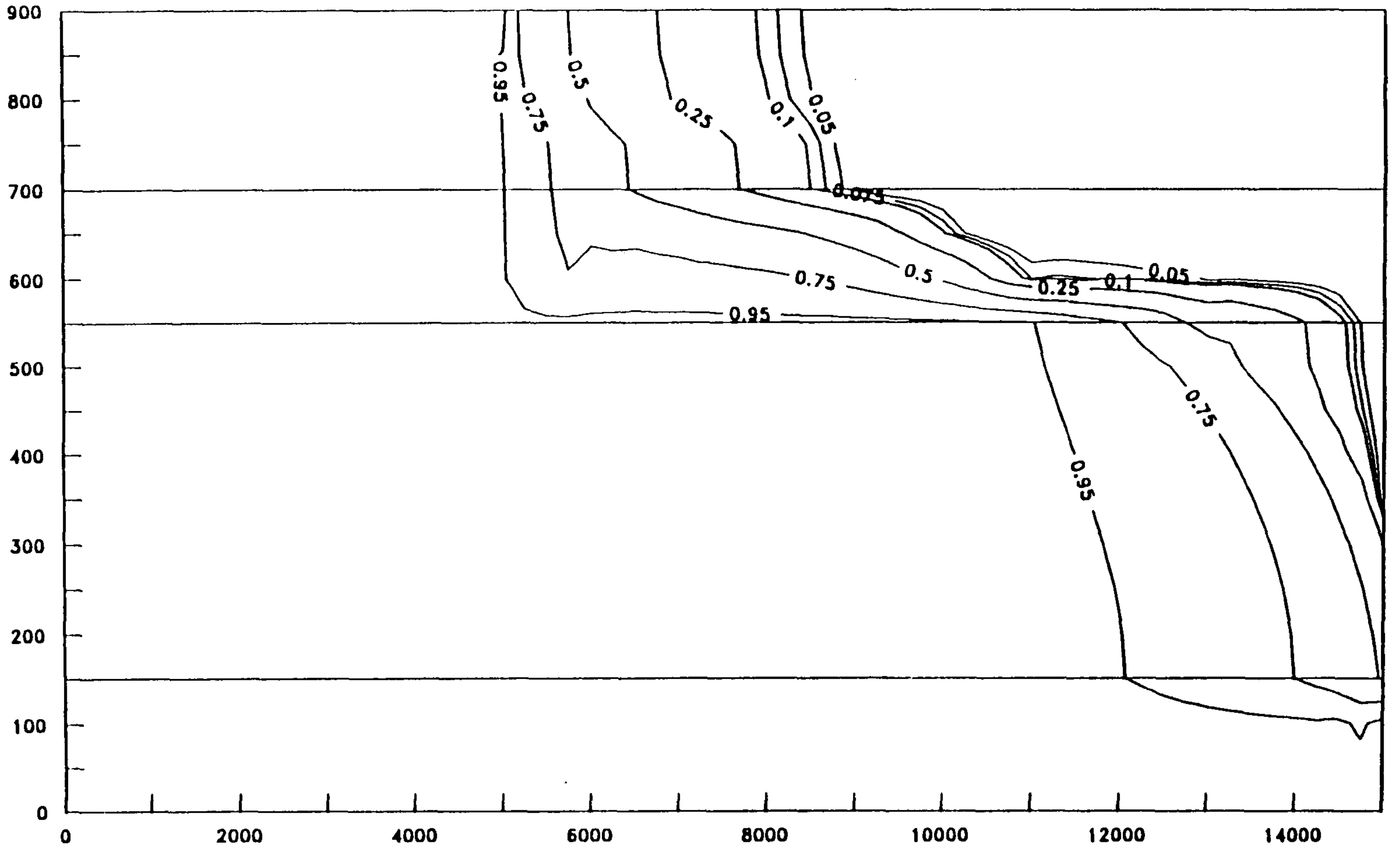

Figure A.3. Simulation results for cross-sectional model using transient method and initial conditions from monotonically decreasing under-relaxation factor simulation.