TECHNICAL PUBLICATION SJ 85-1

Saltwater Intrusion in Volusia County, Florida, Due to Ground Water Withdrawals-Technical Summary

By

James W. Mercer, Stephen D. Thomas,
Barry H. Lester, and Ronald W. Broome
Geotrans, Inc.
Herndon, Virginia

Edited By
David C. Skipp

Prepared For
St. Johns River Water Management District
Palatka, Florida
July 1984

Project Number 20 331 03

PLEASE NOTE

The original document, from which this technical publication was created, can be examined at the Library of St. Johns River Water Management District.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abstract

Volusia County, located in east central Florida, comprises approximately 1,200 square miles between the Atlantic Ocean to the east and the St. Johns River to the west. Most of the county is underlain by a three-aquifer system. The primary source of water is a limestone artesian aquifer of Eocene age known as the Floridan aquifer, which is divided into an upper and lower part. It is overlain by confining beds of low-permeability clay of Miocene or Pliocene age. These are overlain by a water-table aquifer that is composed of sand beds of Pleistocene and Recent age and the uppermost sand and shell beds of Miocene and Pliocene age. Population centers in Volusia County, which create a large water demand, are located near the coast. These population centers are experiencing saltwater intrusion that has resulted in the relocation of public water supply wells further inland. Problems with saltwater intrusion combined with the increased water demand throughout the county have produced the need for a regional management approach to Volusia County's water development.

The tool that has been selected to aid in this management approach is a three-dimensional computer model of the entire county. Such a model provides decisionmakers with the ability to predict the response of the ground water system, both in terms of flow and movement of chlorides, to various developments or management schemes. A phased approach toward model development was used. In the first phase, the ground water flow system was simulated. Once this phase was successfully completed, the

second phase, incorporating solute transport to simulate sea water intrusion and brackish water upconing, was introduced. Both predevelopment and development conditions within the county were simulated to demonstrate the accuracy of the model. The predevelopment or steady-state simulation results were used as initial conditions for the development simulations, which include well discharge data. Sensitivity analyses were performed on the boundary conditions, recharge rates, permeability, and leakage properties.

The response of the Volusia County ground water system to six different hypothetical stresses was also analyzed as part of the study. This analysis provides insight into the dynamics of the system. Results of the model study indicate the utility of computer models as a management tool for the complex ground water system in Volusia County.

1.0 SUMMARY

Ground water withdrawals in Volusia County, Florida have caused both sea water intrusion and brackish water upconing. The county contains several population centers, some of which are located along the Atlantic Coast. With the potential for the interaction between various ground water developments, a management tool is required to help anticipate and avoid county-wide, ground water problems. The objective of this work, therefore, was to prepare a three-dimensional ground water model capable of defining the areal extent of saltwater intrusion under pumping stress. A further objective was to calibrate, verify, and install the model, and instruct St. Johns River Water Management District (SJRWMD) personnel in the use of a final version of the model.

A three-dimensional, flow and transport model on the scale of Volusia County is a complex tool to produce. Therefore, to achieve this objective, a phased approach was taken. Initially, only single dimensionality of flow was considered. As understanding of the Volusia County system improved, solute transport and additional components of dimensionality were added until the final model was obtained.

Several different hydrologic conditions were considered. These included (1) predevelopment conditions, (2) decreased recharge (drought), (3) increased recharge, and (4) different pumping schemes. The effects that these conditions have on saltwater intrusion were examined. Other questions that were considered included: (1) What is the potential for induced

recharge?, (2) How will the recharge affect surface features such as springs?, (3) What locations and what withdrawal rates should be considered for new well fields?

This report describes the results of this modeling effort. The computer code used for this study was the Survey Waste Injection Program, Revised (SWIPR), which is described in Intercomp (1976) and Intera (1979). In order to allow the SJRWMD to use the SWIPR code as early as possible, it was installed on their computer system in October 1982. At that time a course was taught demonstrating the use of SWIPR, both from a theoretical and practical point of view. The final data set representing the calibrated model of Volusia County was delivered to the SJRWMD at the time of this report.

2.0 INTRODUCTION

Volusia County is located in east central Florida along the state's Atlantic Coast (Figure 2.1). Approximately 1,200 square miles in size (Wyrick, 1960), the county had a population of 284,593 as of 1983. Most of the county's largest population centers, Daytona Beach, Ormond Beach, New Smyrna Beach, are located along the coast. Some development has also occurred along the St. Johns River in the western portion of the county. Ground water development stresses have been centered primarily in these areas.

2.1 Study Objectives

Volusia County is underlain at depth by brackish water and is bounded on one side by sea water. Saltwater intrusion has occurred and continues to be a concern of the St. Johns River Water Management District. To enable the District to make more informed decisions about the management of the ground water resources of Volusia County, a model was constructed to simulate county-wide ground water features. The particular objectives of this study include:

(1) Provide the St. Johns River Water Management District (SJRWMD) with a complete computer code for their PRIME 750 that can simulate sea water intrusion or brackish water upconing in three dimensions.

(2) Determine a workable conceptual model of the Volusia County hydrogeology that includes ground water development and water quality.

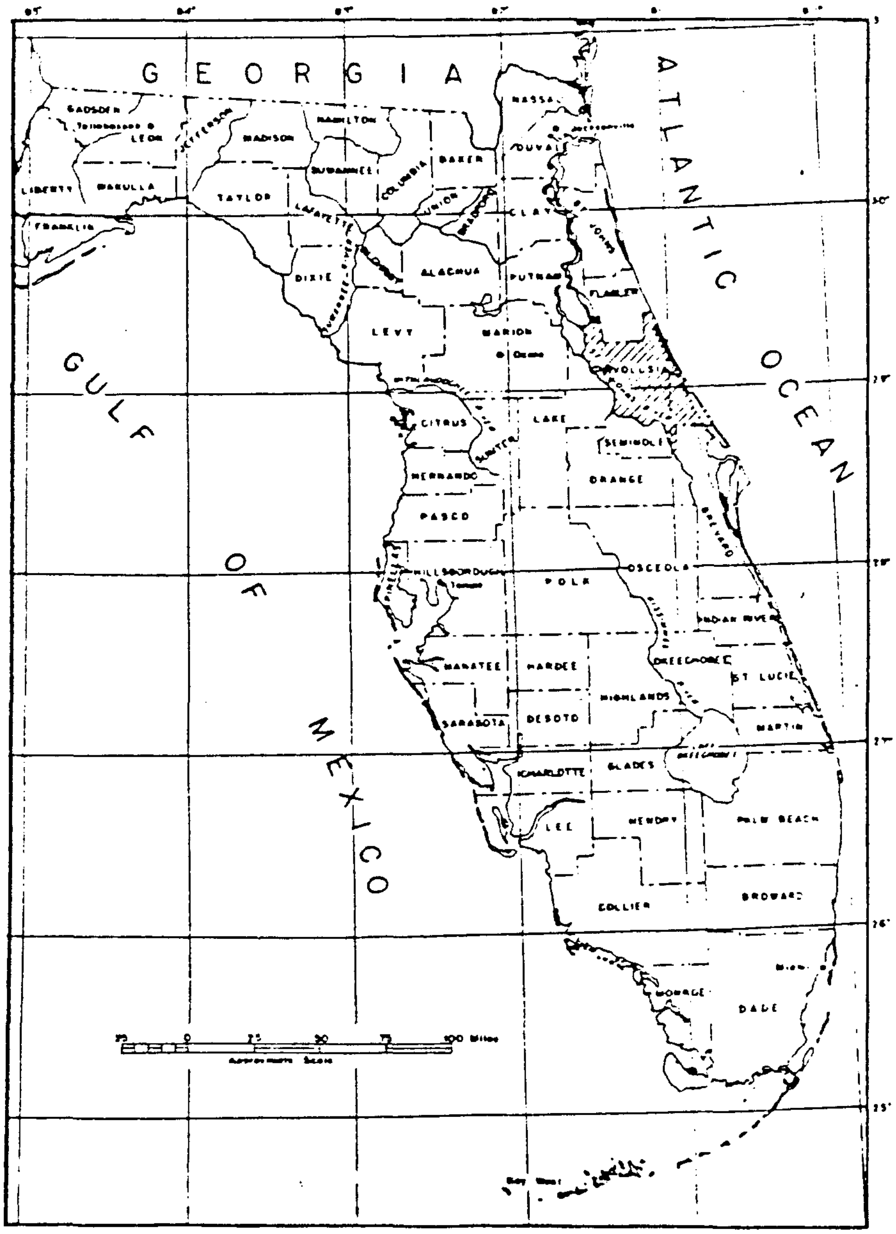


Figure 2.1 Location of Volusia County
(from Wyrick, 1960).

(3) Translate this conceptual model into a calibrated data set that is executable on the code in (1) and that can be used to aid in water management decisions for the county, especially where ground water development results in either sea water intrusion or brackish water upconing.

2.2 Previous Analysis

The general geology and hydrology of Volusia County are described in Wyrick (1960) and Knochenmus and Beard (1971). In addition to these studies, two modeling projects have included Volusia County. The first of these modeling efforts is described in Bush (1978); the second in Tibbals (1981).

Bush (1978) developed a two-dimensional, areal model of Volusia County that simulated ground water flow in the upper Floridan aquifer. The main emphasis of the study was to estimate the impact of a hypothetical wellfield located in the central part of the county in an area known as the central wetlands. Tibbals (1981) work was regional in nature and covered the entire east central portion of Florida, which included Volusia County. Again, only ground water flow was simulated, but in three dimensions, including the upper Floridan aquifer, the lower Floridan aquifer, and the surficial aquifer. Emphasis was placed on predevelopment, steady-state conditions.

The work presented in this report relies on the hydraulic conductivities obtained from the calibrations in the Bush and

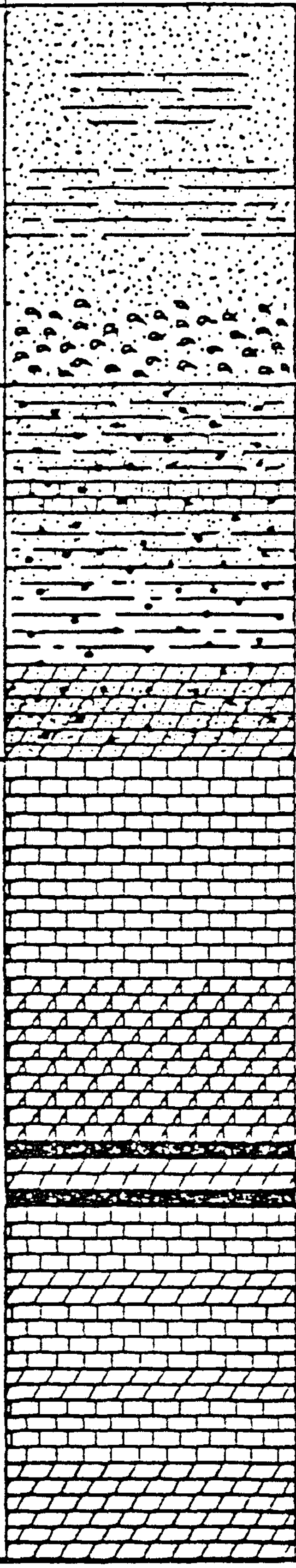
Tibbals work. In addition, their work was extended by considering solute transport. The area modeled was less than that considered by Tibbals, and was similar to that simulated by Bush. Unlike Bush, however, three dimensions were simulated.

3.0 GEOHYDROLOGIC SETTING

3.1 Geology of Volusia County

The geology of Volusia County was described in several reports, including Bush (1978), Wyrick (1960), Knochenmus and Beard (1971), and Johnson (1981). The stratigraphic column is shown in Figure 3.1. According to Johnson (1981), the units range in age from Eocene through Pleistocene and consist, from oldest to youngest, of the Avon Park Limestone, Ocala Limestone, Hawthorn Formation, and surficial material. The Lake City Limestone underlies the Avon Park Limestone, but few wells penetrate it and, therefore, little is known about it in Volusia County.

The Avon Park Limestone (Eocene) consists of interbedded limestone and dolostone containing peat as discrete beds and as inclusions in the rock (Johnson, 1981). Within the Avon Park Limestone is a recognizable and correlatable lithologic zone known as the Avon Park low porosity zone. This term is used by Johnson (1981) to describe the hard, thick beds of brown dolostone interbedded with thin, softer beds of limestone. This bed may be recognized by a peak on an electric log that results from the low porosity (see Figure 3.2).



AGE	FORMATION	THICKNESS	DESCRIPTION
LATE AND POST MIOCENE	SURFICIAL MATERIAL	34 ft. to 139 ft.	Sand, Clay, and Coquina
MIOCENE	HAWTHORN FORMATION	0 ft. to 104 ft.	Sand, Clay, Limestone, and Dolostone, mostly phosphatic
		0 ft. to 32 ft.	Basal Hawthorn: Dolostone, sandy, phosphatic, hard
EOCENE	OCALA LIMESTONE	37 ft. to 75 ft.	Limestone, relatively pure Coquina, bio- and foraminiferal-
		9 ft. to 57 ft.	lower Ocala: Limestone, dolomitic, coquinoid
	AVON PARK LIMESTONE	63 ft. to 162 ft.	Limestone and Dolostone with Peat (disseminated and as beds) or Clay beds
			Avon Park: Dolostone, very hard, low porosity zone

Figure 3.1 Stratigraphic Column of Project Area (Johnson, 1981).

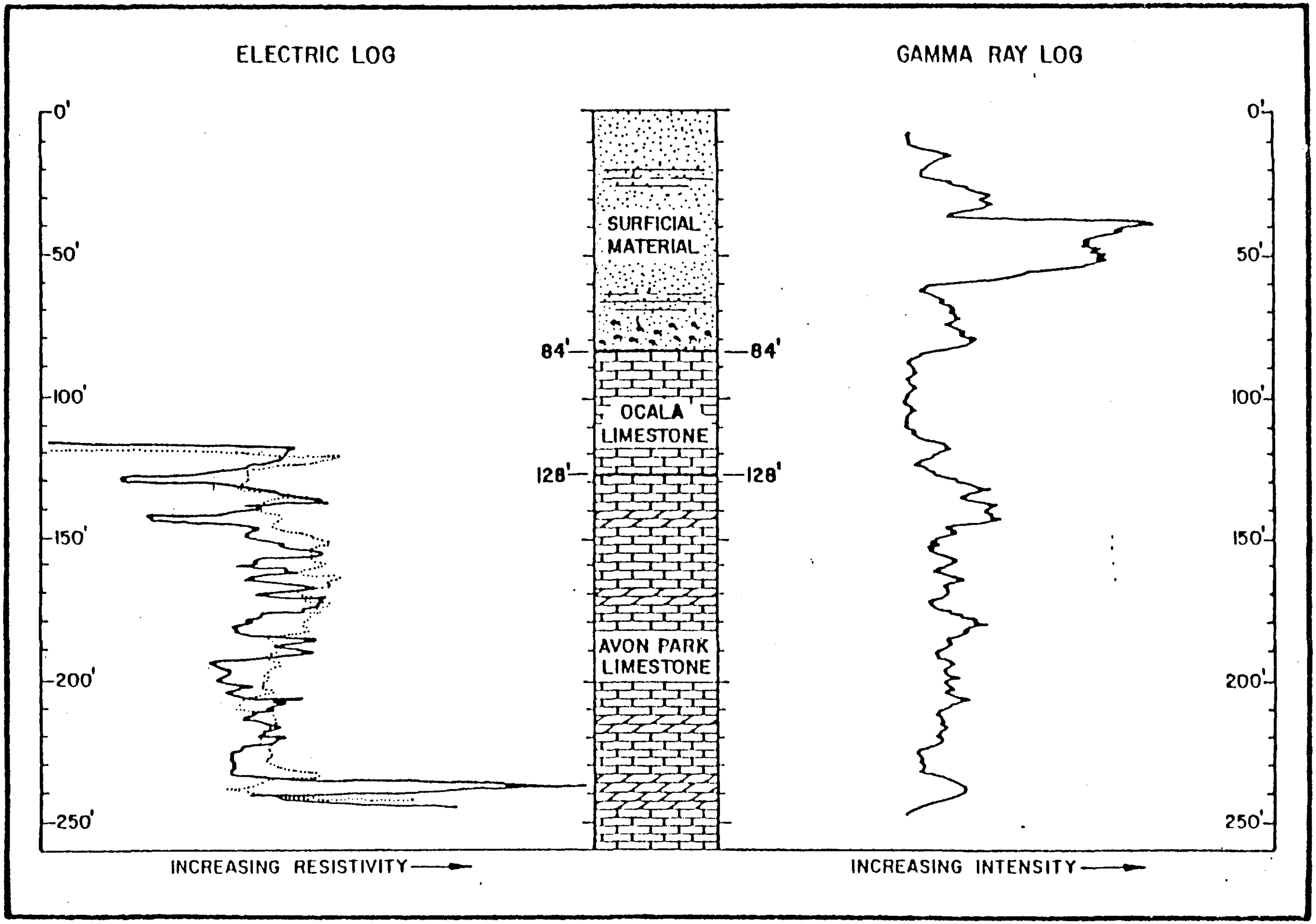


Figure 3.2 Gamma-ray and Electric (Resistivity) Logs of Well V-15 (from Johnson, 1981).

The Ocala Limestone (Eocene) consists of white to tan, poorly to well-cemented biohash, primarily composed of foraminiferal tests and fragments (Johnson, 1981).

The Hawthorn Formation (Miocene) consists of clay, sand, dolostone, limestone, and phosphate mixed in varying proportions (Johnson, 1981). This formation is not continuous throughout Volusia County.

The top of the Floridan aquifer is indicated in Figure 3.3. The low porosity zone, previously discussed, is generally considered the bottom of the upper Floridan aquifer.

The surficial material, late Miocene to Recent in age, consists of sand, clay and admixtures of the two (Johnson, 1981). On gamma-ray logs, the lower part of this unit is usually indicated by a peak, which is also indicated in Figure 3.2, or the entire unit is indicated by increased gamma-ray intensity overall throughout the unit.

Landforms in Volusia County consist of a series of a coast-parallel karst ridges, marine terraces, and shoreline ridges (Knochenmus and Beard, 1971). These are shown in Figure 3.4 The ridges are sandy and well-drained compared to the flat swampy terraces. Thus, the ridges are thought to be areas of higher recharge.

3.2 Ground Water Hydrology of Volusia County

Three major aquifers have been identified in Volusia County. The upper one is a water-table aquifer and is composed of sand beds of Pleistocene and Recent age and the uppermost sand and

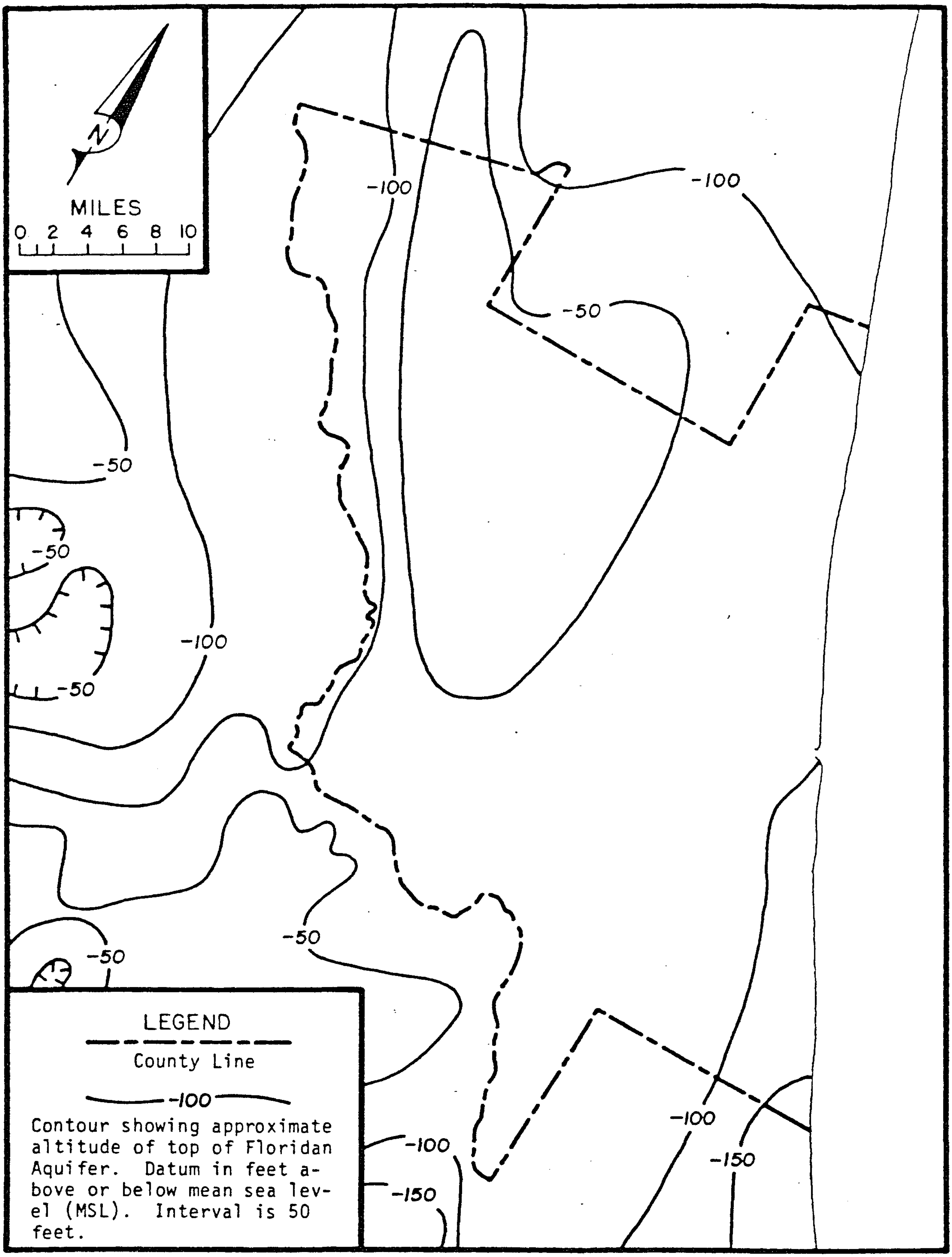


Figure 3.3 Approximate Altitude of the Top of the Floridan Aquifer in Volusia County, Florida, 1973 (from Florida Bureau of Geology).

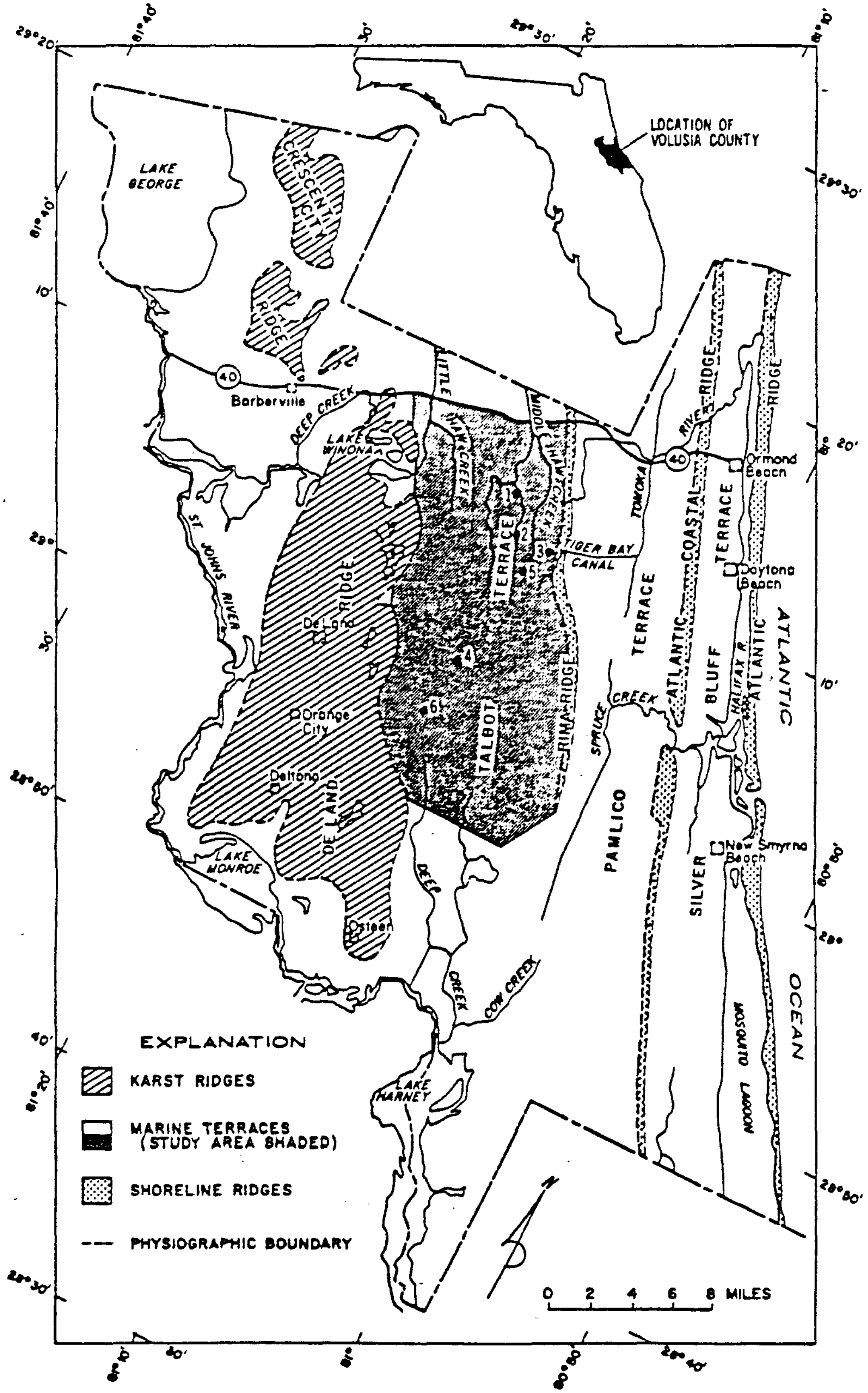


Figure 3.4 Map Showing Physiographic Features of Volusia County (Modified From Knochenmus and Beard, 1971).

shell beds of Miocene or Pliocene age. It generally furnishes sufficient water for domestic use. An artesian aquifer exists in the limestone of Eocene age. Beds of low-permeability clay of Miocene or Pliocene age overlie the artesian aquifer and act as confining units. The artesian aquifer, known as the Floridan aquifer, supplies most of the ground water used in Volusia County.

According to Bush (1978), the Floridan aquifer in Volusia County is characterized by alternative beds of porous dolomitic limestone, limestone, and dolostone with beds of hard, dense dolomitic limestone, limestone, and dolostone. The hard, dense layers are relatively low in hydraulic conductivity, and tend to retard the vertical movement of water within the Floridan aquifer. One particularly thick, hard layer appears to be continuous over a large area and has been referred to as the Avon Park low porosity zone. According to Knochenmus and Beard (1971), this zone or layer acts as a confining bed that divides the aquifer into an upper and lower part. J. Frazee (written communication, 1982) points out that this layer appears to be less significant in east Volusia County, west of the Rima Ridge, where an increase in fresh water thickness is present. According to Knochenmus and Beard (1971), this layer dips eastward from about 200 feet below land surface near the coast. Little is known about the lower Floridan aquifer. It generally contains brackish water and, therefore, water-supply wells are usually terminated before entering it.

Pumping tests in Volusia County indicate that the upper Floridan aquifer has a storage coefficient of approximately 0.0007 and a transmissivity ranging from 30,000 to 370,000 gpd/ft. In modeling the Volusia County area, Tibbals (personal communication, 1982) found that a storage coefficient of 0.001 provided best results. In addition, according to J. Frazee (written communication, 1982), the above transmissivity values fall within the lower range for the area east of DeLand Ridge.

According to Bush (1978), for the conceptual model of Volusia County's hydrologic system, recharge to the Floridan aquifer occurs in the central area, under the ridges, with additional amounts under the wetlands. This is demonstrated in Figure 3.5, which shows the areas of natural recharge to the Floridan aquifer. Flow is laterally away from the central area, down gradient in the Floridan aquifer, and discharges in areas to the east, west, north, and south. This trend is demonstrated in Figure 3.6. It should be noted that a good potential for increased recharge exists in the central wetlands area as well fields are moved to this area (Frazee, written communication, 1982). At present, the area is saturated and excess potential recharge moves toward the Haw Creek natural discharge area where structural relief appears to be present. Surface runoff is also significant both north and south of the central wetlands area.

Figure 3.6 shows the estimated potentiometric surface of the Floridan aquifer prior to development in Volusia County. Figures 3.7 and 3.8 show the potentiometric surface of the Floridan aquifer in May and September 1980, respectively. According to

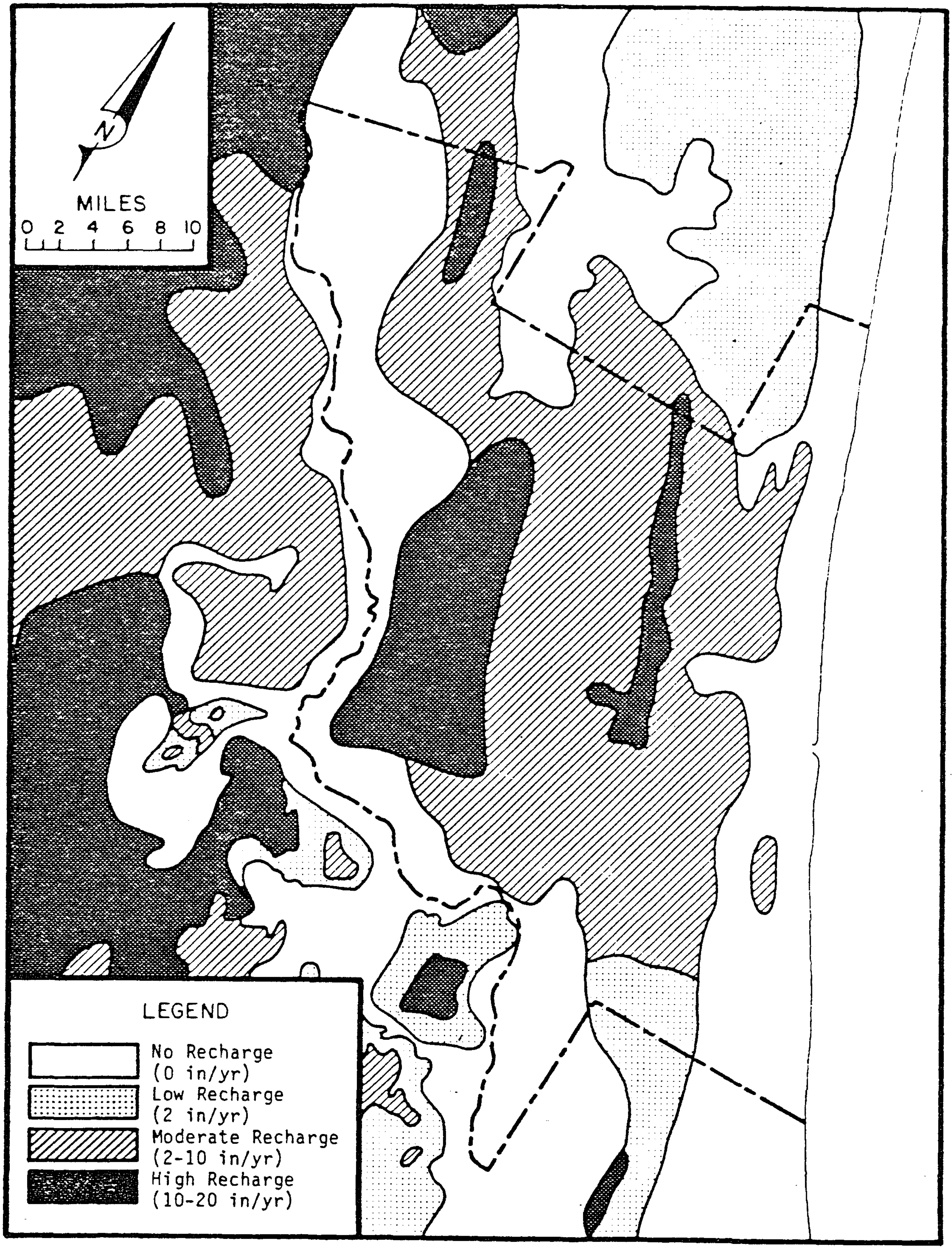


Figure 3.5 Areas of Natural Recharge to the Floridan Aquifer (from SJRWMD).

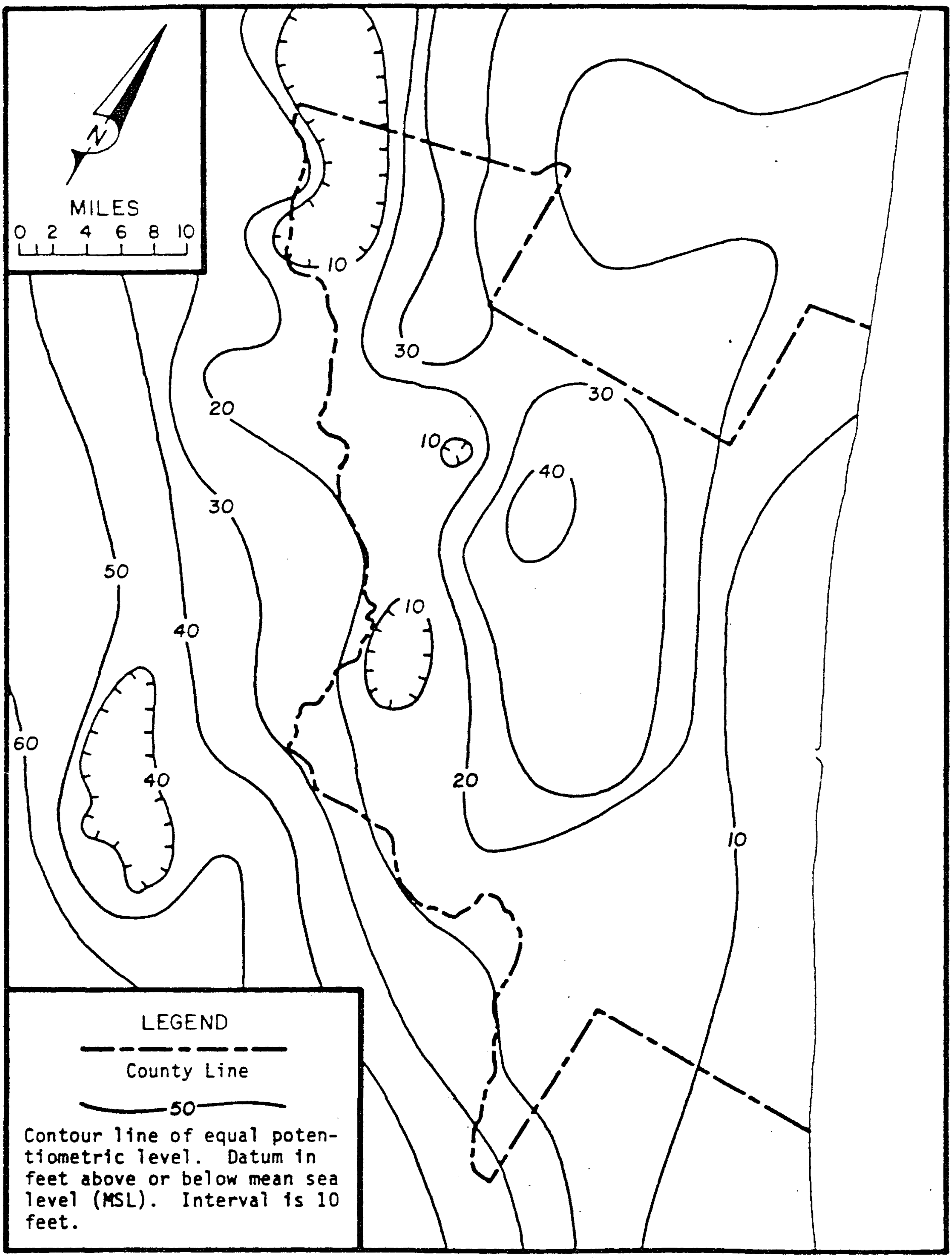


Figure 3.6 Estimated Potentiometric Surface of the Floridan Aquifer Prior to Development in Volusia County, Florida (from SJRWMD).

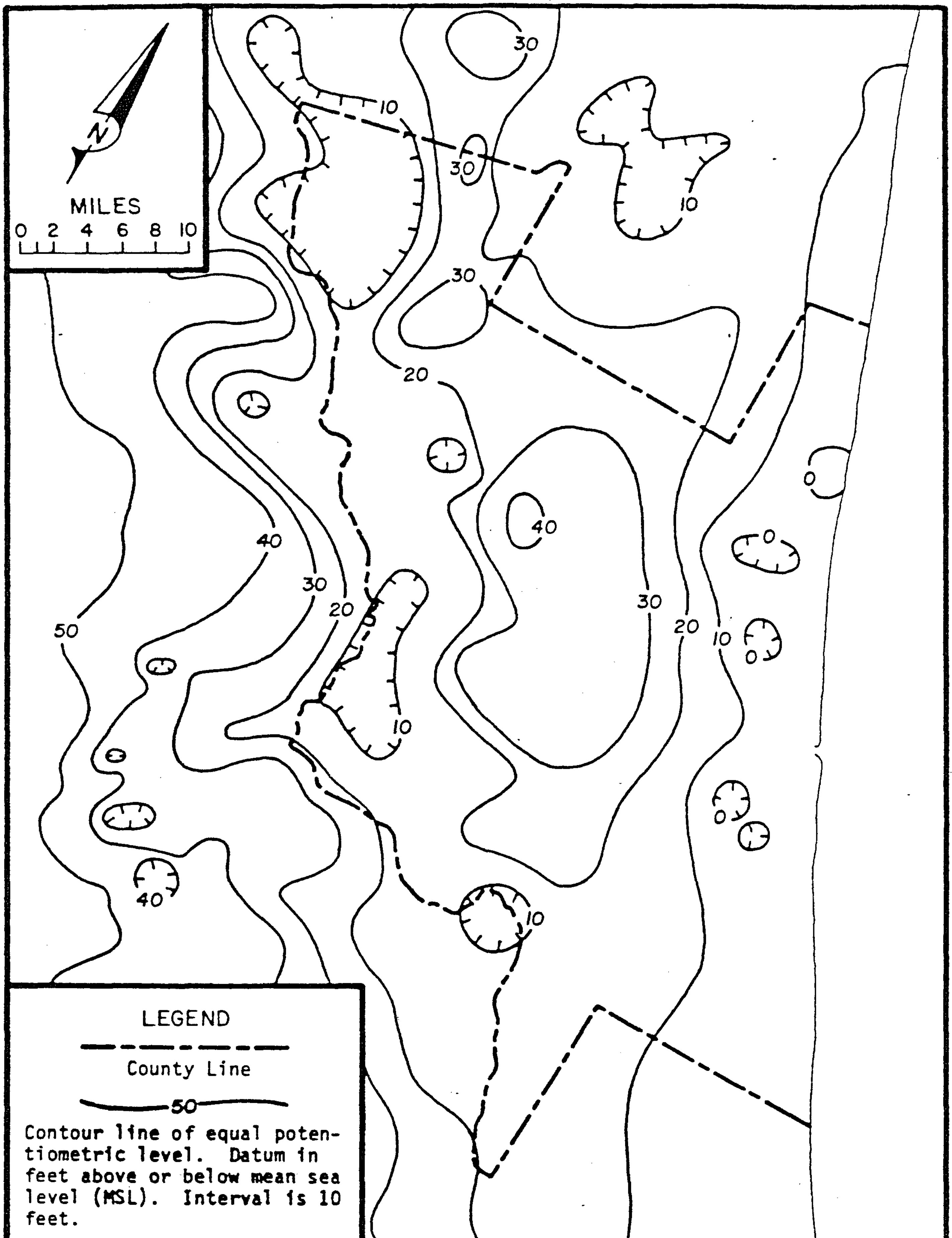


Figure 3.7 Potentiometric Surface of the Floridan Aquifer in Volusia County, Florida, May 1980 (from USGS).

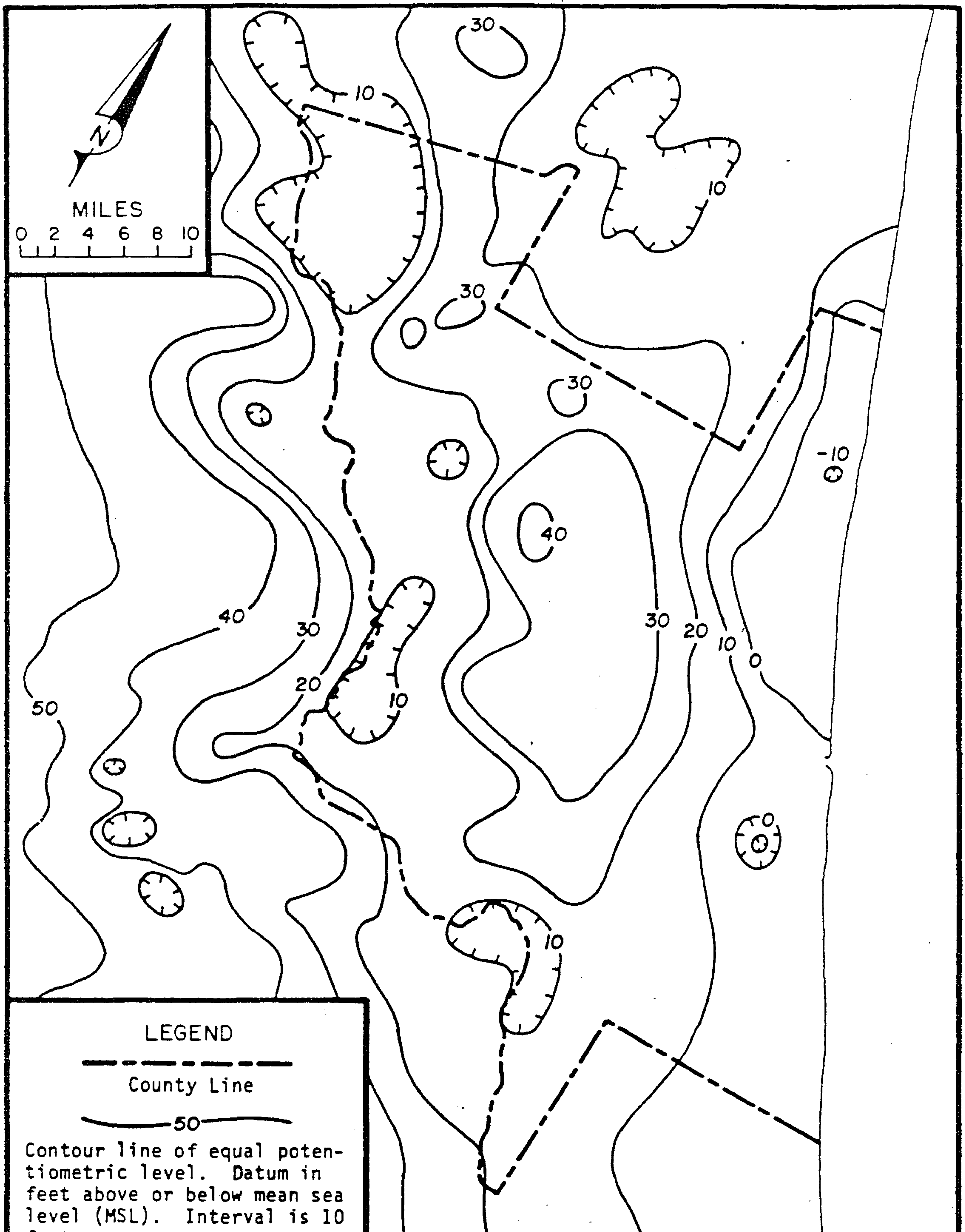


Figure 3.8 Potentiometric Surface of the Floridan Aquifer in Volusia County, Florida, September 1980 (from USGS).

Wyrick (1960), the heaviest rainfall generally occurs in Volusia County from June through October. Normally, water levels are highest in the summer or early fall; this is represented by the September potentiometric surfaces. As a result of low rainfall in the period November to May, the water level begins to decline near the end of the year and is lowest in June or July (Wyrick, 1960). This condition is represented by the May potentiometric surfaces.

There is very little information available on the water-table elevation in the surficial aquifer. The surface estimated by the SJRWMD is presented in Figure 3.9.

3.3 Water Quality of Volusia county

The only water quality problems that were considered here were those associated with saltwater intrusion, that is, chloride concentrations. Saltwater intrusion is a major concern because chloride concentrations in production aquifers are sensitive to stresses on the hydrologic system. Stresses that may have adverse effects on chloride concentrations include increased ground water development and decreased recharge. When ground water is pumped from aquifers that are in hydraulic connection with the sea or other sources of saline water, the gradients that result may induce a movement of saline water toward the well(s). Similarly, decreased recharge lowers the hydrostatic pressure in the aquifer which in turn allows saline water to intrude further into the aquifer. Decreased recharge may be due to climatic conditions or poor land management. Chloride concentrations in

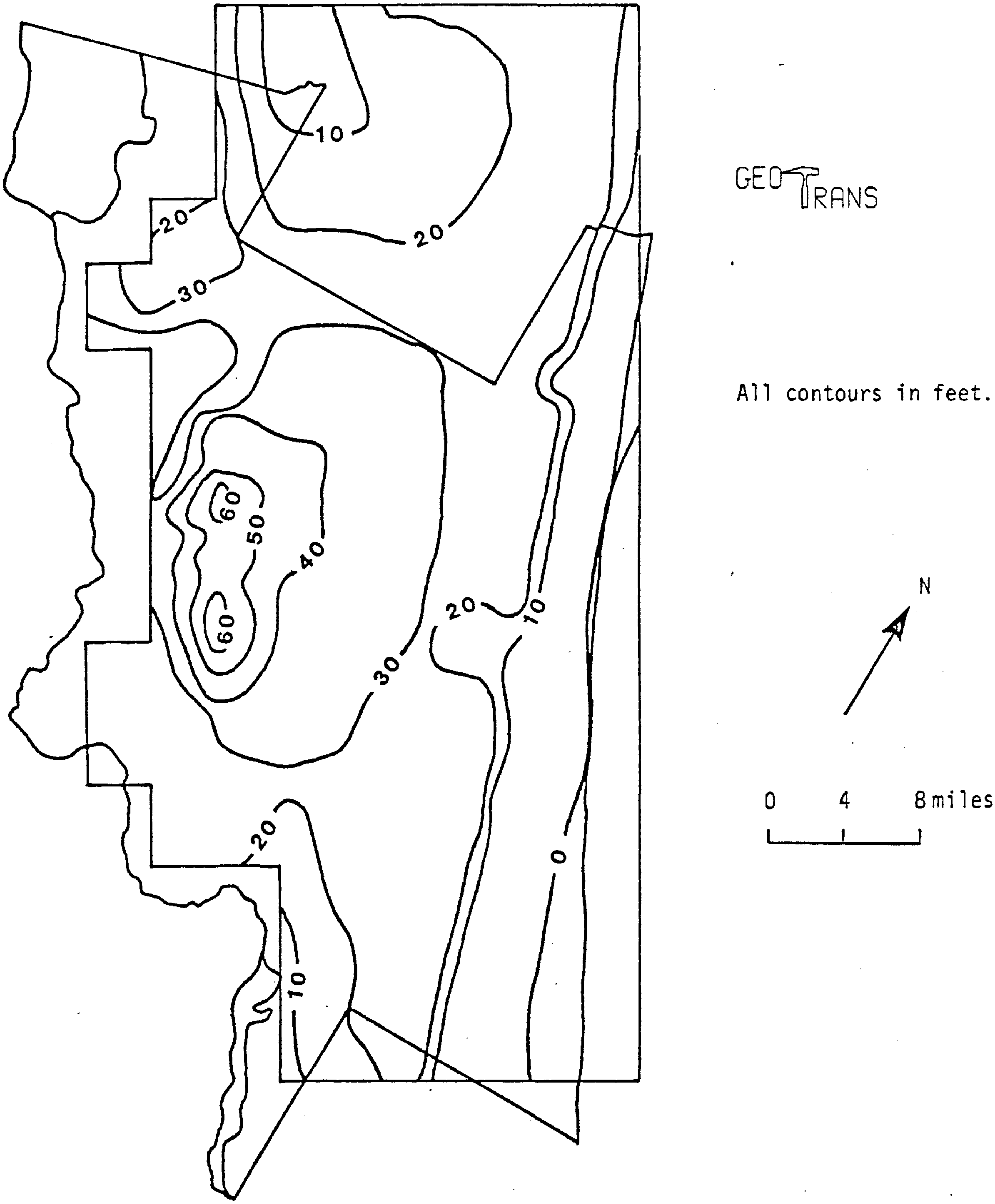


Figure 3.9 Estimated Potentiometric Surface of the Water-Table Aquifer (From SJRWMD).

Volusia County for 1980 are shown in Figure 3.10. Because of density differences, the fresher water overlies the saline water. This is illustrated in Figure 3.11, which shows the approximate altitude of the bottom of potable water in the Floridan aquifer in Volusia County.

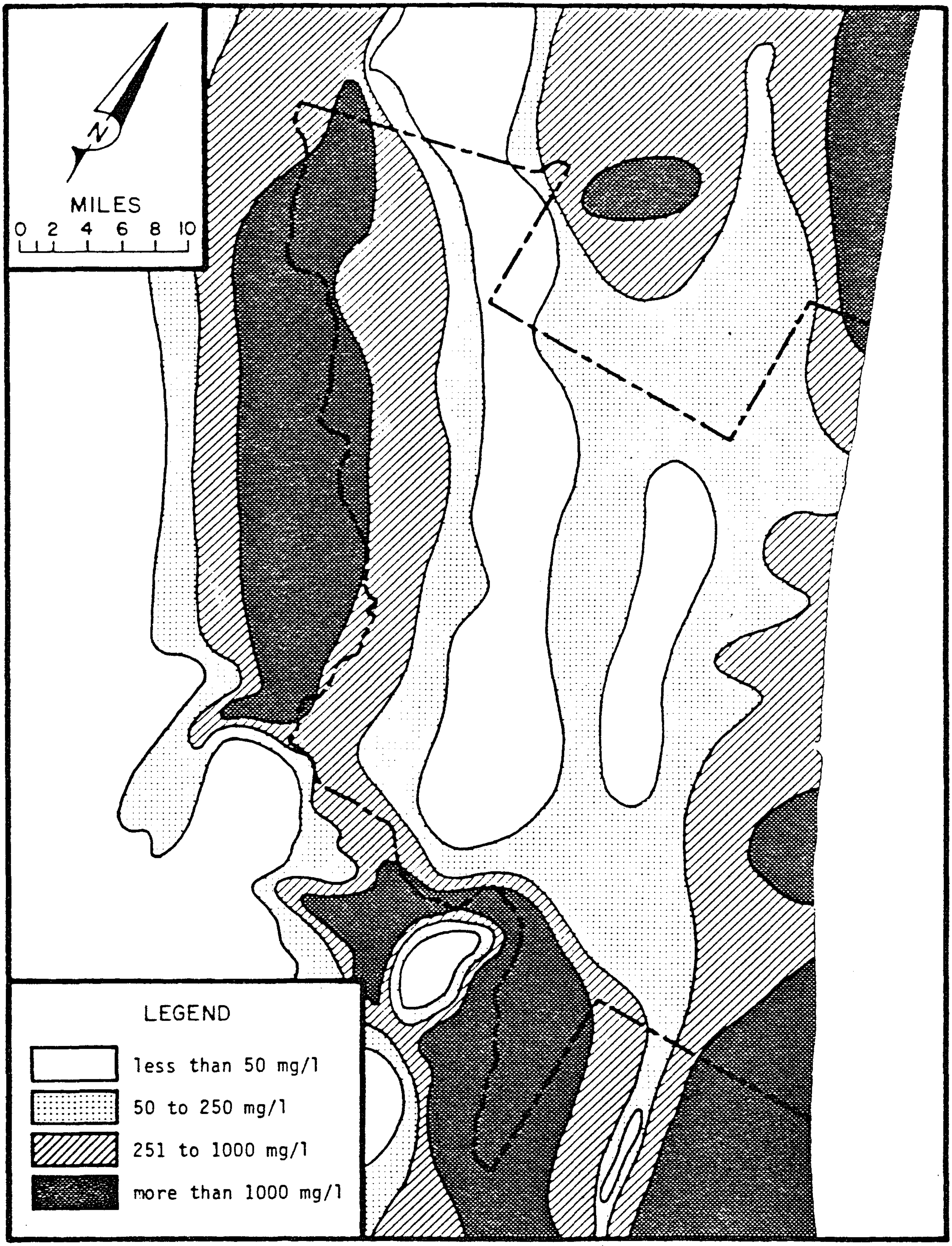


Figure 3.10 Chloride Concentration in the Upper Part of the Floridan Aquifer, 1980 (from SJRWMD).

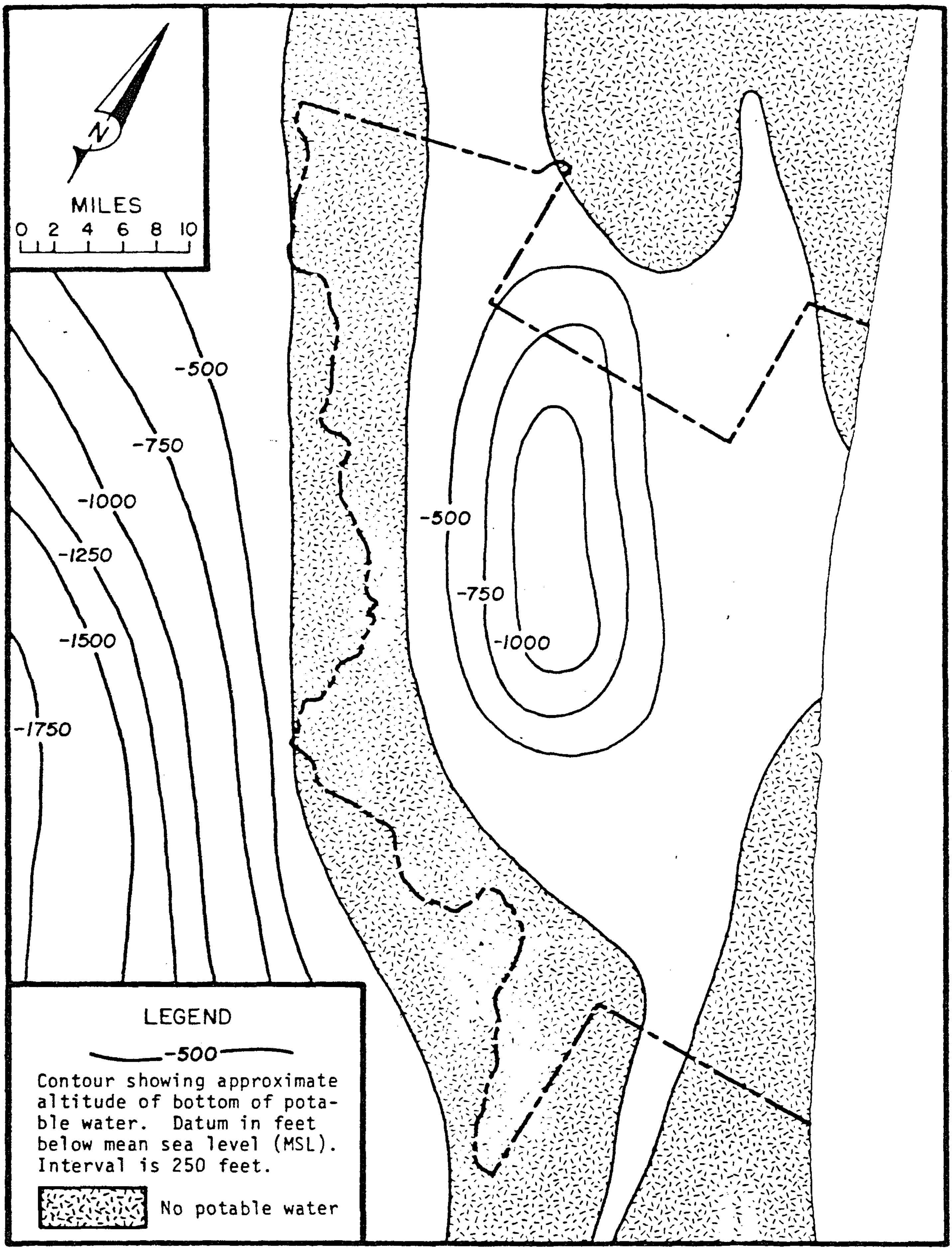


Figure 3.11 Approximate Altitude of the Bottom of Potable Water in the Floridan Aquifer in Volusia County, Florida (from SJRWMD).

4.0 DEVELOPMENT OF GROUND WATER MODEL

4.1 General Approach

The general approach used in applying models to ground water problems has four main phases -- system conceptualization, history matching or model calibration, model verification, and prediction. Most applications involve each of the four phases. However, the relative effort devoted to each phase is application-dependent.

System conceptualization involves organizing available information on the ground water system in an internally consistent framework. Sources of information include: (1) published reports on the geology and hydrology of the system; (2) geological and topographic maps and areal photographs; and (3) unpublished data such as field data, drillers' logs, geophysical survey data, drill cores, and aerial photography. To complete the conceptualization task, the information is posed in terms of a qualitative model. The qualitative model is translated to mathematical terms such as boundary conditions, initial conditions, and hydrologic parameters. An appropriate ground water model, which is quantitative, can then be applied to improve the qualitative model. The use of the model involves checking various observations and determining the sensitivity of system responses to hydrologic parameters and assumptions. The results of the system conceptualization should provide a basis for designing data collection efforts. Use of a model at this stage not only forces the hydrologist to conceptualize within a tested framework, but also gives guidance in terms of data requirements.

History matching or model calibration is used to refine estimates of hydrologic parameters and boundary conditions in the model. This is accomplished by comparing model results with observed data such as the potentiometric surface configuration. Estimates of parameters are changed to improve the comparison. It is important to constrain the changes so that physically realistic parameters are specified. The history matching procedure can be done by either a trial and error approach or by an automatic regression approach. No matter which approach is selected, sensitivity analysis will be part of the matching phase. This sensitivity analysis will be more meaningful than that obtained during the conceptualization phase because it is based on more data. Again, the sensitivity analysis should serve as a guide in continuing data collection activities.

Model verification is undertaken to test the validity of the model prior to its use for prediction. Known stresses such as pumping, which are different from those which may have been used in calibration, are included in the model. Comparison is again made between model results and the known response of the ground water system to these stresses. If the model provides a good result with little or no additional parameter change, the model may be considered verified.

The final phase of the procedure involves prediction of the future behavior of this system. This is normally the shortest part of a study. Predictions are based on model results using the best estimates of system parameters obtained by history matching. Because the set of parameters is not unique, it is important to assess the uncertainty in the predicted results. This is usually accomplished by again using a sensitivity analysis.

4.2 Phased Study

In addition to the phases discussed in the previous section, this work was further divided into various stages of analysis. Initially, only one-dimensional flow in the upper Floridan was considered. Next, the two-dimensional flow was considered by including the lower Floridan. The water-table aquifer was then incorporated. Once flow in this cross-section was satisfactorily reproduced, solute transport was included in the model.

With this cross-sectional modeling experience, work proceeded by considering areal flow in the upper Floridan. The same stages were followed; that is, incorporating the lower Floridan, the water-table aquifer, and solute transport, until all aspects were included in the model. The final product consisted of a three-dimensional model of Volusia County that included in the lower Floridan, upper Floridan, and water-table aquifers and solute transport in the lower and upper Floridan only.

4.3 Description of SWIPR

The model used for this study of Volusia County had to be capable of the following:

* treatment of flow and solute transport;

* simulation of these processes in three dimensions;
* allow for well production;
* allow for the boundary conditions associated with saltwater intrusion; and
* be usable on a PRIME computer.

A model that met these requirements is the code SWIPR. The salient features of this code are described in Table 4.1. Details of SWIPR are given in Intercomp (1976) and Intera (1979). Several copies of these references were provided to SJRWMD, as well as a report entitled, "Application of Finite Difference Code SWIPR to Various Solute Transport Test Problems" by Stephen D. Thomas and James W. Mercer. These references were provided during a course on SWIPR presented to SJRWMD staff during October 1982. Because these references and the course have been presented to SJRWMD, further details of SWIPR are not given in this report.

4.4 Model of Ground Water Flow System

4.4.1 Determination of the Layering

Figure 4.1 represents the geologic units, hydrogeologic and equivalent layers used by Tibbals (1982) in his computer model. We used the same type of conceptual model of the layered system for our purposes. Because of the excessive CPU costs of fully three-dimensional transient simulations of coupled flow and transport system, we required that a minimal number of horizontal layers be used.

Table 4.1 Description of SWIPR, Survey Waste Injection Program, Revised.

USE: The SWIPR model is applicable for modeling the transport of momentum, energy and contaminant mass in porous media due to deep well injection or other sources.

DEVELOPED BY: INTERCOMP Resource Development and Engineering, Inc. and INTERA, Inc.

DEVELOPED FOR: U. S. Geological Survey, Water Resources Division

REFERENCE: INTERCOMP, Inc., 1976, A Model for Calculating Effects of Liquid Waste Disposal in Deep Saline Aquifer, Part I and II, U.S. Geological Survey, Water-Resources Investigations 76-61, June 1976.

INTERA, Inc., 1979, Revision of the Documentation for a Model for Calculating Effects of Liquid Waste Disposal in Deep Saline Aquifers, U. S. Geological Survey, Water-Resources Investigations 79-96, July 1979, 73 p.

ASSUMPTIONS:

- Fluid flow in the aquifer can be described by Darcy's law for flow through a porous medium.
- Fluid density can be a function of pressure, temperature and contaminant concentration. Fluid viscosity can be a function of temperature and concentration.
- The waste or contaminating fluid is totally miscible with the in-place fluid.
- Hydrodynamic dispersion is described as a function of fluid velocity.
- The energy equation can be described as "enthalpy in - enthalpy out = change in internal energy of the system." This is rigorous except for kinetic and potential energy which have been neglected.
- Water table conditions in an unconfined aquifer can be approximated by no capillarity and no residual water saturation (specific retention).
- Contaminant reaction can be described by a first order reaction - similar to radioactive decay.
- Contaminant adsorption on rock surface can be described by linear adsorption isotherms.
- Aquifer properties vary with position-porosity, permeability, thickness, depth, specific heat and adsorption distribution coefficient.
- Boundary conditions allow natural water movement in the aquifer, vertical recharge in the uppermost layer; heat losses to the adjacent formations, and the location of injection, withdrawals and observation wells anywhere within the aquifer system.

Table 4.1 Continued

APPROXIMATING METHOD:
- Finite-difference

SOLUTION TECHNIQUES:
- Reduced bandwidth direct
- L2SOR

GEOMETRY:
- 1-, 2-, or 3-dimensional Cartesian
- Cylindrical

OPTIONS:
- Steady or transient flow
- Solute transport
- Heat transport
- Wellbore
- Heterogeneous and/or anisotropic media
- Confined and/or water-table conditions
- Recharge and/or wells

BOUNDARY CONDITIONS:
- Specified value
- Specified flux
- Aquifer influence function

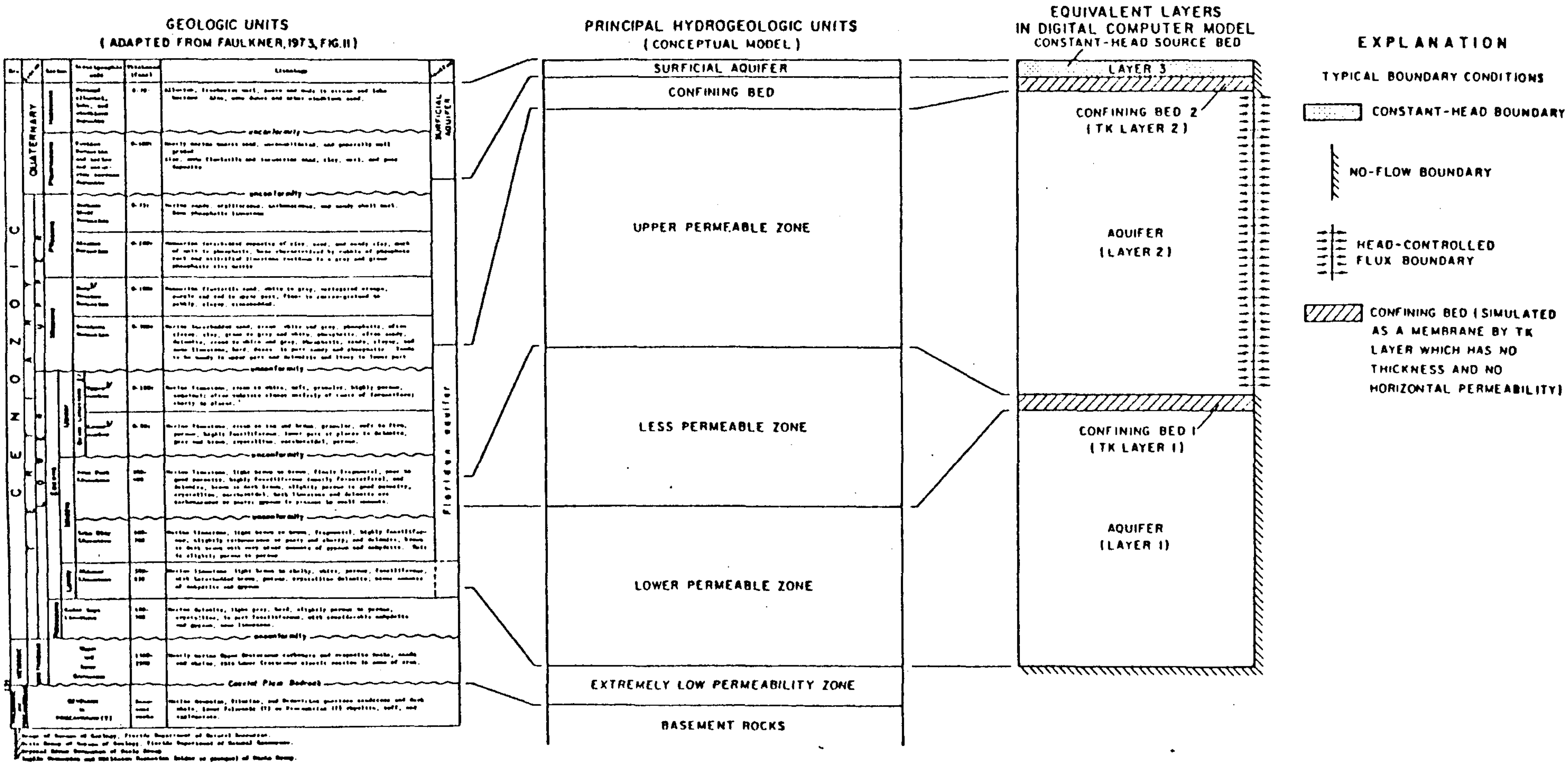


Figure 4.1 The Geological Units, Hydrogeological and Equivalent Layers for Volusia County, Florida (from Tibbals, 1982).

It was proposed that a three-layer model be used whereby the two confining layers between the water-table aquifer and the upper Floridan, and the lower and upper Floridan be approximated by combining their resistances to vertical flow in series with that of the aquifers. This approach offered the advantage of requiring a minimum number of horizontal layers. The main disadvantage was that storage in the confining beds was ignored. Comparison of results obtained using both a three-layer and a five-layer model indicated that the ground water system can be modeled just as adequately using the former as the latter. A three-layered model was consequently used.

4.4.2 Grid Design and Boundary Conditions

Modeling Volusia County using a finite-difference method required that a rectangular domain, containing the regions of interest within the county, be defined. If the system is anisotropic, then it is essential that the rectangular grid is orientated such that the sides are orthogonal with the principal directions of the hydraulic conductivity tensor. From previous studies, there is no indication of anisotropy and therefore we shall assume none. Consequently, the design of the grid in this study may be orientated in any direction.

A plan view of the grid, superimposed on a map of Volusia County, is shown in Figure 4.2. As may be seen, the grid was designed to give more detail (smaller spacing) along the coast, especially near Ormond Beach, Daytona Beach, and New Smyrna

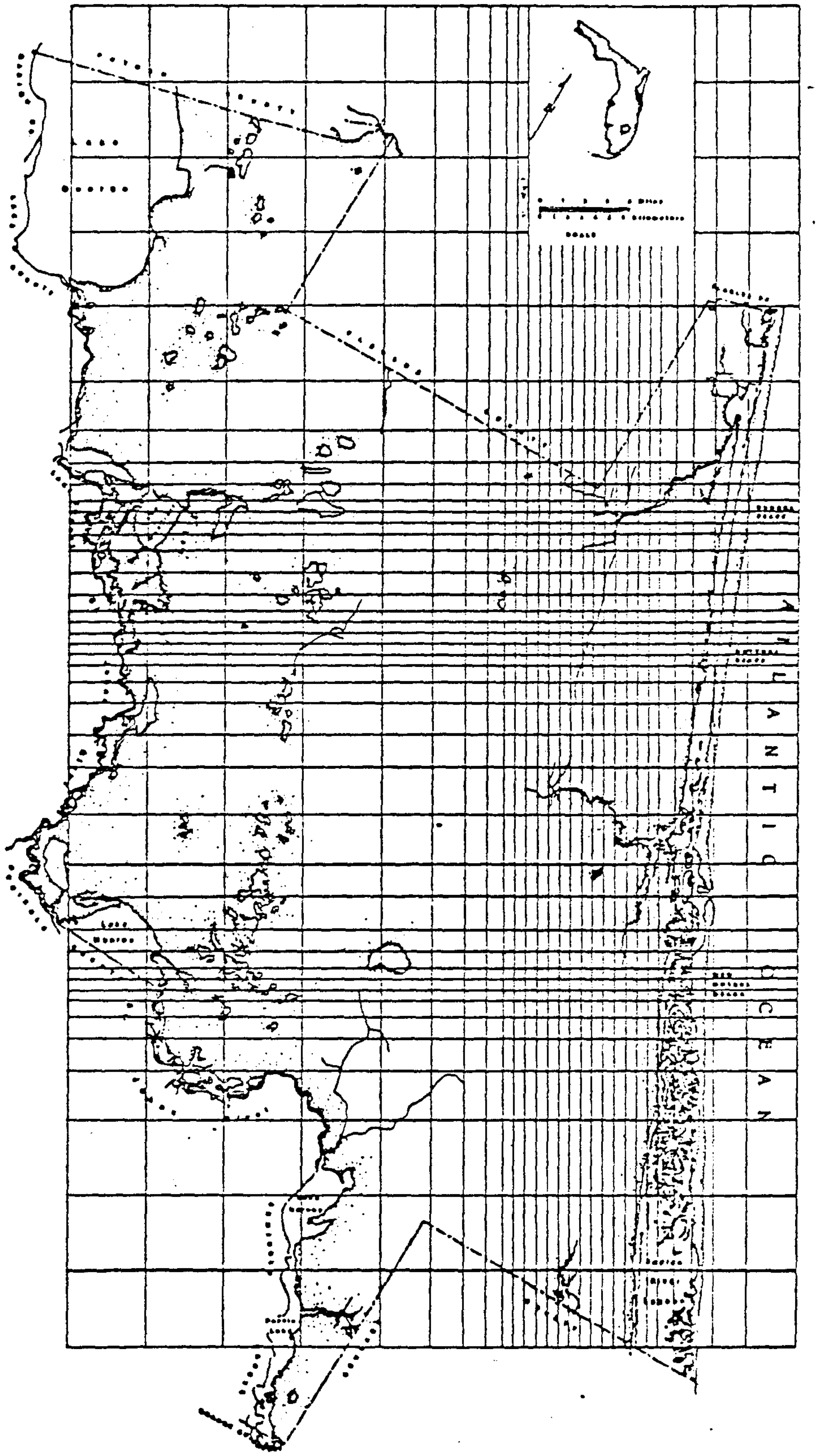


Figure 4.2 Finite-Difference Grid Superimposed on Map of Volusia County.

Beach. A view of the grid in cross-section is given in Figure 4.3. The boundary conditions around the grid are as follows.

Toward the east and northeast, the Atlantic Ocean was considered to be the boundary and was also treated as constant hydraulic head. The grid was extended far enough seaward so that the constant head was fixed at sea level (h=0). This was the same boundary condition used by Bush (1978).

Toward the west and southwest, the St. Johns River was considered to be the boundary and was also treated as constant hydraulic head. This was the same boundary condition used by Bush (1978) and was justified by noting that the hydraulic head near the St. Johns River has not changed much over time. In addition, this boundary was away from the major pumping centers near the coast and was not expected to greatly influence the transient simulations containing well production. Although the heads at this boundary were constant with respect to time, they do vary spatially to represent the observed head values. Because this boundary follows the river, several nodes west of the St. Johns River were not included and are considered inactive. These nodes include: (1) i=1; j=1 to 10, 17 to 34, 38 to 41; (2) i=2; j=1 to 4, 39 to 41; and (3) i=3; j=1 to 4. This reduces the number of active grid blocks per layer by 43, giving 1,064 active grid blocks per layer or 3,192 for the three-layer system.

The southeastern boundary was located just outside Volusia County. Although the hydraulic head at this southeastern boundary changed with time, the potentiometric surface contours remained roughly parallel to the coast. Therefore, this boundary

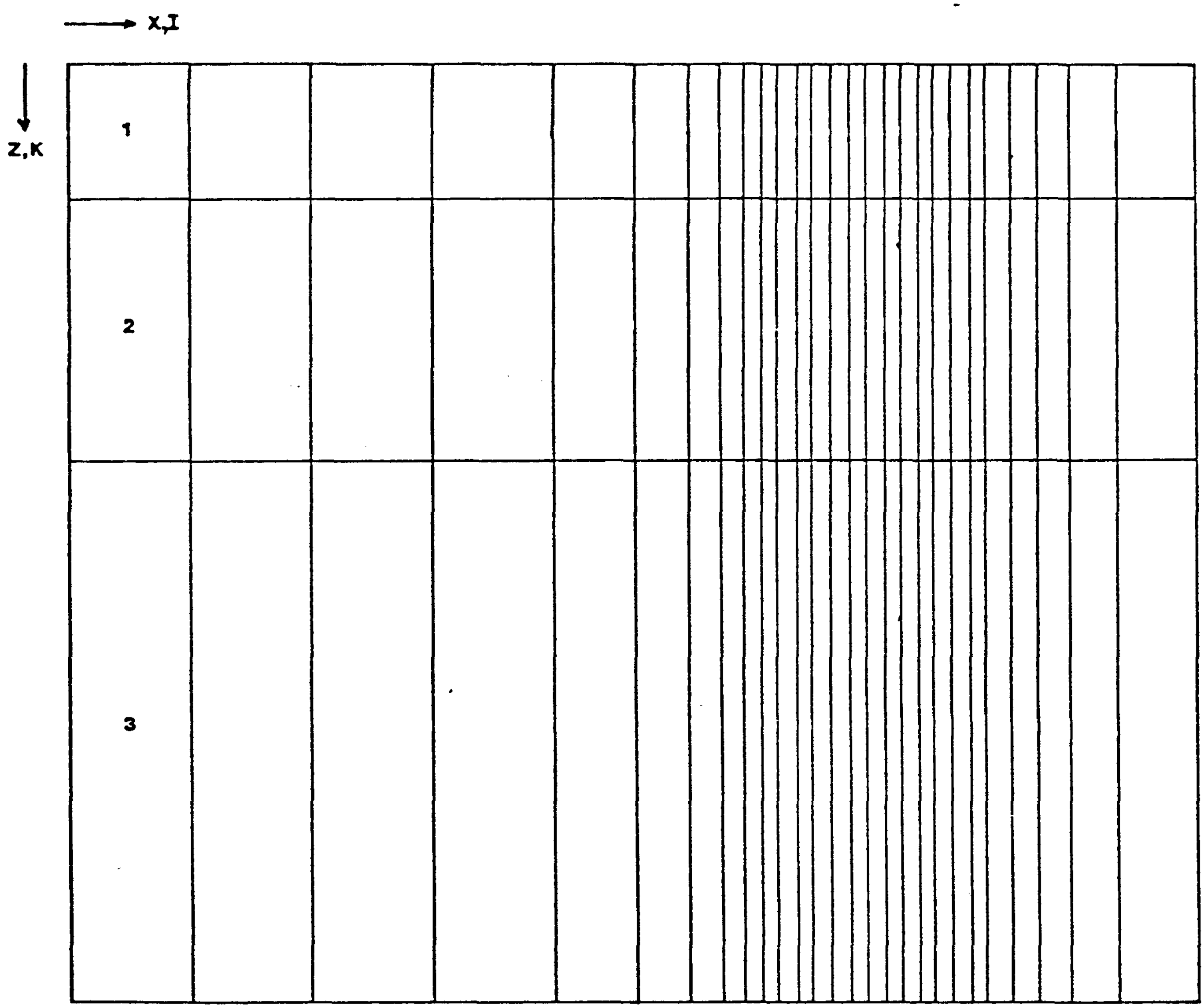


Figure 4.3 Two-Dimensional, Finite-Difference Grid Used for the Three-Layer Flow and Transport Model (vertical exaggeration ~ 230:1).

roughly followed a flow line and was treated using a no-flow boundary condition.

The northwest boundary was also located just outside Volusia County. The hydraulic heads at this boundary changed with time in a complex way. Although there was uncertainty associated with this boundary, a conservative approach was used whereby the boundary was treated as no-flow.

4.4.3 Flow Model Calibration

As previously noted in Section 4.2, a phased approach was utilized in developing the ground water flow model of Volusia County. Each of three aquifers were added successively to the model and system parameters were adjusted to give good comparison between the simulated and observed system. The parameters that were adjusted during calibration were recharge and vertical hydraulic conductivity. Transmissivity values for the upper and lower Floridan aquifer were obtained from previous analysis by Bush (1978) and Tibbals (1981), respectively, and were not altered.

The simulated potentiometric surfaces for the water table, upper Floridan, and lower Floridan aquifers are presented in Figures 4.4, 4.5, and 4.6, respectively. Observed potentiometric surface configurations for the water table and upper Floridan aquifers were previously presented in Figures 3.9 and 3.6, respectively.

The values of recharge to the water table aquifer that were obtained through modeling are presented in Figure 4.7. Each

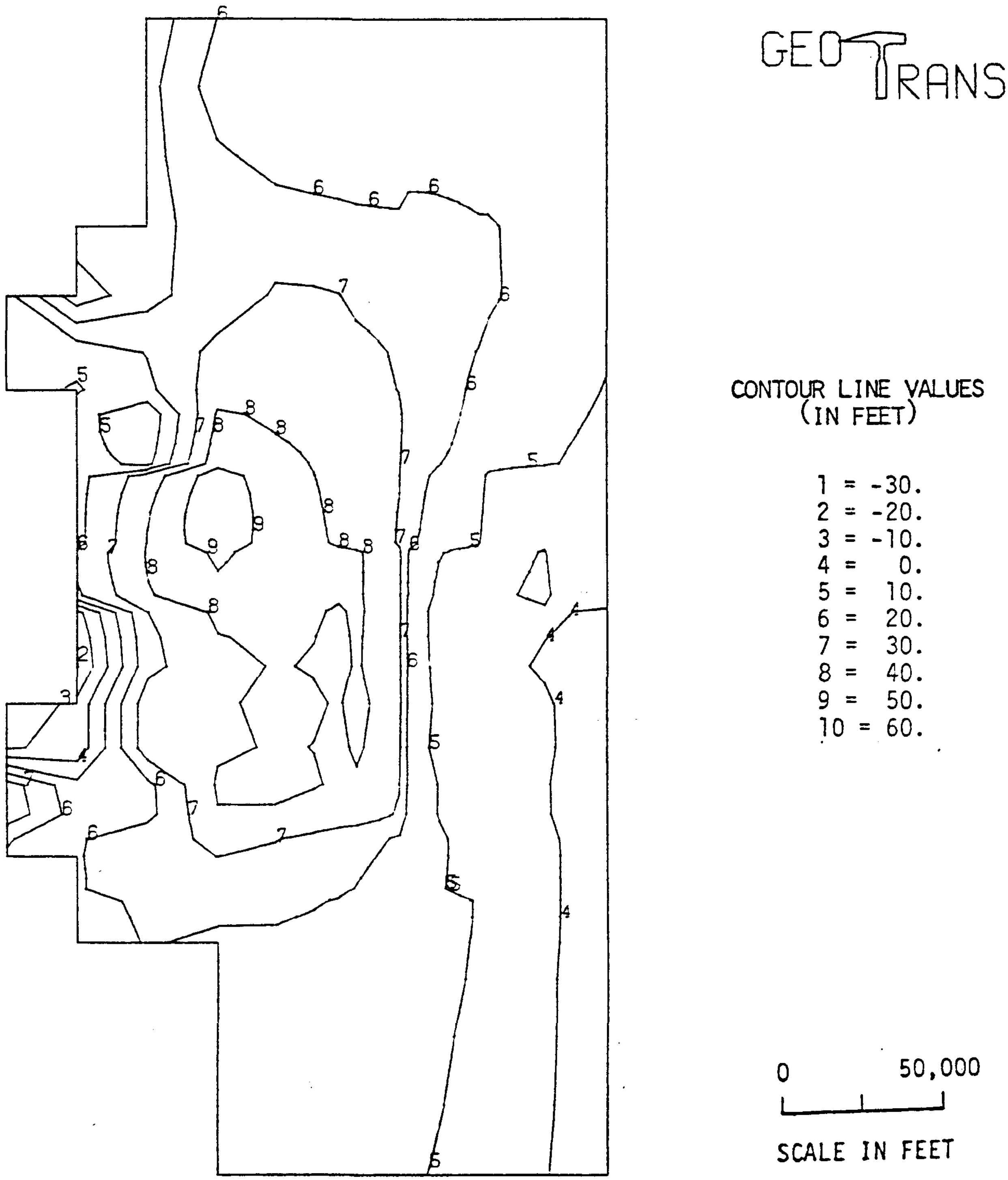


Figure 4.4 Potentiometric Head Distribution in the Water-Table Aquifer Using a Three-Layer Model.

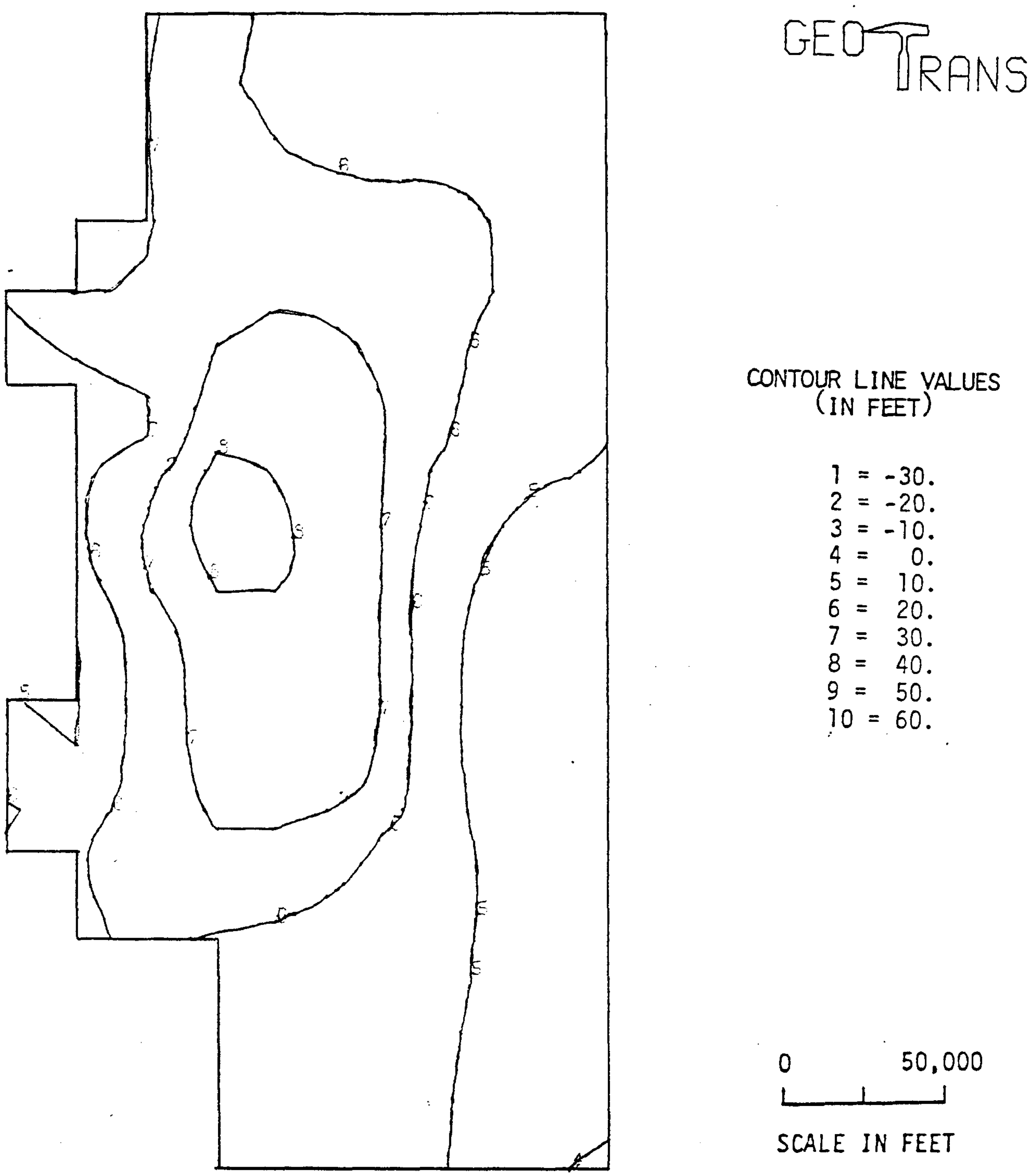


Figure 4.5 Potentiometric Head Distribution in the Upper Floridan Aquifer Using a Three-Layer Model.

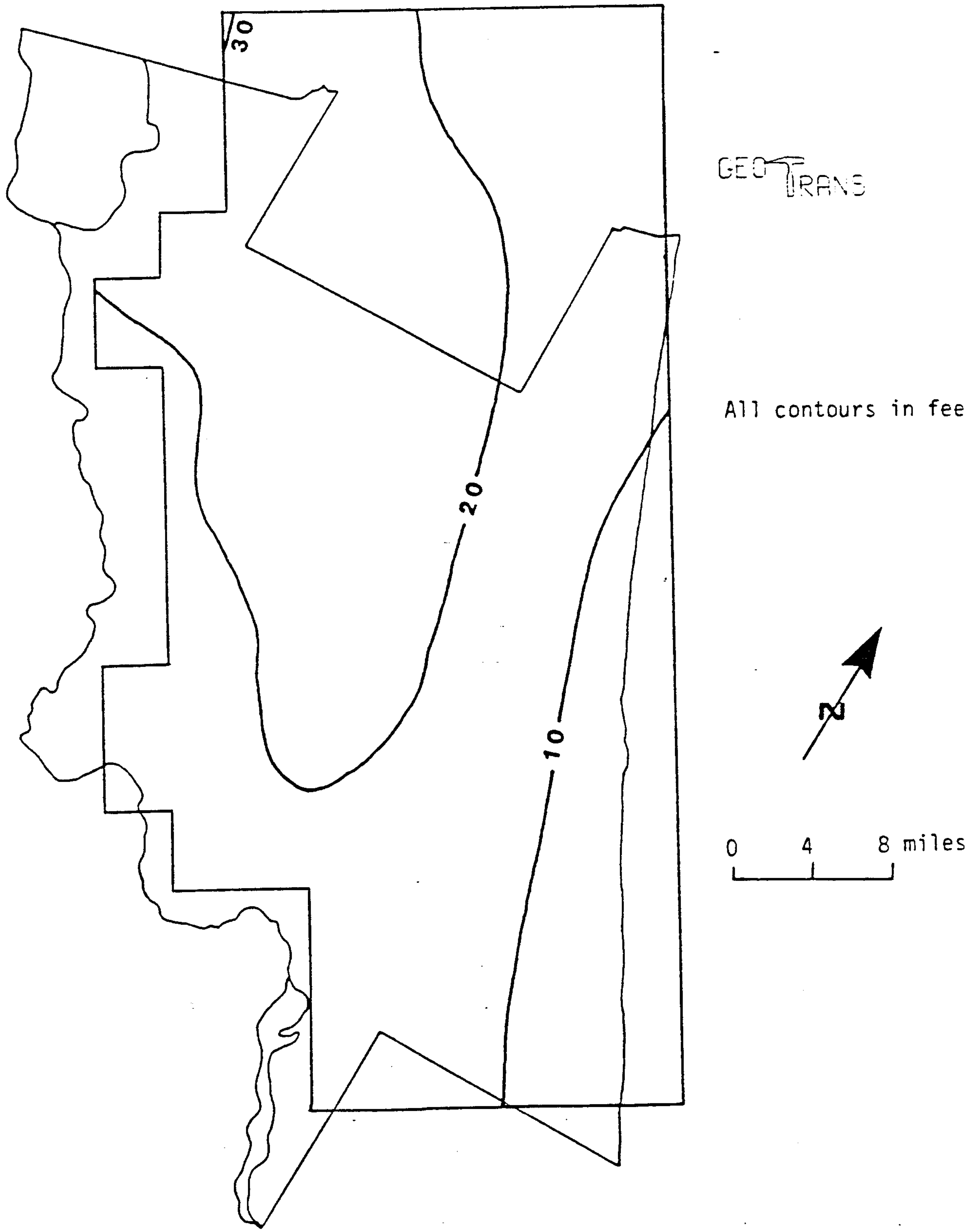


Figure 4.6 Potentiometric Head Distribution in the Lower Floridian Aquifer using a Three-Layer Model.

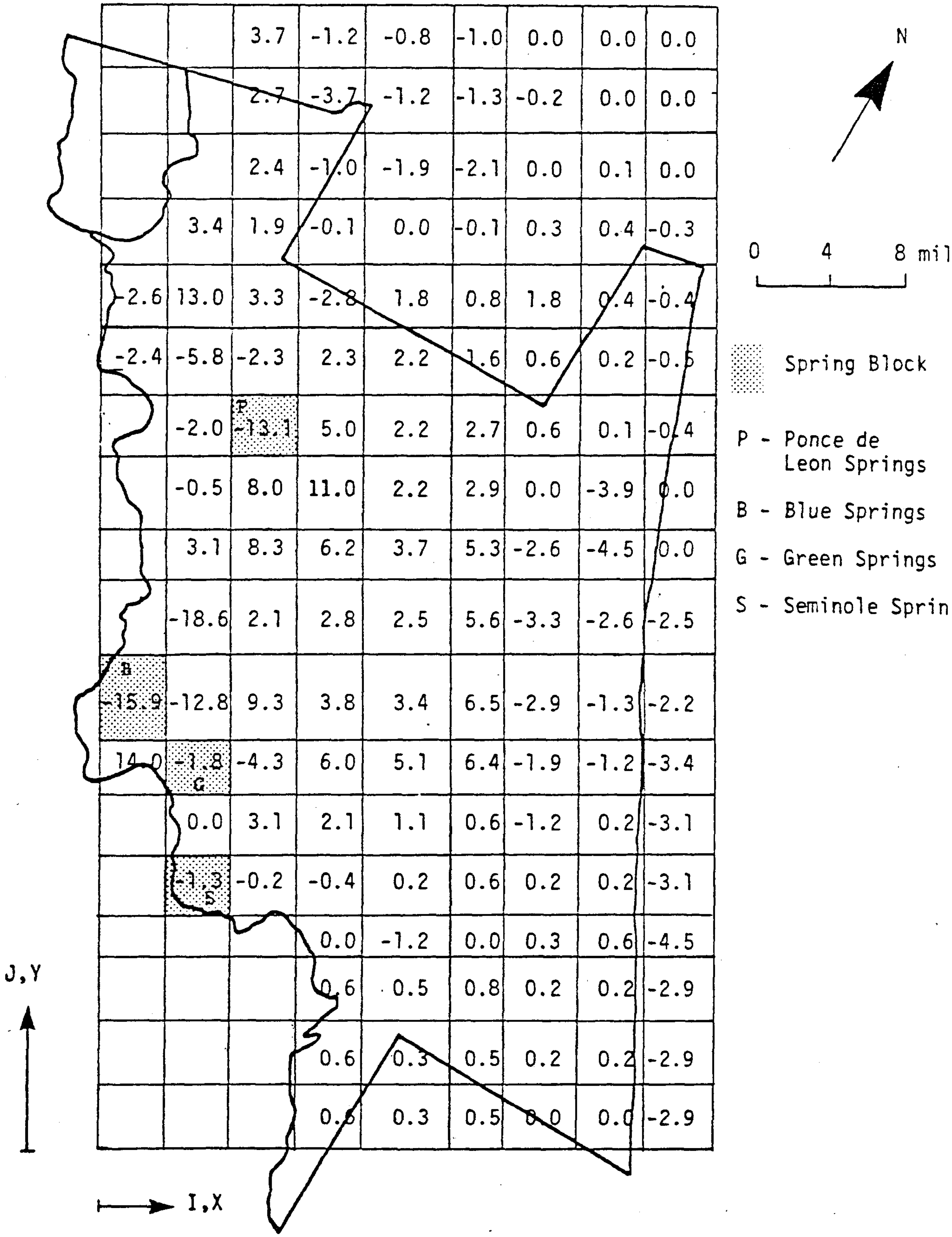


Figure 4.7 Final Recharge Distribution (Inches/Year), for the Three-Layer Model.

large block represents one or more finite-difference blocks. Note that from Figure 4.7, it can be seen that, as expected, the areas of high recharge to the ground water system were present in the DeLand Ridge, Talbot Terrace, Rima Ridge, and Crescent River Ridge areas. These locations are illustrated in Figure 3.4.

In addition, the locations of four major springs are illustrated in Figure 4.7. It was important to note that the value of recharge in these blocks were not prescribed prior to the potentiometric head matching process. Thus, the fact that large block discharges coincided with the locations of the springs, lead to increased confidence in the flow model.

4.4.4 Conclusions

The major conclusions arrived at while simulating the three-dimensional steady-state flow field during the predevelopment stage included:

(1) To match the observed head distribution using reasonable recharge values and the lower Floridan aquifer had to be included in the model.

(2) The recharge used to produce a good match of the head distribution in the upper Floridan was similar to that estimated by SJRWMD.

(3) The water table aquifer could be modeled such that the flow remained predominantly vertical in this aquifer, but the recharge from the two-layer model was modified slightly to obtain a good head match in the upper Floridan and a fair match in the water table aquifer.

4.4.5 Flow Model Verification

The previous section described an attempt to simulate the preproduction flow conditions of ground water in the aquifers of Volusia County. In all the numerical simulations, the simulations were run to steady-state under the assumption that the recharge and discharge to the aquifer system were constant with time. Seasonal variations in recharge were averaged over the year.

The verification phase of the flow model development involved attempting to reproduce the potentiometric surfaces in the upper Floridan aquifer for May 1980. The pumping rates, as estimated by SJRWMD for all wells in Volusia County that discharge from the upper Floridan aquifer, were modeled as constant with time. These estimated rates may be low since they were based on the assumption that all farmers are good land managers. The potentiometric surface in the upper Floridan aquifer for May 1980 is illustrated in Figure 3.7.

In the first simulation, the well discharge was incorporated into the model and the recharge obtained from the preproduction runs was used. The system was again modeled as a steady-state problem. Comparison of the simulated and observed head distributions of the upper Floridan revealed that the simulated head was generally lower than that observed. This was probably due to one or more of the following reasons:

(1) The actual recharge was higher than that used in the simulation.

(2) The actual transmissivity was higher than that used in the model.

(3) The system under natural conditions and including pumpage may not be at steady-state.

Based on pre-development simulations performed by Bush (1978) and Tibbals (1981), the aquifer transmissivities used in the model were thought to be reasonably accurate. Therefore, the transmissivities were not changed. Both the upper and lower Floridan aquifers were confined and, therefore, should reach steady-state rapidly due to their low storage coefficients. However, as the water table aquifer had a large storage coefficient, it was possible that the natural system was not at steady-state when the head measurements were taken.

This possibility, however, was dismissed based on both oral communication with Ron Bartel (1983) and on results from a transient simulation using a high storage coefficient in the water table aquifer. For the transient simulation, steady-state conditions were reached in less than one month after the beginning of the pumping period. Therefore, the recharge to the upper Floridan was probably higher than that estimated for preproduction conditions. This seemed likely since a reduction of surface water loss would provide a source of greater recharge to the upper Floridan.

A matching process was again conducted by adjusting the recharge to the water table aquifer in order to obtain a better comparison between the simulated and observed hydraulic head distribution in the upper Floridan aquifer. The resulting simulation of potentiometric surfaces for the upper Floridan is presented in Figure 4.8. The overall recharge was higher than

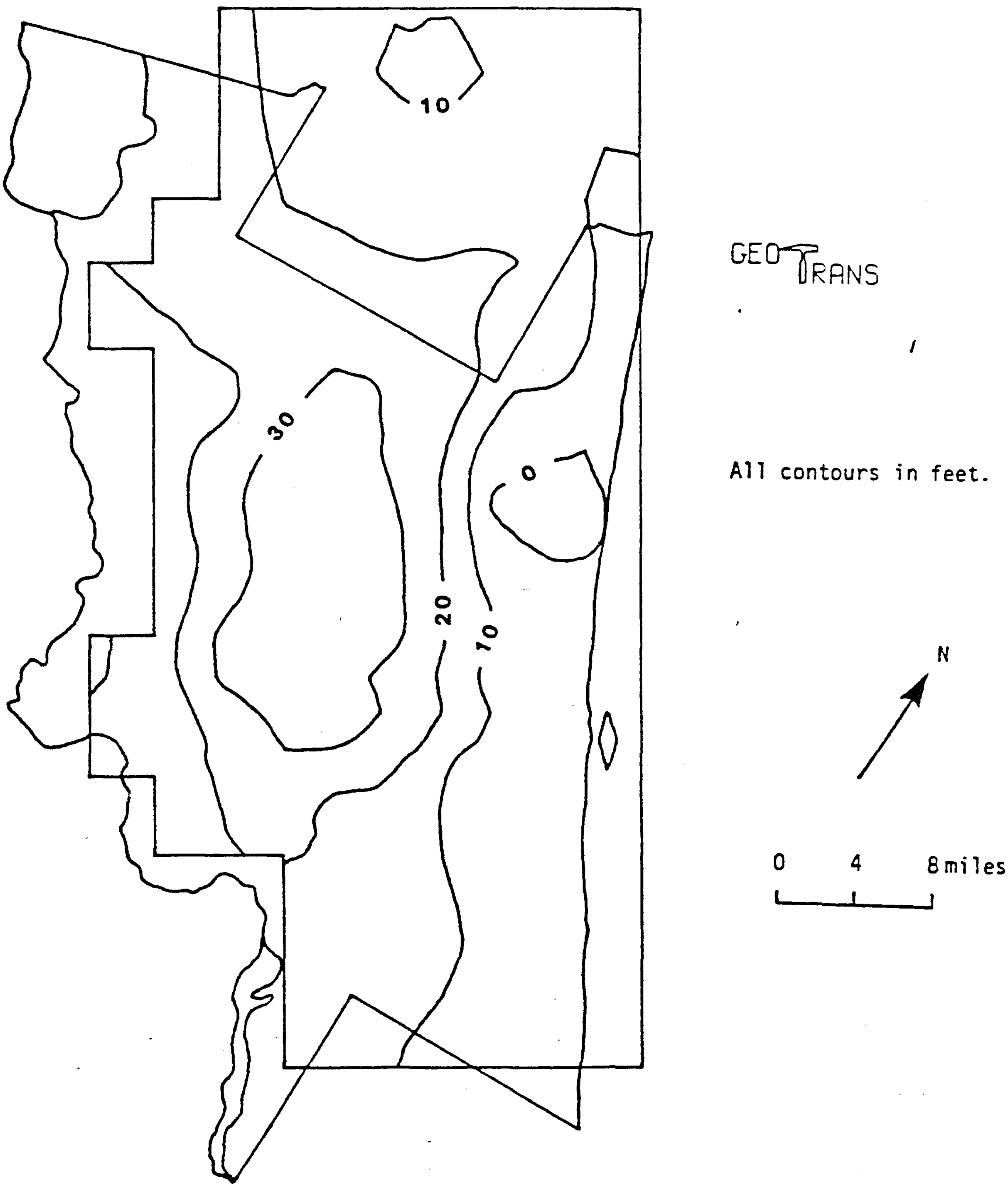


Figure 4.8 Simulated May 1980 Potentiometric Surface of Upper Floridan Aquifer in Volusia County, Florida, Using SWIPR with Post-Production Recharge Distribution.

that obtained from the preproduction process. In addition, the present recharge distribution was similar to that estimated by SJRWMD.

4.5 Model of Solute Transport System

Ultimately, it was the purpose of this study to provide insight into possible saltwater intrusion into the Floridan aquifer. This intrusion could be in the form of sea water encroachment from the ocean or in the form of upconing underlying brackish water. Before the transport of the solute could be analyzed, it was important to accurately represent the flow field. This has been done in the previous sections.

In this portion of the study, the three-dimensional flow model was coupled with a solute transport model and run to steady-state. These steady-state simulations were important because they represent pre-development conditions used as the starting or initial conditions for the transient simulations representing ground water development. The steady-state simulations consisted of setting boundary conditions and flow and transport parameters, making a guess at the concentration distribution, then letting the code calculate through an artificial time period until steady-state was reached, that is, concentrations no longer changed with additional time steps. The object was to obtain a satisfactory match with field data depicted in Figures 3.10, 4.9 and 4.10. Main consideration was given to matching the concentrations in the upper Floridan aquifer where the most data was available.

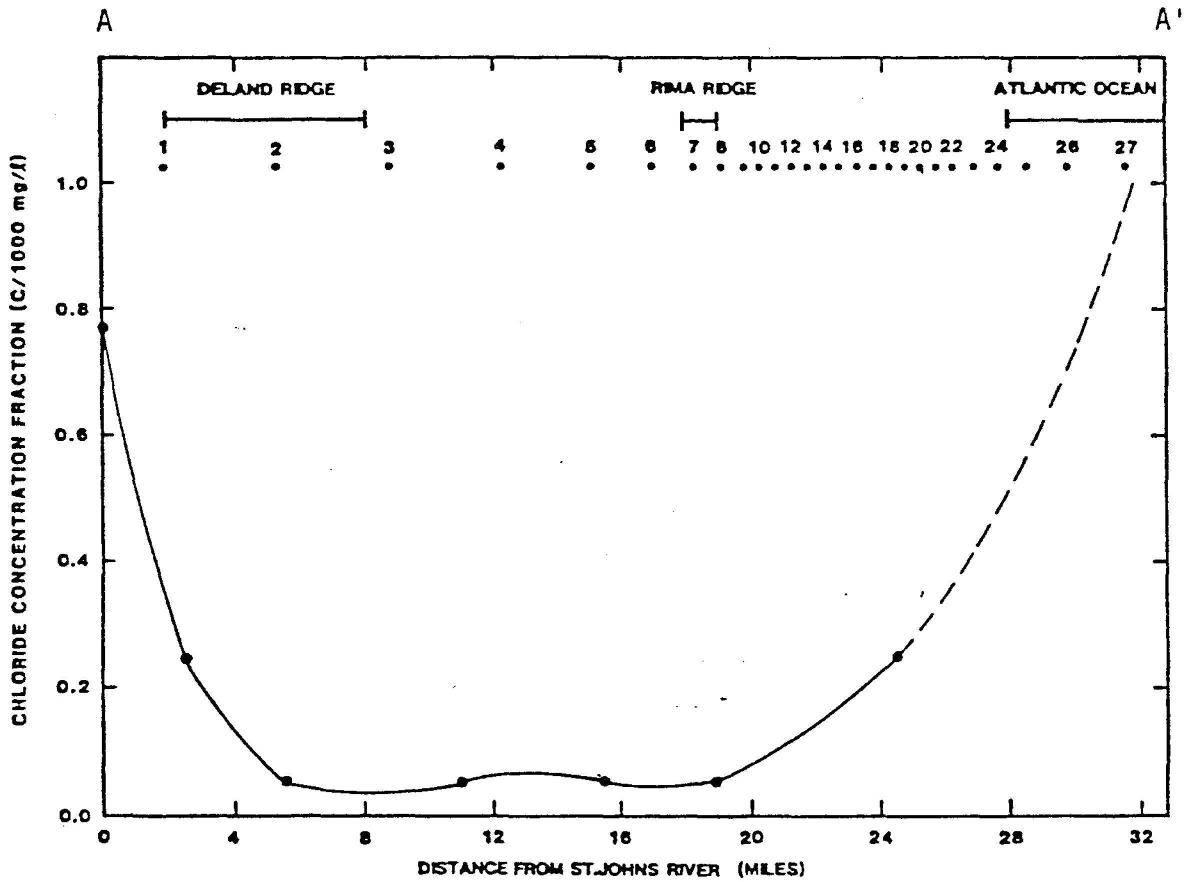


Figure 4.9 Chloride Concentration Fraction in the Upper Floridan Aquifer, 1980, Along Section A-A' (from SJRWMD).

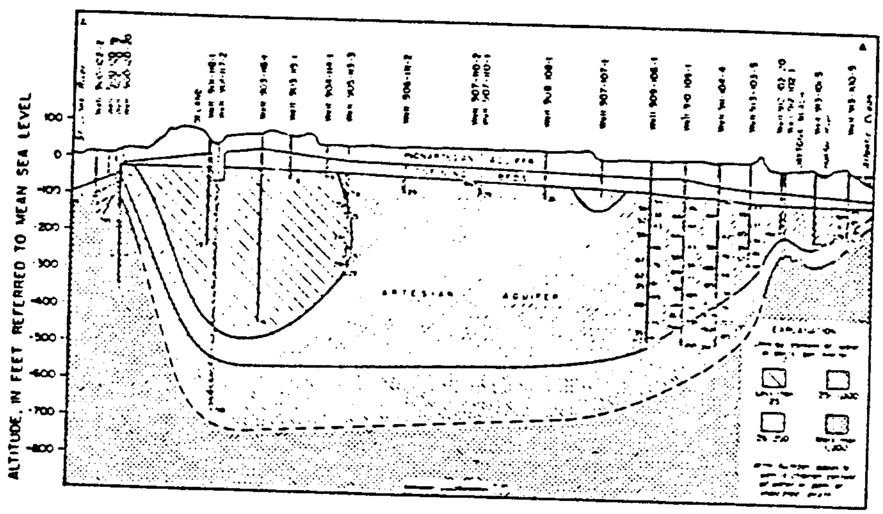


Figure 4.10 Chloride Content of Floridan Aquifer Parallel to Line A-A' in Figure 5.2. (From Wyrick, 1960).

Transport parameters and boundary conditions used for the three-dimensional coupled analyses were based on two-dimensional cross-section analysis. By starting with the cross-sectional analysis, much effort involved in the three-dimensional transport history matching was alleviated.

The best results were obtained utilizing the following boundary conditions. The concentration of chlorides in the upper Floridan boundary along the St. Johns River was kept at a constant dimensionless concentration of 0.77. The upper Floridan boundary along the Atlantic Ocean was set to a concentration of 1.0 and the bottom boundaries of the lower Floridan blocks were all kept at a 1.0 concentration. All other transport boundaries (except for surface recharge of fresh water) were considered to be zero-flux boundaries.

The chloride distribution in the upper Floridan from this steady-state simulation is depicted in Figures 4.11 and 4.12. Figure 4.11 shows the chloride distribution in the upper Floridan aquifer along cross-section A-A'. The results were similar to concentration distributions given by SJRWMD as presented in Figure 4.9. The simulated areal chloride distribution in the upper Floridan is presented on the contour map depicted in Figure 4.12. The simulated distribution shows similar tendencies to the data presented by SJRWMD in Figure 3.10.

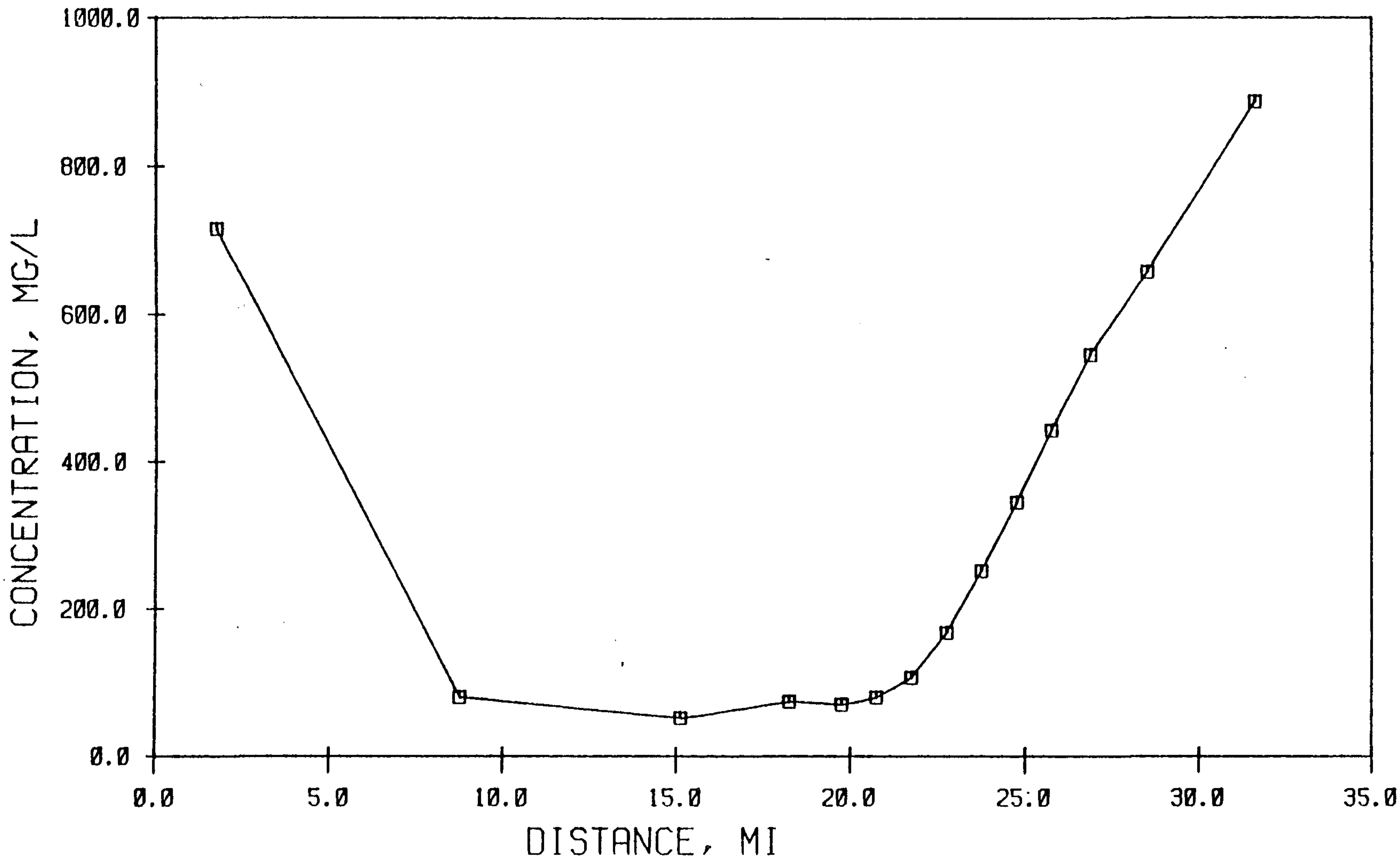


Figure 4.11 Steady-State Chloride Distribution, From Run SS1, Along Cross Section A-A' in Upper Floridan Aquifer.

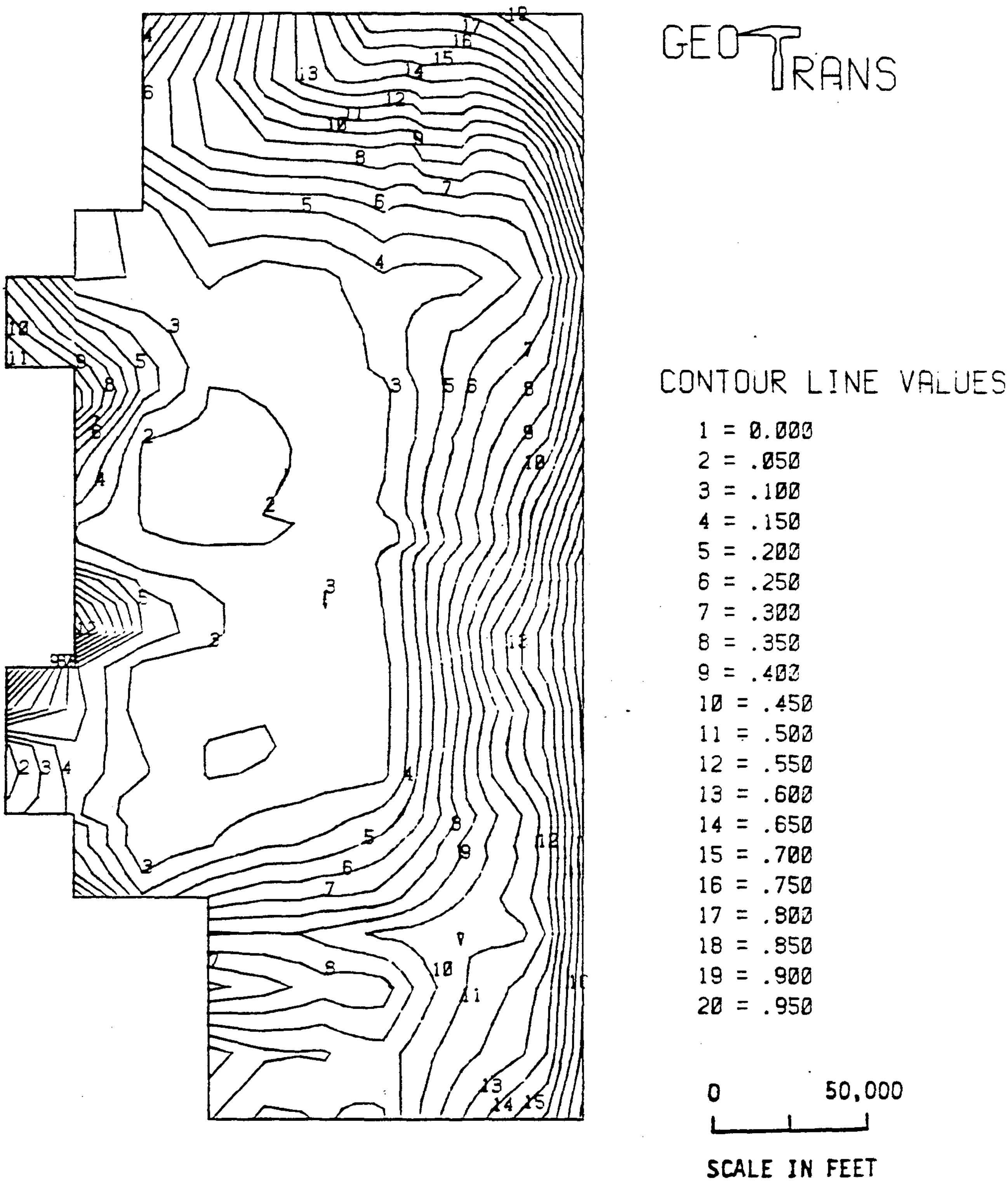


Figure 4.12 Contour Map of Steady State Chloride Distribution in Upper Floridan Aquifer - Run SS1.

5.0 PREDICTION OF AQUIFER BEHAVIOR

The final phase of this project was to analyze the response of the Volusia County ground water system to several different development and natural conditions scenarios. Such analysis was conducted to provide insight into the dynamics of the system in a general sense. The particular scenarios analyzed are outlined in Table 5.1.

Although we previously concluded that the flow system achieves steady-state quickly, the simulations described in this section treat flow and solute transport as transient phenomenon. The first four (T1-T4) transient cases were run with production from 91 wells representing present production and located as depicted in Figure 5.1. In addition to the 91 currently producing wells, the wells proposed in Bush (1978) are also shown. These wells, located in the central wetlands area, were considered as a potential alternative to continued ground water development in the coastal area of the county. Run T5 included production from Bush's proposed field of 20 mgd as well as production from the present production wells. Run T6 examined the effects of stresses from the proposed field when present production was not included. Note that the wells are shown at the grid-block center, where the nodes were located. Any well within the grid block had its production assigned to that node. The wells were assumed to be open to the upper Floridan aquifer. A listing of all transient simulations is provided in Table 5.1.

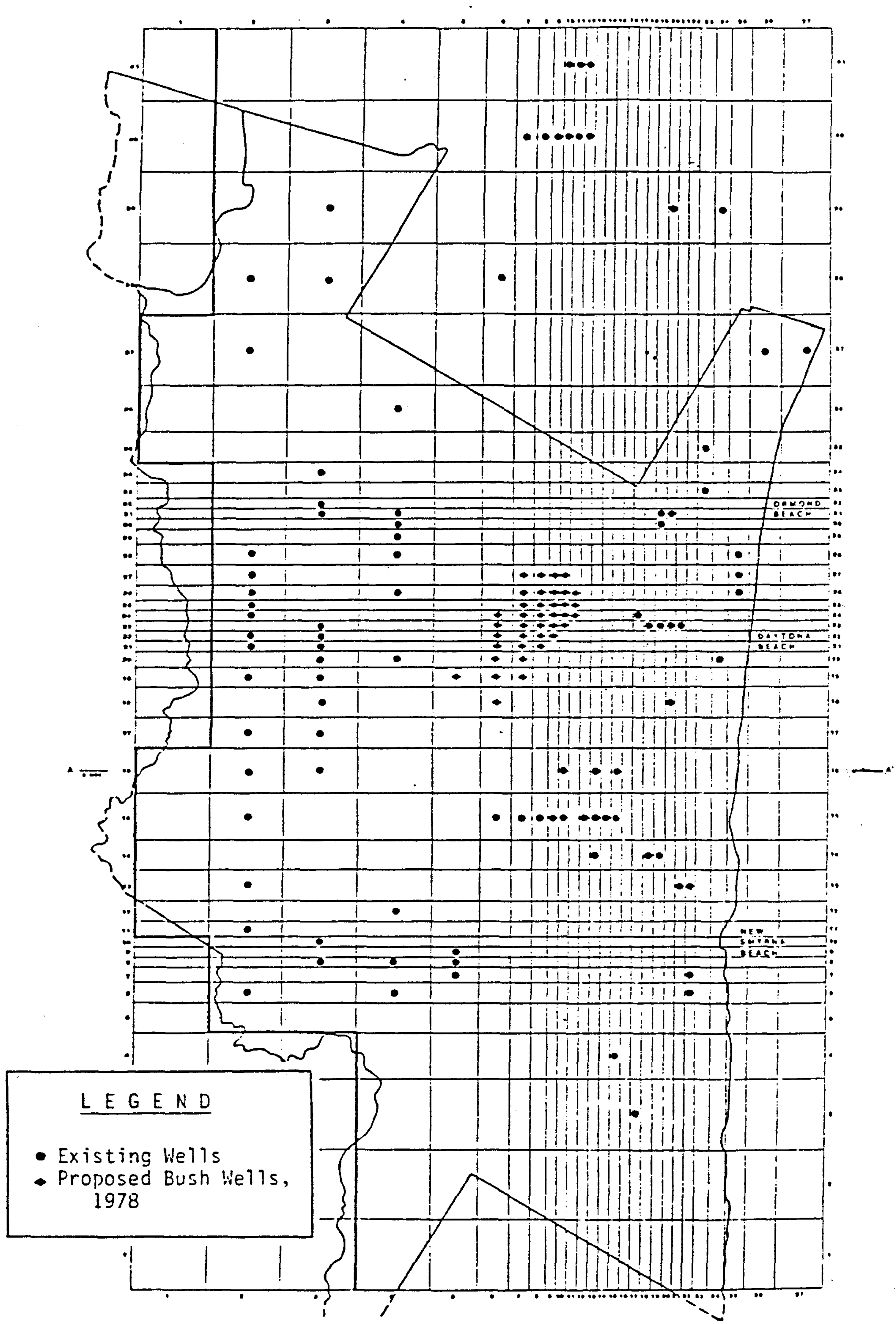


Figure 5.1 Grid Showing Location of Production Nodes Used in Transient Simulations.

Table 5.1 Description of Transient Simulations.

Run Number	Model Condition	Field Condition
T-1	Pumping Rates in Tabel 5-24.	Current level of pumpage.
T-2	Same as T-1 with ½* recharge.	Drought conditions.
T-3	Same as T-2 with 2* recharge.	Wet conditions.
T-4	Pumping Rates in T-1 doubled.	Increased demand.
T-5	Pumping Rates in T-1 plus Bush (1978) wells.	New well field.
T-6	Bush (1978) wells only.	(Mainly for comparison to Bush's results, showing incremental effect).

Although the model used initial conditions that represented a steady-state for flow and transport, the actual field conditions were probably not at steady-state. In performing the steady-state simulations, flow conditions were determined to reach steady-state quickly (see Section 4.4.5). Movement of solute was slower, and concentration reached steady-state after a much longer time. The ground water system in Volusia County could very well have changing chloride concentrations as a result of stresses that were placed on the system many years ago. Such changes were not included in the transient simulations presented in this section.

5.1 Changes in Potentiometric Surfaces During Transient Runs

It is important to note in the transient simulations the effect of changes in system stresses on the potentiometric surface in the upper Floridan aquifer and the water table. Figures 4.4 and 4.5 represent the pre-pumping potentiometric surfaces in the water table aquifer and upper Floridan, respectively. As previously discussed, recharge values used for the following transient runs are higher than those used for steady-state runs. Some of the differences in potentiometric surfaces and concentration levels between steady-state and transient runs, is therefore a product of the recharge changes. This is not unrealistic because, as previously discussed, the production would tend to induce recharge and decrease evapotranspiration losses. For this reason system changes due to transient stresses should be evaluated by comparison of transient runs to steady-state and additionally by relative comparison of transient simulations.

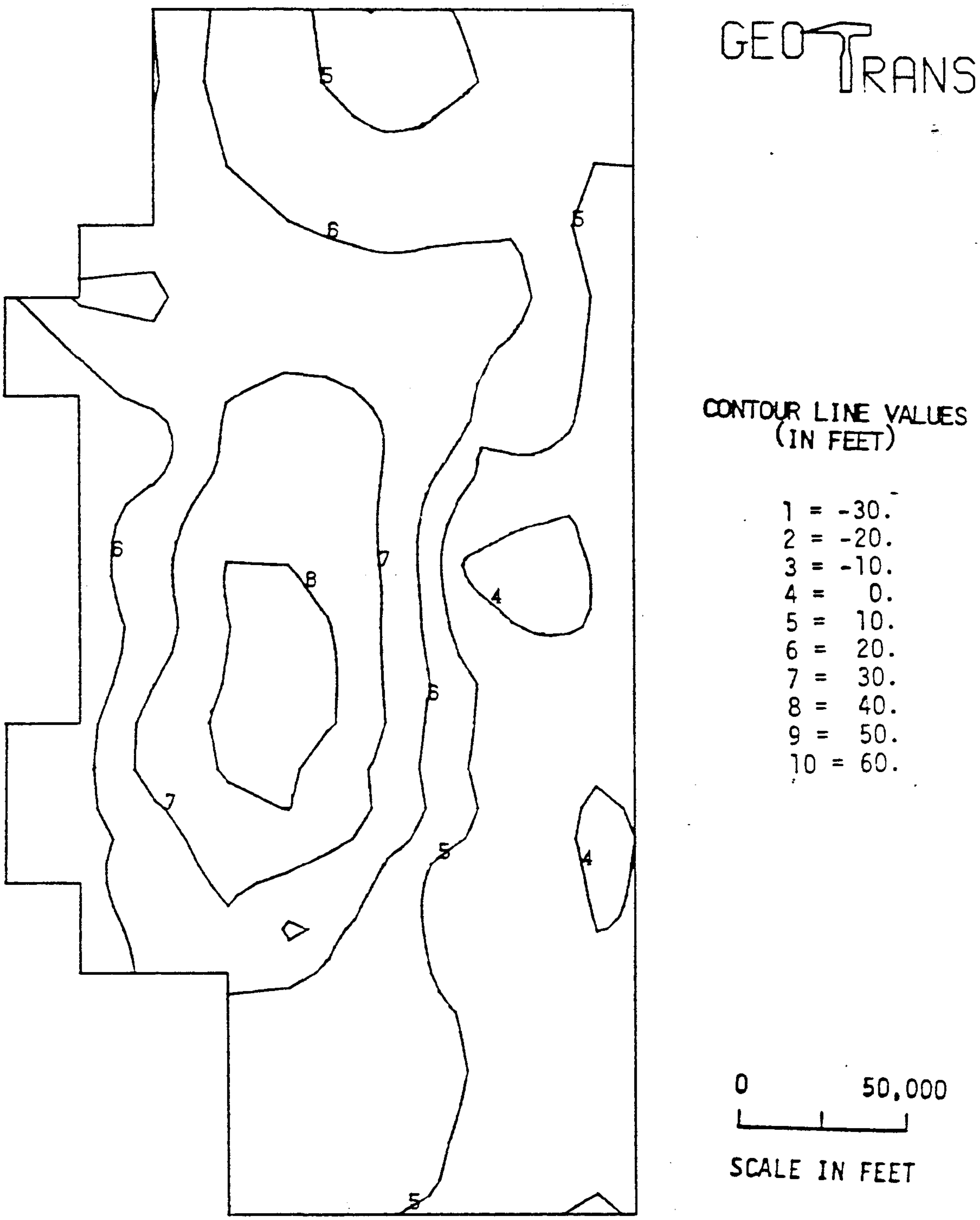


Figure 5.2 Computed Potentiometric Surface for the Upper Floridan From Run T-1.

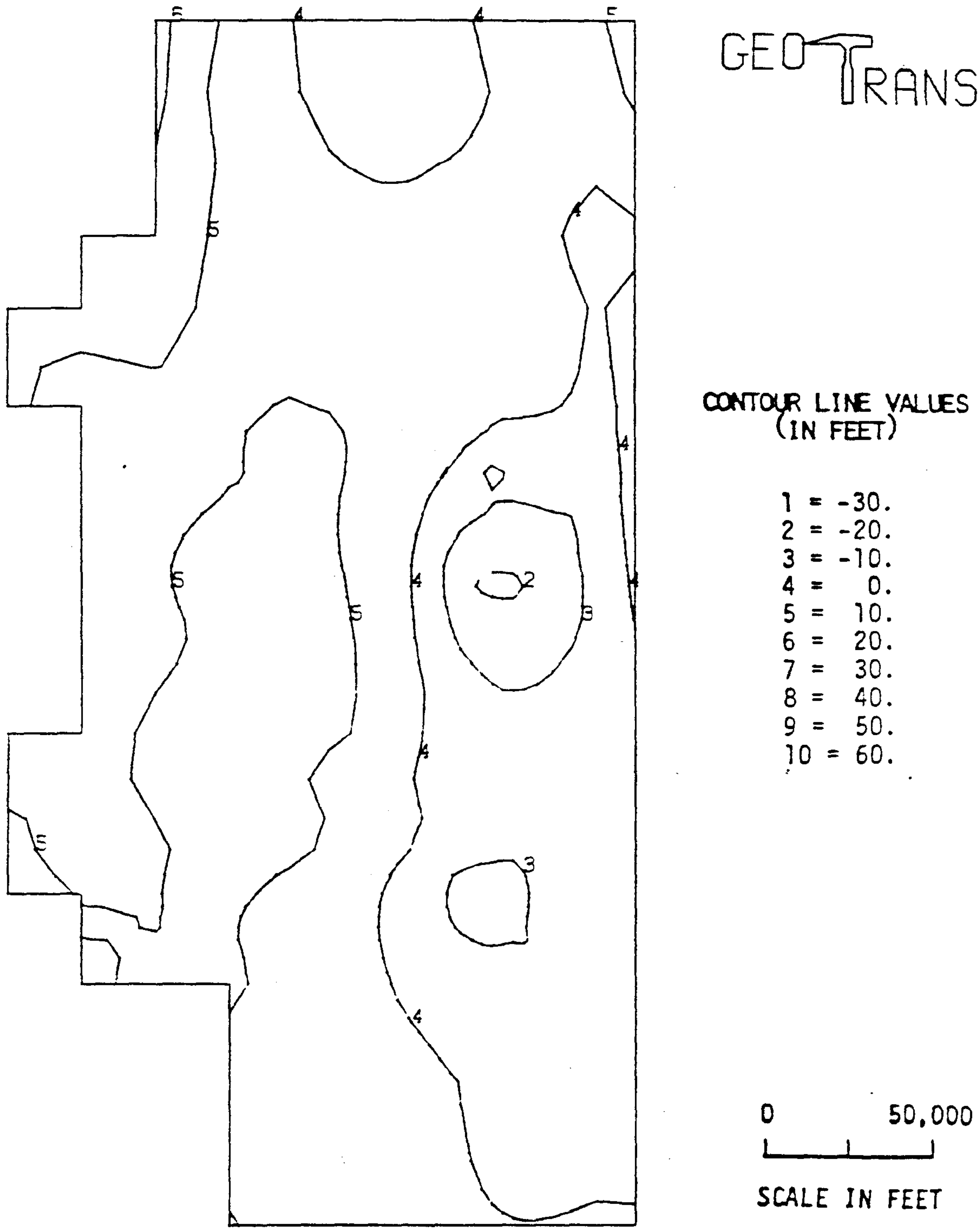


Figure 5.3 Computed Potentiometric Surface for the Upper Floridan From Run T-2.

Along the Atlantic Coast, production of 91 wells for 50 years (Run T-1) produced a decrease in the potentiometric surface of up to 10 ft. in the upper Floridan (see Figures 4.5 and 5.2). Changes in the water table elevation also occurred. It should be noted that accurate evaluation of the influence of the major well fields on the water table adjacent to those fields cannot be achieved with this model. The low horizontal transmissivity used to define the water table aquifer as a source bed for the upper Floridan will effect a steeper cone of depression with a smaller area of influence than should be expected. In a subsequent section, the influence of transient stresses on the water table near the springs is investigated. Since the springs are not in the major areas of well production, this does provide an approximate indication of the transient effects.

In Run T2, simulation of long-term effects of combined well production and recharge reduced by 50 percent produced large additional declines of the potentiometric in the upper Floridan (see Figures 5.2 and 5.3). The simulated potentiometric surface west of the DeLand Ridge recharge area declined as much as 30 additional feet compared with results of a run with normal recharge rates. The surface around the Daytona and New Smyrna Beach wells declined 10 feet beyond normal recharge levels.

Doubling the recharge (Run T-3) while using the original well production rates causes a rise in the upper Floridan potentiometric surface of 30 to 40 feet higher in recharge areas than that computed for the preproduction case (see Figures 4.5 and

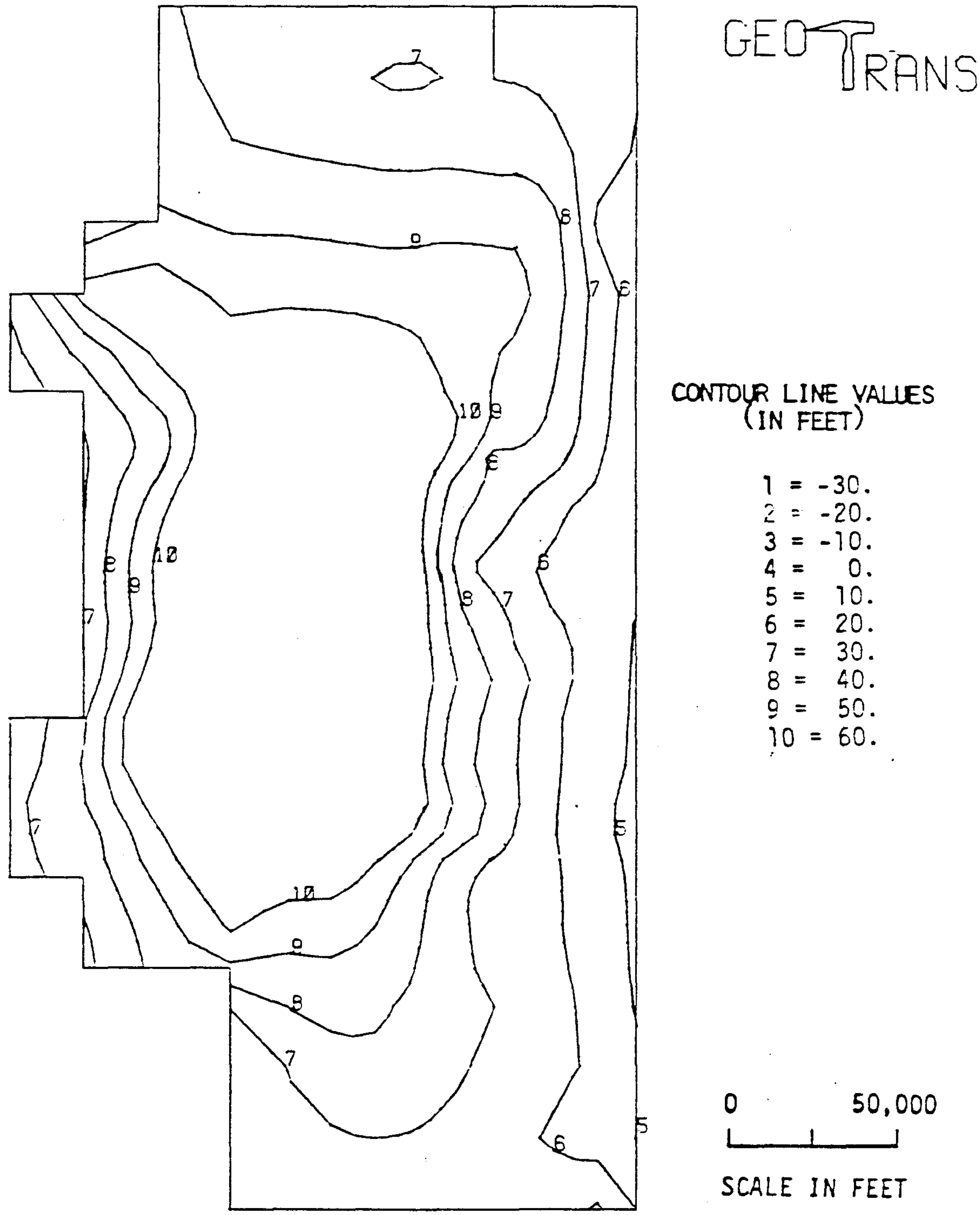


Figure 5.4 Computed Potentiometric Surface for the Upper Floridan From Run T-3.

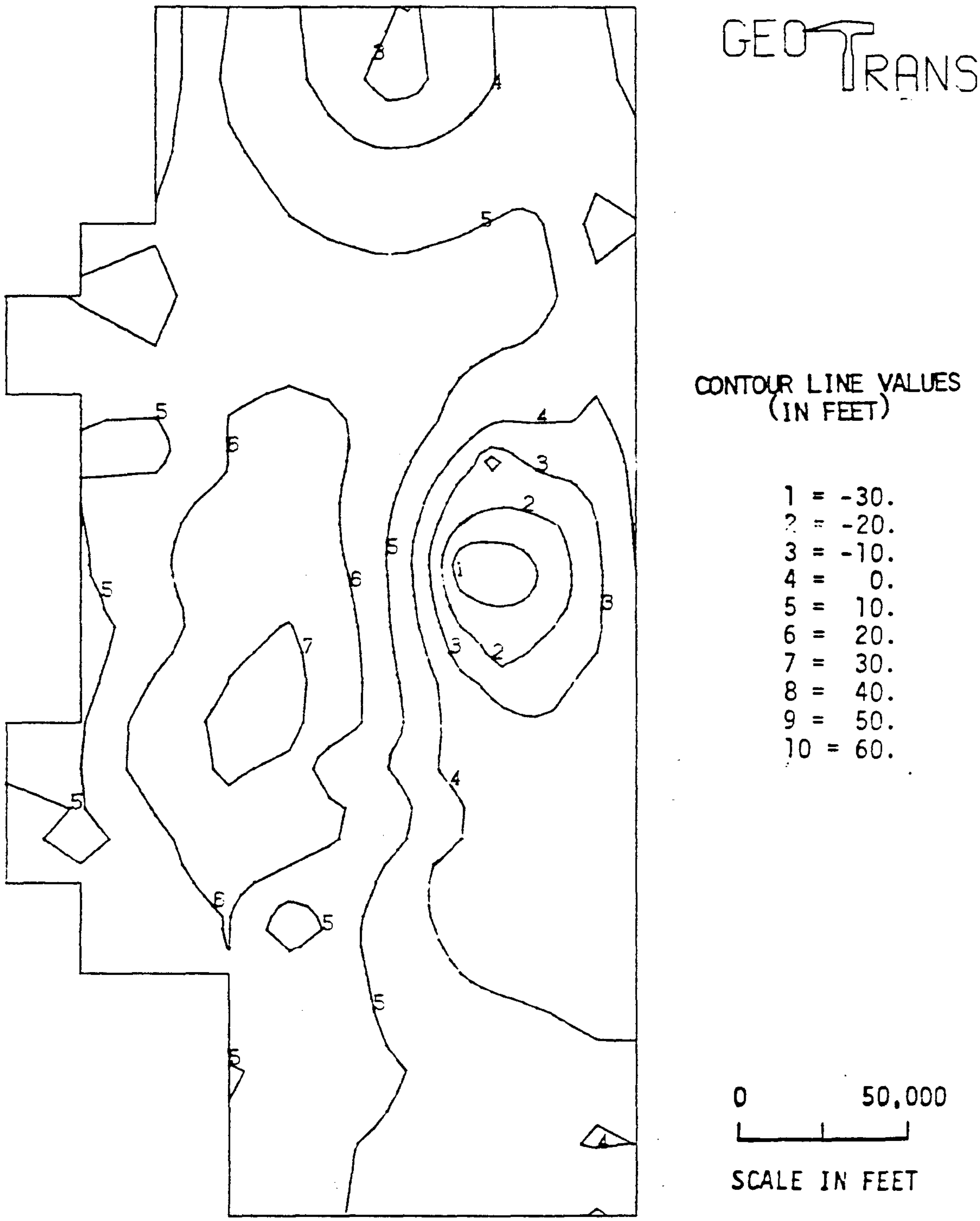


Figure 5.5 Computed Potentiometric Surface for the Upper Floridan From Run T-4.

5.4). The area around the Daytona Beach wellfield showed a minimal effect from production as compared with Run T-1 (see Figures 5.2 and 5.4). Care should be taken to note that in the actuality, the recharge increase was limited in areas where the water table was near or at the surface (i.e. East of DeLand Ridge) so a doubling of recharge may not be possible in these areas even with pumping. Despite this fact, when considering the relatively short time at which the flow system starts to approach steady-state (less than a month), the effects of rainy periods as a transport driving force must not be overlooked.

In Run T-4 the recharge was the same as for T-1 but the production rates were doubled. The increased well production for 50 years effectively lowered the upper Floridan potentiometric surface 10 ft. in the recharge areas relative to the original well production case (see Figures 5.2 and 5.5). In the area adjacent to the Daytona Beach wells the surface declined 20 to 30 ft. more than with the original well production. Comparing Figures 5.2 and 5.5, the increased area of influence of the cone of depression around the Daytona wells was readily seen.

Runs T-5 and T-6 were performed to study the influence of the 20 million gallon per day wellfield modeled by Bush (1978) over a 50 year period. Run T-5 includes an approximation of Bush's wellfield superimposed on the original wellfield configuration (see Figure 5.1). Run T-6 represents a 50-year simulation using only Bush's wellfield. The purpose of Bush's proposed field was to produce water for coastal use from a location further inland, reducing the possibility of saltwater intrusion around the coast. In addition, runoff in the wellfield area was converted to recharge as the water table was reduced due to well production. A comparison of Figures 5.2 and 5.6 shows a general change of upper Floridan potentiometric surface in the DeLand Ridge area of 5-10 ft. for T-5 and a cone of depression around the superimposed wellfield of up to 20 ft.

Run T-6 represented the use of the proposed central Volusia County wellfield (Bush, 1978) as the main water supply for the county. As can be readily discerned from Figures 4.8 and 5.7, except for the cone of depression around the wellfield, the general affect on the potentiometric surface in the upper Floridan is less than 10 ft. of decline. A cone of depression with a 20-ft. maximum was formed near the wellfield. This compared well with the calculations made by Bush (1978).

5.2 Changes in Chloride Concentrations During Transient Runs

The first transient simulation (T-1) represented 50 years of pumping at the current rates. As can be seen by comparing Figures 4.12 and 5.8, these transient effects on chloride in the upper Floridan were especially noticeable along the St. Johns River and the Atlantic Ocean. Careful comparison of the results along the Atlantic Coast shows the importance of monitoring chloride in wells along the Ormond Beach, Daytona Beach and New Smyrna Beach area. The steep concentration gradients along the coast were indicative of the potential for chloride intrusion. Concentration changes along New Smyrna Beach and Ormond Beach were relatively small but the effect of production around certain

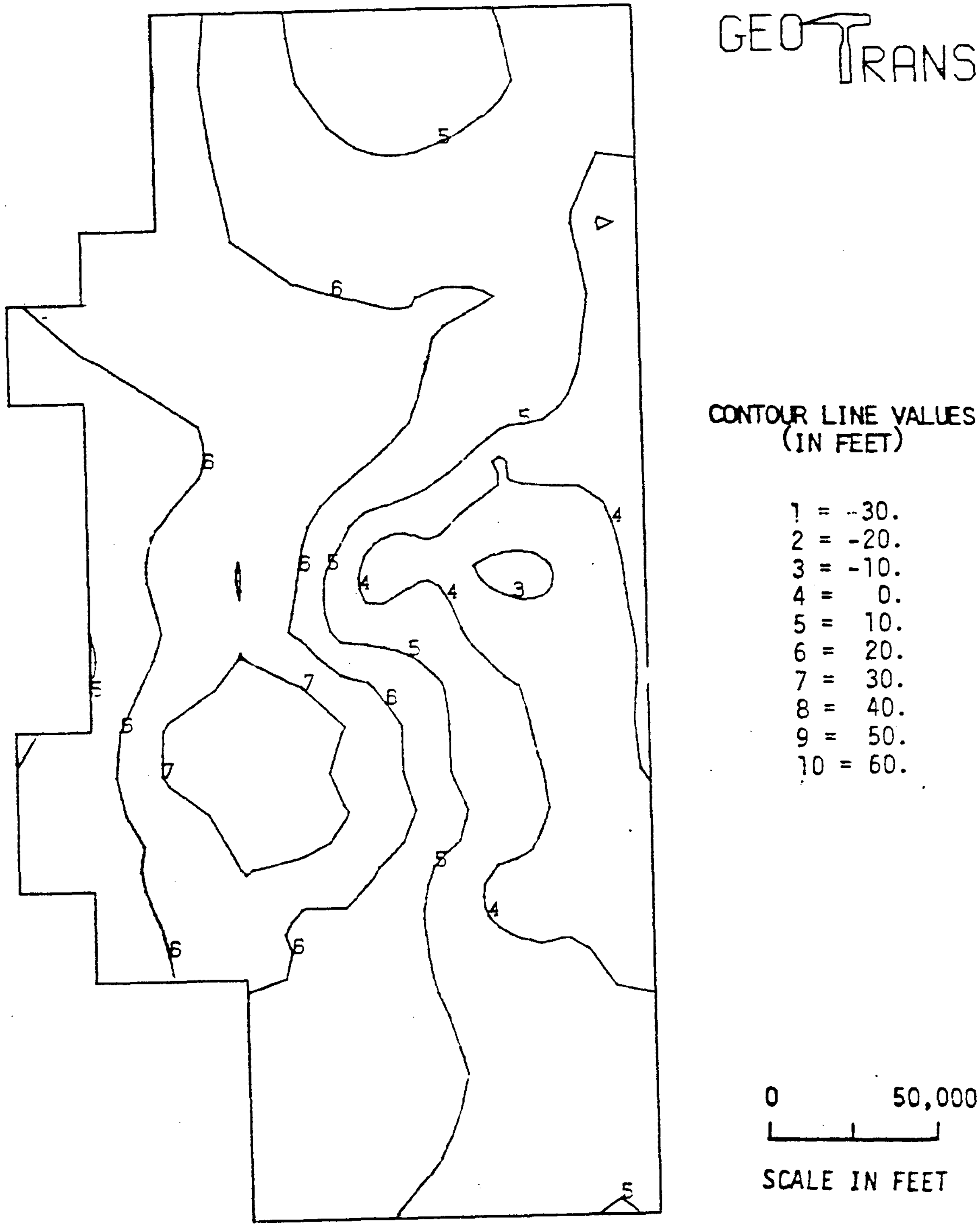


Figure 5.6 Computed Potentiometric Surface For The Upper Floridan From Run T-5.

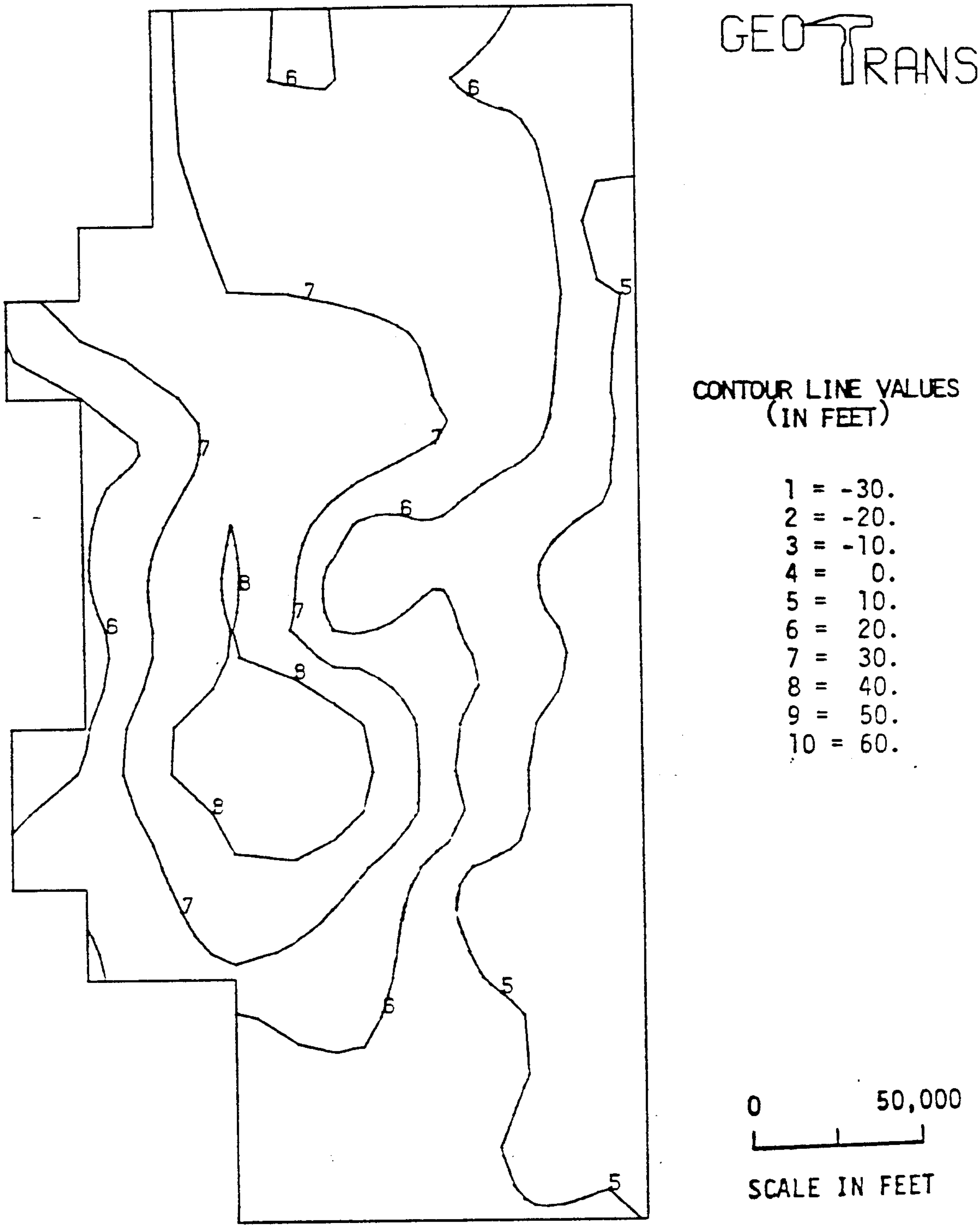


Figure 5.7 Computed Potentiometric Surface For The Upper Floridan From Run T-6.

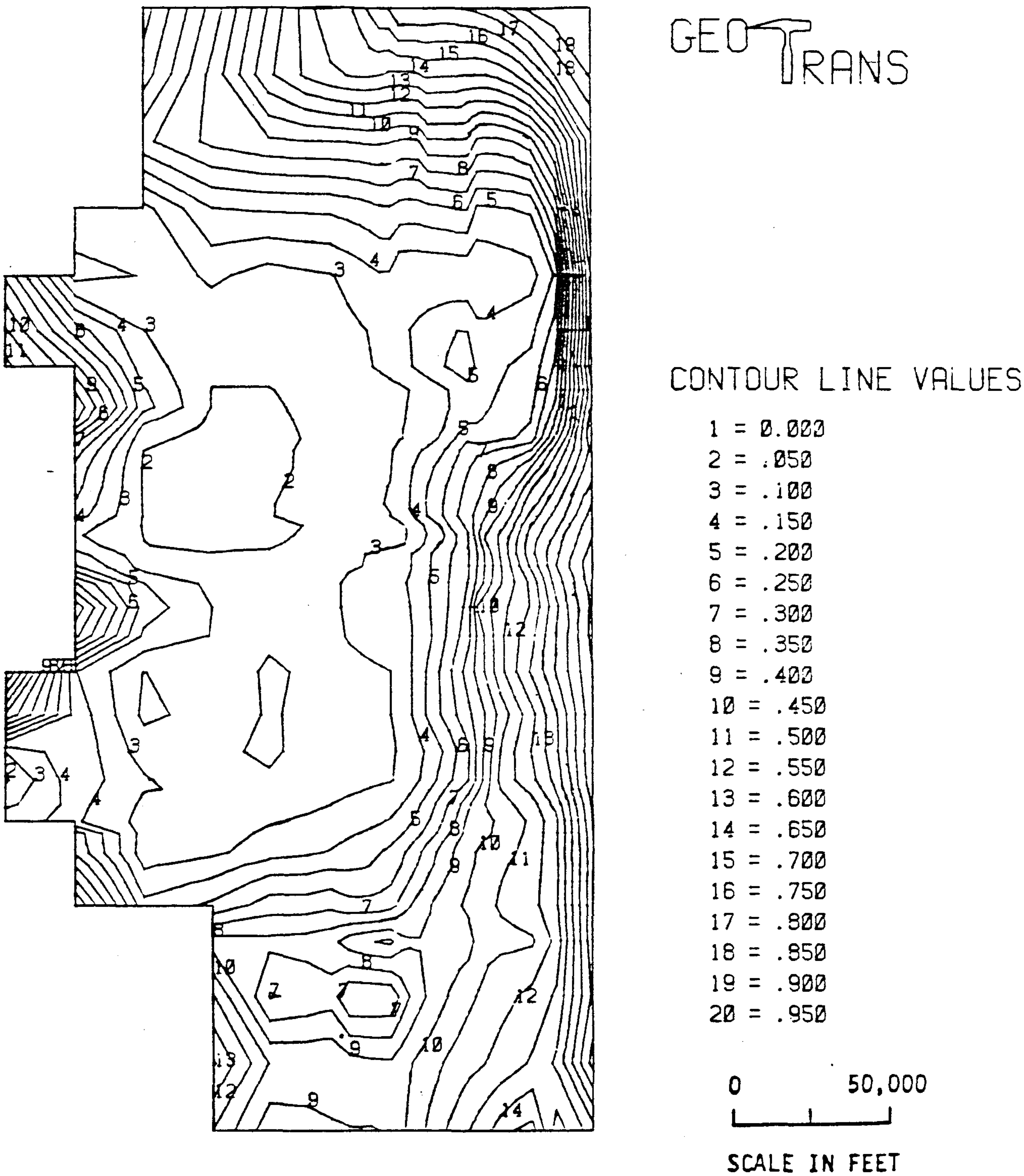


Figure 5.8 Contour Map of Chloride Distribution in Upper Floridan Aquifer After 50-Years Production For Run T-1.

Daytona Beach wells was quite noticeable. The salt water front moved inland around 2-3 miles as a result of 50 years of pumping. Most of the other wellfields modeled showed little change of water quality in the immediate area. It should be noted that the fresh water lens in the middle of the county was reduced slightly in size west of Daytona Beach.

The second transient run (T-2) was also run for 50 years to evaluate the effects of the same well pumpage but now under drought conditions. The recharge rates were halved for this run to estimate the combined effects. As can be seen by comparing Figures 4.12, 5.8 and 5.9, the drought simulation had its greatest influence along the St. Johns River and the Atlantic Ocean. Water quality around the Daytona Beach wellfield showed further deterioration. In addition, water quality near Ormond and New Smyrna beaches showed increased chloride concentrations. Wellfields along the St. Johns River were also affected by the decreased recharge as the fresh water lens decreased its lateral extent.

Similar to the second run, the third run (T-3) used the original well pumpage for 50 years, but this time the recharge rates were doubled to evaluate the influence of a high precipitation period. As can be seen by comparing Figures 4.12 and 5.8 through 5.10, the greatest area of influence was, as expected, along the coast and the St. Johns River. It should also be noted by comparing Figures 5.10 and 5.8 that the period of high recharge was enough to offset water degradation due to well production.

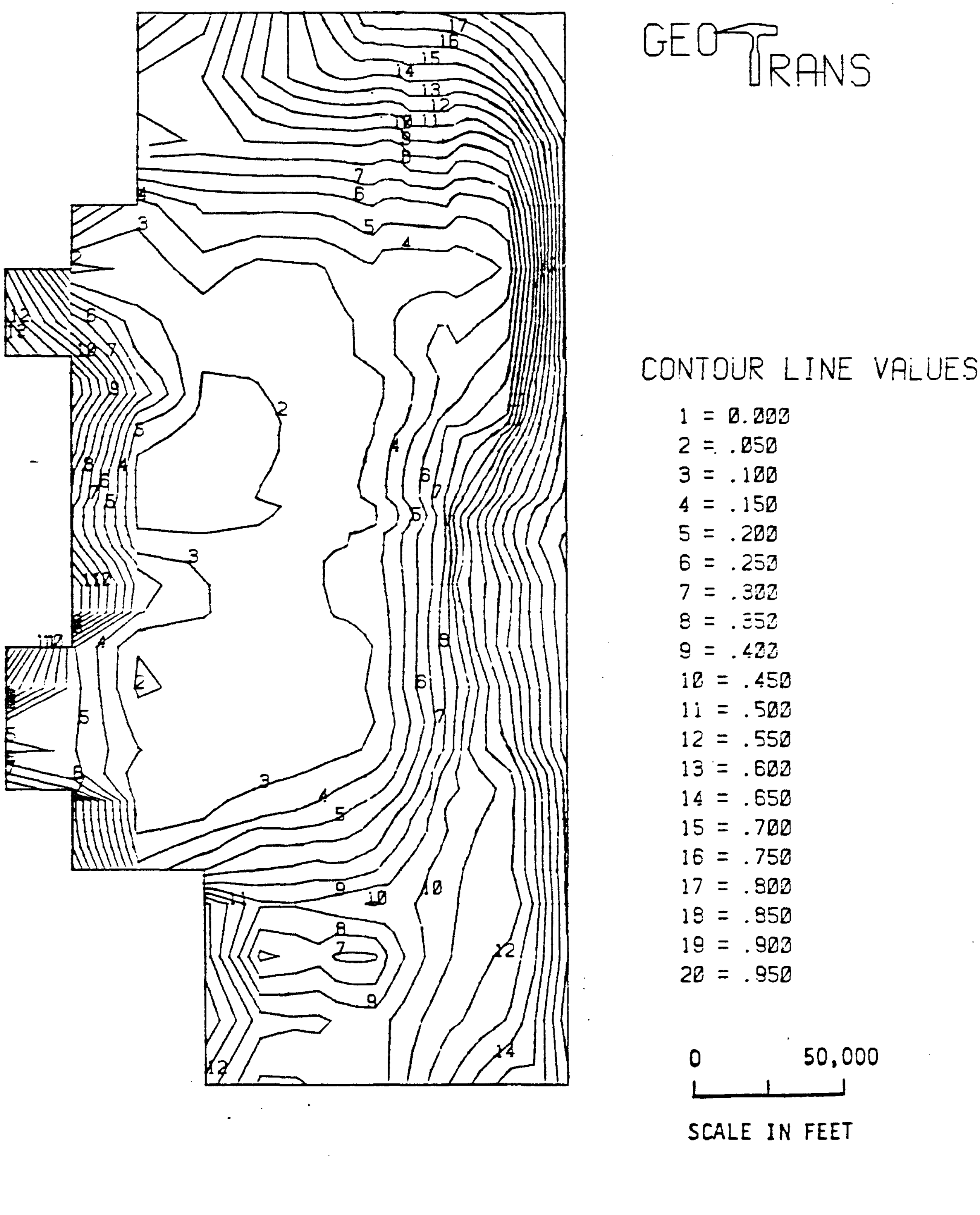


Figure 5.9 Contour Map of Chloride Distribution in Upper Floridan Aquifer After 50-Years Production For Run T-2.

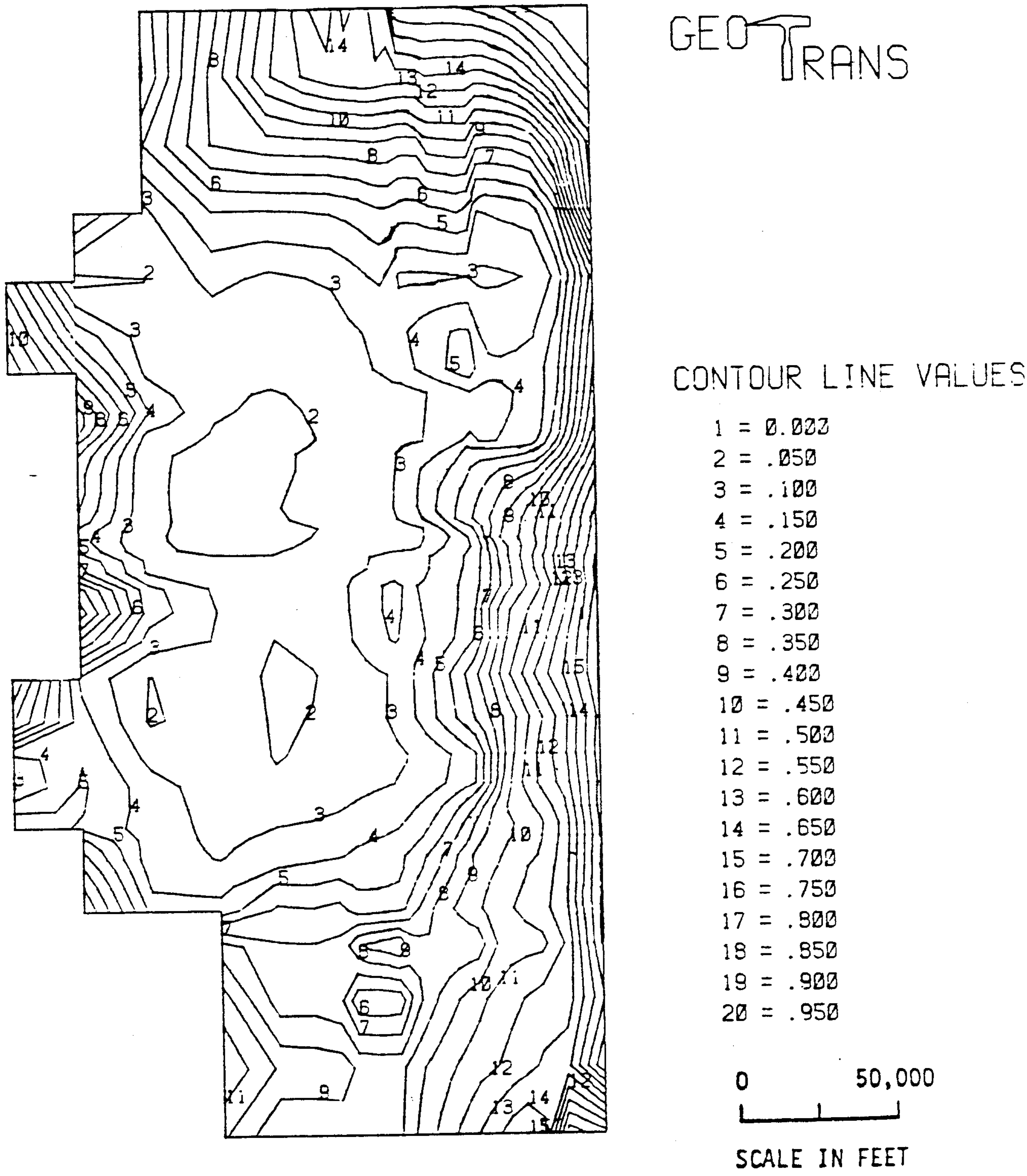


Figure 5.10 Contour Map of Chloride Distribution in Upper Floridan Aquifer After 50-Years Production For Run T-3.

For the fourth transient run, T-4, the well production rates were doubled while the recharge rates were held the same as in T-1. As can be seen by comparing Figures 5.8 and 5.11, chloride concentration levels in the upper Floridan increased along the St. Johns River and the Atlantic Coast. Of major concern was the increase of chloride concentration in the Daytona Beach area. There was a major shift in the chloride concentration contours due to the pumping in the Daytona Beach wellfield. Care must be taken in interpreting the magnitude of the change in concentration in this area as it was influenced by the chosen boundary condition. As more data is gathered in this area, assembling a refined model using boundary conditions given by the present model would help characterize highly localized conditions.

Simulation results from T-5 showed changes in concentrations along the St. Johns River and the Atlantic Coast compared to those from T-4 (see Figures 4.12, 5.11 and 5.12). One apparent difference was that the area near Daytona Beach showed a lesser degradation than in Run T-4. This has major implications when considering the utility of the wellfield described by Bush (1978). The central Volusia County wellfield allowed for increased production without additional degradation in water quality near Daytona Beach. The economics of such a wellfield and the necessary transportation system was obviously not considered in this study. It should be noted that a slight degradation in water quality in central Volusia County resulted from this scheme.

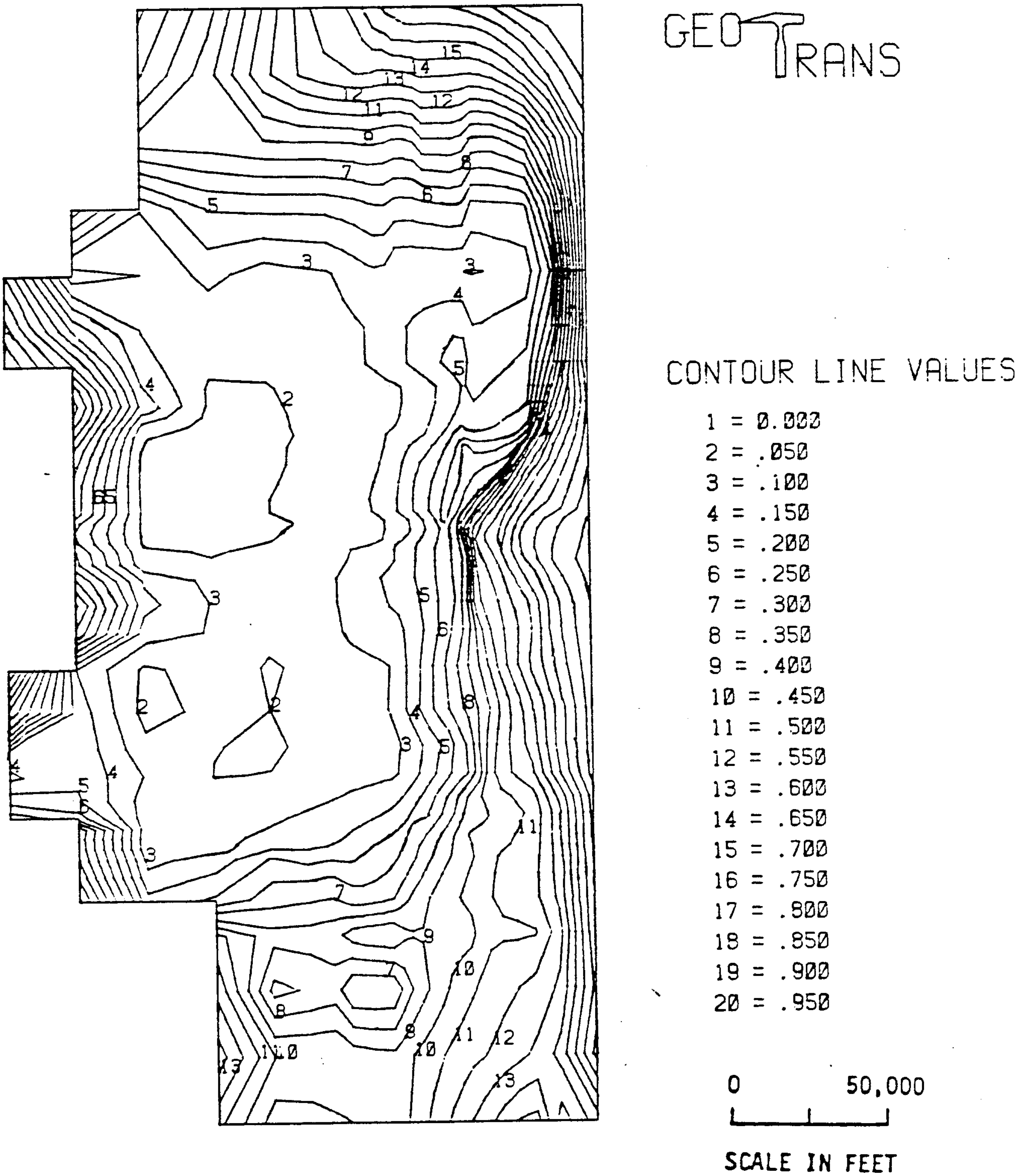


Figure 5.11 Contour Map of Chloride Distribution in Upper Floridan Aquifer After 50-Years Production For Run T-4.

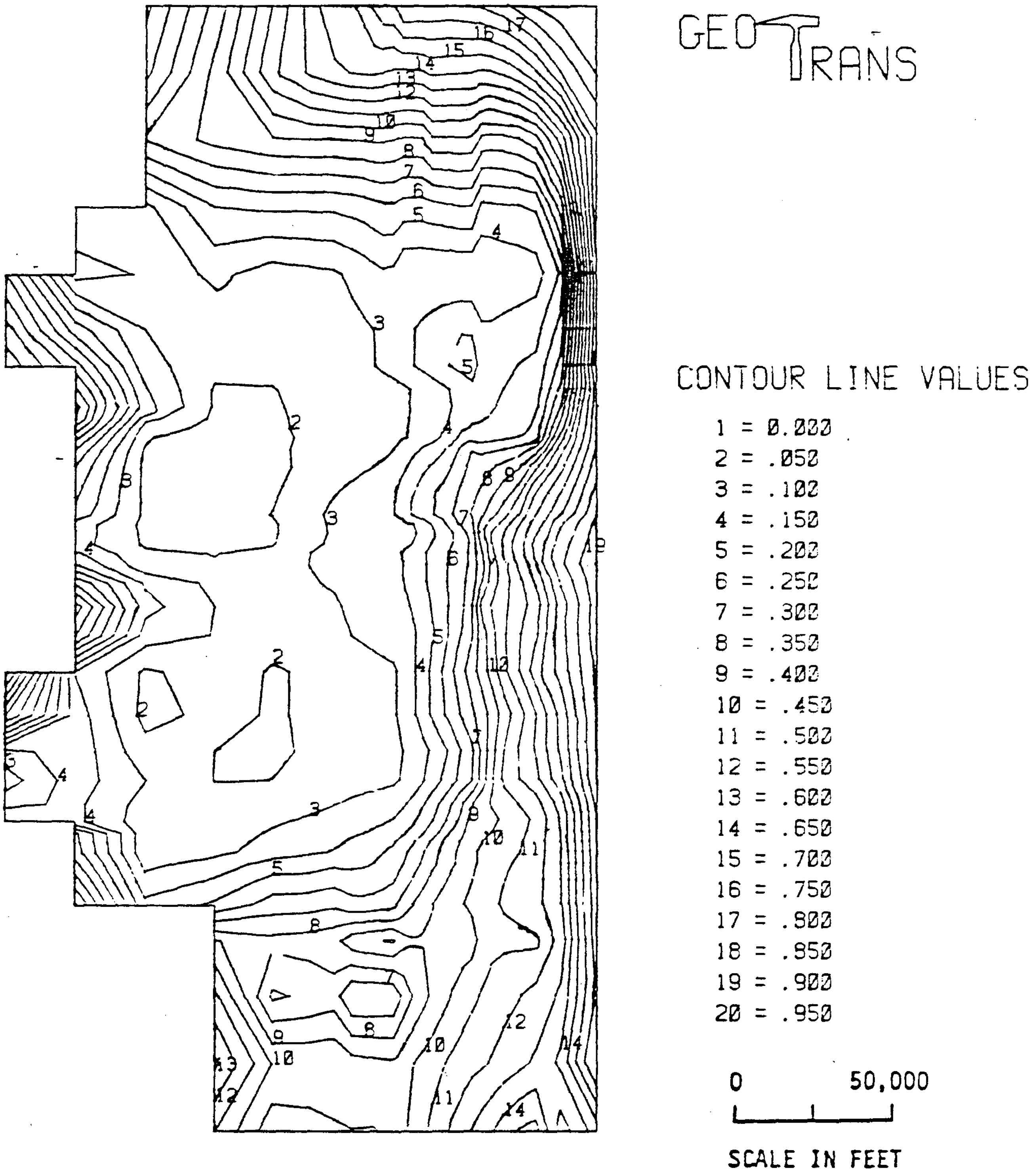


Figure 5.12 Contour Map of Chloride Distribution in Upper Floridan Aquifer After 50-Years Production For Run T-5.

Run T-6 (Figure 5.13) which included only the central Volusia wellfield, showed the potential for improvement of water quality near Daytona and Ormond beaches by turning off the nearby wellfields and replacing it with the central Volusia field.

5.3 Effects of Pumping Stresses on Springs

A point of economic interest in Volusia County was the effect of pumping stresses on potentiometric surface changes in spring areas. The springs discussed herein include Ponce de Leon Springs, Blue Springs, Green Springs, and Seminole Springs (see Figure 4.7). Of the transient simulations, the one that had the most detrimental effect on water table surface levels was the simulation of decreased recharge or drought conditions (Run T-2). Compared to normal post production levels (Figure 5.14), the water table surface dropped around 10 ft. in the Blue Springs area, the Green Springs area, the Ponce de Leon area, and in the Seminole Springs area (Figure 5.15). Also of consequence was doubling the production rates in the present wells, (Run T-4) causing the water table to decline up to 10 ft. in the four spring areas (see Figures 5.14 and 5.16).

It was most interesting to note that the superposition of the central Volusia wellfield (see Figures 5.14 and 5.17) had a relatively small effect (2-4 ft. decline) on the water table around the springs along the St. Johns River. This is especially important when considering the economic importance of the springs and the aforementioned conclusion about the Daytona Beach water supply.

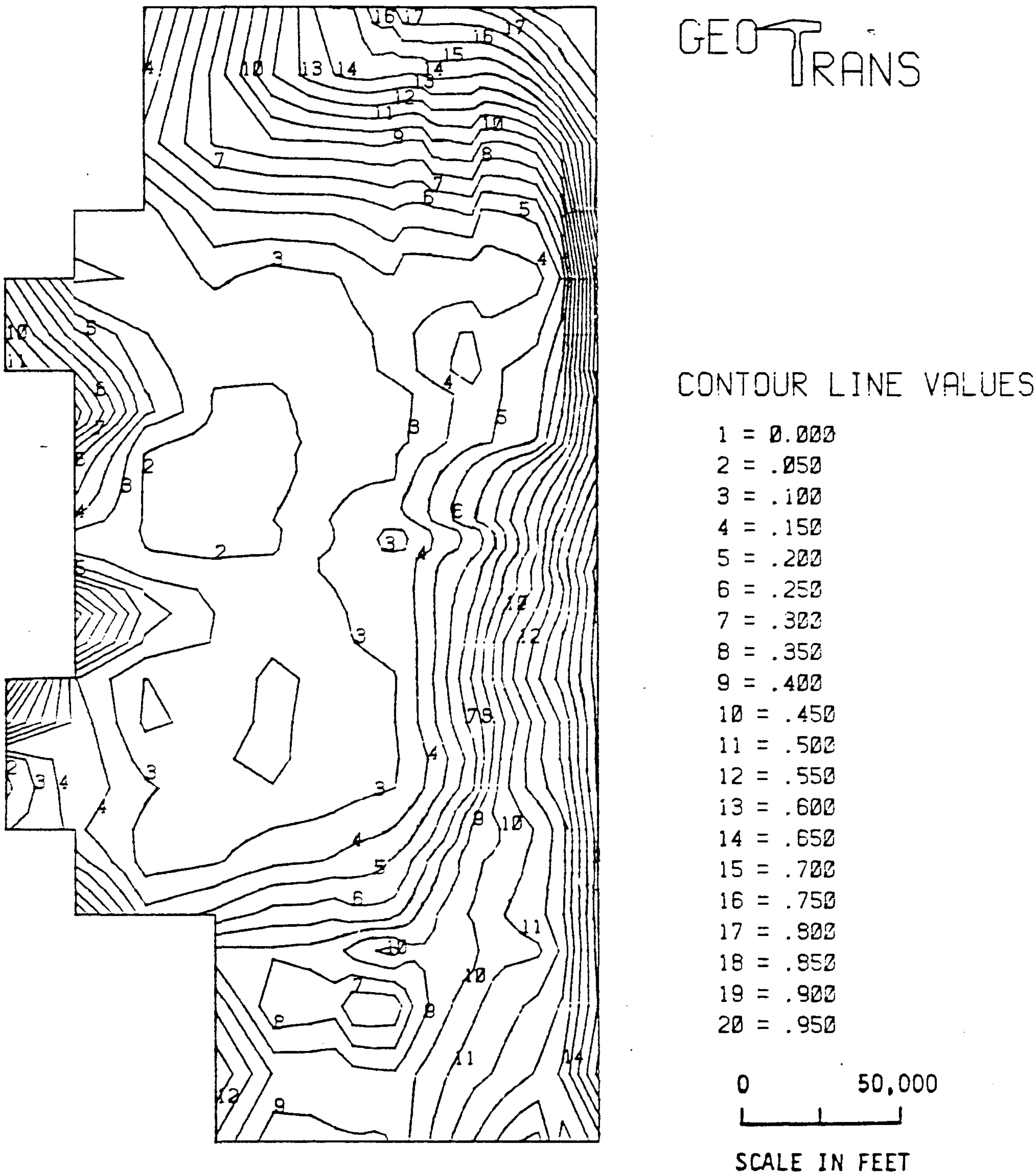


Figure 5.13 Contour Map of Chloride Distribution in Upper Floridan Aquifer After 50-Years Production For Run T-6.

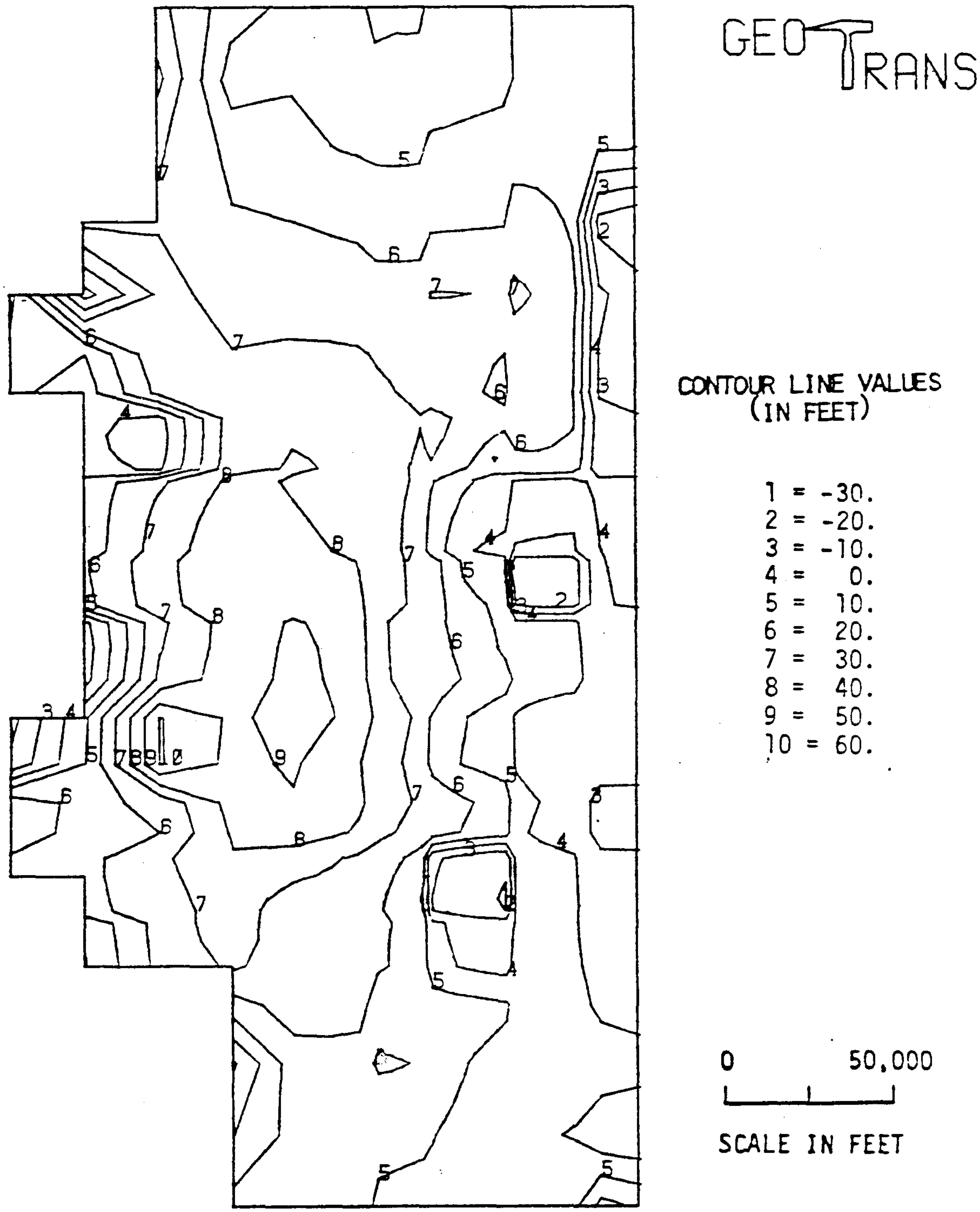


Figure 5.14 Computed Water Table From Run T-1.

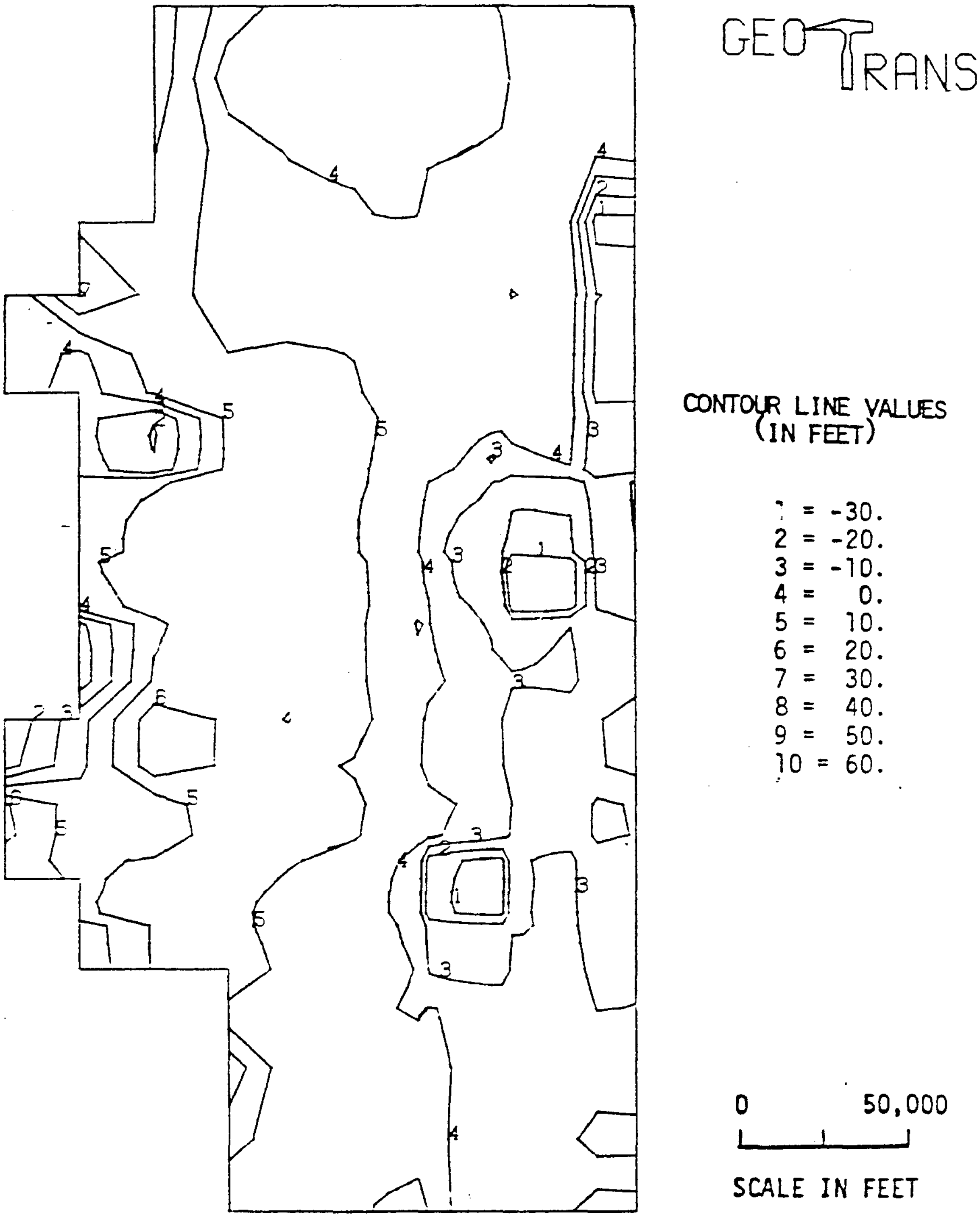


Figure 5.15 Computed Water Table From Run T-2.

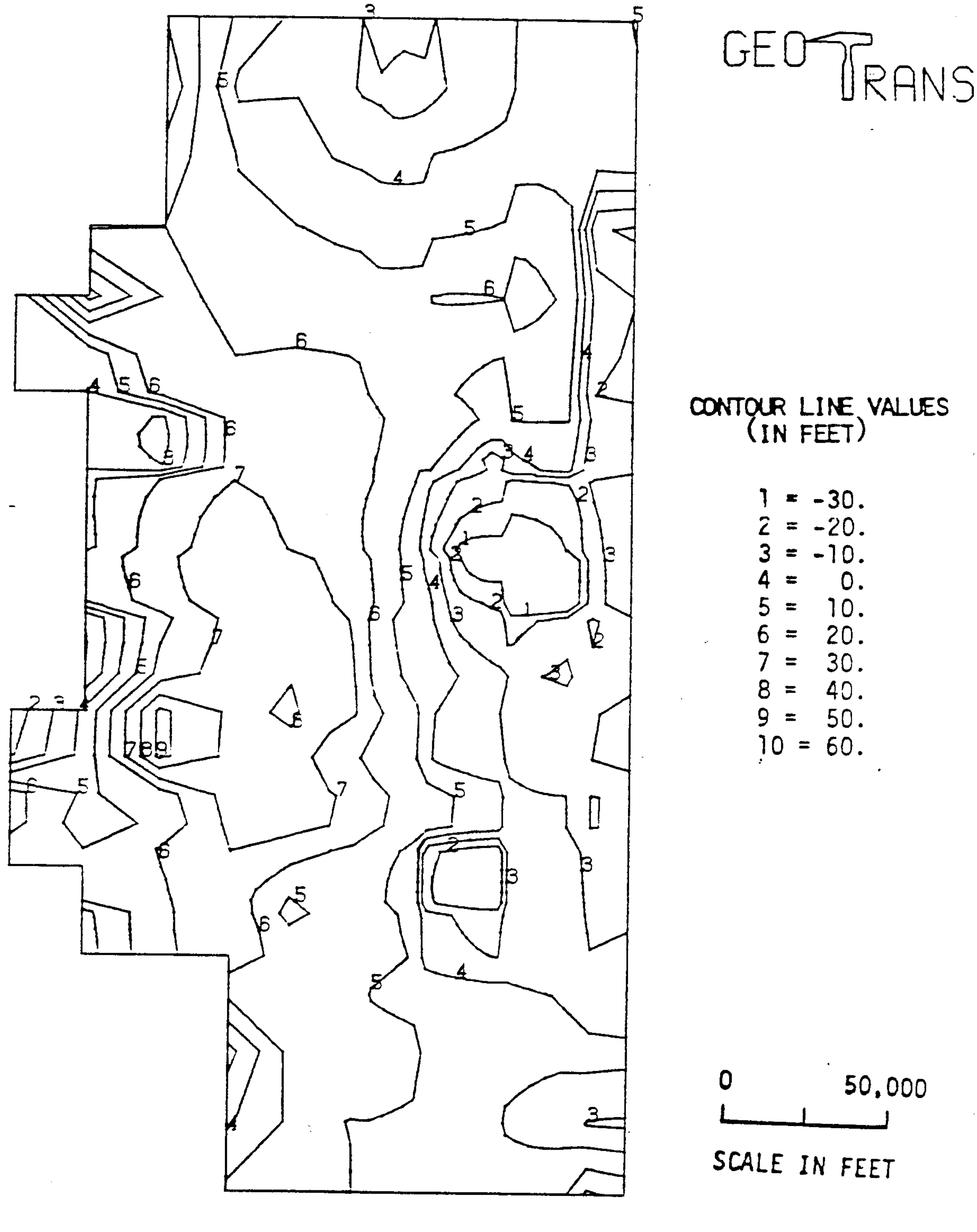


Figure 5.16 Computed Water Table From Run T-4.

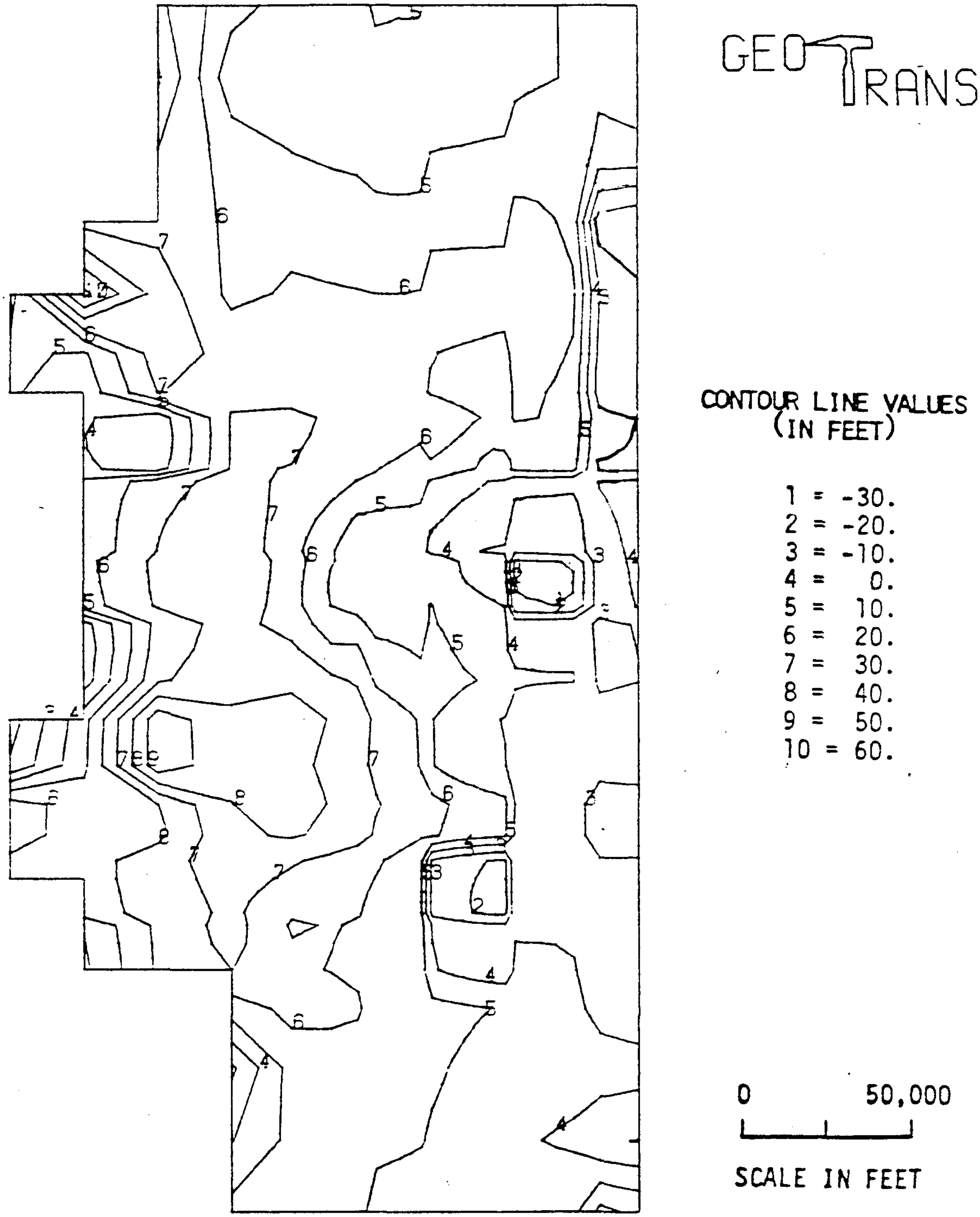


Figure 5.17 Computed Water Table From Run T-5.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The conclusions are divided into two parts, those that deal with the hydrogeology of Volusia County and those concerning the modeling approach.

Conclusions about the hydrogeology of Volusia County include:

(1) Recharge near Rima Ridge to the upper Floridan was of the same magnitude as that given by SJRWMD; it was generally lower at other locations.

(2) The flow system under Volusia County achieved steady-state within a few months after new stresses were applied. The concentration distribution of chloride takes much longer to reach steady-state. Stresses that were imposed on the system many years ago still may be affecting changes in concentration.

(3) Several different transient simulations were made using various combinations of pumpage and recharge. Conclusions from these runs include:

* The effects of well production for 50 years at present locales and rates were most noticeable at the St. Johns River and Atlantic Coast boundaries. The most radical changes in concentration and potentiometric surface were found in the area adjacent to the Daytona Beach wellfield.

* Simulating present well production while severely decreasing recharge indicated the potential for a major decrease in the thickness of the fresh water lens adjacent to DeLand Ridge. In addition, severe declines in the upper Floridan potentiometric surface near the Daytona Beach area may be expected during times of drought.
* Increasing the recharge levels showed the potential for large increases in the thickness of the fresh-water lens adjacent to DeLand Ridge and more generally for increased recharge to offset most of the well production. When the results of simulations including changes in recharge rates were considered in context with the quickness that the flow system reaches steady-state, the sensitivity of Volusia County's water supply to severe weather conditions and/or poor land management becomes quite apparent.
* Increasing the well production rates in present locations caused a major decline in the upper Floridan potentiometric surface with changes most severe in the Daytona Beach area. Water quality degraded near the St. Johns River and Atlantic Ocean with the area near Daytona Beach showing the potential for large changes in concentration level.
* The addition of a central Volusia County wellfield to the present well production yielded relatively

small declines in potentiometric surface levels except in areas adjacent to the wellfield. It was interesting to note that the use of the central Volusia County wellfield as opposed to increasing production in the Daytona Beach wellfield is a positive step towards prevention of water quality degradation in the Daytona Beach area.

* The simulation of production only from the central Volusia County wellfield indicated the relatively small effect this field alone would have on the fresh water lens near DeLand Ridge.

(4) The springs near the St. Johns River were sensitive to changes in recharge. Well production in central Volusia County had less of an effect on these springs than increases in production near the St. Johns River.

Conclusions on the modeling approach are:

(1) The general approach of starting with the simple and proceeding to the more complex was very appropriate for modeling the hydrogeology of Volusia County. The preliminary study using a cross-sectional model provided a cost-effective means to gain experience with the Volusia County system. Input was easy, as was interpretation of output, and many sensitivity simulations could be made inexpensively. The experience gained allowed additional savings of money and mantime when the three-dimensional modeling was performed.

(2) Confining beds do not have to be explicitly included as additional layers. Instead, they may be included by appropriately modifying the vertical interblock transmissibility terms.

(3) Because of the effect of the increased transmissivity to the entire Floridan aquifer flow system, the lower Floridan should be included in any modeling effort.

(4) Because the variable leakage depended upon changes in water level in the water table aquifer, this layer should also be included in any modeling effort.

(5) Given the size of the grid blocks used in this simulation, a backward difference scheme may be used to represent the convective transport term.

(6) Based on the various layering used for the simulations, three layers were adequate to simulate the Volusia County ground water system.

(7) Because of the scale of the vertical dimension compared to the scale of the horizontal dimensions, treating each aquifer as a single layer was appropriate.

(8) Given that one layer per aquifer is utilized, and the relatively low concentration (<1000 mg/l) of brackish water, density contrasts between brackish water and fresh water did not significantly affect simulated flow.

6.2 Recommendations

The recommendations for future work, both field and analysis, on the Volusia County hydrogeology include:

(1) The data set as developed for Volusia County may be used to examine county-wide behavior. If interest is centered around a more localized area, then model refinement will be necessary to obtain the desired local detailed results. For this type of simulation, a method needs to be developed whereby telescoping of regions can be performed by enlarging areas, refining data, and making use of output from the county-wide model, without loss of accuracy.

(2) The approximation of the flow regime is based mainly on reproduction of the potentiometric surface in the upper Floridan aquifer. To more accurately model the transport system, more detailed field data are needed in regards to the water table in the surface aquifer, as the vertical gradient between the surface and Floridan aquifers provides a major driving force for the system.

(3) Additional information is needed about the concentration distribution in the upper Floridan in the central portions of Volusia County. The extent of this fresh water lens in the central portion of the county is a major controlling factor on the system and needs to be more accurately defined. In addition, more information is needed pertaining to concentration versus depth throughout the system.

(4) Ground water modeling and data collection are an integrated approach to understanding any ground water system. This study represents the first of its kind to simulate solute transport in Volusia County. Besides utilization in a predictive mode, the model should continue to be used in

conjunction with data collection to assess what data is needed to refine the model for more accurate predictive analyses.

7.0 REFERENCES

Bush, P.W., 1978, Hydrologic Evaluation of Part of Central Volusia County, Florida, U.S. Geol. Surv. Water-Resources Investigations 78-89, 50 p.

Intera, 1979, Revision of the Documentation for a Model for Calculating Effects of Liquid Waste Disposal in Deep Saline Aquifer, U.S. Geol. Surv. Water-Resources Investigations 79-96, 73 p.

Intercomp, 1976, A Model for Calculating Effects of Liquid Waste Disposal in Deep Saline Aquifers, Part I and II, U.S. Geol. Surv. Water-Resources Investigations 76-61.

Johnson, R.A., 1981, Structural Geologic Features and Their Relationship to Saltwater Intrusion in West Volusia, North Seminole, and Northeast Lake Counties, Florida, St. Johns River Water Management District Technical Report No. 9, 32 p.

Knochenmus, D.D. and M.E. Beard, 1971, Evaluation of the Quantity and Quality of the Water Resources of Volusia County, Florida, Florida Dept. of Nat. Resources, Bur. Geol. Rept. Inv. 57, 59 p.

Mercer, J.W. and C.R. Faust, 1981, Ground Water Modeling, National Water Well Association, Worthington, OH, 60 p.

Tibbals, C.H., 1981, Computer Simulation of the Steady-State Flow System of the Tertiary Limestone (Floridan) Aquifer System in East-Central Florida, U.S. Geol. Surv. Water-Resources Investigations Open-File Report 81-681, 31 p.

Wyrick, G.G., 1960, The Ground Water Resources of Volusia County, Florida, Florida Geol. Surv. Rept. Inv. 22, 65 p.