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WEKIVA RIVER BASIN GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELING STUDY

PHASE I: REGIONAL GROUNDWATER FLOW MODEL DEVELOPMENT

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

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EXECUTIVE SUMMARY

This report presents the results of the first phase of a three-phase study of the Wekiva River basin. The overall objective of the study is to provide the St. Johns River Water Management District with a tool to aid in the establishment of minimum groundwater levels within the basin to protect the quality of its water resources. The objective of Phase I was to develop a three-dimensional groundwater flow model of the Floridan Aquifer system that encompasses the Wekiva River Basin. This regional-scale model will be used to determine boundary flows and boundary conditions for two- and three-dimensional flow and saltwater transport models of a smaller sub-regional area.

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. Overall simulated water levels agree with observed levels. The fact that simulated results for 1988 conditions were less accurate than those simulated 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 simulated groundwater levels associated with pumping conditions in 1988 were consistent with the groundwater levels defined (average of observed May and September potentiometric surfaces).

Simulated declines in spring discharges between predevelopment and 1988 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 largely due 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 presented in this Phase I report is believed to provide an 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 for the Phase II and Phase III solute transport models. Further evaluation of the springs should be made during Phase III in an effort to better account for observed discharges.

Subsequent modeling efforts in the project area would benefit from additional data on the Lower Floridan aquifer, particularly water levels and transmissivity data. In particular, a deep observation well at Wekiva or Rock Springs could provide important information on the influence of the Lower Floridan on these springs, both in terms of water quantity and quality.

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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). 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

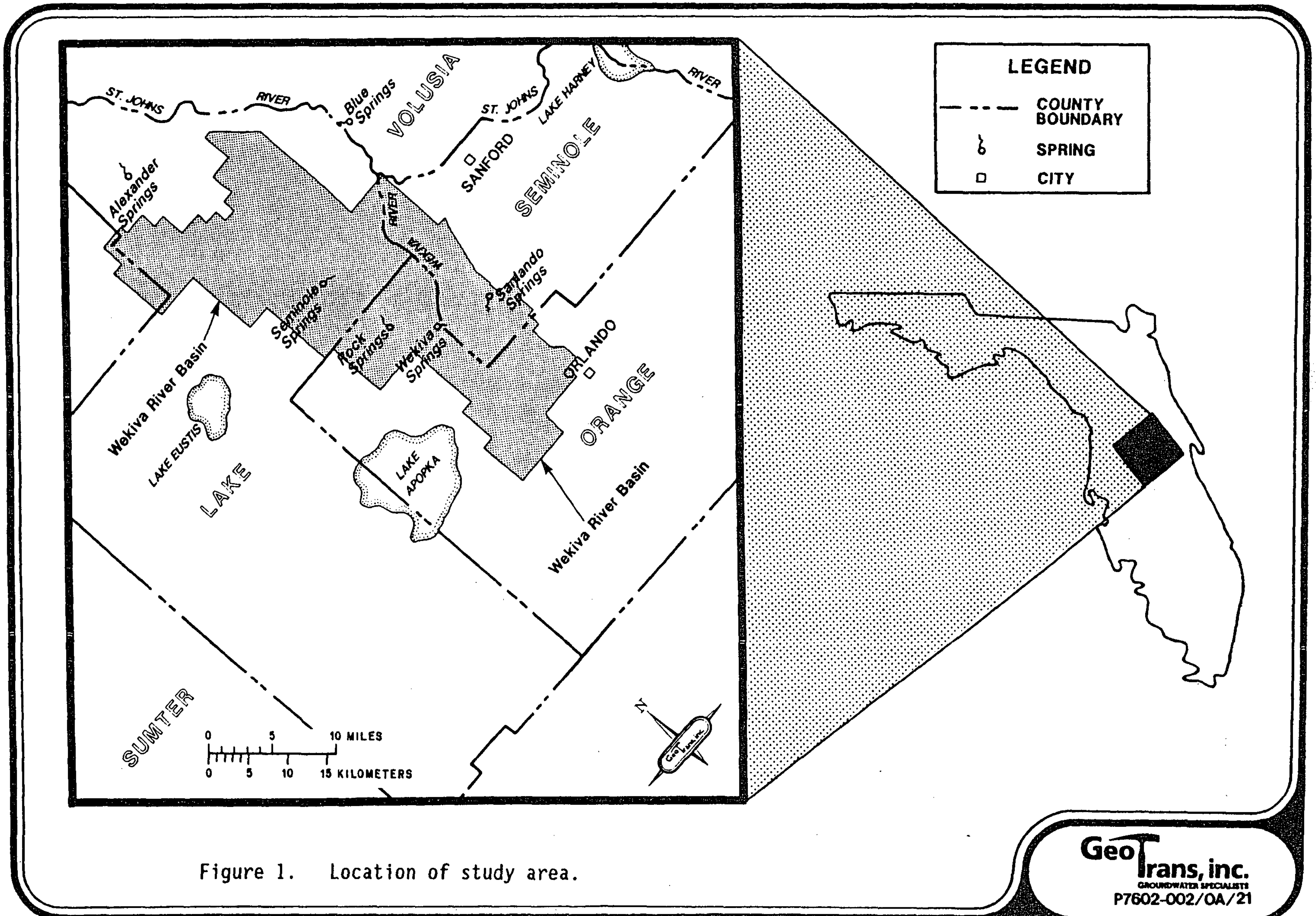

Figure 1. Location of study area.

already contain water with chloride concentrations in excess of 250 milligrams per litre (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 first phase of a three-phase study of the Wekiva River basin. The overall objective of the study is to provide the St. Johns River Water Management District with a tool to aid in the establishment of minimum groundwater levels within the basin to protect the quality of its water resources. Emphasis is on the Floridan aquifer system.

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

- The potentiometric surface of the Upper Floridan aquifer within the project area;
- The flow magnitudes of various springs within the project area;

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

The objective of Phase I is to develop a three-dimensional groundwater flow model of the Floridan aquifer system that encompasses the Wekiva River basin. This regional-scale model will be used to determine boundary flows and boundary conditions for two- and three-dimensional flow and saltwater transport models of a smaller sub-regional area. Specific tasks associated with Phase I include the following:

- Task 1—Provide the District with a technical memorandum prior to the start of numerical modeling which summarizes the hydrogeology of the study area and outlines the general approach to modeling in Phase I.
- Task 2—Construct and calibrate a three-dimensional, numerical groundwater flow model of the regional groundwater flow system using the modular finite-difference code MODFLOW (McDonald and Harbaugh, 1984).

- Task 3—Conduct a one-day reporting and training briefing at District headquarters on the model and on the ModelCad software package (Geraghty and Miller, 1989).

The technical memorandum specified in Task 1 was completed and forwarded to the District in October 1990 (Skipp, 1990). The present report summarizes the work conducted in completing Task 2.

2 HYDROGEOLOGY OF STUDY AREA

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

2.1 HYDROGEOLOGIC FRAMEWORK

2.1.1 Surficial Aquifer

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

2.1.2 Floridan Aquifer System

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 on the top of the Floridan aquifer system (Figure 2) 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.

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

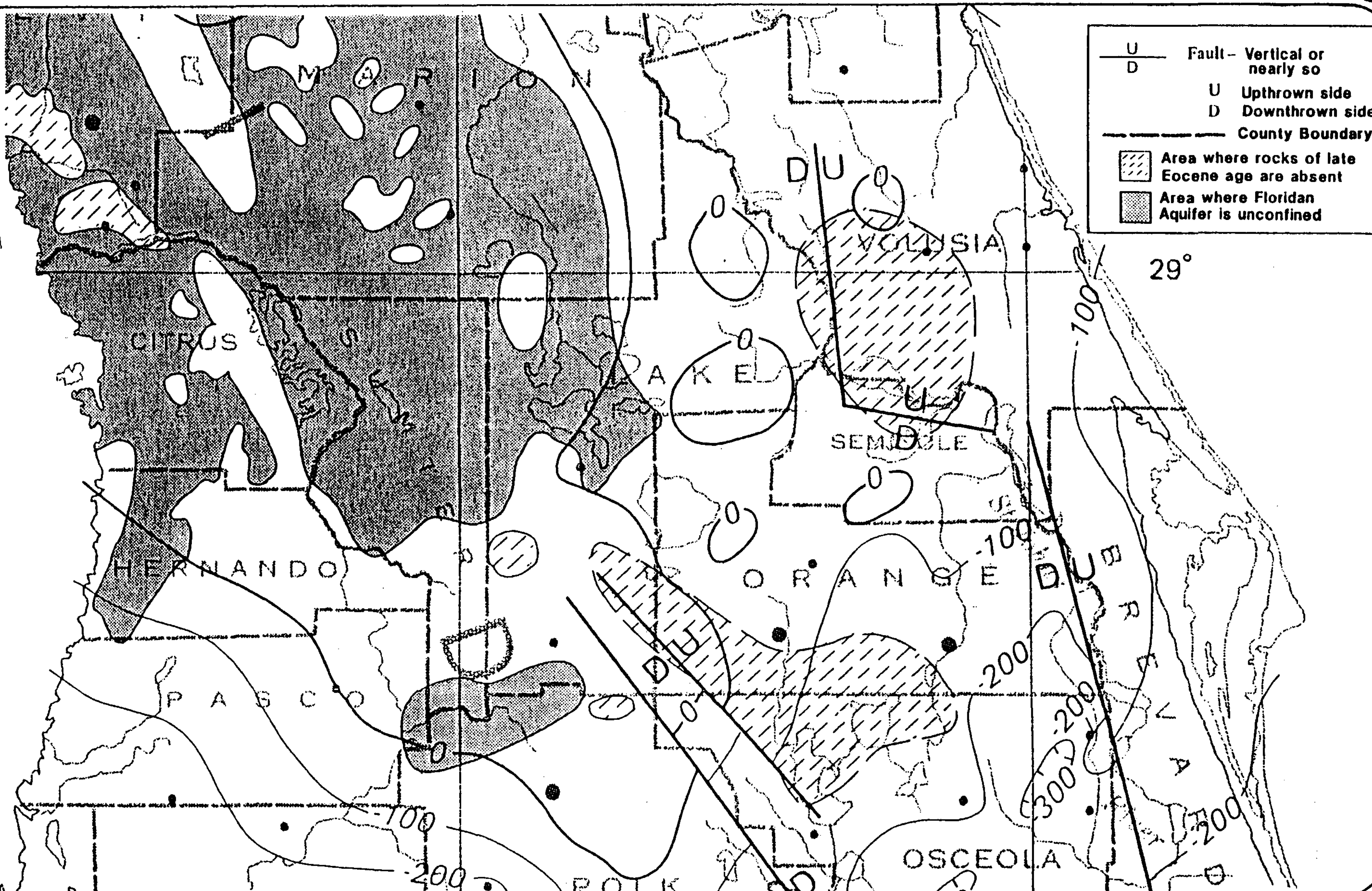

Figure 2. Altitude of the top of the Floridan aquifer relative to mean sea level, in feet (from Miller, 1986), and including fault-line.

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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 3).

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

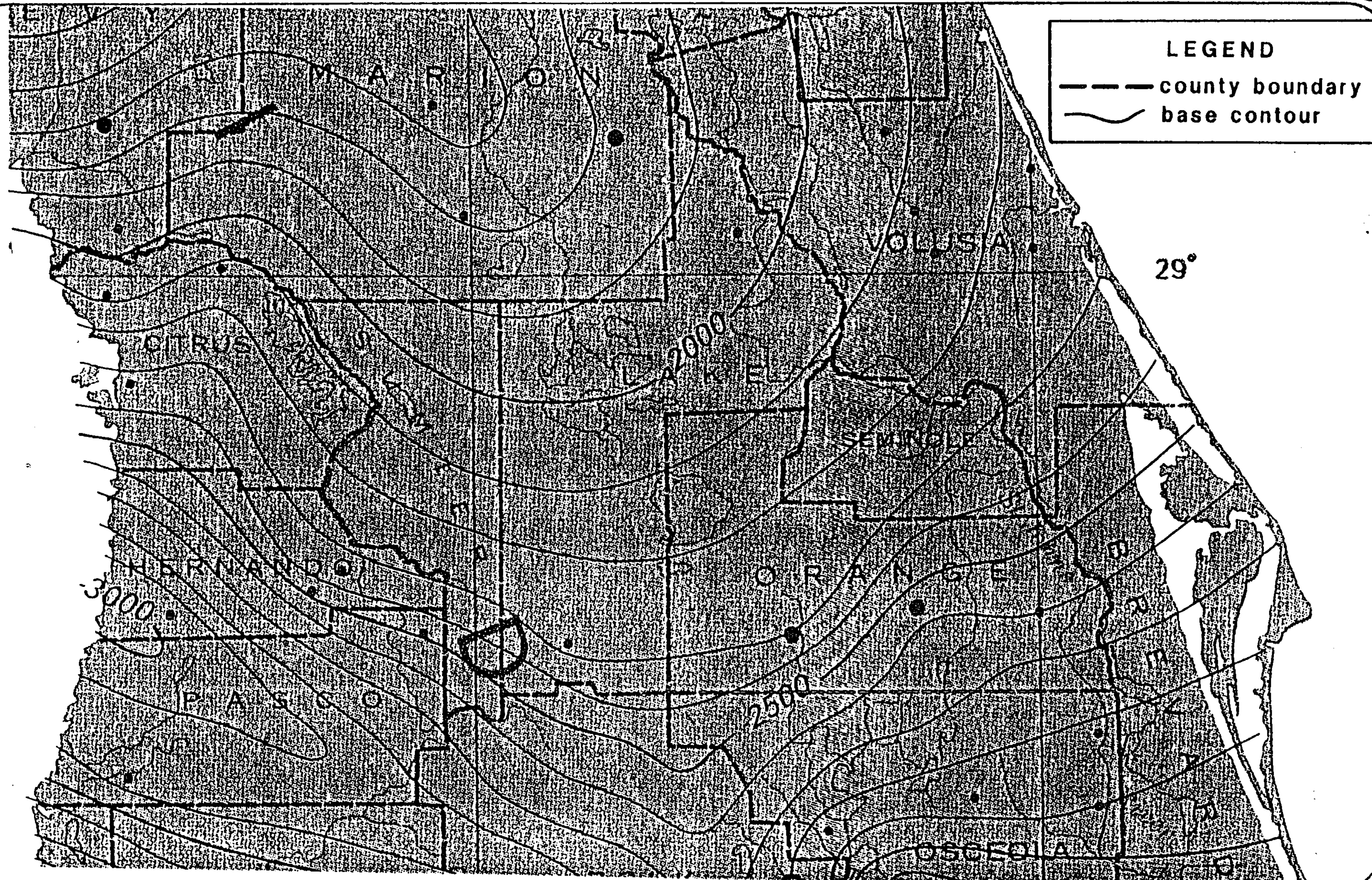

Figure 3. Altitude of the base of the Floridan Aquifer relative to mean sea level, in feet (from Miller, 1986).

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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 permeable, soft, chalky limestone and dolomitic limestone sequence referred to as the "middle semiconfining unit" (Figure 4). 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 semiconfining unit occurs at elevations between 300 and 350 ft below MSL. The middle semiconfining unit is leaky, and the hydraulic connection between the Upper and Lower Floridan aquifers varies from place to place (Tibbals, 1990). However, given the relatively little head differential between the upper and lower aquifers, typically less than 4-5 feet, it is apparent that this unit provides only minimal impedance to flow between them. Lichtler et al. (1968) reported that water levels in the Upper Floridan

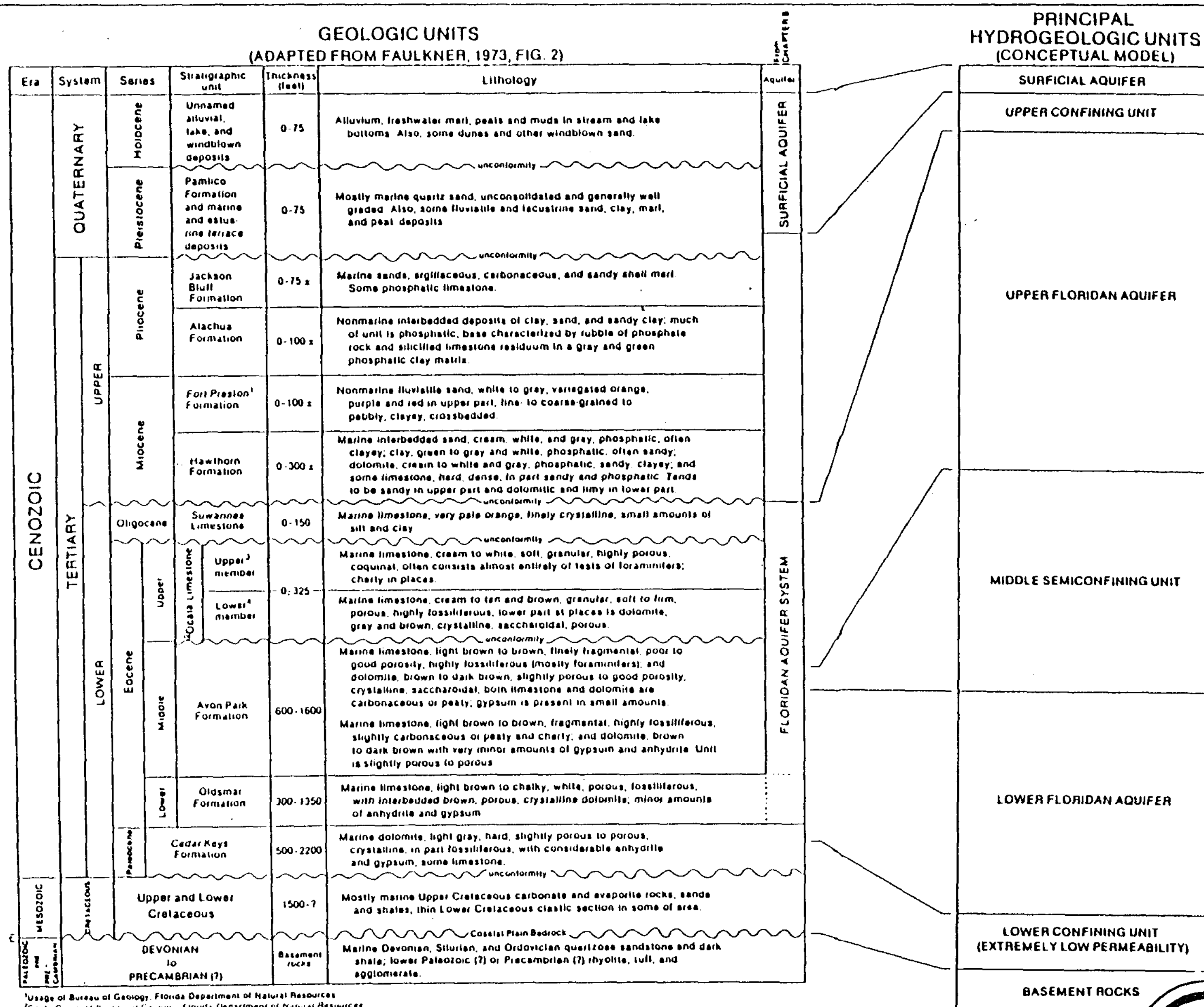

Figure 4. Geologic and hydrogeologic units in the project area (from Tibbals, 1990).

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in the Orlando area displayed a "direct and immediate correlation" with pumping from wells in the Lower Floridan aquifer.

2.2 AQUIFER HYDROLOGY

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

Surficial aquifer hydrology differs from the Floridan in many ways. The surficial 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 seldom 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. In aquifer recharge areas, the water table in the surficial aquifer system is above the potentiometric surface of the Upper Floridan. The rate of recharge depends on the difference between hydraulic head in the surficial aquifer system and the Upper Floridan and on the thickness and permeability of the confining beds. Recharge rates are proportional to head difference and confining bed permeability and are inversely proportional to confining bed thickness. Within the study area, recharge rates are as high as 20 in/yr (Tibbals, 1990).

The 20 in/yr rate is limited by the amount of evapotranspiration and surface runoff that can be captured by lowering the water table. Tibbals (1990) estimates that the minimum evapotranspiration rate in east-central Florida is 30 in/yr and the maximum is 48 in/yr, depending on water-table depth. The minimum occurs when the water table is at or below 13 feet below land surface, the maximum when it is at land surface. Thus, a maximum of 18 inches can potentially be captured by groundwater. Based on an average precipitation for the project area of 53 in/yr, 5 in/yr on average is also lost by overland runoff or groundwater runoff to streams (P-ETMAX = 5 in/yr). We assume that as much as 2 in/yr of the 5 in/yr going to runoff can also be captured. Thus, 20 in/yr is the maximum downward leakage rate (recharge) available to the Upper Floridan aquifer in the project area.

In addition to natural downward leakage, Floridan 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, the wells 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 drainage wells were used to drain wetlands, to dispose of surplus effluent from industrial sites, and to receive effluent from septic tanks. While estimates of the quantity of water entering the aquifer are as high as 50 million gallons per day (mgd), Tibbals (1990) used a rate of 33 mgd in his simulations.

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

Nineteen named Upper Floridan springs in the study area have discharges of 1 cubic foot per second (ft^3/s) or more (Table 1). 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). They are Alexander Springs Creek (just upstream of its confluence with Tracy Canal), Lake Jessup, northern Lake Harney, and southern Lake Harney (Table 2). In several areas, including the St. Johns River and Lake Jessup, depressions in the potentiometric surface of the Upper Floridan indicate relatively large groundwater discharges by other than known springs.

Table 1. Springs in the project area.

Name	Latitude			Longitude			Discharge (cfs)		Chloride
	Deg.	Min.	Sec.	Deg.	Min.	Sec.	Maximum	Minimum	Maximum (mg/l)
Apopka Spring	28	34	0	81	40	51	70.40	30.00	7.00
Blue Sp. (Lake Co.)	28	44	55	81	49	41	-	-	7.00
Holiday Spring	28	43	54	81	49	5	4.75	3.00	8.00
Alexander Spring	29	4	50	81	34	30	162.00	74.50	230.00
Camp La-No-Che Spring	28	57	2	81	32	24	1.10	0.66	10.00
Messant Springs	28	51	21	81	29	56	24.60	18.40	10.00
Seminole Spring	28	50	44	81	31	22	37.10	10.20	6.00
Blue Springs	28	56	50	81	20	23	214.00	63.00	780.00
Gemini Spring	28	51	44	81	18	39	-	-	580.00
Rock Springs	28	45	20	81	29	58	83.00	52.00	7.50
Witherington Springs	28	43	53	81	29	22	12.00	3.80	7.50
Wekiva Springs	28	42	43	81	27	36	92.00	62.00	10.00
Clifton Spring	28	41	56	81	14	14	-	-	140.00
Miami Springs	28	42	36	81	26	34	7.40	4.40	7.00
Sanlando Springs	28	41	19	81	23	44	33.00	4.30	10.00
Palm Springs	28	41	27	81	23	34	12.00	7.50	10.00
Starbuck Springs	28	41	48	81	23	28	21.40	12.00	13.00
Lake Jessup Springs	28	42	36	81	16	5	1.40	0.70	12.00
Island Spring	28	49	22	81	25	3	-	-	1200.00

Source: Rosenau, et al., 1977; USGS Measurements
cfs - cubic feet per second; Deg. - degrees, Min. - minutes, Sec. - seconds

Table 2. Model location of project area springs and related variables.

	Name	Row	Column	Pool Elevation (ft)	Aquifer Head	Discharge (cfs)	CD (sfd)	
1	Apopka Spring	22	6	67	77	-	1.30E+06	**
2	Blue Sp. (Lake Co.)	5	7	65	73	3	3.24E+04	
3	Holiday Spring	6	7	65	73	3.9	4.21E+04	
4	Alexander Spring & Creek	2	32	9	18	100+30	1.25E+06	
5	Camp La-No-Che Spring	6	29	34	43	1	9.60E+03	
6	Messant Springs	12	26	26	35	20	1.92E+05	
7	Seminole Spring	11	23	32	36	36	8.40E+05	**
8	Blue Springs *	14	35	1	8	40	4.94E+05	
9	Gemini Spring	21	33	1	13	8	5.76E+04	
10	Rock Springs	18	17	NA	35	65	2.24E+06	**
11	Witherington Springs	21	16	25	40	.4	2.30E+04	
12	Wekiva Springs	24	17	13	32	74.2	3.40E+05	**
13	Clifton Spring	32	30	3	35	1.7	4.59E+03	
14	Miami Springs	25	18	15	35	5	2.16E+04	
15	Sanlando Springs	29	21	26	32	19	2.42E+05	**
16	Palm Springs	29	21	26	32	10	1.28E+05	**
17	Starbuck Springs	29	22	26	32	17	2.10E+05	**
18	Lake Jessup Springs	32	29	3	35	1	2.70E+03	
19	Island Spring	18	28	2	15	6	3.99E+04	
20	Alexander Springs Creek	4	33	5	15	30	2.59E+05	
21	Lake Jessup	32	33	1	20	5.6	2.55E+04	
22	St. Johns River	32	36	1	15	8.9	5.49E+04	
23	L. Harney, North *	32	38	2	5	10.1	2.91E+05	
24	L. Harney, South *	34	37	3	10	12.3	1.52E+05	

Note: All elevations are referenced to mean sea level; Esimated spring discharges from Tibbals, 1990
sfd - square feet per day
* Only part of the basin in model area.
** Conductance adjusted during model calibration.

3 REGIONAL 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), and HydroGeologic (1990). The work by Bush (1982) included the entire Floridan aquifer system at a spatial resolution of 256 mi^2 (16 mi x 16 mi). Tibbals (1981) carried this analysis further by focusing on the east-central Florida area and a more refined spatial resolution of 16 mi^2 (4 mi x 4 mi). His later work in 1990 utilized the same model and incorporated a transient analysis of the effects of pumping 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. Likewise, we have used this model as a starting point in our analysis.

3.2 COMPUTER CODE

The U.S. Geological Survey modular, three-dimensional, finite-difference model (MODFLOW) was used to simulate groundwater flow in the project area. The program uses a block-centered discretization of the flow domain and the resulting linear equations are solved using the strongly implicit procedure (SIP). The program allows variable grid dimensions, heterogeneous distribution of aquifer parameters and variable layer thicknesses. MODFLOW also has several boundary conditions of options including specified head, head dependent flux (drains), and specified flux. The program is widely used, well tested, and extensively documented (McDonald and Harbaugh, 1984).

3.3 CONCEPTUAL MODEL

The hydrogeology of the project area has been described in Section 2.2. However, prior to presenting the development of the numerical model, it is worthwhile to present the most important assumptions in that model, which are as follows:

1. The groundwater system consists of three aquifers: the surficial or water-table aquifer, the upper permeable zone of the Floridan aquifer (Upper Floridan) and the lower permeable zone (Lower Floridan).
2. Each aquifer is separated from adjacent aquifers in varying degrees by less-permeable zones or confining layers.

3. The surficial aquifer serves as a source of diffuse downward leakage to the Upper Floridan (recharge) as well as a sink of diffuse upward leakage (discharge) from the Floridan. The elevation of the water table is kept constant in the model and the rate of leakage is proportional to the difference between it and the potentiometric surface in the Upper Floridan aquifer.
4. All water that enters the Upper Floridan aquifer is ultimately discharged via either diffuse discharge, springs, or wells.
5. Groundwater flow in the two permeable zones of the Floridan aquifer is assumed to be predominantly horizontal while flow through the confining bed is primarily vertical. This is justified based on the large contrast between the transmissivity of the permeable zones and the confining beds.
6. Head differential between the Upper Floridan and Lower Floridan aquifers are between 0-5 feet on a regional basis (Tibbals, 1981; 1990; Lichtler et al., 1968). Lateral hydraulic boundaries of the two zones are assumed to be similar as a result.

3.4 MODEL BOUNDARIES AND GRID

The model boundaries (Figure 5) are designed to coincide as much as possible with natural groundwater boundaries and to encompass the entire Wekiva River basin. The base of the Floridan aquifer is also treated as an impermeable boundary. The beds of anhydride that constitute this base have very low permeability (Miller, 1986; Tibbals, 1990). The lateral boundaries coincide with groundwater flow lines while the downgradient boundary coincides with a groundwater discharge divide (Figure 6). All lateral boundaries are treated as no-flow in the regional flow model. All groundwater elevations are referenced to mean sea level (msl). Overall, given the fact that water levels are very similar, the boundaries of the model for the upper and lower permeable zones are assumed to be the same, however the location of the lateral no-flow boundary in the Lower Floridan aquifer is defined as being different from that of the Upper Floridan, as shown in Figure 5. This was done to reduce potential boundary effects in the model caused by pumping in the Orlando area. Significant groundwater withdrawals from the Upper Floridan occur in this area and it is probable that the flow boundary of the Upper Floridan aquifer is somewhat different from that of the Lower Floridan. The presence of a no-flow boundary so

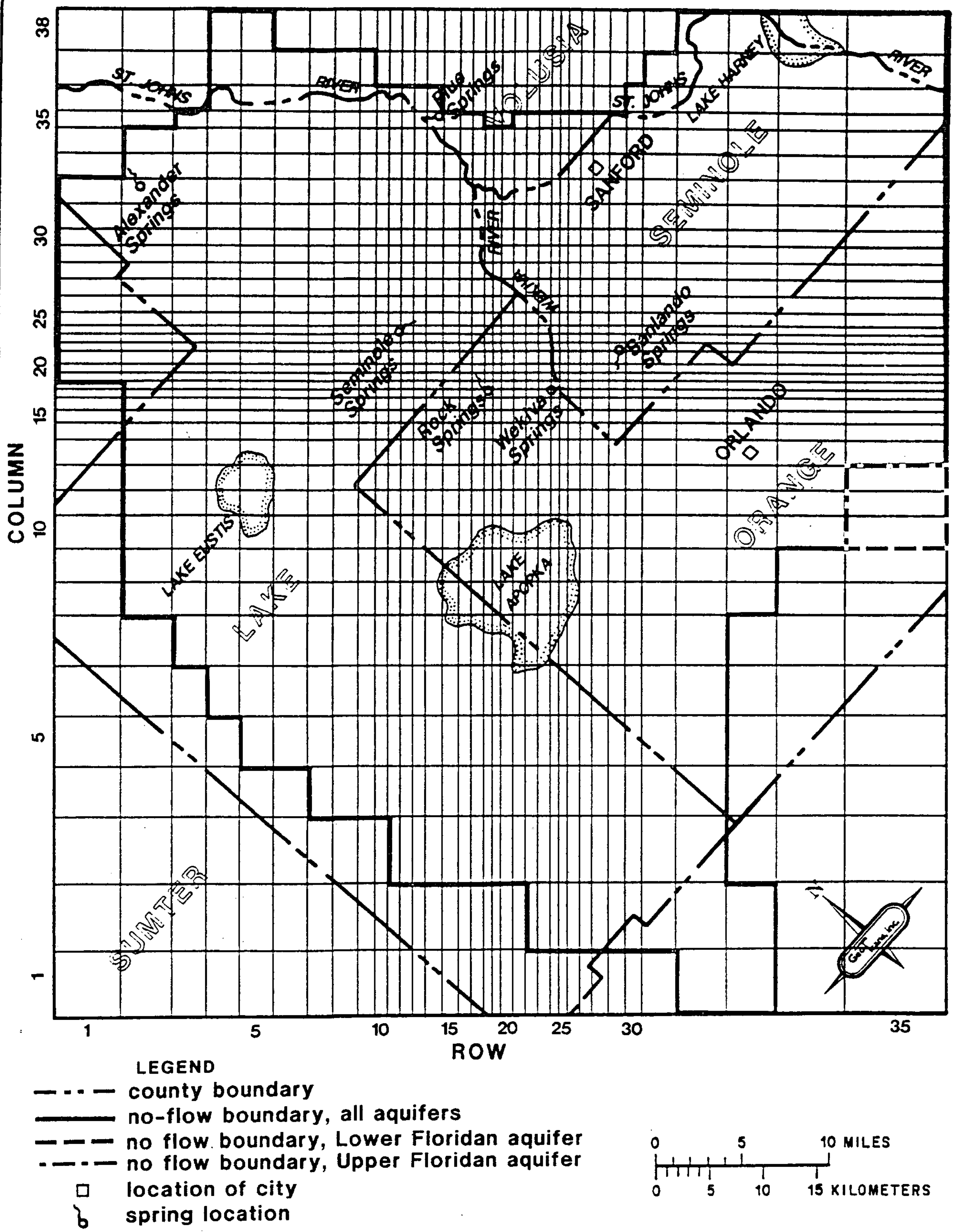

Figure 5. Finite-difference grid and boundary conditions for the regional flow model.

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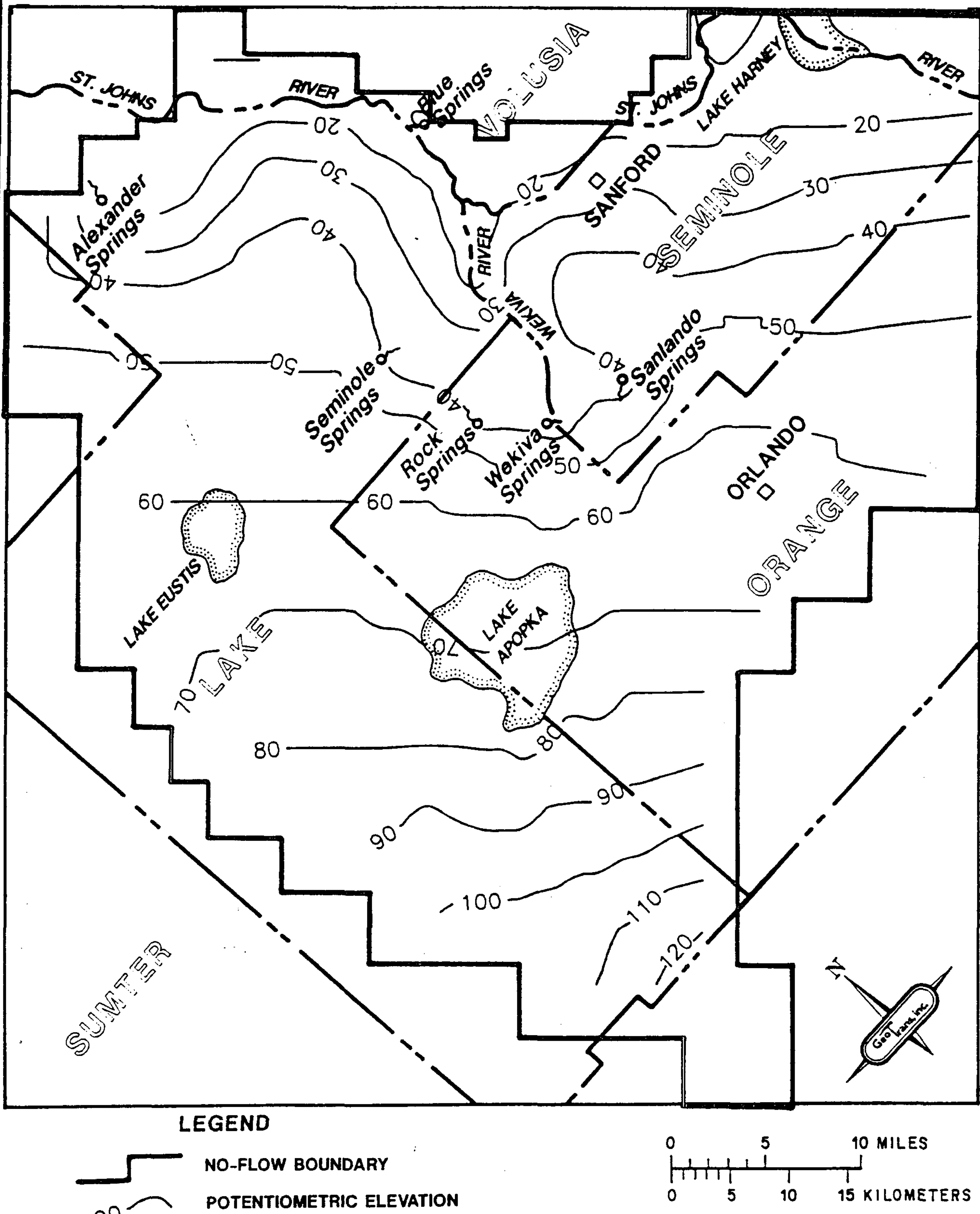

Figure 6. Estimated potentiometric surface of the Upper Floridan aquifer under predevelopment conditions, ft msl (after Tibbals, 1977; 1981).

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close to the pumping centers could cause simulated drawdowns to be greater than they really are.

The surficial aquifer in the model is treated as a source/sink for the Upper Floridan layer via the imposition of a fixed water table. Flow between the two aquifers is assumed to be proportional to their head differential. The water table aquifer is unlikely to provide more than 20 inches per year (in/yr) to the Floridan aquifer in recharge at any particular location (Tibbals, 1990).

A potentially important consequence of utilizing a fixed water table in the surficial aquifer is that the aquifer acts as an infinite source of water to the Upper Floridan aquifer. That is, the greater the decline in the head in the Upper Floridan model layer, more water will be delivered by downward leakage. This is unrealistic. The additional downward leakage that can be induced into the Upper Floridan is limited to that which can be captured from three sources: water in storage in the overlying units, water that was previously lost by evapotranspiration from the water table, and groundwater runoff.

MODFLOW offers a convenient way to limit the amount of downward leakage from the surficial aquifer to the Upper Floridan aquifer. The MODFLOW code has a confined-unconfined option (LAYCON = 2 in the BCF package) that can be used to model aquifers that are both overlain by a surficial aquifer and are likely to change from being confined to unconfined in response to simulated stresses. Under this option, if the simulated potentiometric surface of an initially confined aquifer drops below its specified top within an area of a given model, MODFLOW will begin to simulate the aquifer as being unconfined within the area. Accordingly, the simulated vertical hydraulic gradient between the overlying surficial aquifer and the formerly confined aquifer will be calculated in the affected area by using the difference in altitudes of the water table of the surficial aquifer and the top of the formerly confined aquifer, rather than the difference in altitudes of the water table and the potentiometric surface of the formerly confined aquifer. Under this new condition, the rate of simulated downward leakage between the surficial aquifer and the formerly confined aquifer will be the maximum that is possible in the affected area, assuming the water table of the surficial aquifer is represented as a constant-head boundary in the model. This is due to the following: (1) the simulated rate of downward leakage between the surficial aquifer and formerly confined aquifer will be proportional to the simulated vertical hydraulic gradient between the two aquifers; (2) the simulated vertical hydraulic gradient will be dependent on the displacement between the water table and the top of the formerly confined aquifer; and (3) the displacement will be fixed and therefore will not be subjected to further increases.

There is little possibility that the altitude of the potentiometric surface of the Upper Floridan aquifer will drop below the top of the Upper Floridan aquifer under present or foreseen pumping conditions. However, by entering artificial top-of-the-aquifer altitudes into the model, a maximum rate of simulated leakage from the surficial aquifer to the Upper Floridan aquifer can be specified. This procedure has been used to specify the maximum rate of downward leakage in the present model as 20 in/yr, in accordance with the discussion in section 2.2. Thus, if simulated pumping causes the potentiometric surface of the Upper Floridan aquifer to drop below the artificial top-of-the-aquifer altitude at a particular node, the leakage rate simulated by the model becomes fixed at a maximum of 20 in/yr at that node. This is because the leakage computed by the model under this condition is based on the difference between the altitudes of the water table and the artificial top of the Upper Floridan aquifer. Although the simulated rate of leakage becomes fixed, the difference between the water table of the surficial aquifer and the potentiometric surface of the Upper Floridan aquifer can continue to increase. At the same time, transmissivity of the aquifer is kept constant (i.e., not adjusted for apparent change in saturated thickness). When the potentiometric surface in the Floridan aquifer drops below the artificial top-of-the-aquifer altitude (A), the equation for leakage per unit area (q) in the model becomes:

$$q = \frac{k'}{b'} (H_s - A) \tag{1}$$

where: k' is the vertical hydraulic conductivity of the confining bed, [l/t];
b' is the thickness of the confining bed, [l]; and
H_s is the head in the surficial aquifer [l].

The result of treating leakage this way in the model is compatible with what will happen in the real system. The implications of this boundary condition are discussed in Section 6.1.

Development of an appropriate model grid, both in the horizontal and vertical planes, requires consideration of, among other things: the desired level of predictive detail, data availability, hydraulic gradients, hydraulic and geologic zonation, and overall model objectives. The finite-difference grid used in this analysis was designed to provide the greatest degree of resolution in the vicinity of the Wekiva River and in the area where much of the groundwater from the regional project area converges to be discharged via either springs or diffuse discharge. The spacing in the direction of grid rows ranges between one-half and four miles, and column spacing ranges between one-half mile and six miles.

Ideally, the vertical grid to be used in a groundwater flow model must be designed to allow reasonably accurate representation of pumping intervals, account for significant vertical variations in hydrogeologic zonations, and account for important data limitations. All three factors must be balanced to develop an optimum layering.

The Upper Floridan aquifer is approximately 350 feet thick throughout the project area and includes the Ocala Limestone (where present) and the upper part of the Avon Park Formation (Miller, 1986). Data on the differences in permeability between the two units is extremely limited. In general, however, groundwater flow is typically greatest in the top portion of the aquifer (in the Ocala and along the contact between it and the Avon Park Formation) and decreases with depth. Such variations will have greater importance to the transport models. On the other hand, the Upper Floridan aquifer is commonly treated as a single unit when developing potentiometric surface maps and when evaluating pumping demands. In addition, vertical gradients between the two units are typically quite small, except, perhaps, in discharge areas. However, discharge areas occur further downgradient of the likely boundary for the subregional model. Given these considerations and the fact that few data are available to support a distinction between the two zones, the Upper Floridan is treated as a single model layer.

The Lower Floridan aquifer also will be considered a single layer in the model. This aquifer averages approximately 1,400-feet thick and includes the lower part of the Avon Park Formation (approximately 700 feet), the Oldsmar Formation (500 feet), and the upper part of the Cedar Keys Formation (Miller, 1986). There are significant withdrawals from the Lower Floridan aquifer in the Orlando area for public and industrial supply purposes. These are primarily from the upper 200 to 400 feet of the aquifer (Szell, 1987) in the Avon Park Formation. Data on water levels in the Lower Floridan aquifer, as well as hydraulic characteristics, are nearly non-existent and, therefore, the Lower Floridan aquifer will also be represented as one layer.

3.5 TREATMENT OF SPRINGS

Nineteen springs with discharges equal to or in excess of one cubic foot per second (cfs) have been identified in the active model area (Rosenau, et al., 1977). Five additional discharge locations were identified by Tibbals (1990) based on stream-gaging measurements and water quality analysis. These nineteen known springs have been represented in the numerical model using the MODFLOW drain package. Discharge from the springs is calculated by the model using the equation:

$$Q = CD\ (H_1 - D_1) \tag{2}$$

where: Q is the rate of flow to the spring $[l^3/t]$;
CD is the spring conductance $[l^2/t]$;
H_1 is the head in the aquifer at the drain block [l];
D_1 is the spring pool elevation [l].

The equation only applies when $H_1 \geq D_1$; that is, the spring only acts as a sink, never as a source. This treatment is similar to that used by Tibbals (1981).

Spring discharge rates used in model simulations are estimated for predevelopment conditions and were generally taken from those estimated by Tibbals (1981; 1990) and are listed in Table 2. Blue Spring and the two Lake Harney discharges are assumed to be less than those reported by Tibbals (1981) because not all of their respective recharge basins are included in the modeled area. The majority of Blue Spring's discharge (approximately 75%) is obtained from recharge in Volusia County, to the east of the model domain, which represents approximately 65 percent of the spring's recharge area (Tibbals, 1990, Figure 21). Therefore, 25 percent of the total discharge of Blue Springs comes from 35 percent of the recharge area within the model boundaries. Blue Springs discharge in the model was treated accordingly. Lake Harney discharges were treated similarly.

Spring conductance is calculated by dividing each spring's predevelopment discharge by the head differential between the spring pool and estimated predevelopment head in the Upper Floridan aquifer (Table 2). Some conductance values were refined during model calibration. Pool elevations were obtained from the U.S. Geological Survey (C. Tibbals, personal communication, 1990); aquifer head values were estimated from potentiometric surface maps for predevelopment conditions (Johnston et al., 1980; Tibbals, 1981; Tibbals, 1977). Total spring discharge under predevelopment conditions (not including Apopka Spring) is estimated at approximately 512 cfs or 44.2 x 10^6 ft^3/day. No discharge is presented for Apopka Spring because recent discharge measurements by the USGS (58.5 to 70.4 cfs) are far in excess of the rate estimated by Tibbals (28.6 cfs) in 1990. For the purposes of the predevelopment calibration a value of 70.4 cfs was used to represent the discharge at Apopka Springs.

Aquifer head and, consequently, spring conductance, as calculated in the model are dependent on grid resolution. Estimated aquifer head will vary depending on the size of the finite-difference grid block in which the spring is located. This is particularly true since hydraulic gradients in the immediate vicinity of the larger springs will be quite steep. For example, in the present analysis, Wekiva Springs is located in a grid block which covers 0.25 square miles (0.5 mile x 0.5 mile) while in Tibbals' (1981) model it is located in a grid block covering 16 mi^2 (4 miles x 4 miles). According to the estimated potentiometric surface map of predevelopment conditions presented in Tibbals (1977), head in the Floridan aquifer within a two-mile radius of Wekiva Springs varies by as much as twenty-five (25) feet. The coarser-grid model will utilize a lower spring conductance than the finer-grid model due to the greater head differential between the spring pool and the aquifer. If the grid is more resolute, spring-discharge predictions will be more sensitive to simulated groundwater levels.

3.6 WATER-TABLE ELEVATIONS

Water-table elevations were estimated using USGS 1:100,000 and 1:24,000-scale topographic maps. The finite-difference grid was overlaid on the topographic maps and an average elevation for each grid block determined based primarily on the elevation of surface-water bodies within the grid block. In cases where no surface waters were present in the block, elevations of surface waters in surrounding blocks were used.

3.7 GROUNDWATER WITHDRAWALS

The Floridan aquifer provides a source of potable water for a variety of uses -- municipal drinking supplies, industrial processing, domestic drinking water, and agricultural irrigation. However, withdrawals by individual domestic users were not considered in this analysis. For the purposes of the present modeling study, estimates of the quantity of water utilized for these purposes, as well as the locations of withdrawals, were made for the year of 1988 and used for the verification stage of the model. The methodology used for making these estimates is described below.

Municipal and Industrial. Municipal and industrial withdrawals can be accurately estimated because large-scale municipal and industrial users are required to report withdrawal quantities to the District, by month, at quarterly intervals. The locations of municipal and industrial groundwater withdrawals in the project area were provided by the District along with reported monthly withdrawals. Reported quantities are for municipal water-supply treatment plants or industrial facilities, not by individual wells. Total withdrawal rates are assumed to be equally distributed among all wells associated with a particular facility. This may introduce slight error into the simulation of pumping effects, but it is not considered significant. In most cases, actual rates for 1988 were available, however in a few instances, only 1989 rates were known and had to be used.

The total average estimated 1988 rate of groundwater withdrawal by municipal and industrial users within the active model area is 25.3 x 10^6 ft^3/d (189 mgd). The majority, 16 x 10^6 ft^3/d (120 mgd), is pumped from the Upper Floridan aquifer. The remaining 9.3 x 10^6 ft^3/d (69 mgd) is pumped from the Lower Floridan aquifer in the Orlando area. The grid location in the model and average 1988 pumping rates for municipal and industrial users are presented in Table 3 (a complete listing of these users and withdrawal rates is included in Appendix A).

Agricultural. Agricultural withdrawals are more difficult to estimate than municipal/industrial withdrawals since this data are generally not collected by the District. Agricultural water use in the project area was divided into two categories -- citrus and other. The District provided GeoTrans with data on the estimated number of acres by crop type being irrigated and the Section, Township, and Range location. For citrus groves, the majority of the irrigation demand in the project area, pumping rates, were estimated from data provided by the District using the Blaney Criddle model (USDA Soil Conservation Service, 1967; 1970).

The Blaney Criddle model estimates supplemental irrigation requirements based on a variety of factors including crop type, temperature, and rainfall. Temperature

Table 3. Model locations and estimated pumping rates for non-agricultural groundwater withdrawals.

Layer	Row	Column	Pumpage (cfd)	Layer	Row	Column	Pumpage (cfd)
2	34	2	-9.9000E+03	2	27	31	-1.6300E+04
2	34	4	-2.5700E+04	2	26	7	-2.0000E+04
2	34	5	-1.6000E+06	2	26	12	-2.7000E+03
2	34	6	-5.6500E+05	2	26	19	-7.6090E+05
2	34	7	-1.7380E+05	2	26	28	-4.2200E+04
2	34	8	-6.5260E+05	2	25	6	-2.9520E+05
2	34	9	-8.2660E+05	2	25	15	-1.7790E+05
2	34	12	-8.8000E+03	2	25	37	-1.9490E+05
2	34	21	-5.0940E+05	2	24	27	-2.0700E+04
2	34	22	-1.8000E+04	2	23	31	-1.7700E+04
2	34	26	-7.0900E+04	2	23	35	-1.2900E+04
2	34	27	-3.3100E+04	2	23	37	-1.9490E+05
2	34	28	-1.6650E+05	2	22	5	-1.2900E+04
2	34	29	-2.9200E+04	2	22	11	-2.0500E+04
2	34	30	-5.0600E+04	2	22	32	-4.2800E+04
2	34	32	-2.6400E+04	2	22	36	-1.9490E+05
2	33	7	-1.8000E+05	2	21	14	-2.6800E+04
2	33	8	-5.3990E+05	2	21	37	-1.9490E+05
2	33	9	-2.2320E+05	2	20	7	-1.6400E+04
2	33	18	-2.7100E+04	2	20	12	-2.8700E+04
2	33	22	-2.5240E+05	2	20	26	-1.8000E+06
2	33	25	-3.6070E+05	2	20	35	-1.8900E+04
2	33	26	-2.1100E+04	2	19	5	-7.0000E+04
2	33	30	-7.0400E+04	2	18	5	-6.3000E+04
2	32	6	-7.3190E+05	2	18	36	-1.9200E+04
2	32	8	-3.3700E+04	2	17	5	-2.5800E+04
2	32	9	-1.3400E+04	2	17	36	-7.2700E+04
2	32	10	-1.3400E+04	2	16	12	-6.4500E+04
2	32	16	-1.3670E+05	2	16	17	-2.5800E+04
2	32	17	-3.3440E+05	2	16	36	-6.8700E+04
2	32	18	-7.7700E+04	2	14	6	-1.5100E+04
2	32	19	-1.5550E+05	2	14	12	-2.3300E+04

cfd - cubic feet per day

Table 3. Model locations and estimated pumping rates for non-agricultural groundwater withdrawals (Continued).

Layer	Row	Column	Pumpage (cfd)	Layer	Row	Column	Pumpage (cfd)
2	32	21	-6.4990E+05	2	13	4	-1.6970E+05
2	32	22	-1.7220E+05	2	13	23	-3.8000E+04
2	32	23	-1.0460E+05	2	11	12	-1.8100E+04
2	32	27	-8.4000E+04	2	10	3	-2.3400E+04
2	32	28	-2.3800E+05	2	9	12	-3.0000E+03
2	31	7	-2.1000E+03	2	9	19	-1.8030E+05
2	31	8	-3.9000E+03	2	8	7	-4.2400E+04
2	31	15	-1.9400E+03	2	8	13	-3.1700E+05
2	31	18	-1.9700E+04	2	7	7	-9.5400E+04
2	31	19	-4.3200E+05	2	6	10	-1.5650E+05
2	31	22	-2.6100E+04	2	6	12	-1.6650E+05
2	31	23	-2.8000E+03	2	6	13	-4.6500E+04
2	31	26	-2.9480E+05	2	5	6	-1.4000E+05
2	31	27	-7.9100E+04	2	5	13	-2.1700E+05
2	30	3	-1.1740E+05	2	4	10	-7.6800E+04
2	30	9	-4.4900E+04	2	4	11	-9.6900E+04
2	30	17	-5.6100E+04	2	4	16	-5.7980E+05
2	30	20	-5.9400E+04	2	4	19	-6.4300E+04
2	30	21	-8.7400E+04	2	3	7	-3.5230E+05
2	30	26	-1.0540E+05	2	2	7	-6.9600E+04
2	30	31	-4.3430E+05	2	2	8	-5.3000E+03
2	29	3	-2.5000E+05	2	2	13	-2.7300E+04
2	29	8	-2.5310E+05	2	1	8	-7.3000E+03
2	29	9	-8.3600E+04	3	34	17	-1.8840E+05
2	29	10	-1.5930E+05	3	34	14	-7.2350E+05
2	29	14	-9.0000E+03	3	34	13	-1.3498E+06
2	29	15	-5.2520E+05	3	34	12	-7.6520E+05
2	29	16	-4.6200E+04	3	33	21	-6.8600E+05
2	29	17	-6.9500E+04	3	33	14	-1.1411E+06
2	29	18	-3.2000E+03	3	33	13	-3.1180E+05
2	29	24	-4.5930E+05	3	33	12	-3.7820E+05
2	29	25	-1.6700E+05	3	33	10	-2.8210E+05

cfd - cubic feet per day

Table 3. Model locations and estimated pumping rates for non-agricultural groundwater withdrawals (Continued).

Layer	Row	Column	Pumpage (cfd)	Layer	Row	Column	Pumpage (cfd)
2	29	28	-2.0000E+03	3	33	9	-5.6420E+05
2	28	8	-7.5900E+04	3	32	16	-4.5210E+05
2	28	12	-5.8000E+03	3	32	11	-1.5129E+06
2	28	15	-3.5000E+03	3	31	16	-1.7800E+04
2	28	20	-3.4900E+04	3	31	15	-1.9400E+05
2	28	27	-1.7000E+05	3	28	8	-1.1880E+05
2	27	5	-1.6720E+05	3	27	13	-2.7740E+05
2	27	9	-5.2000E+03	3	22	13	-2.7740E+05
2	27	12	-1.3400E+04				
2	27	18	-2.8000E+03				

cfd - cubic feet per day

and rainfall data from four National Oceanographic and Atmospheric Administration weather stations -- Sanford, Clermont, Lake Alfred, and Orlando -- were used and applied to appropriate parts of the project area. The estimated irrigation requirements ranged between a low of 8.7 in/yr (Sanford) to a high of 17.1 in/yr (Lake Alfred). All withdrawals were assumed to be from the Upper Floridan aquifer. The location of irrigated acreage was keyed to individual grid blocks within the regional model by overlaying the finite-difference grid on to a map delineating Section, Township, and Range and assigning the pumping rates from the Blaney Criddle model to the closest grid block. Table 4 lists the model grid locations and rates of all agricultural withdrawals considered in this analysis.

Irrigation groundwater withdrawals for non-citrus crops were less substantial than those of citrus crops. Data were supplied by the District in the form of crop-type and acreage, keyed to Section, Township, and Range. Non-citrus crops considered included watermelon, corn, ferns, cabbage, and golf course grasses. Withdrawal rates were estimated using data collected as part of the District's Benchmark Farms program (SJRWMD, 1990). Based on these data, water use per acre of crop was estimated. An average rate per acre was calculated using the total number of irrigated acres reported for the appropriate crop in a particular

Table 4. Model locations and estimated pumping rates for agricultural groundwater withdrawals.

Layer	Row	Column	Pumpage (cfd)	Layer	Row	Column	Pumpage (cfd)
2	1	11	-1.8500E+04	2	22	7	-6.0400E+04
2	1	12	-3.2400E+04	2	22	11	-1.7800E+04
2	2	14	-1.1000E+03	2	23	2	-2.5600E+03
2	2	16	-1.6000E+03	2	23	3	-1.6500E+04
2	3	12	-2.7400E+04	2	23	4	-1.7100E+04
2	3	13	-1.6000E+04	2	23	5	-1.8000E+04
2	3	14	-1.4100E+04	2	23	12	-1.9100E+04
2	3	16	-1.4800E+04	2	24	3	-5.1300E+04
2	4	20	-1.3300E+04	2	24	5	-8.0400E+04
2	5	13	-2.4000E+03	2	25	3	-2.5600E+03
2	5	14	-2.4000E+03	2	25	5	-6.4600E+04
2	5	15	-1.4300E+04	2	26	3	-5.0300E+04
2	5	16	-1.4300E+04	2	26	7	-1.4400E+04
2	5	23	-4.2000E+03	2	27	3	-6.6300E+04
2	5	24	-4.2000E+03	2	27	6	-5.1200E+04
2	5	25	-2.5000E+03	2	27	7	-5.0400E+04
2	5	26	-1.3000E+03	2	27	9	-1.5700E+04
2	5	27	-1.3000E+03	2	27	12	-2.2100E+04
2	6	6	-3.6800E+04	2	27	17	-2.7000E+04
2	6	7	-2.7200E+04	2	28	3	-3.5600E+04
2	6	9	-3.8500E+04	2	28	4	-4.4900E+04
2	6	11	-1.3400E+04	2	28	6	-1.0340E+05
2	6	12	-1.9700E+04	2	28	7	-5.2700E+04
2	7	6	-2.0200E+04	2	28	8	-1.9400E+04
2	7	7	-1.9900E+04	2	28	16	-4.1000E+03
2	7	8	-1.5900E+04	2	29	4	-5.6900E+04
2	7	9	-1.7100E+04	2	29	6	-8.7400E+04
2	7	11	-1.4500E+04	2	29	7	-4.8100E+04
2	7	12	-1.8000E+04	2	29	9	-2.2000E+04
2	8	6	-2.6600E+04	2	29	15	-4.1000E+03
2	8	7	-6.3100E+04	2	29	20	-2.1000E+04
2	8	13	-2.7200E+04	2	29	21	-2.1000E+04
2	8	15	-1.4400E+04	2	30	3	-4.1810E+05
2	9	5	-2.1700E+04	2	30	4	-7.8000E+04
2	9	7	-1.5900E+04	2	30	7	-1.6510E+05
2	9	10	-2.1500E+04	2	30	8	-5.6000E+04
2	9	15	-2.0000E+04	2	31	4	-9.7600E+04
2	9	22	-5.8900E+04	2	31	5	-1.2400E+04
2	10	5	-1.7100E+04	2	31	6	-1.8500E+04
2	10	14	-2.2600E+04	2	31	7	-1.3020E+05
2	11	4	-4.7400E+04	2	31	8	-3.2900E+04
2	11	5	-3.9300E+04	2	31	9	-3.3600E+04

cfd - cubic feet per day

Table 4. Model locations and estimated pumping rates for agricultural groundwater withdrawals (Continued).

Layer	Row	Column	Pumpage (cfd)	Layer	Row	Column	Pumpage (cfd)
2	11	10	-4.6700E+04	2	31	33	-1.8500E+04
2	11	11	-4.0200E+04	2	31	38	-2.5800E+04
2	11	12	-1.3600E+04	2	32	1	-3.3500E+04
2	12	7	-1.5300E+04	2	32	3	-1.2760E+05
2	12	10	-6.6500E+04	2	32	4	-4.6600E+04
2	13	10	-6.6500E+04	2	32	5	-4.8500E+04
2	13	11	-1.9800E+04	2	32	6	-1.5510E+05
2	14	7	-1.5000E+04	2	32	7	-1.8600E+05
2	14	10	-3.9600E+04	2	32	25	-1.7500E+04
2	14	12	-4.8000E+03	2	33	1	-1.4600E+04
2	15	7	-1.9400E+04	2	33	2	-3.3300E+04
2	15	10	-1.9800E+04	2	33	3	-2.1810E+05
2	16	3	-1.3300E+04	2	33	4	-6.3900E+04
2	16	4	-2.3400E+04	2	33	5	-3.1500E+04
2	16	6	-2.0500E+04	2	33	6	-1.7100E+04
2	16	7	-2.7200E+04	2	33	29	-6.5200E+04
2	17	6	-1.5300E+04	2	33	31	-8.0000E+03
2	18	3	-1.3800E+04	2	33	32	-6.3500E+04
2	18	6	-3.5100E+04	2	33	33	-8.0000E+03
2	19	3	-3.2900E+04	2	34	2	-1.4030E+05
2	20	4	-1.7300E+04	2	34	3	-1.7800E+04
2	21	3	-4.4200E+04	2	34	7	-1.4500E+04
2	22	3	-2.7700E+04	2	34	28	-3.8000E+03
2	22	4	-5.1400E+04	2	34	32	-3.8000E+03

cfd - cubic feet per day

county and the total irrigation rate estimated by the District. Total agricultural withdrawals (all crops) were estimated at 4.5 x 10^6 ft^3/d (34 mgd).

3.8 DRAINAGE WELLS

It is estimated that there are approximately 400 drainage wells in the Orlando area (Kimrey and Fayard, 1984; Szell, 1987). These wells were constructed primarily as a means of controlling drainage and runoff. The majority of wells (90%) are in the Upper Floridan aquifer. Estimates of the rate of recharge from these wells are as high as 50 mgd (Kimrey, 1978). However, Tibbals (1990) has estimated, based on double mass curve analysis, that the rate is about 33 mgd, which is the rate assumed for the present analysis. Given an absence of data, the total rate of recharge is divided equally among all the drainage wells; the model grid locations and rates of groundwater recharge from drainage wells are presented in Table 5.

Table 5. Model locations and estimated injection rates for drainage wells.

Layer	Row	Column	Pumpage (cfd)
2	34	10	3.2680E+05
2	34	11	1.9970E+05
2	34	12	4.5390E+05
2	34	13	3.2680E+05
2	34	14	2.7230E+05
2	34	15	1.2710E+05
2	34	16	5.4500E+04
2	33	10	1.2710E+05
2	33	11	2.5420E+05
2	33	12	6.7180E+05
2	33	13	5.2650E+05
2	33	14	1.9970E+05
2	33	15	7.2600E+04
2	33	16	5.4500E+04
2	32	10	7.2600E+04
2	32	11	7.2600E+04
2	32	12	7.2600E+04
2	32	13	1.9970E+05
2	32	14	5.4500E+04
2	32	15	3.6300E+04
2	32	16	7.2600E+04
2	31	10	5.4500E+04
2	31	11	5.4500E+04
2	31	12	5.4500E+04

cfd - cubic feet per day

4 MODEL CALIBRATION AND VERIFICATION

4.1 APPROACH

Model calibration is the process in which preliminary model estimates of hydraulic parameters and boundary conditions are adjusted as necessary so that the model reproduces observed conditions. The majority of model adjustment is made during the first calibration. A second calibration phase involves evaluating an alternative stress condition giving further assurance that the model adequately represents the system. In the present analysis, the regional-flow model is first calibrated based on estimated predevelopment levels and rates to simulate groundwater levels in the Upper Floridan aquifer and spring discharges under predevelopment conditions (e.g., Tibbals, 1977; 1981). In the second calibration of the model, estimated average pumping conditions for 1988 are simulated and the resultant groundwater levels compared to an average 1988 potentiometric surface. In addition, simulated impacts of pumping stress on spring discharges are evaluated.

4.2 CALIBRATION TO PREDEVELOPMENT CONDITIONS

The regional groundwater flow model was calibrated to estimated groundwater conditions in the project area prior to substantial development. Tibbals (1981) provided a modified version of the predevelopment potentiometric surface developed by Johnston et al. (1980). The predevelopment surface used to calibrate this model (Figure 6) is based on Tibbals (1981) with one exception. Water levels in Seminole County were slightly modified to be more consistent with the levels presented in Tibbals (1977). A pronounced potentiometric surface trough was estimated to be adjacent to the Wekiva River between Seminole and Lake Counties. Tibbals' (1977) data suggested this trough likely was present, and he confirmed this in 1990 (personal communication). No data were available on either the Lake or Orange County side of the river to confirm the existence of the trough.

4.2.1 Adjustment of Hydraulic Parameters

4.2.1.1 Transmissivity

Initial estimates for the transmissivity of both the Upper and Lower Floridan aquifer were based on (1) calibrated values derived by Tibbals (1981, 1990) in his regional modeling analysis, and (2) those presented by Tibbals (1977) in his analysis of well yields in Seminole County. The range of values reported in Tibbals (1977) for Seminole County were consistent with the values derived in Tibbals' regional model analysis. Because, in both cases, the published data only presented ranges of transmissivity for different zones or areas (e.g., 100,000 to 200,000 ft^2/d), the initial estimates (resulting from the present study) for the Upper Floridan aquifer were not exactly the same as those derived by Tibbals. Throughout the present model, initial estimates of transmissivity range from 10,000 ft^2/day to 300,000 ft^2/day.

Values of transmissivity for the Upper and Lower Floridan aquifers were determined for the present model during calibration (Figures 7 and 8) and are still consistent with those derived by Tibbals (1981, 1990). The highest values of transmissivity (300,000 ft^2/d) in the Upper Floridan aquifer occur in western Orange and adjacent Lake County, and in southeastern Marion and adjacent Lake County. The lowest values occur in Seminole County, particularly in groundwater discharge areas adjacent to the Wekiva River.

The general trend in the distribution of transmissivity is consistent with observed groundwater flow patterns. Values are greater where hydraulic gradient is relatively low and lower where it is relatively high. Transmissivity values also tend to be relatively high in the vicinity of springs where the large magnitude of converging flow results in enhanced dissolution of the limestone.

The model-derived transmissivities do not always agree with values that can be obtained from pump tests. Tibbals (1990) explained this fact as follows:

> "Generally, the model-derived transmissivities are higher than those obtained from aquifer tests. This is mainly because the wells used in the aquifer tests generally tap less than the full

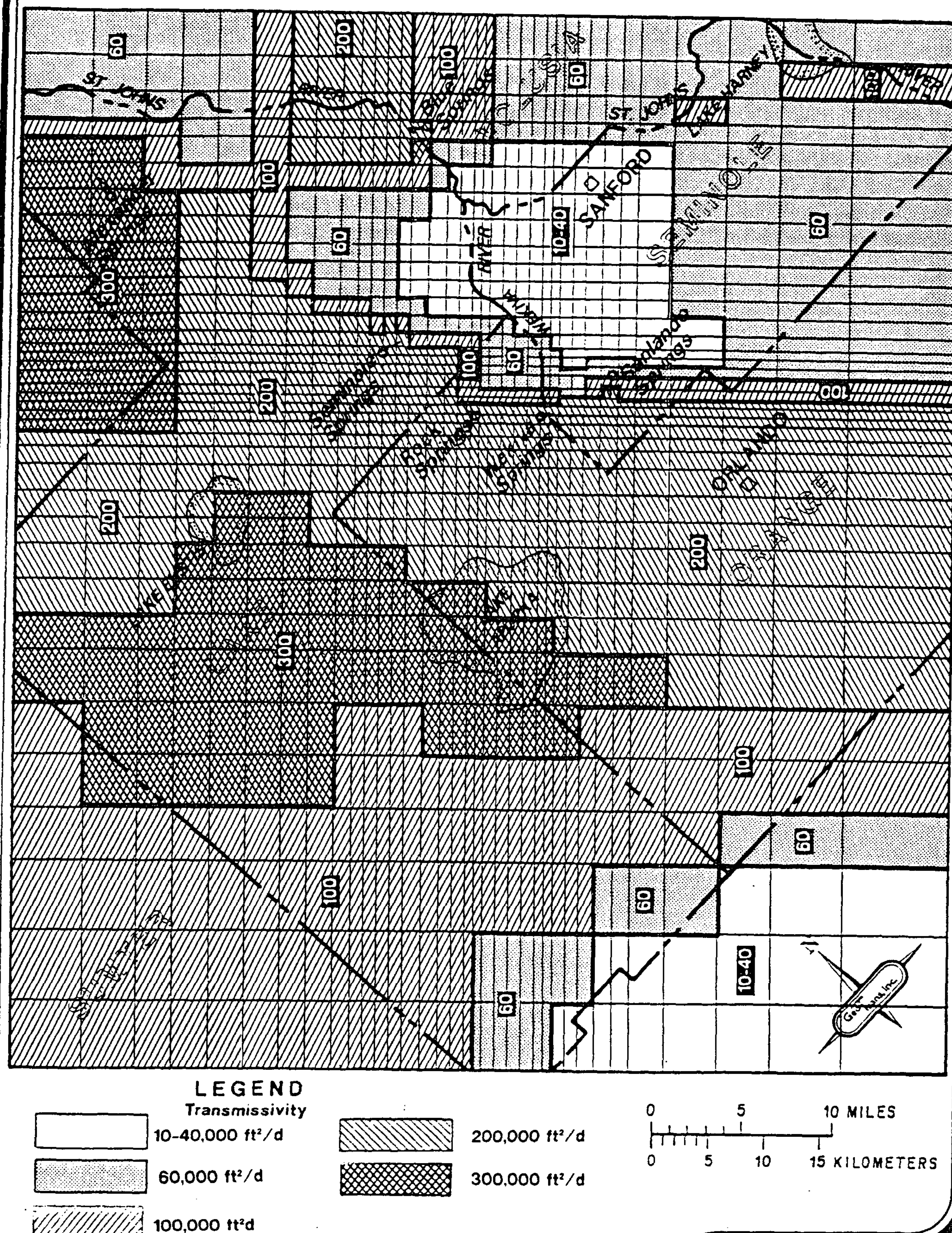

Figure 7. Model-derived transmissivity of the Upper Floridan aquifer.

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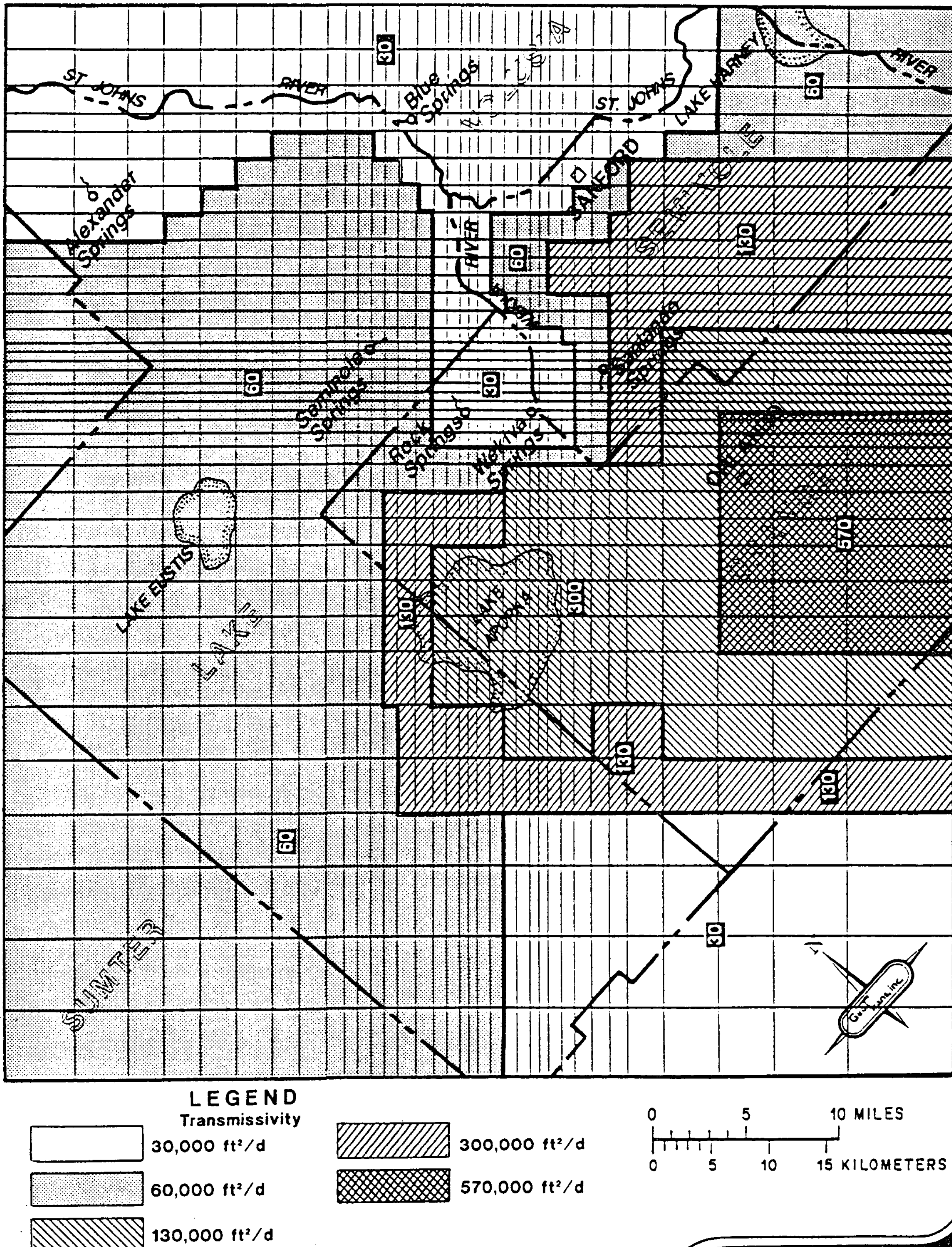

Figure 8. Model-derived transmissivity of the Lower Floridan aquifer.

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> thickness of the Upper Floridan. Such partial penetration plus the highly heterogeneous and anisotropic nature of the cavernous limestone aquifer system make the application of standard methods of aquifer test analysis uncertain and the results questionable. For example, in east Orange County, three aquifer test sites within an area of about 16 mi^2 has transmissivity values of 74,000, 210,000, and 510,000 ft^2/d, respectively. Furthermore, counter to what would be expected, the test that had the most penetration of the aquifer had the lowest transmissivity. The transmissivity range obtained from model calibration in the same 16-mi^2 area, about 10,000 to 200,000 ft^2/d, is considered to have more regional significance than the individual test values."

The transmissivities of the Lower Floridan aquifer resulting from the present calibration (Figure 8) are similar in distribution to those of Tibbals (1981). The highest differences occur in Orange County, and the lowest occur along the Wekiva and St. Johns rivers. In Orange County, transmissivity of 570,000 ft^2/day is equal to that obtained from a pump test in this area as reported by Lichtler et al. (1968). This high value is consistent with head differentials of a few feet between the Upper and Lower Floridan (Lichtler et al., 1968; Szell, 1987; Tibbals, 1990) despite 69 mgd being withdrawn from the Lower Floridan aquifer while 33 mgd is being recharged via drainage wells into the Upper Floridan. Along the Wekiva and St. Johns rivers, model-derived transmissivities are lower than those of Tibbals (30,000 ft^2/d vs 60,000 ft^2/d respectively). However, because of the lack of data to calibrate the Lower Floridan aquifer model (layer 3), transmissivity values in the Lower Floridan are not as precise as those of the Upper Floridan.

4.2.1.2 Leakance

The Hawthorn Formation acts as a semi-confining layer between the water-table aquifer and the Upper Floridan aquifer. Initial estimates of the leakance coefficient for this layer were derived primarily from data as provided by the District on its thickness. These data were prepared as part of the District's Recharge Area Mapping Project (on going). Initial leakance values were calculated using these data and a vertical hydraulic conductivity of 2.8×10^{-3} ft/d, which is the value that the District is reportedly using in the aforementioned mapping project (D. Durden, Personal Communication, 1990). The leakance values derived from calibration of the present model (Figure 9) are similar to those determined by Tibbals (1990). Leakance values range from a low of 5×10^{-5} d^{-1} to a high of 5×10^{-4} d^{-1}, where the semi-confining layer is thin to absent, (west-central and eastern Seminole County and west and northeast Lake County). Again, the presented values are the final ones after both calibration phases were completed.

Tibbals (1980) used a leakance of 5×10^{-5} d^{-1} in his model everywhere except near Blue Springs; Planert and Aucott (1985) used a value of 1.3×10^{-2} d^{-1} throughout their model. In the present analysis, a uniform value of

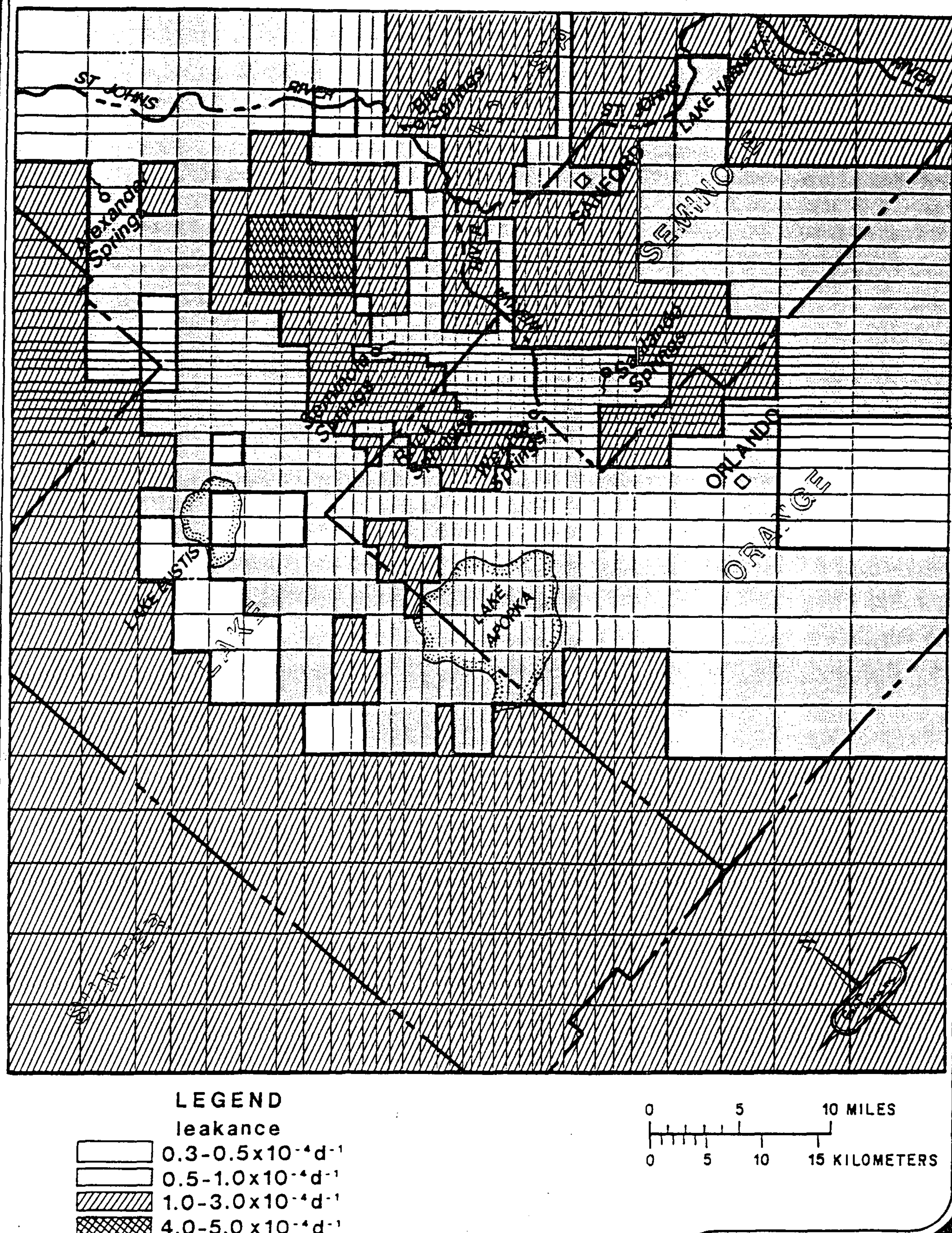

Figure 9. Model-derived leakance of the upper confining unit of the Floridan aquifer system (x 10^{-4} d^{-1}).

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2×10^{-4} d^{-1} (determined through model calibration) was applied everywhere except near Blue Springs. A value of 2×10^{-3} d^{-1} was applied to model blocks that extend between Blue Springs and the Seminole County line to the south, along the fault path (see Miller, 1986; Tibbals, 1990).

4.2.2 Simulated Groundwater Levels

The estimated predevelopment potentiometric surface of the Upper Floridan aquifer and that simulated using the regional groundwater flow model has been compared (Figure 10). Simulated levels are within ± 5 ft of the estimated levels for 91% or 1,047 of the active model grid blocks (layer 2). The greatest deviation occurs in east-central Lake County where simulated levels range between 5 and 9 feet lower than estimated (Figure 11). Other blocks with deviations in excess of 5 feet are generally scattered throughout the model domain. The maximum range of deviation between estimated and simulated was between 8.2 feet low and 7.8 feet high. The comparison between estimated and observed is considered to be good.

No concerted effort was made to calibrate the Lower Floridan aquifer layer of the model (layer 3) due to the extreme paucity of water-level data as outlined in Section 3.4. For evaluation purposes, estimated water levels for this layer were set to plus or minus two feet of those in the Upper Floridan, depending on the assumed direction of

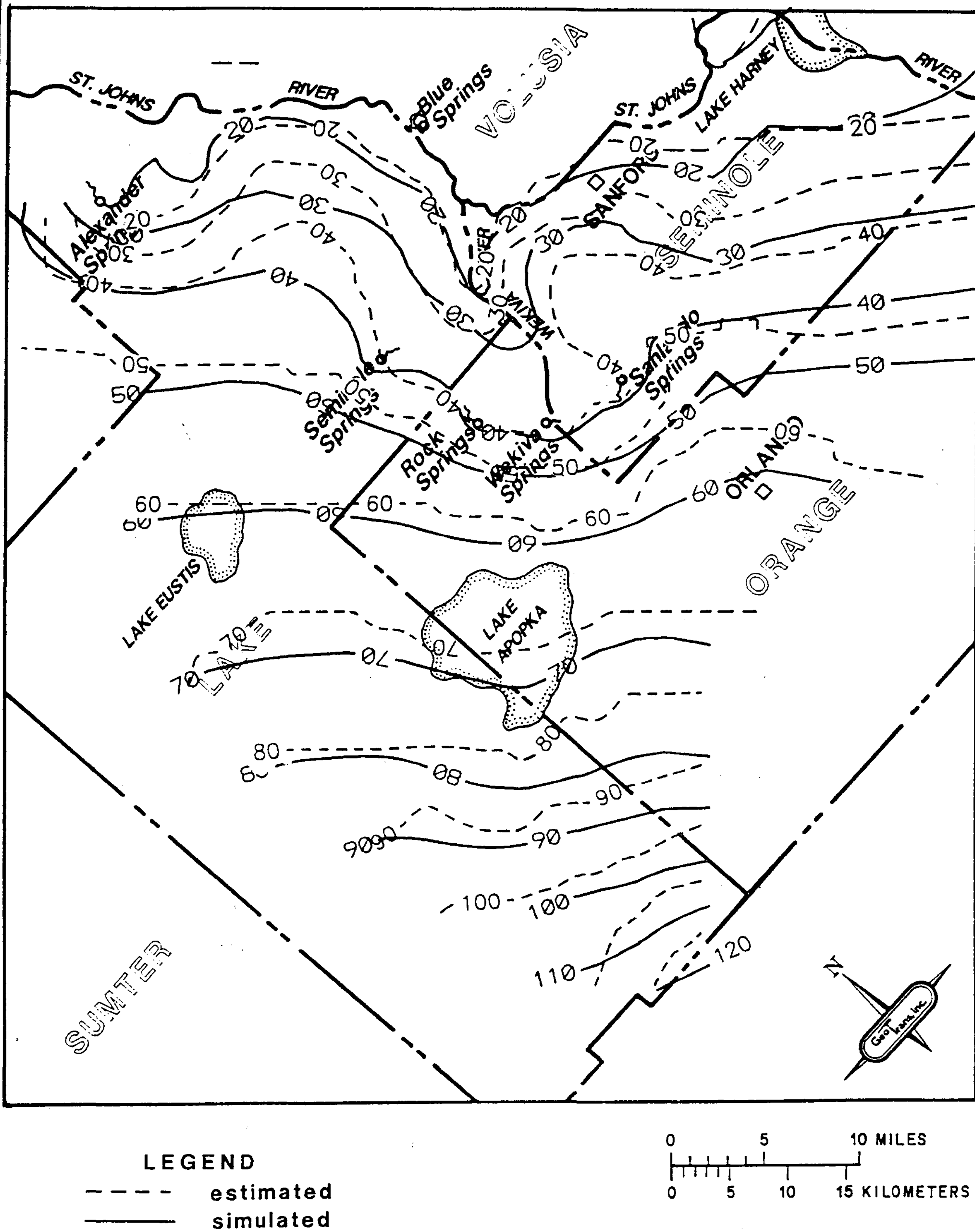

Figure 10. Estimated and simulated predevelopment potentiometric surfaces of the Upper Floridan aquifer, ft msl.

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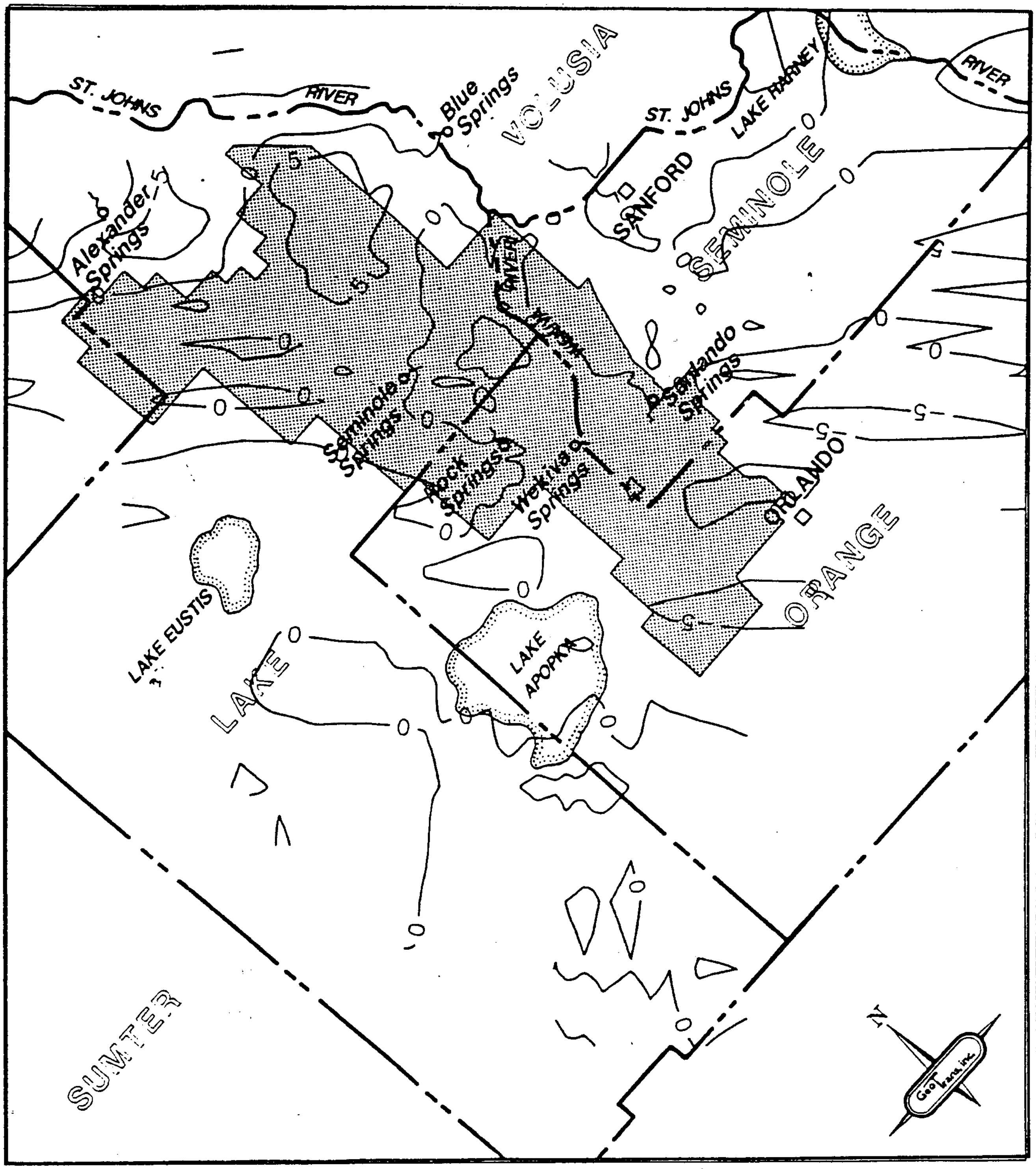

LEGEND

1.0 : SIMULATED LEVEL IS LOW (feet)
-1.0 : SIMULATED LEVEL IS HIGH (feet)

CONTOUR INTERVAL: 5 feet

0 5 10 MILES
0 5 10 15 KILOMETERS

Figure 11. Difference between the simulated and estimated potentiometric surface under predevelopment conditions.

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groundwater exchange between the two layers. Simulated water levels in the Lower Floridan aquifer are within five feet of those estimated at 80% of all active nodes. In addition, the simulated head differential between the Upper and Lower Floridan aquifers is less than 5 feet at 85% of all active blocks.

4.2.3 Simulated Spring Discharges

Estimated and simulated spring discharges have been compared (Table 6). Total discharge from the Floridan aquifer system via springs is approximately 580 cubic feet per second (cfs); simulated spring discharge equals approximately 575 cfs. Simulated discharges at individual springs ranged between 70 and 137 percent of the estimated values. The simulated discharge at a majority (76%) of the springs was within plus or minus 15 percent of the estimated discharge rate. Seminole, Messant, Wekiva, and Rock springs are the most critical springs within the Wekiva River basin, because the springs supply baseflow to Blackwater Creek, the Wekiva River, and the Little Wekiva River. The high discharge estimates at the two Lake Harney springs are not believed to be very significant since they are only apparent locations of focused discharge, not well defined springs (Tibbals 1981).

Table 6. Estimated and simulated spring discharges, predevelopment conditions, in cubic feet per second (cfs).

Name	Predevelopment Estimated Discharge (cfs) (1)	Predevelopment Simulated Discharge (cfs)	Predevelopment Percentage of Estimate
Apopka Spring	70.4	65.9	94
Blue Sp. (Lake Co.)	3	3.4	113
Holiday Spring	4	4.8	120
Alexander Spring & Creek	100+30	121	93
Camp La-No-Che Spring	1	0.7	70
Messant Springs	20	17.2	86
Seminole Spring	36	38.9	108
Blue Springs *	40	36.6	92
Gemini Spring	8	6.8	85
Rock Springs	65	60.7	93
Witherington Springs	4	4.6	115
Wekiva Springs	74	67	90
Clifton Spring	2	1.7	85
Miami Springs	5	5.4	108
Sanlando Springs, Palm Springs, and Starbuck Springs	46	53	115
Lake Jessup Springs	1	1.1	110
Island Spring	6	6.4	114
Alexander Creek	30	35.1	117
Lake Jessup	5.6	6.4	114
St. Johns River	8.9	8	90
L. Harney, N *	10.1	12.9	128
L. Harney, S *	12.3	16.9	137
Total (cfs)		574.5	

cfs - cubic feet per second

* Only part of basin in active model area.

1 Source : Tibbals, 1990

4.3 CALIBRATION TO AVERAGE 1988 CONDITIONS

The second model calibration phase consisted of simulating average groundwater conditions for 1988 under assumed quasi-steady-state conditions. Steady-state conditions are advantageous to modeling because they allow direct simulation of an observed condition without consideration of the effects of variations in pumping or of aquifer storage. Quasi-steady-state conditions mean that, while groundwater levels are not strictly static, they are generally fluctuating around an average elevation for a relatively long period of time. That is, they do not display an average declining or rising trend. Transient simulations conducted by Tibbals (1990) indicate that simulated groundwater levels are close to steady-state after 210 days of pumping and assuming an aquifer storage coefficient of 1×10^{-3}.

Hydrographs of five Upper Floridan aquifer observation wells (Figures 12 through 16) indicate that quasi-steady-state conditions occurred in 1988. Groundwater-level fluctuations during this period ranged from relatively small, with less than 2 feet of observed annual fluctuation (Figures 12 through 14), to moderate, with 5 to 6 feet of observed variation (Figures 15 and 16). Estimated groundwater levels for this pumping period were developed by, first, estimating actual levels at each model block for May and September, 1988. These levels were then used to

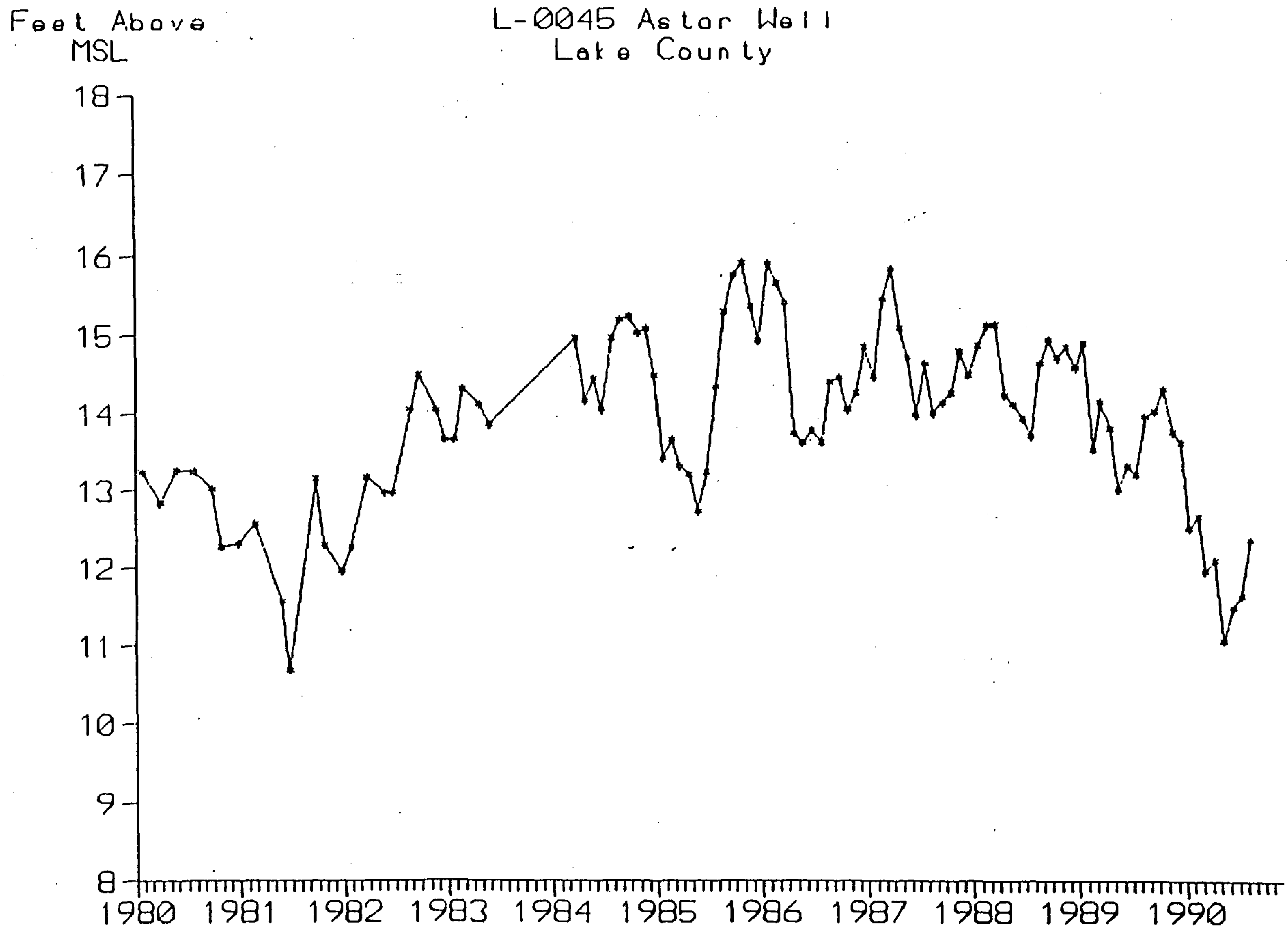

Figure 12. Hydrograph of Floridan aquifer at the Astor well, Lake County.

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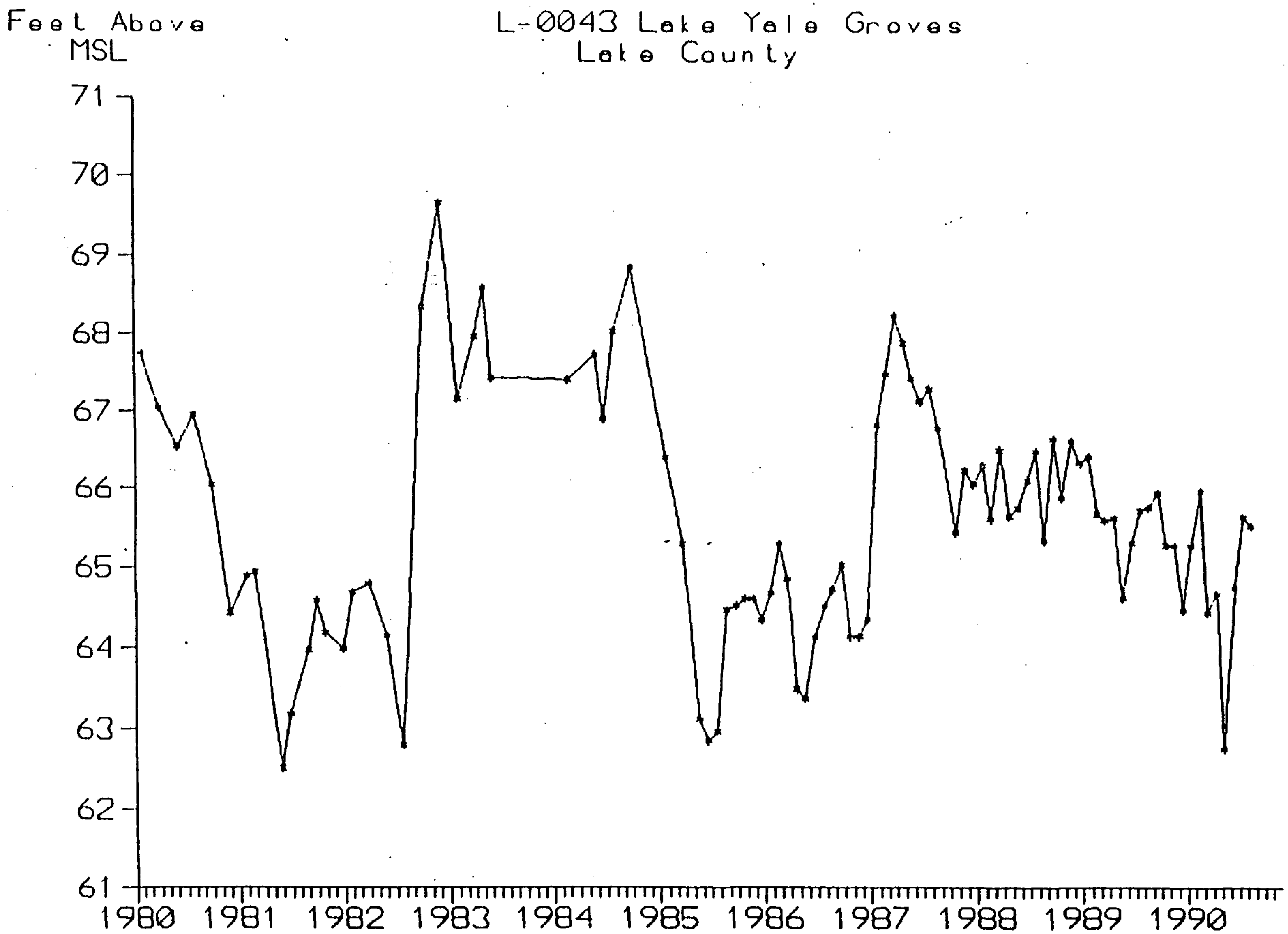

Figure 13. Hydrograph of Floridan aquifer at the Lake Yale Groves well, Lake County.

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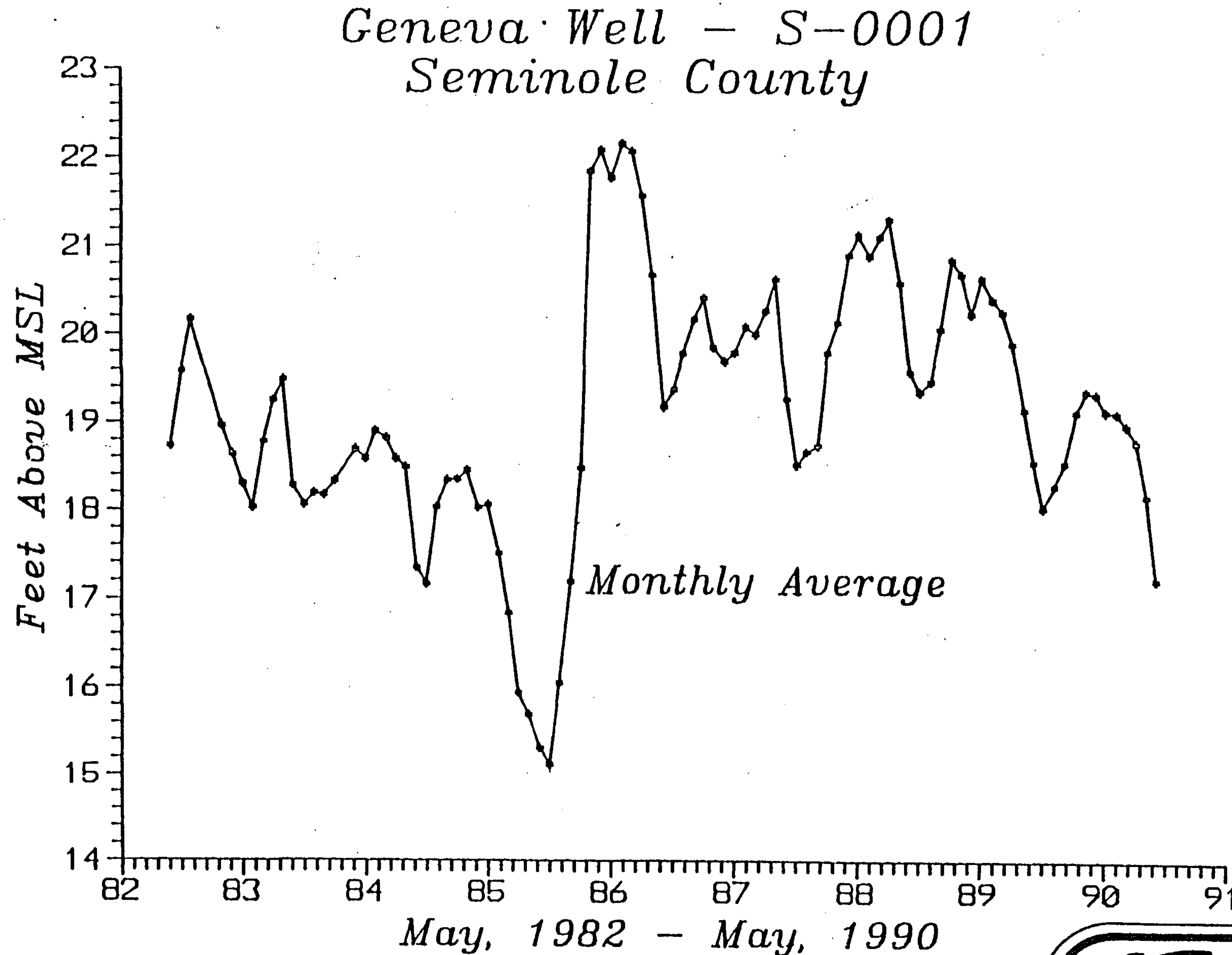

Figure 14. Hydrograph of Floridan aquifer at the Geneva well, Seminole County.

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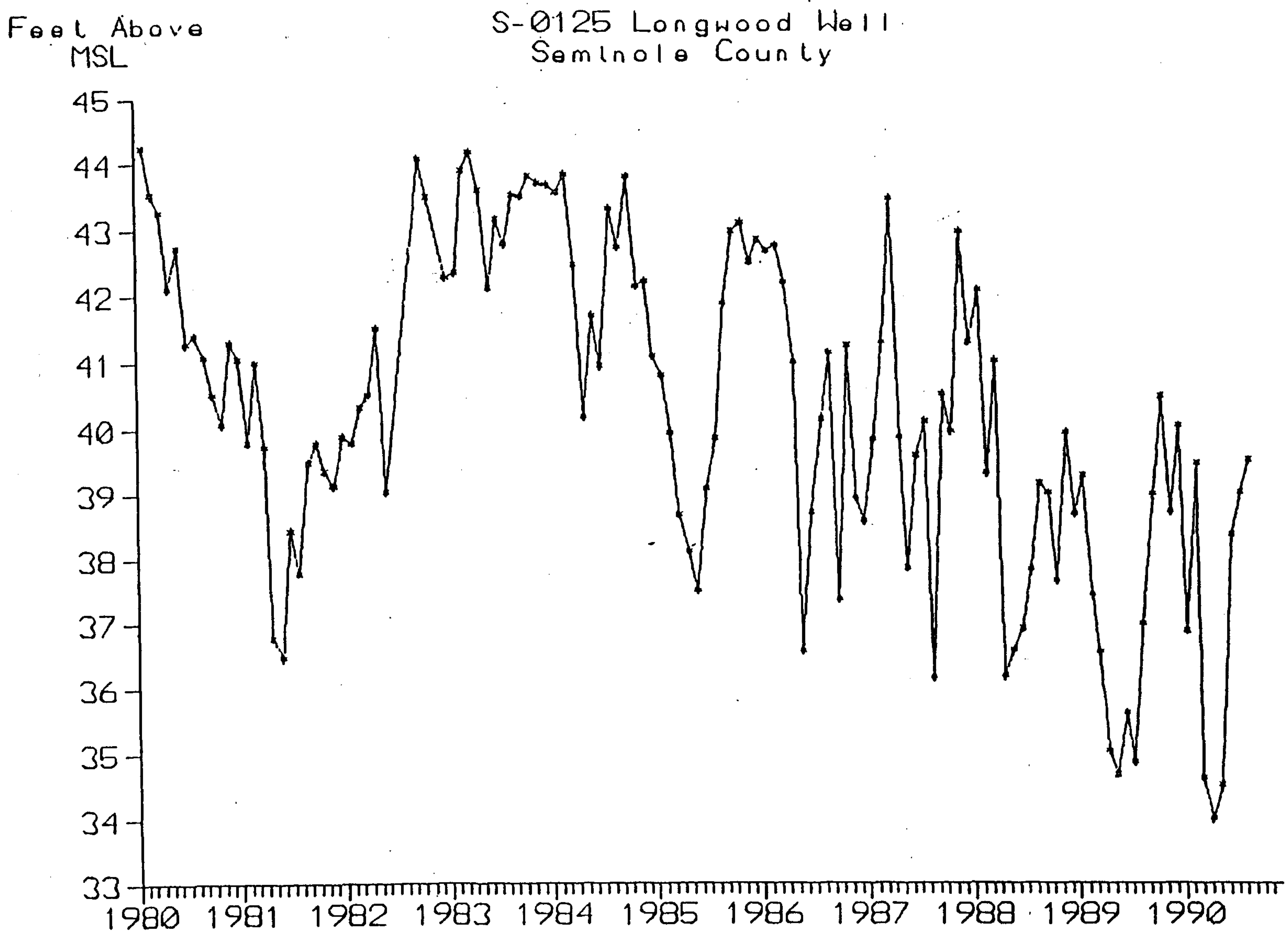

Figure 15. Hydrograph of Floridan aquifer at the Longwood well, Seminole County.

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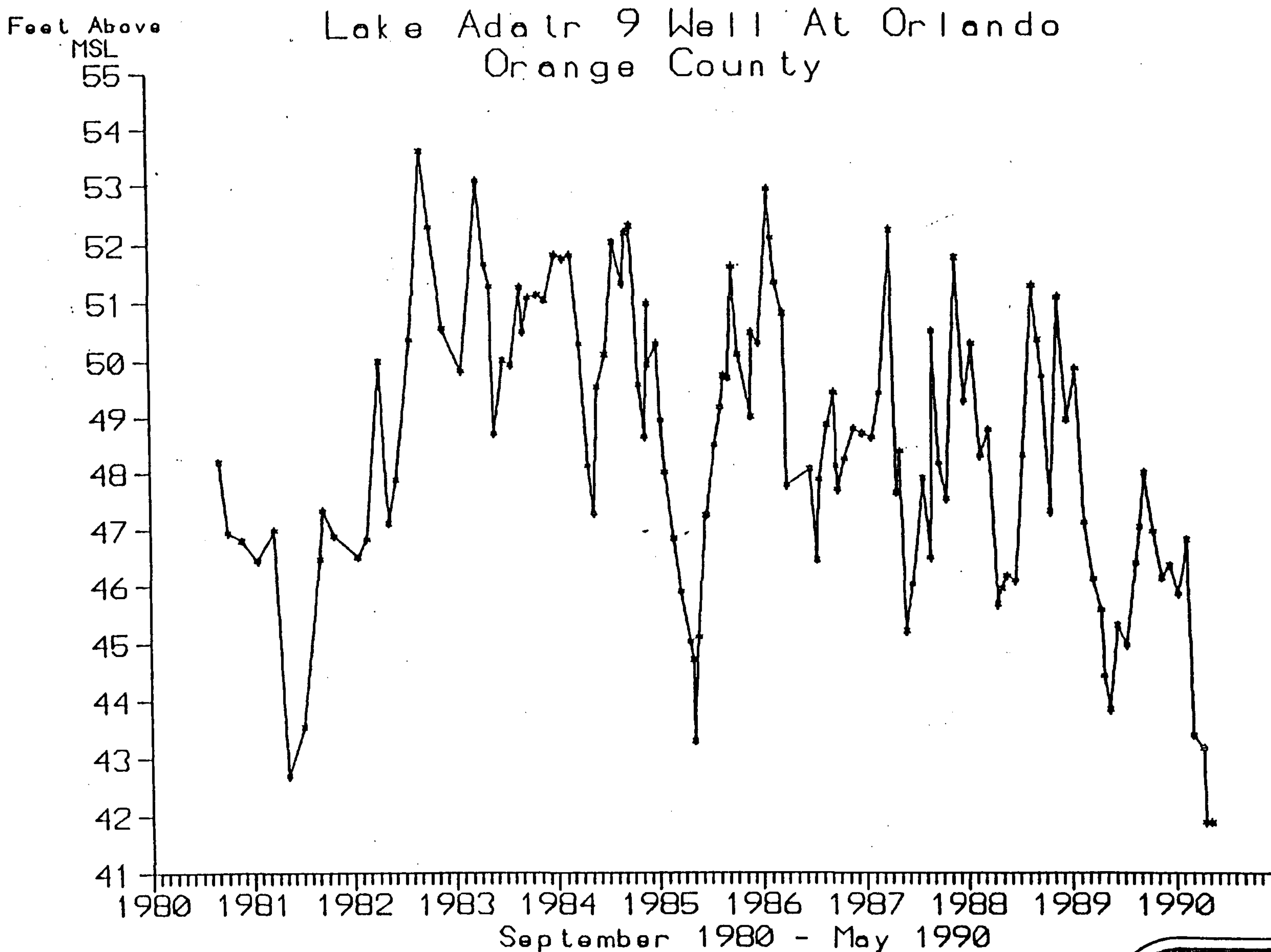

Figure 16. Hydrograph of Floridan aquifer at the Lake Adair well, Orange County.

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define an average 1988 potentiometric surface (Figure 17).

The simulated 1988 potentiometric surface under average pumping conditions was shown superimposed on the estimated potentiometric surface map (Figure 18). Simulated groundwater levels are within 5 feet of estimated levels in 86% of active model grid blocks. Simulation errors in excess of 5 feet mainly occur outside the Wekiva River basin (Figure 19) and particularly outside of the area that will be included in the sub-regional transport model. Overall, simulated water levels are representative of average 1988 conditions.

The greatest deviation of simulated levels from those estimated is in the Orlando area. Simulated drawdowns in the Upper Floridan aquifer are in the range of 5 to 10 feet while drawdowns of 12 to 18 feet were estimated. This area is in close proximity to model boundaries whose configurations are uncertain (Figure 5). It is possible that some amount of water is lost across this boundary that is not presently accounted for in the model. The only identified stress in this area is from drainage wells that introduce an estimated 33 mgd of water into the Upper Floridan. Groundwater withdrawals in this area on the other hand, are primarily from the Lower Floridan aquifer, totaling approximately 64 mgd. Simulated groundwater levels in the Lower Floridan aquifer in the same area are within 5 feet of estimated levels. This suggests that the hydraulic

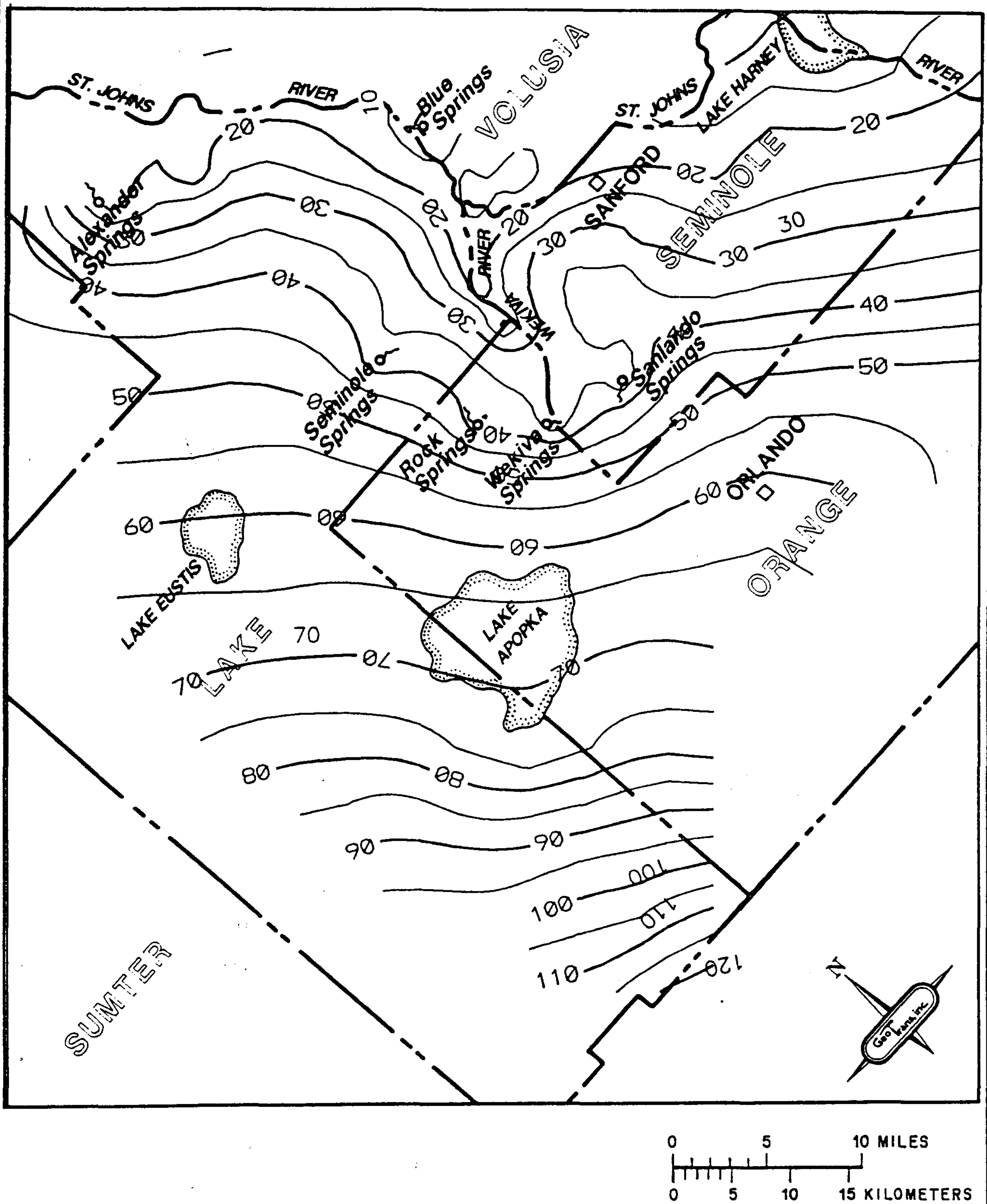

Figure 17. Predicted average 1988 potentiometric surface for the Upper Floridan aquifer in the project area.

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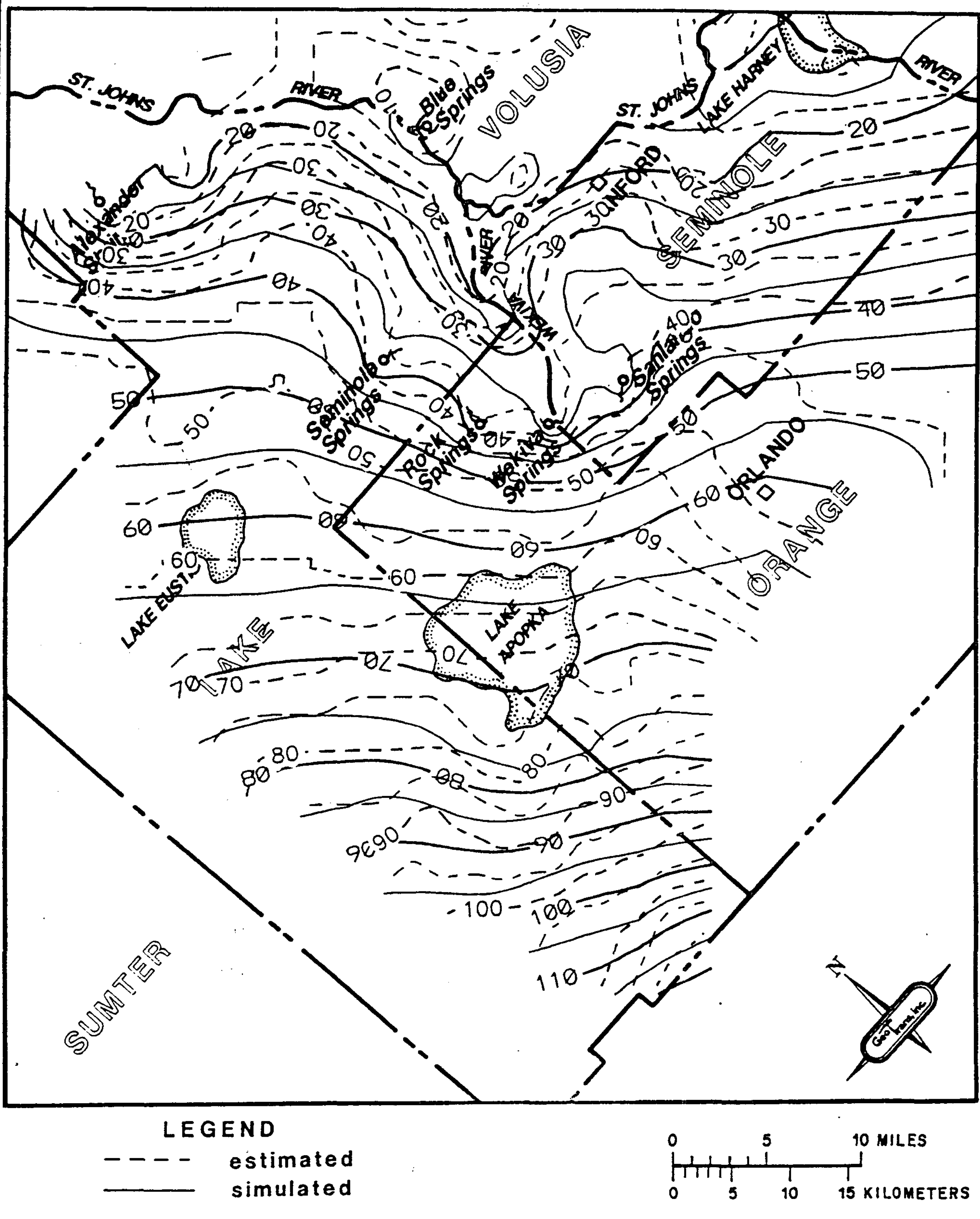

Figure 18. Estimated and simulated average 1988 potentiometric surface for the Upper Floridan aquifer in the project area.

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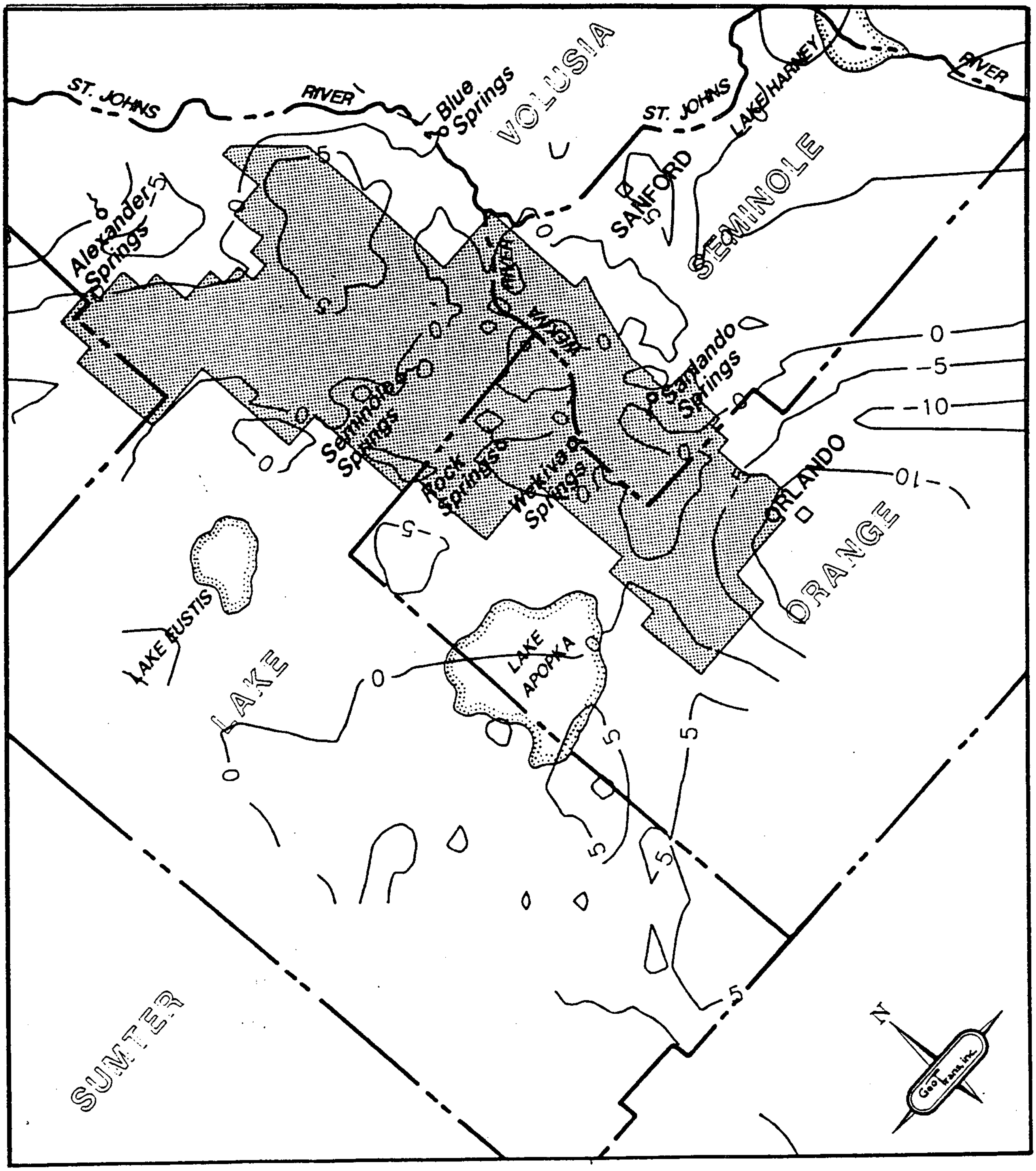

LEGEND

1.0 : SIMULATED LEVEL IS LOW (feet)
-1.0 : SIMULATED LEVEL IS HIGH (feet)

CONTOUR INTERVAL: 5 feet

Figure 19. Difference between the simulated and estimated average 1988 potentiometric surface.

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connection between the Upper and Lower Floridan aquifers in this area may be even greater than that simulated.

The only notable area within the Wekiva River basin where simulated groundwater levels in the Upper Floridan aquifer are in excess of 5 feet below estimated levels is in part of northeastern Lake County. The potentiometric surface in this area shows a distinct mounding, which the model did not precisely match (Figure 18). Some improvement in predicted results in this area might be achieved by either increasing the leakance of the Hawthorn Formation or raising the water table in the model. Neither of these changes can be justified based on existing data.

Table 7 presents a comparison between simulated and observed or estimated discharges at the springs within the model under both predevelopment and average 1988 conditions. Modelwide a 14 percent reduction in spring discharge was simulated, equivalent to 82.5 cfs.

Simulated recharge rates predicted under average 1988 pumping conditions from the Floridan aquifer can be divided into three categories (Figure 20). Typically, recharge rates of 6 in/yr or less are simulated in those areas classified by the District as areas of low recharge. Rates in the 6-20 in/yr range are simulated in western Lake and western Orange Counties, classifying the areas as high recharge zones.

Table 7. Estimated and simulated spring discharges under average 1988 pumping conditions in cubic feet per second (cfs).

Name	Predevelopment			1988			
	Estimated Discharge (cfs) (1)	Simulated Discharge (cfs)	Percentage of Estimate	Source	Observed Discharge (cfs) (2)	Simulated Discharge (cfs)	Percentage of Estimate (cfs)
Apopka Spring	-	65.9	-	3	64.3(3)	45.3	70
Blue Sp. (Lake Co.)	3	3.4	113	-	-	2.5	-
Holiday Spring	4	4.8	120	-	-	3.6	-
Alexander Spring & Creek	100+30	121	93	3	105.0	118.0	112
Camp La-No-Che Spring	1	0.7	70	3	0.6	0.6	100
Messant Springs	20	17.2	86	3	14.0(1)	15.3	109
Seminole Spring	36	38.9	108	3	39.0(1)	33.2	85
Blue Springs *	40	36.6	92	2	36.0(6)	35.7	99
Gemini Spring	8	6.8	85	1	8.0	6.2	78
Rock Springs	65	60.7	93	2	57.5(6)	49.8	87
Witherington Springs	4	4.6	115	4	3.8	3.8	100
Wekiva Springs	74	67	90	2	66.8(6)	57.0	85
Clifton Spring	2	1.7	85	-	-	1.4	-
Miami Springs	5	5.4	108	3	5.2	4.4	85
Sanlando Springs, Palm Springs, and Starbuck Springs	46	53	115	2	40.2(2)	35.0	87
Lake Jessup Springs	1	1.1	110	-	-	0.9	-
Island Spring	6	6.4	114	1	6.0	5.4	90
Alexander Creek	30	35.1	117	1	30.0	34.5	115
Lake Jessup	5.6	6.4	114	1	5.6	5.5	98
St. Johns River	8.9	8	90	1	8.9	7.1	80
L. Harney, N *	10.1	12.9	128	1	10.1	11.5	114
L. Harney, S *	12.3	16.9	137	1	12.3	15.3	124
Total (cfs)		574.5				492	

cfs - cubic feet per second

* Only part of basin in active model area.

1 Source : Tibbals, 1990

2 Source : SJRWMD data for 1988; number in () refers to number of measurements used to calculate discharge.

3 Source : USGS data for 1988

4 Source : SJRWMD estimated long term averages

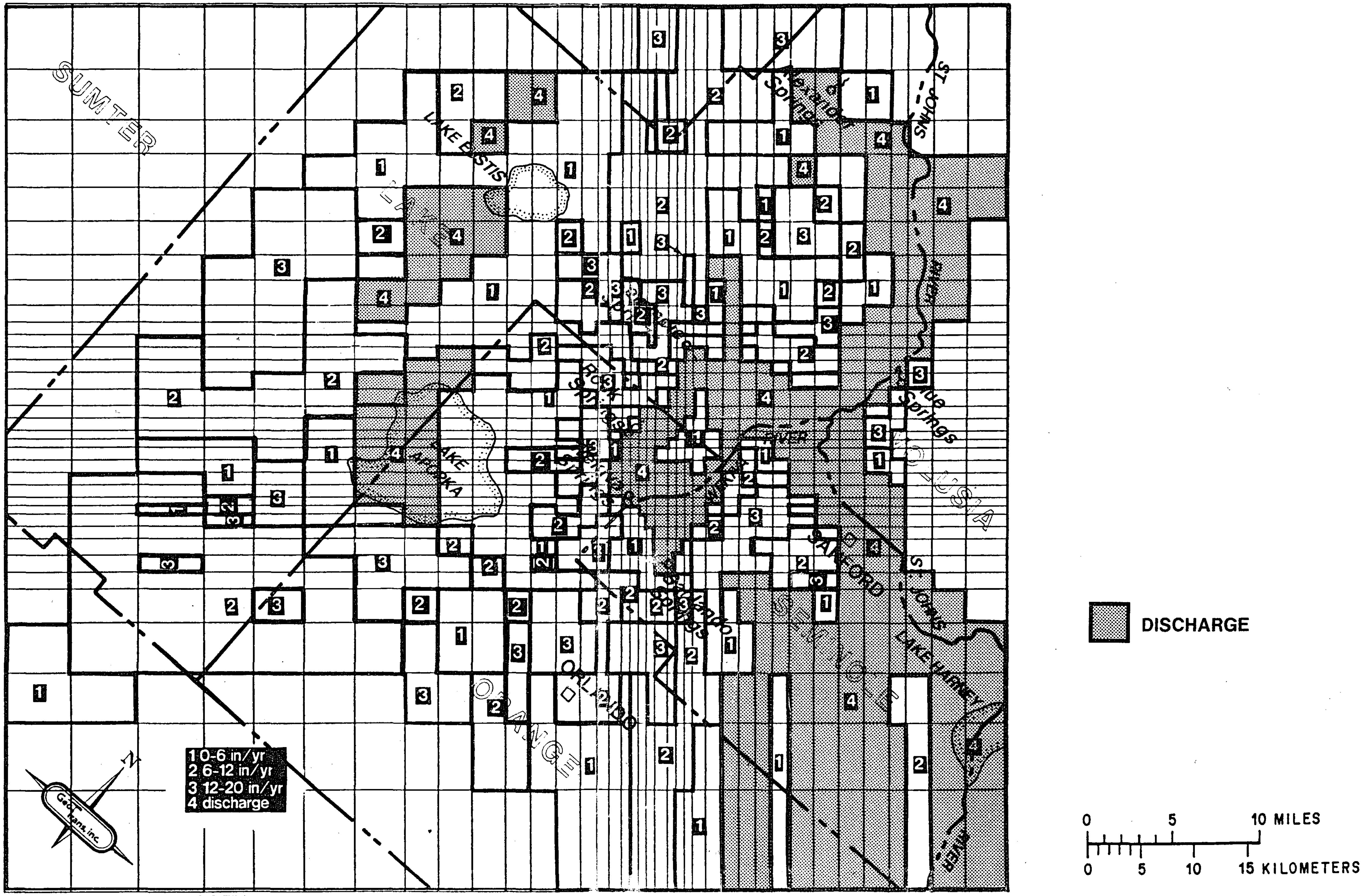

Figure 20. Simulated rates of recharge to and discharge from the Floridan aquifer system under average 1988 pumping conditions.

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Simulated discharge rates are higher than those predicted by Tibbals (1990). He reported discharges on the order of one to two inches per year in the upper Wekiva River discharge area in Orange and Seminole Counties. The model simulated discharges between 0.2 and 6.8 in/yr and averaged about 5.7 in/yr in this area. Simulated discharges in the immediate vicinity of the lower Wekiva River between the Orange County/Lake County line to the confluence with the St. Johns River are 6-10 in/yr, but range as high as 25 in/yr in localized regions.

5 SENSITIVITY ANALYSIS

Developing a groundwater model requires estimating values for numerous hydrologic parameters at regular intervals throughout the study area. Calibration and verification of a model suggests some degree of accuracy in the values used. However, by assessing the response of the model to changes in parameter values throughout the model area, an additional measure of accuracy of the original estimated values can be made. This assessment is referred to as a sensitivity analysis. In this analysis the value of each parameter is varied throughout the model by some constant factor while all other parameters are maintained at their original values. The analysis was conducted using the steady-state predevelopment system as a baseline.

The sensitivity analysis involved systematically increasing and decreasing the values of the following parameters and evaluating the associated changes in the potentiometric surface.

1. transmissivity, layer 2
2. transmissivity, layer 3
3. leakance, layer 1 to 2
4. leakance, layer 2 to 3
5. spring conductance
6. water-table elevation

Model row 18 was chosen for its centralized location in the model to depict simulated changes in the potentiometric surface of the Upper and Lower Floridan aquifers under predevelopment conditions. This row includes Rock Springs (mile 38) and Island Springs (mile 43).

Groundwater levels in the Upper Floridan were quite sensitive to both the transmissivity of layer 2 and the leakance between layers 1 and 2 (Figure 21). Changes in groundwater levels caused by these variations in leakance and transmissivity differ between recharge and discharge areas. In recharge areas, doubling the leakance causes groundwater levels to rise, reflecting the increase in the amount of water entering the system as recharge. At the same time, water levels in the discharge area decrease as a result of the lower head differential needed between the Floridan and water table to move a given volume of water out of the system (Figure 22). Doubling the transmissivity of the Upper Floridan aquifer results in water level changes that are opposite, but approximately equivalent in magnitude (Figure 23). Halving the value of leakance or transmissivity results in changes in water levels that are roughly equivalent to those induced by doubling the values, but in the opposite direction (not shown).

Doubling the transmissivity of model layer 3 (Lower Floridan aquifer) and the leakance between layers 2 and 3 results in less pronounced changes in the potentiometric surface of the Upper Floridan aquifer. The changes caused by doubling layer 3 transmissivity are about half that of those induced by doubling the transmissivity of layer 2

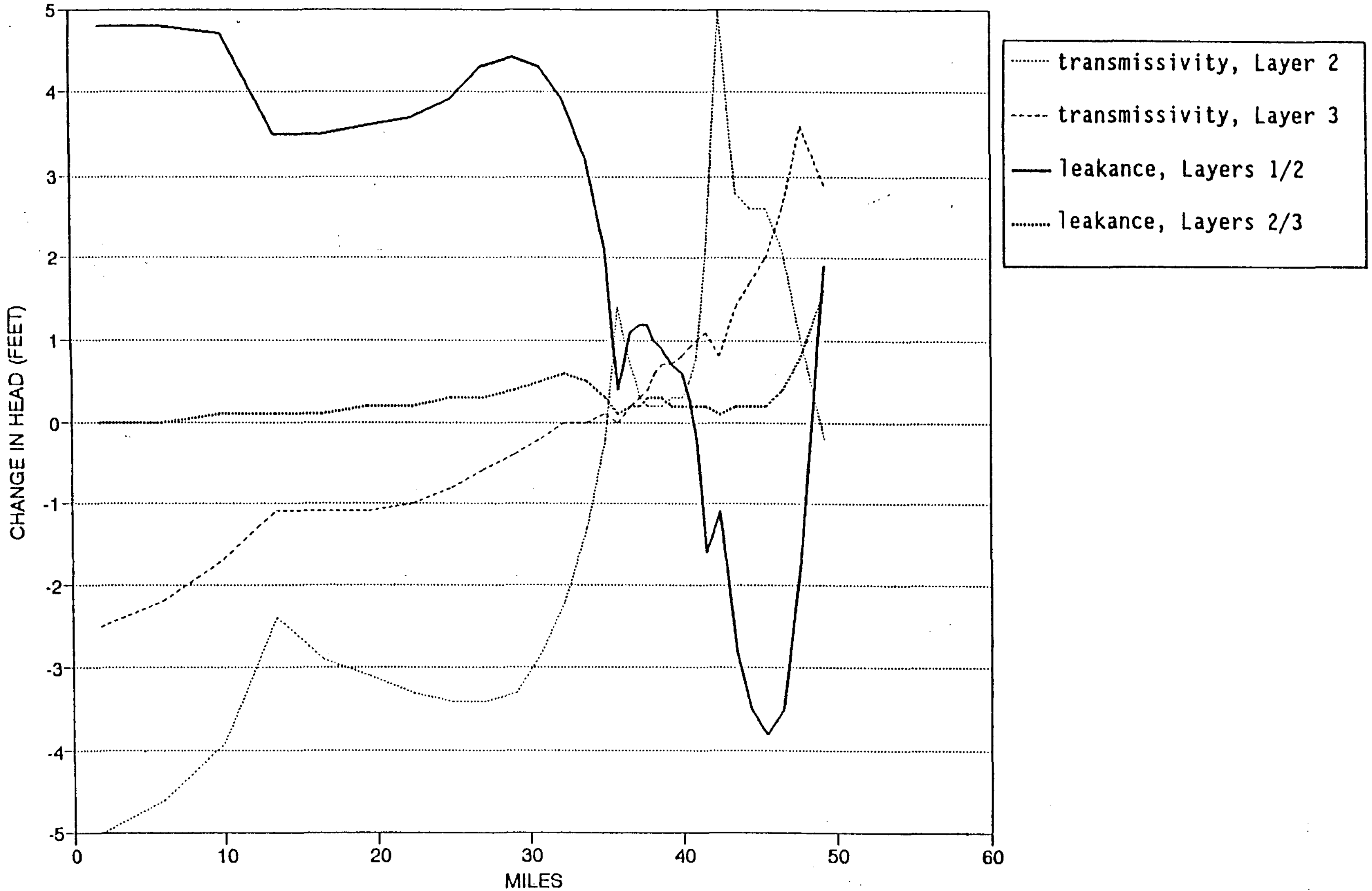

Figure 21. Simulated change in the Upper Floridan potentiometric surface along model row 18 due to changes in transmissivity and leakance values.

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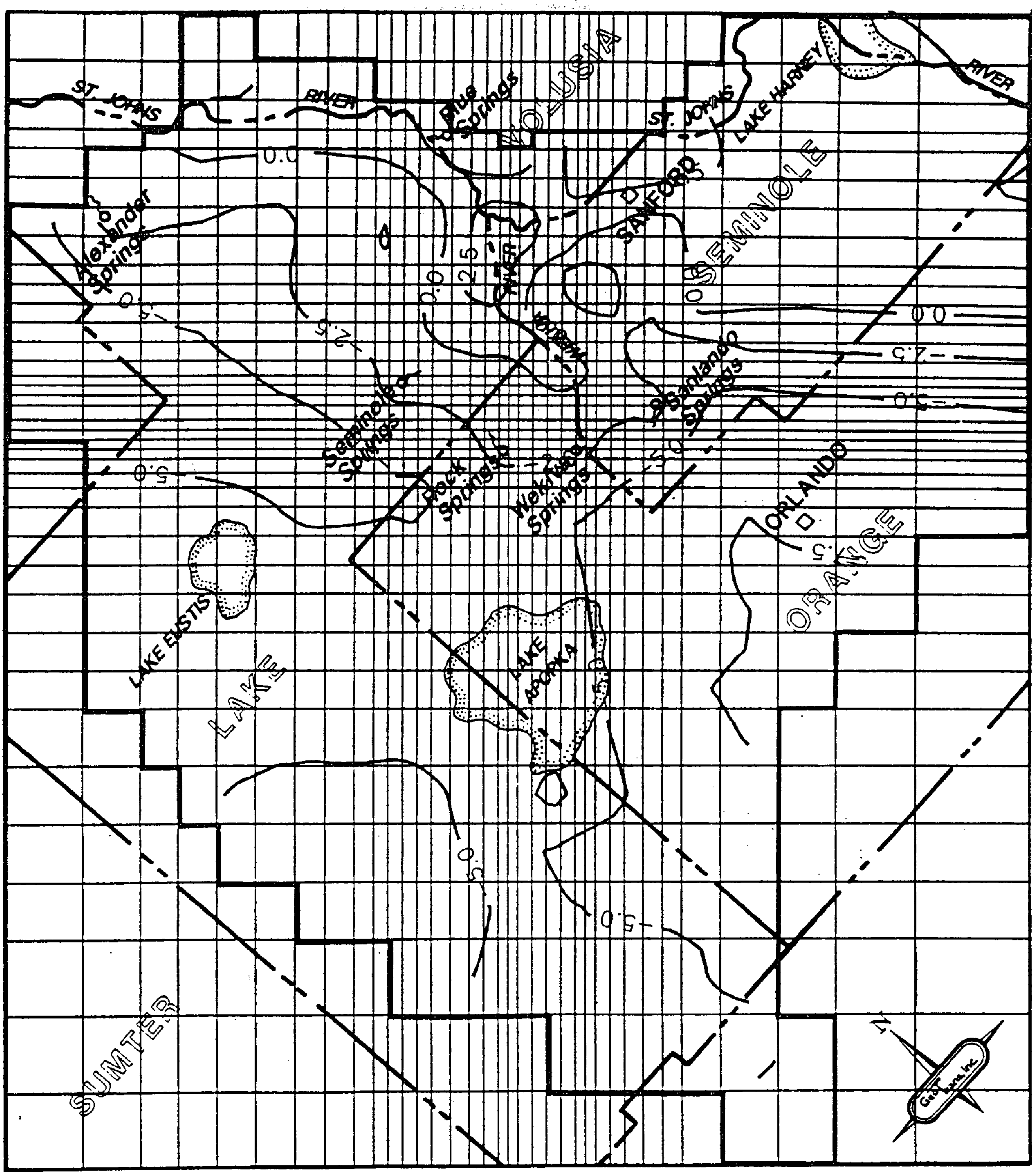

LEGEND

1.0 : REDUCTION IN WATER LEVEL (feet)

-1.0 : INCREASE IN WATER LEVEL (feet)

0 5 10 MILES

0 5 10 15 KILOMETERS

Figure 22. Simulated change in the Upper Floridan potentiometric surface due to doubling of the leakance between model layers 1 and 2 (contour interval = 5 feet).

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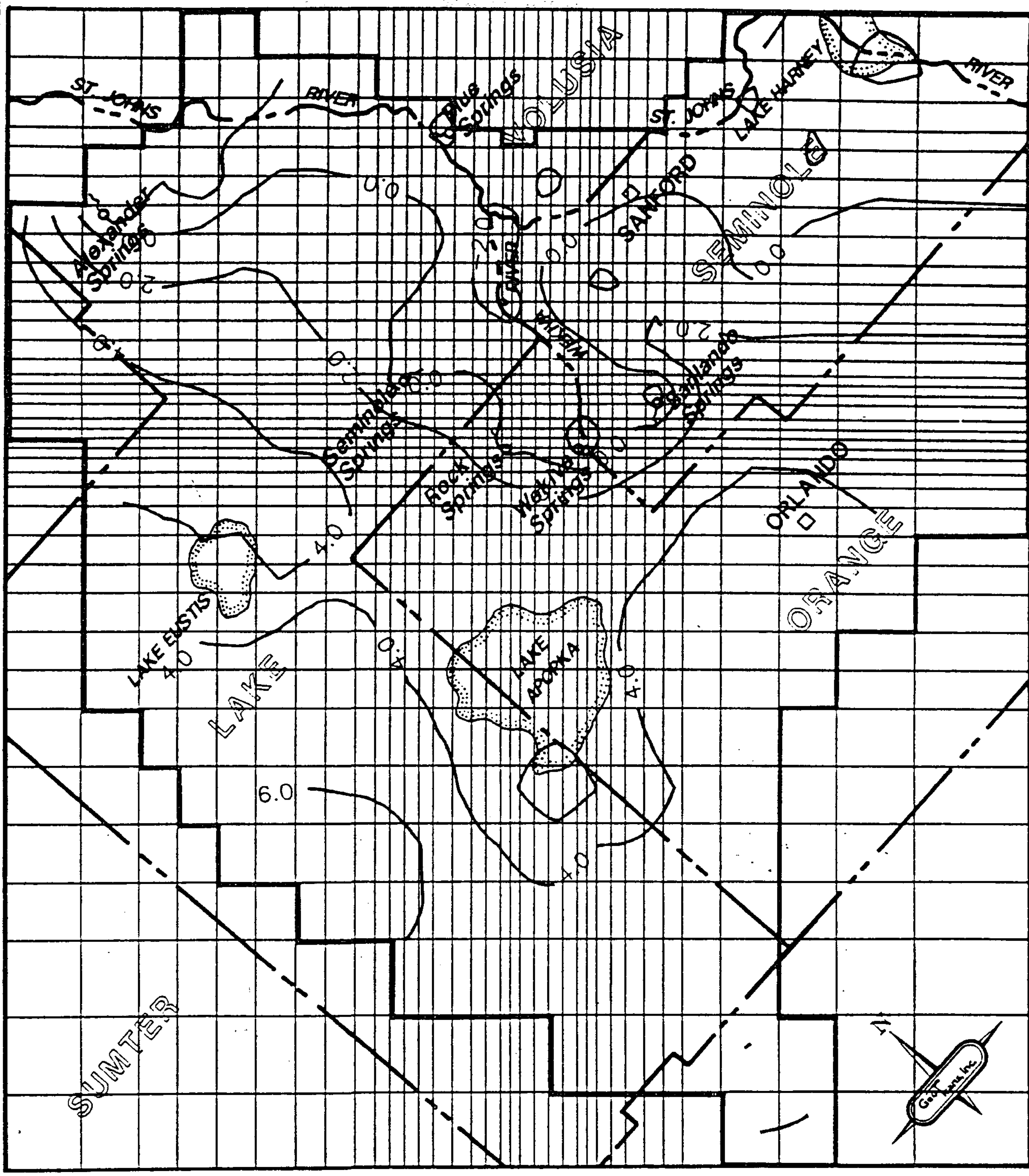

LEGEND

1.0 : REDUCTION IN WATER LEVEL (feet)

-1.0 : INCREASE IN WATER LEVEL (feet)

0 5 10 MILES

0 5 10 15 KILOMETERS

Figure 23. Simulated change in the Upper Floridan potentiometric surface due to doubling of the transmissivity of model layer 2 (contour interval = 2 feet).

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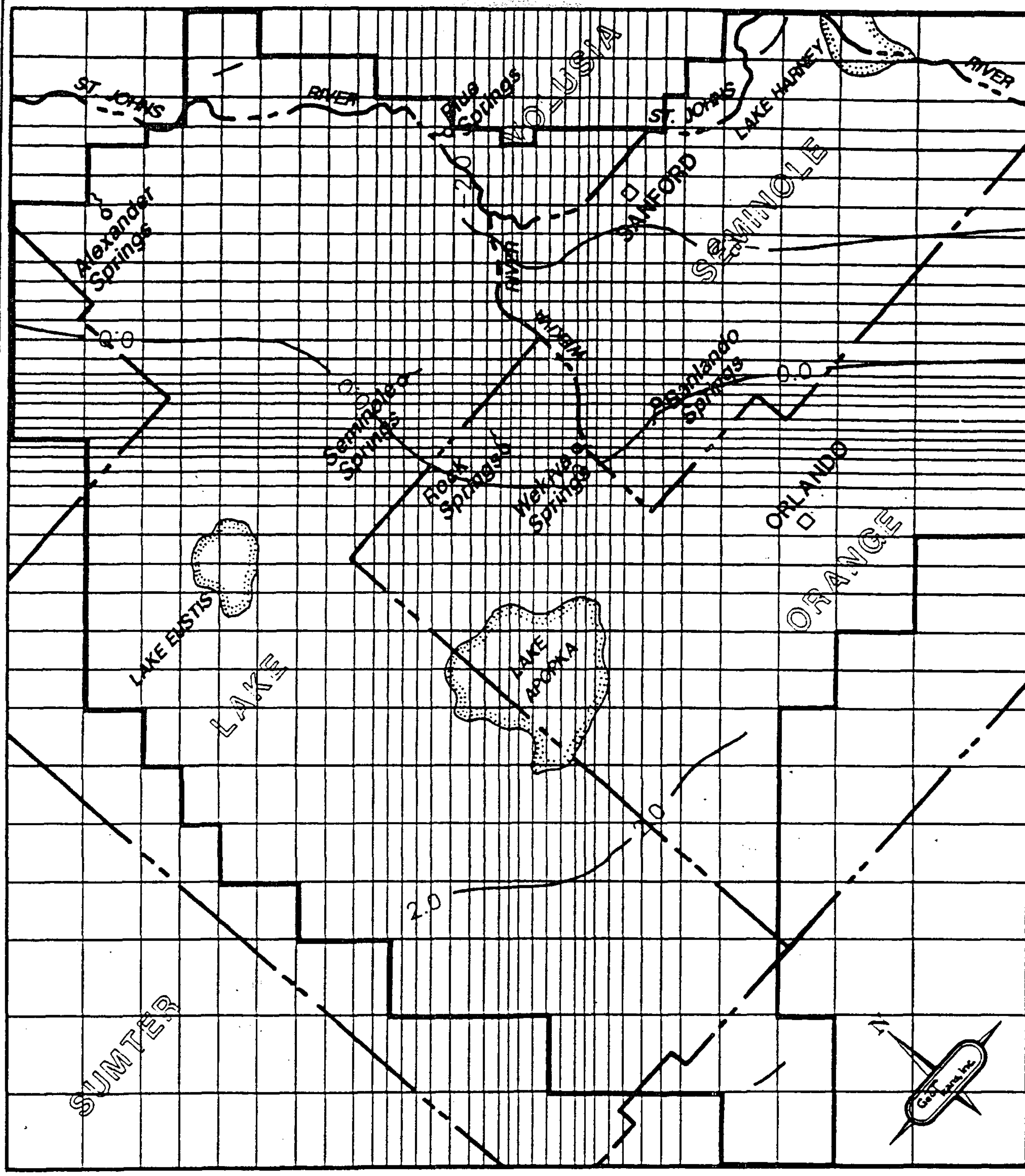
(Figure 23 and 24). As can be seen in Figure 21, doubling the leakance between layers 2 and 3 has little effect on water levels in layer 2.

An increase in the elevation of the water table by 5 feet and an increase by a factor of 1.5 in the conductance of all area springs was evaluated (Figure 25). Water levels in both aquifers rise between 3 and 4 feet over much of the modeled area in response to the raised water table (Figure 25). Figure 26 presents the simulated change that occurs in model layer 2 over the entire domain. The relatively slight change that occurs near model springs is consistent with their high conductances (Figures 25 and 27). Increasing spring conductances by a factor of 1.5 causes groundwater levels to decline in response to the increased ability of the spring to discharge water. That is, a lower head differential between spring pool and aquifer is needed to discharge the same volume of water. Water level declines are focused in the area of the major springs.

Simulated changes in water levels in the Lower Floridan aquifer to increasing the transmissivity of layer 2 and layer 3 (Figure 28) are similar to the results of the same procedure on layer 2. The similar response of both aquifers to similar parameter changes is consistent with the apparently very good connection between the two aquifers.



LEGEND

1.0 : REDUCTION IN WATER LEVEL (feet)

-1.0 : INCREASE IN WATER LEVEL (feet)

0 5 10 MILES

0 5 10 15 KILOMETERS

Figure 24. Simulated change in the Upper Floridan potentiometric surface due to doubling of the transmissivity of model layer 3 (contour interval = 2 feet).

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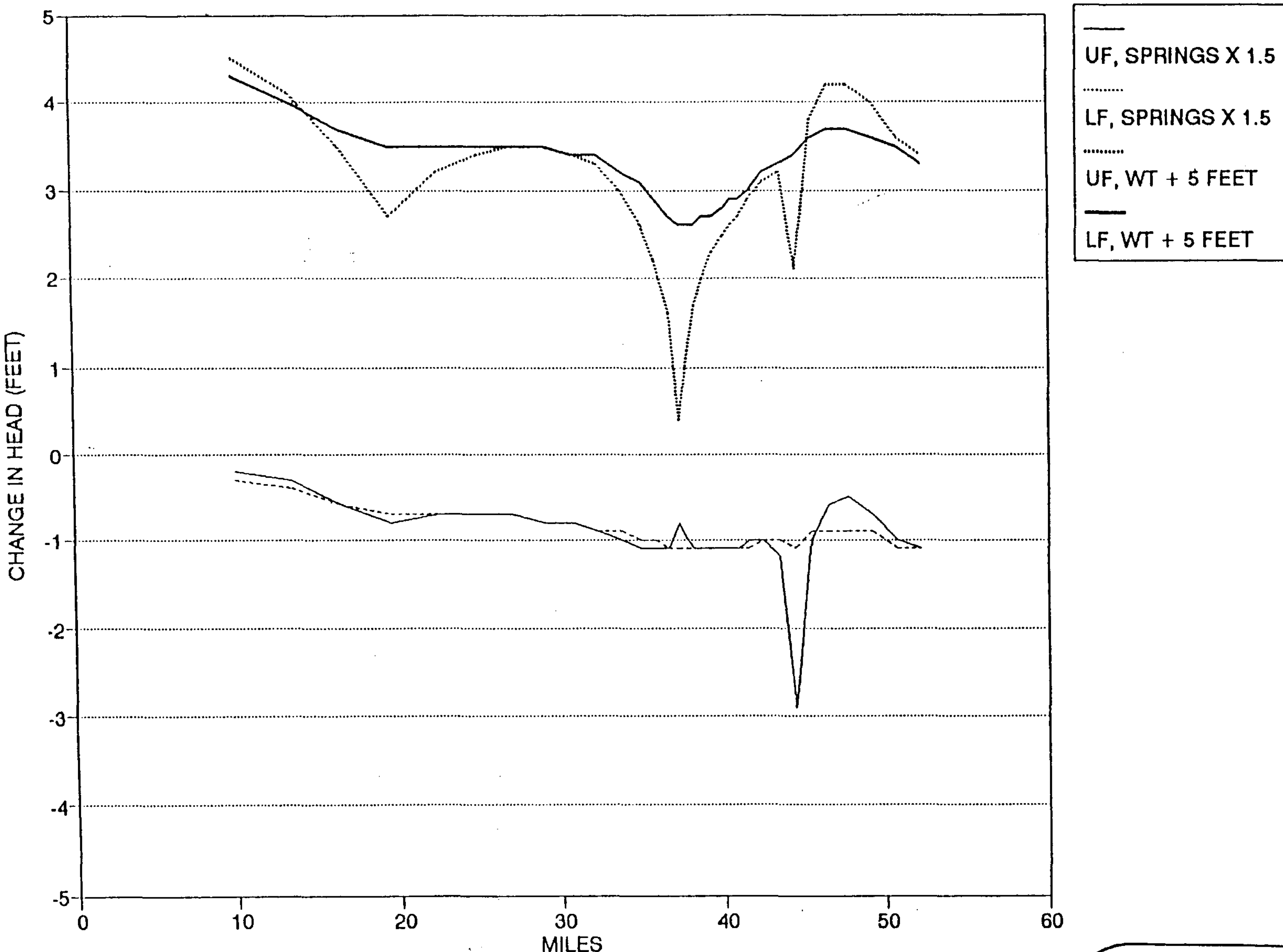

Figure 25. Simulated change in the Upper and Lower Floridan potentiometric surfaces along model row 18 due to increases in water-table elevation and drain conductance.

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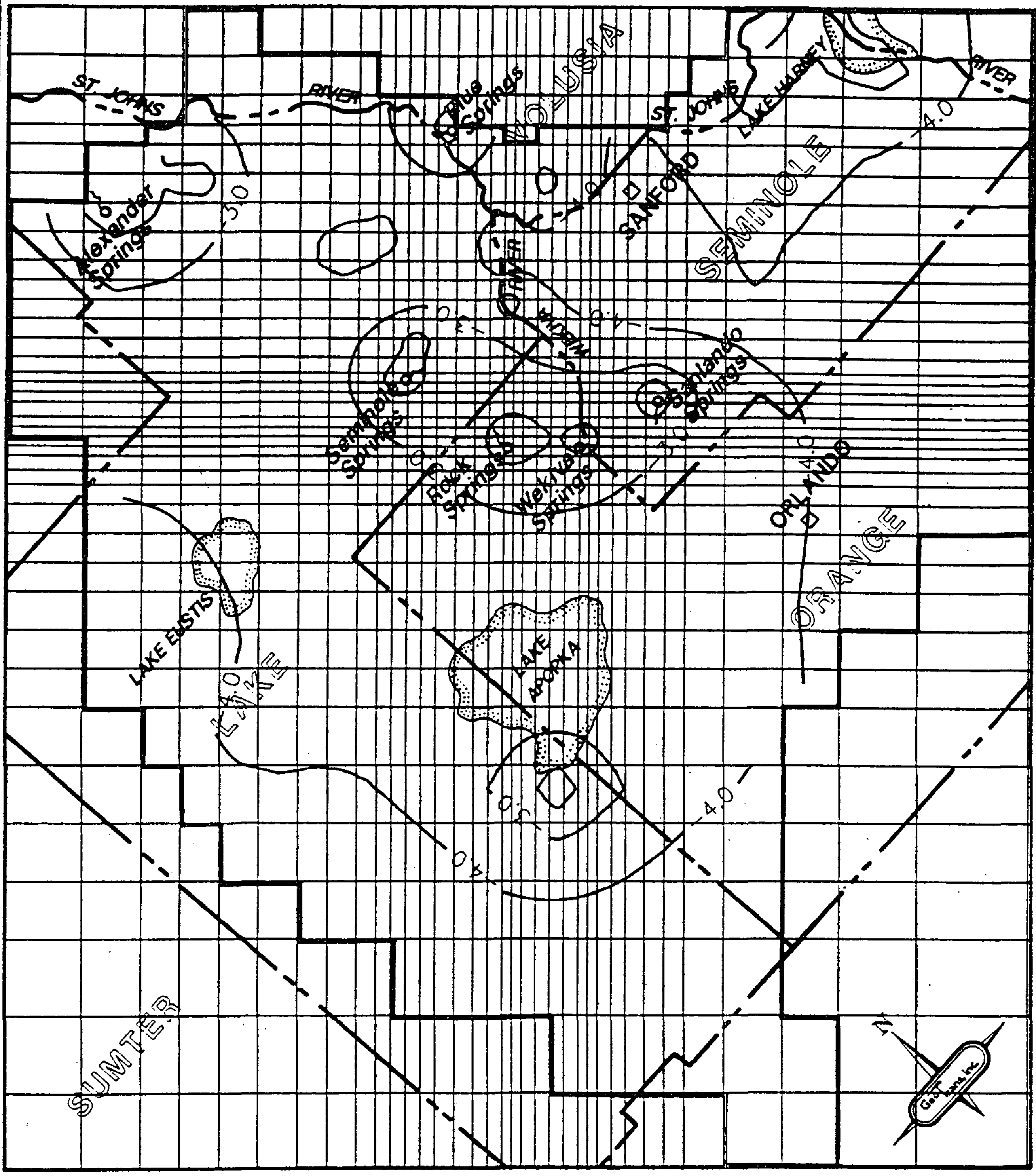

LEGEND

1.0 : REDUCTION IN WATER LEVEL (feet)

-1.0 : INCREASE IN WATER LEVEL (feet)

0 5 10 MILES

0 5 10 15 KILOMETERS

Figure 26. Simulated change in the Upper Floridan potentiometric surface due to increasing the elevation of the water table by 5 feet (contour interval = 1 foot).

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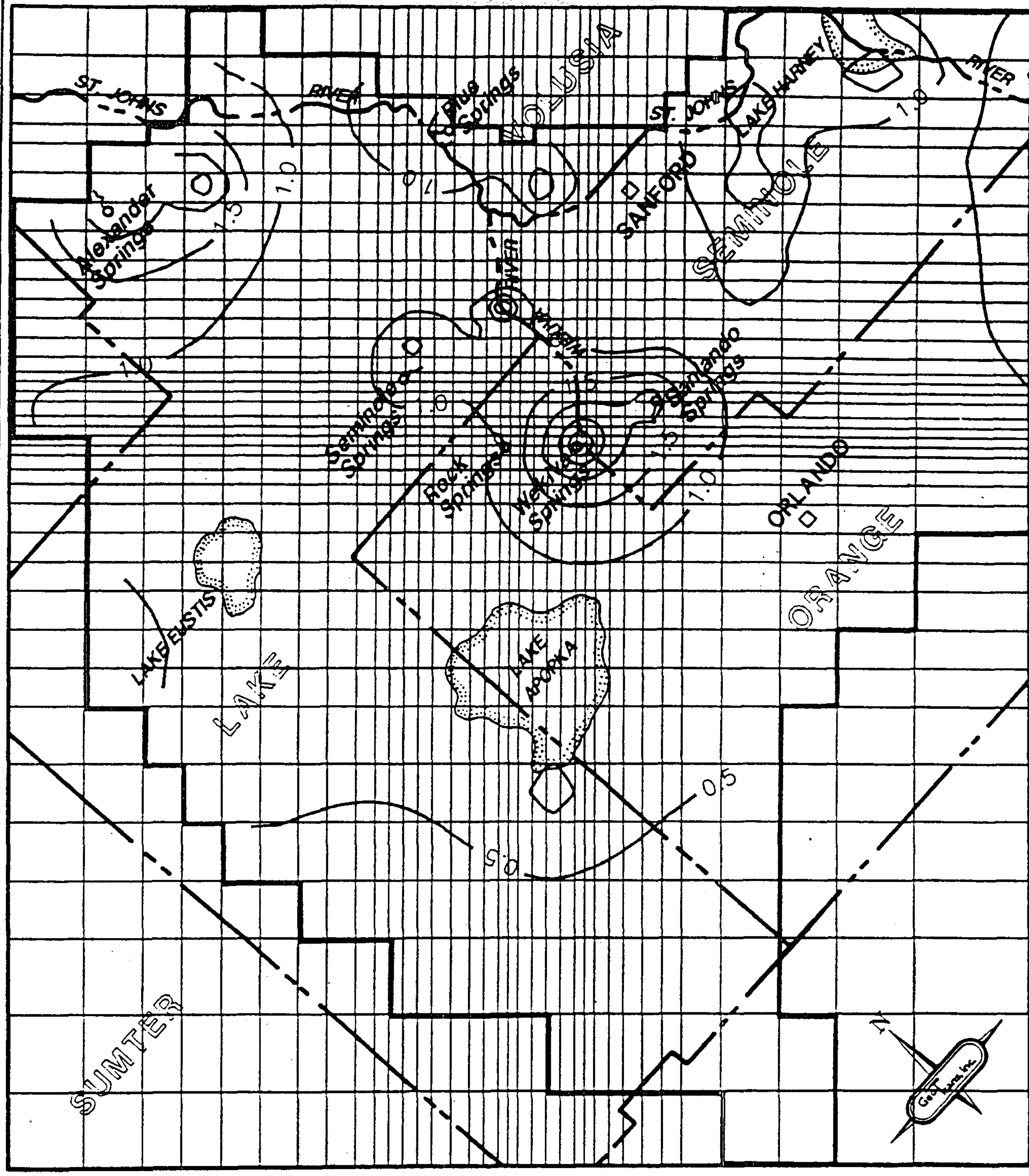

LEGEND

1.0 : REDUCTION IN WATER LEVEL (feet)

-1.0 : INCREASE IN WATER LEVEL (feet)

Figure 27. Simulated change in the Upper Floridan potentiometric surface due to increasing the spring conductance by a factor of 1.5 (contour interval = 0.5 feet).

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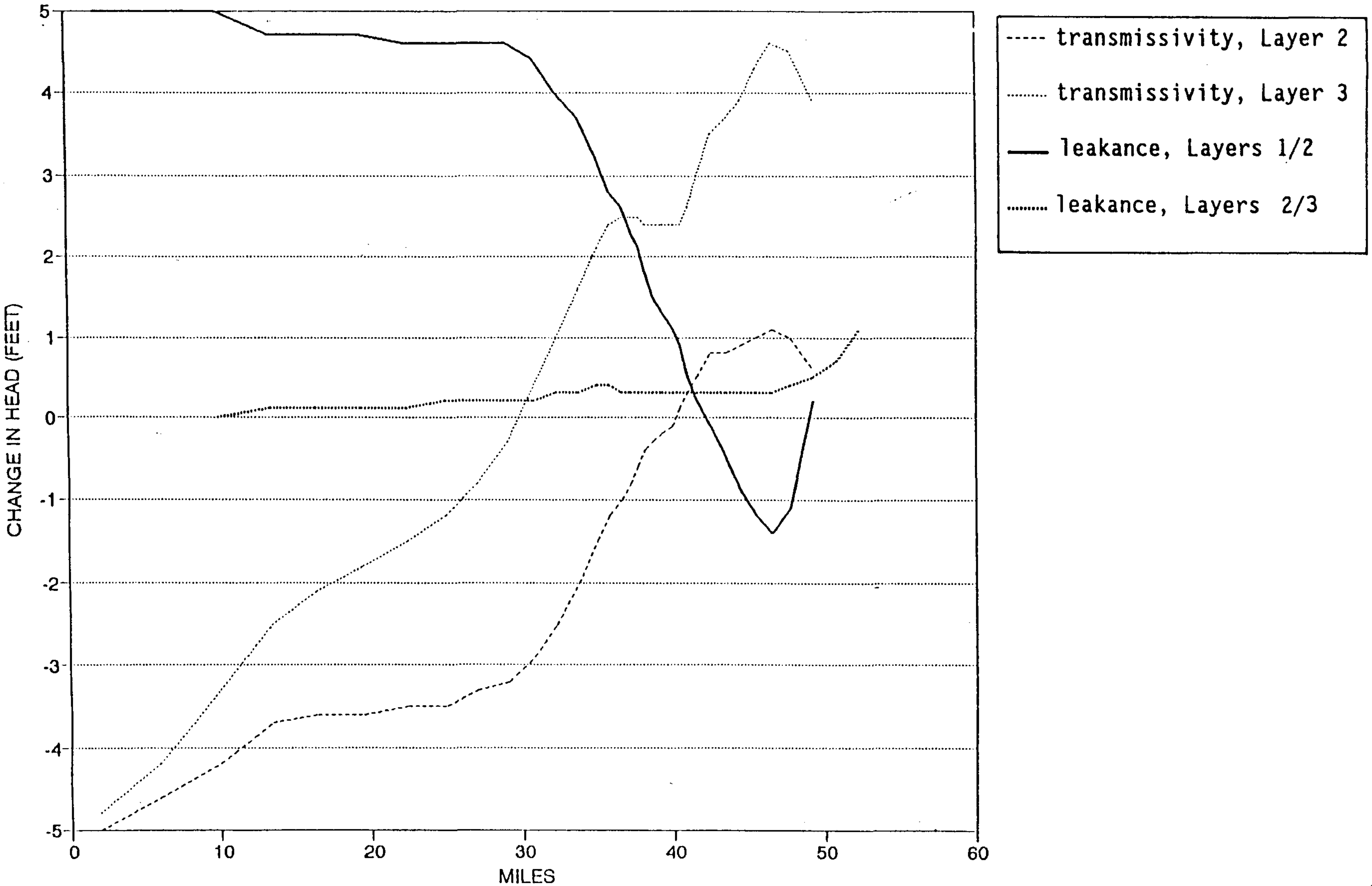

Figure-28. Simulated change in the Lower Floridan potentiometric surface along model row 18 due to changes in transmissivity and leakance values.

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6 DISCUSSION

6.1 IMPLICATIONS OF USING A FIXED WATER TABLE

As a result of fixing the maximum recharge rate, simulated model-wide recharge was reduced slightly over that which would be calculated without the restriction. Under predevelopment conditions, recharge was reduced by approximately 1 x 10^6 ft^3/d or 1.6 percent. Under 1988 pumping conditions, recharge was reduced by approximately 1.4 x 10^6 ft^3/d or 1.7 percent. Maximum recharge rates of 20 in/yr were reached at approximately five percent of the active model blocks, which represent areas previously classified as high recharge zones (e.g., Phelps, 1984).

Some error is also introduced in the simulated potentiometric surface of the Upper Floridan aquifer when a fixed water table is used. Again, under steady-state conditions, the downward leakage rate is assumed to be proportional to the difference in head between the water table and the potentiometric surface. In order to capture water from the surficial aquifer (i.e., reduce evapotranspiration and runoff) to balance additional pumping demands, a reduction in water-table elevation must occur. However, because the water-table elevation is fixed, the new head differential simulated to provide this additional leakage is attributed to a decline in the potentiometric surface only. This under-predicts the decline in the potentiometric surface. In reality, under steady-state conditions, the water table must decline by the amount necessary to capture the necessary amount of evapotranspiration and runoff. Therefore, the potentiometric decline is under-predicted by an equivalent amount. That is, the true decline equals the amount of water-table decline plus the decline required to increase the head differential by the amount necessary to satisfy the equation for leakage. Therefore, if a water-table decline of 13 feet is required to capture a maximum 20 in/yr of recharge, a decline of 1 foot in the water table is necessary to provide an additional 1.5 inches of recharge. Model wide, simulated increases in recharge due to pumping were less than or equal to 1.5 inches. Consequently, potentiometric drawdowns are likely to be under-predicted by less than 1 foot.

6.2 SIMULATED GROUNDWATER DISCHARGES

Simulated 1988 discharges are within 15 percent of observed or estimated discharge rates at all springs within the Wekiva River and Blackwater Creek subbasins. This includes Rock, Wekiva, Sanlando, Palm, Starbuck, Island, Seminole, and Messant Springs. Discharges from these springs constitute the vast majority of the baseflow of the Wekiva River. Simulated discharges at springs located outside of these two subbasins are all within 30 percent of observed or estimated discharge rates. As noted, the estimated conductance at several springs was refined during model calibration. With the exception of Apopka Spring, all refinements are consistent with observed water levels and discharges. The conductance for Apopka Spring had to be increased beyond that which is strictly justifiable in order to simulate appropriate discharge.

Rates of groundwater discharge simulated by the present model via diffuse upward leakage from the Floridan aquifer under average 1988 pumping conditions are higher than those simulated by Tibbals (1990). He simulated discharges on the order of one to two inches per year in the upper Wekiva River discharge area in Orange and Seminole Counties. In the present analysis, simulated discharges range between 0.1 and 6.6 in/yr and average about 5.5 in/yr in the same area. In the present analysis, simulated discharges in the immediate vicinity of the lower Wekiva River between the Orange County/Lake County line to the mouth of the river at the St. Johns River are on the order of 6-10 in/yr, but locally range as high as 25 in/yr. Much of the difference between Tibbals' (1990) values and those simulated in the present analysis may be accounted for by the much finer spatial refinement used the latter analysis and more accurate leakance values.

Detailed evaluation of rates simulated by the present analysis indicate that they are reasonable. For example, the recharge/discharge maps prepared by Tibbals (1975) and the District indicate that as much as 75 cfs discharges into the lower Wekiva River (down stream of the Orange County line) and immediately adjacent sections of the St. Johns River as a result of the recharge from Seminole and Lake Counties. Discharge from the two flowing wells at Wekiva Falls and discharge from Island Spring only account for about 30 of the 75 cfs. Model-simulated discharge in these areas is approximately 31 cfs, a rate that appears to be well within reason. Similarly, simulated recharge rates in the associated source areas such as in west central Seminole County (10-20 in/yr) and in adjacent Lake County (0-5 in/yr) are in the range estimated by others (Tibbals, 1975; Phelps, 1984). The extreme potentiometric trough along the lower Wekiva River and adjacent St. Johns is a good indication that substantive discharge is taking place in this area.

Simulated Floridan aquifer discharge near the upper Wekiva River (upstream of the Orange County line) is approximately 18 cfs for average 1988 pumping conditions. Again, such a rate is not unreasonable. Some of the 18 cfs of modeled discharge is also probably captured by Wekiva, Rock, or other smaller springs in the area after it enters the surficial aquifer in their vicinity. The model is not capable of simulating such a transfer. Note that Tibbals' (1990) model represented this area with only three 16 mi^2 model blocks, each of which contained one or more springs.

Such a representation does not allow discharging water to go anywhere but to the springs. That is, no diffuse discharge to the surficial aquifer could be simulated using such a scale.

6.3 SIMULATED EFFECTS OF ESTIMATED GROUNDWATER WITHDRAWALS

The most substantial simulated reductions in groundwater levels in the Upper Floridan aquifer between predevelopment and average 1988 conditions occur in Orange and Seminole counties. Greatest drawdown in the Upper Floridan occurs in the Orlando/Winter Park area, and in the Wekiva River area at Wekiva Falls resort (Figure 29). Drawdowns in the aquifer in the Orlando/Winter Park area are attributable to pumpage from both the upper and lower Floridan or model layers 2 and 3 (approximately 35 percent). Total non-agricultural withdrawals are estimated at approximately 25.3 x 10^6 ft^3/d (184 mgd) (Table 8). Drawdown near the Wekiva River is attributed to the discharge in excess of 1.8 x 10^6 ft^3/d (Tibbals, 1990) from two Upper Floridan free flowing wells. A maximum drawdown of 15 feet is simulated. However, drawdowns in upper and lower aquifers are offset by the influx, primarily to the Upper Floridan aquifer in the Orlando area, of an estimated 4.4 x 10^6 ft^3/d (33 mgd) of water from drainage wells. Figure 30 shows the simulated rise in groundwater levels in the Upper Floridan aquifer caused by the drainage wells.

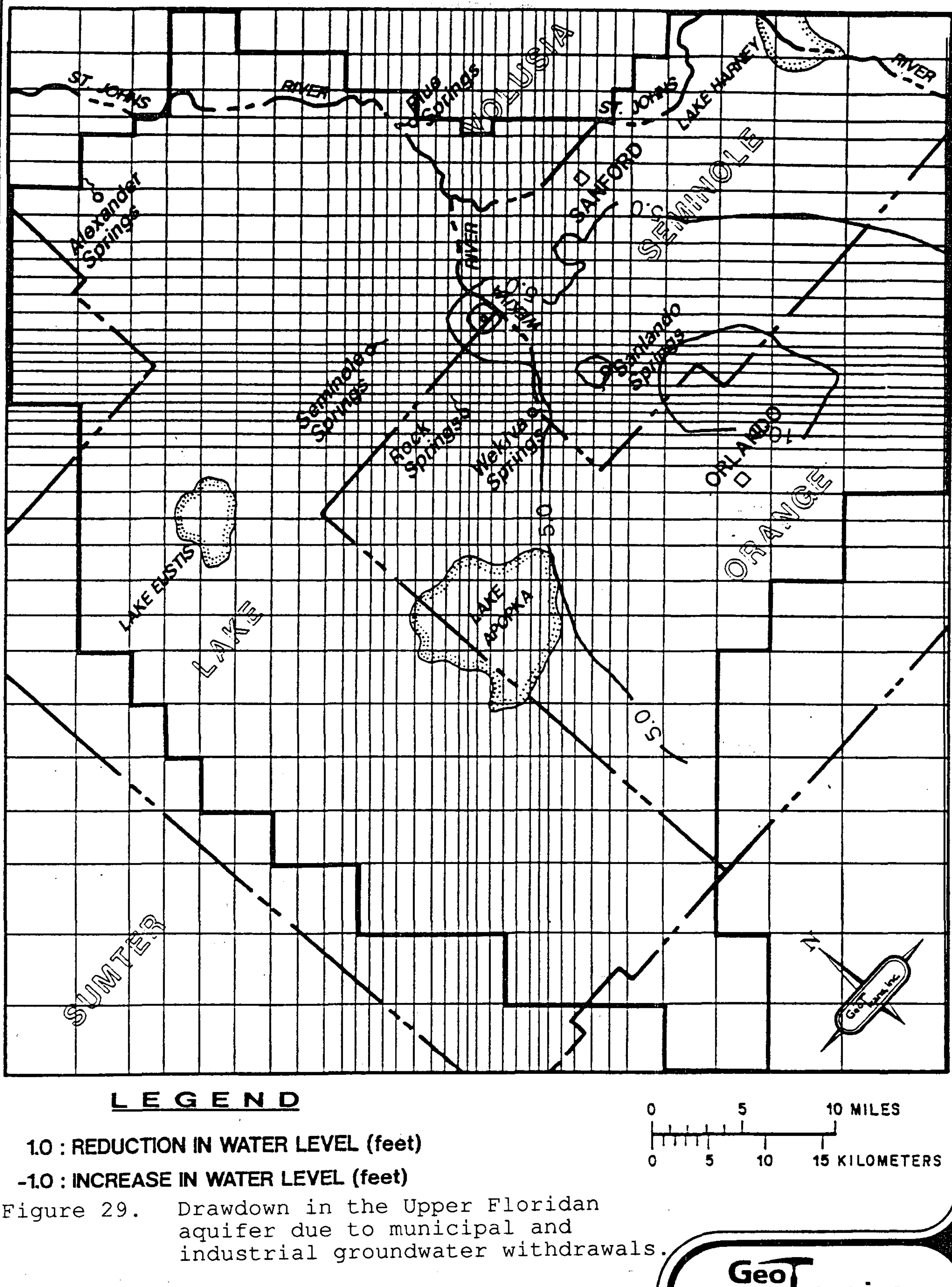

Figure 29. Drawdown in the Upper Floridan aquifer due to municipal and industrial groundwater withdrawals.

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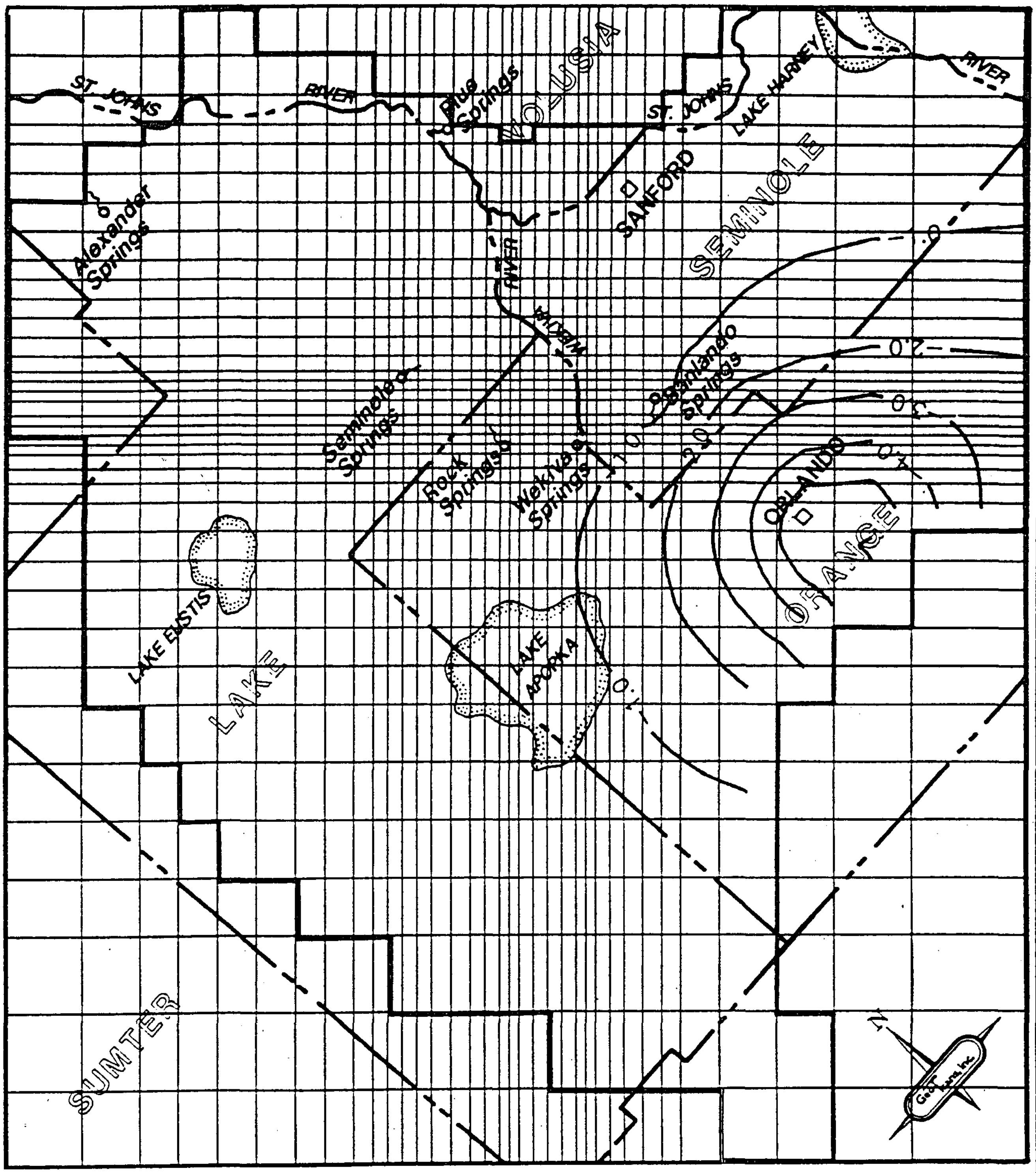
Table 8. Estimated water budget for the Floridan aquifer system, average 1988 conditions.

		Source	Rate (10^6 ft^3/d)
I.	Inflow	Water Table	81.9
		Drainage Wells	4.4
		TOTAL	86.3
		Sink	Rate (10^6 ft^3/d)
II.	Outflow	Water Table	14.0
		Spring	42.5
		Agricultural Withdrawals	4.5
		Upper Floridan, Non-Agricultural* Withdrawals	16.0
		Lower Floridan, Non-Agricultural Withdrawals	9.3
		TOTAL	86.3

NOTE: Withdrawals and drainage well rates are known or estimated; other rates are those simulated by model.

*Excluding domestic use



LEGEND

1.0 : REDUCTION IN WATER LEVEL (feet)

-1.0 : INCREASE IN WATER LEVEL (feet)

0 5 10 MILES

0 5 10 15 KILOMETERS

Figure 30. Estimated rise in the potentiometric surface of the Upper Floridan aquifer due to recharge from drainage wells.

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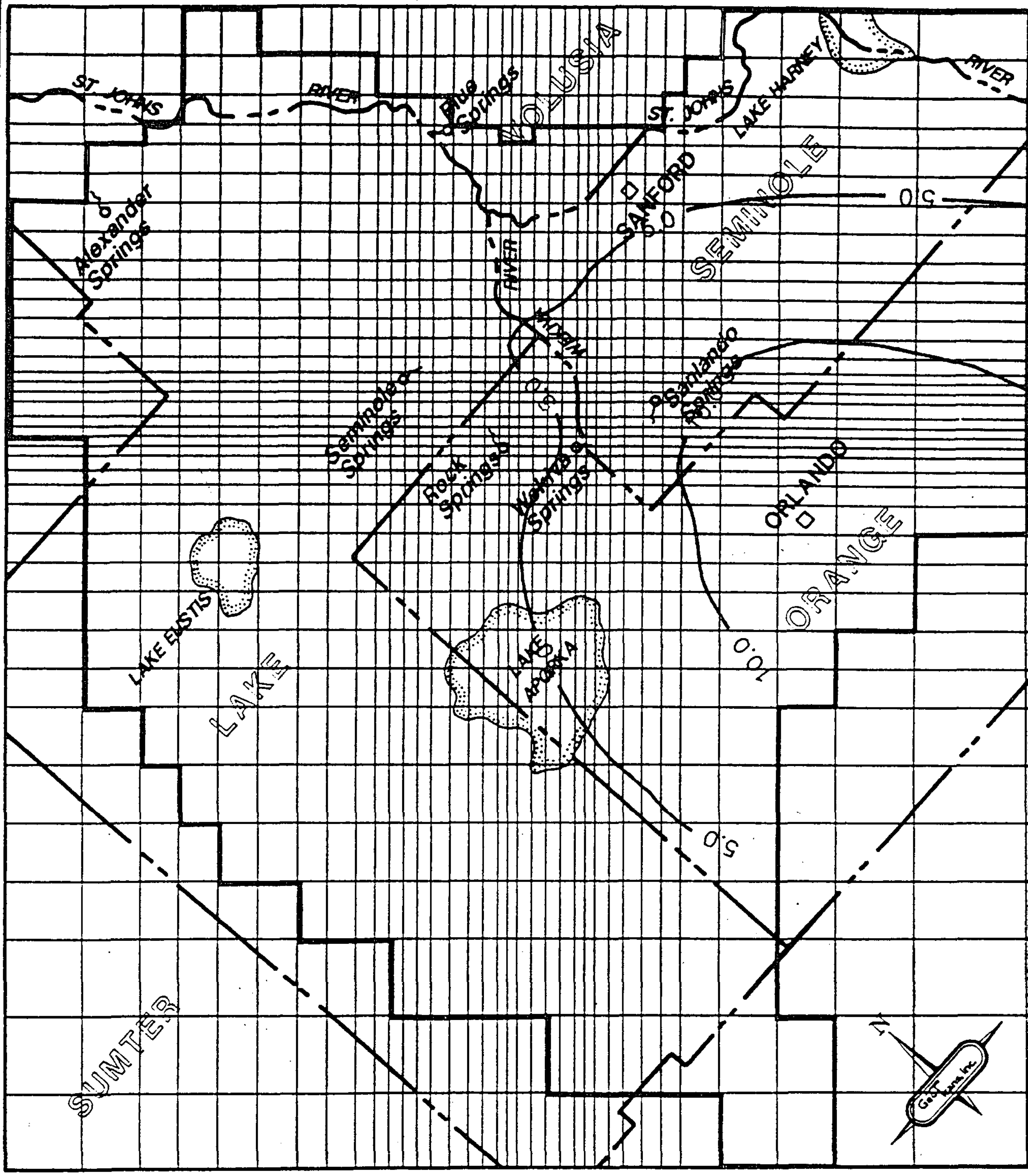
The greatest drawdown in the Lower Floridan aquifer due to the pumping of non-agricultural wells occurs in the Orlando area where an average estimated 9.3 x 10^6 ft^3/d (69 mgd) is being pumped from the Lower Floridan (Figure 31). However, estimates of as much as four feet of this predicted drawdown are attributable to the pumping of Upper Floridan aquifer wells.

Drawdowns associated with the pumping of an estimated 4.5 x 10^6 ft^3/d (34 mgd) of groundwater from the Upper Floridan aquifer for agricultural irrigation are substantially less than those due to non-agricultural pumping. A maximum drawdown of approximately 2.5 feet is predicted in southeastern Lake County (Figure 32). Simulated water level reductions across the entire project area as a result of agricultural pumping is on the order of one foot or less.

6.4 MODEL ACCURACY

The relative accuracy of the groundwater flow model for the Wekiva River basin project area has been assessed based on the following criteria:

- Ability to match estimated or observed heads in the Floridan aquifer, primarily the upper permeable zone;
- Ability to match estimated or known spring discharges; and



LEGEND

1.0 : REDUCTION IN WATER LEVEL (feet)

-1.0 : INCREASE IN WATER LEVEL (feet)

0 5 10 MILES

0 5 10 15 KILOMETERS

Figure 31. Drawdown in the Lower Floridan aquifer due to non-agricultural groundwater withdrawals.

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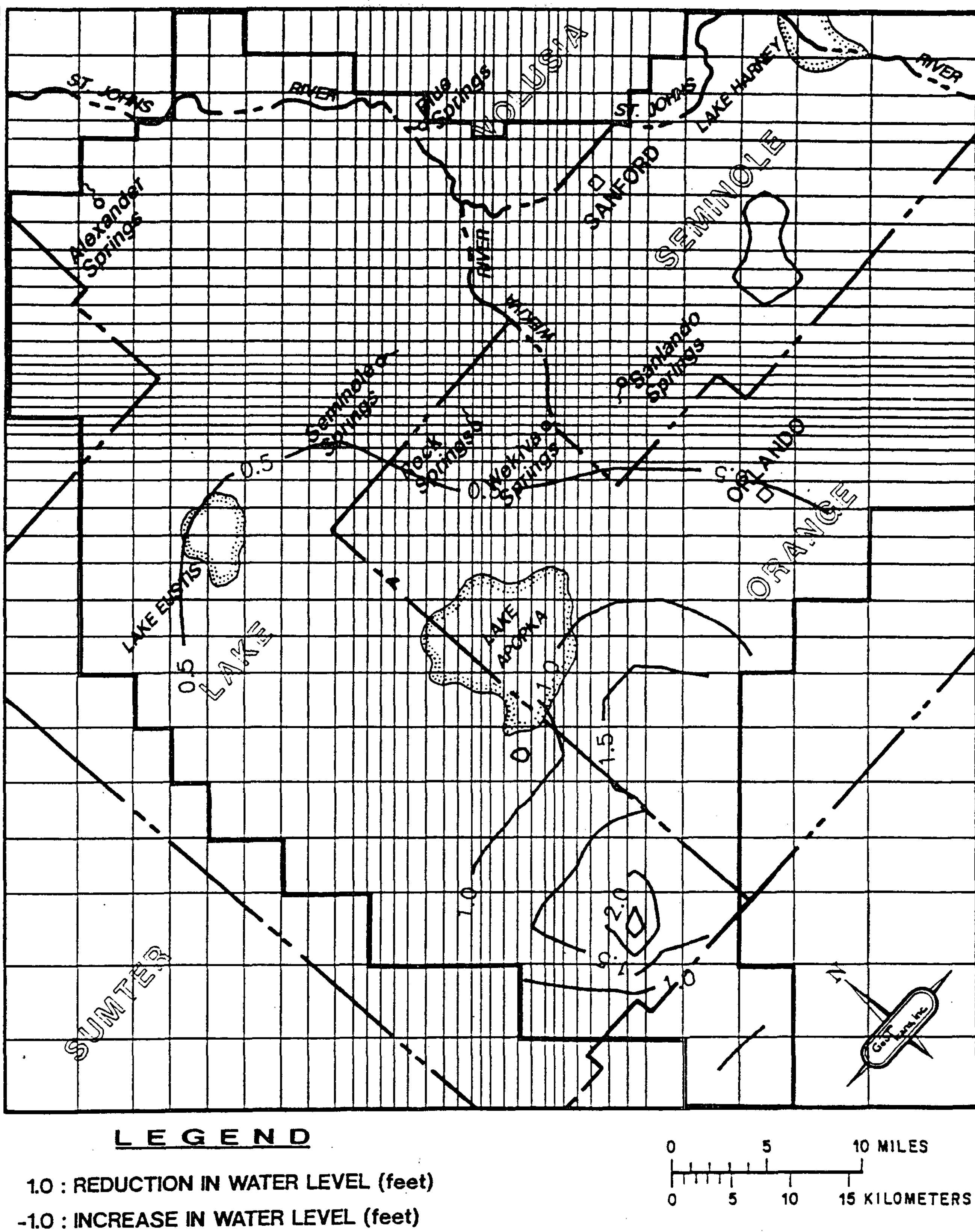

Figure 32. Drawdown in the Upper Floridan aquifer due to agricultural groundwater withdrawals.

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- Ability to predict reasonable rates of diffuse discharge.

The groundwater system that is being simulated is a closed system which is advantageous for modeling. Having a relatively good idea of how much water is moving though the groundwater system makes it harder to develop unrealistic models. Groundwater levels in an isotropic, homogeneous aquifer are proportional to the ratio between recharge (R) and transmissivity (T). For such an aquifer, the water levels simulated could be the same in two different models despite different values of recharge and transmissivity as long as the ratio, R/T, is constant. This is evident in the present model by the roughly equivalent but opposite response of the potentiometric surface to reductions in leakance and transmissivity as shown in the sensitivity analysis. Clearly, however, simulated recharge and discharge rates would be different in the two simulations.

In the present analysis, simulated recharge rates, spring discharges, and diffuse leakage rates are in agreement with observed rates. Simulated discharges from Rock, Wekiva, Palm, Sanlando, and Starbuck Springs under average 1988 conditions are somewhat lower than observed. However, discharge of all springs within the Wekiva River and Blackwater Creek sub-basins are within 85 percent of their estimated average rates. Furthermore, some of the actual discharge of these springs is being lost in the model via diffuse upward leakage to the surficial aquifer in the immediate vicinity. Bear in mind that the model is unable to account directly for Floridan aquifer water that discharges to the surficial aquifer and is subsequently captured and discharged by springs. However, given the significant influence of these springs on groundwater flow in the Floridan aquifer in their immediate vicinity, it is not unlikely that some percentage of the 18 cfs is captured by the springs in this manner. The majority of this 18 cfs is likely lost to the atmosphere through evapotranspiration.

Simulated groundwater levels for both predevelopment conditions and average 1988 conditions are also within an acceptable range, particularly given the uncertainties and errors associated with (a) estimating predevelopment and average 1988 conditions, (b) utilizing average annual pumping rates for individual facilities and wells, (c) estimating agricultural withdrawals, and (d) having essentially little or no data on the Lower Floridan aquifer. Overall, model results agree with those presented by Tibbals (1981; 1990).

7 SUMMARY

This report presents the results of the first phase of a three-phase study of the Wekiva River basin. The overall objective of the study is to provide the St. Johns River Water Management District with a tool to aid in the establishment of minimum groundwater levels within the basin to protect the quality of its water resources. The objective of Phase I was to develop a three-dimensional groundwater flow model of the Floridan Aquifer system that encompasses the Wekiva River Basin. This regional-scale model will be used to determine boundary flows and boundary conditions for two- and three-dimensional flow and saltwater transport models of a smaller sub-regional area.

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. Overall simulated water levels agree with observed levels. The fact that simulated results for 1988 conditions were less accurate than those simulated 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 simulated groundwater levels associated with pumping conditions in 1988 were consistent with the groundwater levels defined (average of observed May and September potentiometric surfaces).

Simulated declines in spring discharges between predevelopment and 1988 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 largely due 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 presented in this Phase I report is believed to provide an 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 for the Phase II and Phase III solute transport models. Further evaluation of the springs should be made during Phase III in an effort to better account for observed discharges.

Subsequent modeling efforts in the project area would benefit from additional data on the Lower Floridan aquifer, particularly water levels and transmissivity data. In particular, a deep observation well at Wekiva or Rock Springs could provide important information on the influence of the Lower Floridan on these springs, both in terms of water quantity and quality.

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APPENDIX A

Municipal and Industrial Water Users

Owner	Pumpage (cfd) Total
HYATT HOUSE	20,300.0
HYATT HOUSE	20,300.0
OSCEOLA SERV	257,000.0
POLK CTY UTILITIES	9,890.0
REEDY CREEK (DISNEY)	13,400.0
REEDY CREEK (DISNEY)	346,000.0
REEDY CREEK (DISNEY)	731,900.0
REEDY CREEK (DISNEY)	1,590,000.0
SEA WORLD OF FLA.	53,000.0
SEA WORLD OF FLA.	120,000.0
WEKIVA FALLS	1,810,000.0
MASCOTTE WATER SEPT	23,396.1
DEANZA MID FLORIDA LAKES	96,879.2
CITY OF MINNEOLA	25,765.3
HOWEY WATER DEPT	42,350.7
ORANGE BLOSSM GARDENS UTILITY	194,609.8
CITY OF TAVARES	156,480.0
CITY OF FRUITLAND PARK	60,452.3
CITY OF MOUNT DORA UTILITIES	317,032.1
MONTVERDE WATER DEPARTMENT	16,399.5

cfd - cubic feet per day

Owner	Pumpage (cfd) Total
HAWTHORNE AT LEESBURG	63,265.8
CITY OF EUSTIS	46,459.1
CITY OF GROVELAND	38,537.0
CITY OF LEESBURG	483,322.2
UMATILLA WATER WORKS	64,302.3
CITY OF EUSTIS	166,512.2
CITY OF EUSTIS	180,283.3
CLERMONT	63,043.6
CLERMONT	69,966.2
SILVER LAKE ESTATES	76,777.8
SOUTHERN STATES UTILITIES INC.	5,309.6
SOUTHERN STATES UTILITIES INC.	7,255.8
LAKE COUNTY UTILITIES SUNSHINE PARKWAY SYSTEM	9,106.7
CITY OF LEESBURG	2,787.5
CITY OF LEESBURG	45,052.3
UTILITIES INC. OF FLORIDA	12,882.7

cfd - cubic feet per day

Owner	Pumpage (cfd) Total
SUNLAKE ESTATES SUNLAKE ESTATES	27,283.1
WATER OAK UTILITY WATER OAK ESTATES	28,541.8
ORANGE COUNTY PUBLIC UTILITIES	223,235.2
ORANGE COUNTY PUBLIC UTILITIES	2,146.0
ORANGE COUNTY PUBLIC UTILITIES	239,289.7
ORANGE COUNTY PUBLIC UTILITIES	141,892.6
ORANGE COUNTY PUBLIC UTILITIES	3,914.8
ORANGE COUNTY PUBLIC UTILITIES	1,896.1
ORANGE COUNTY PUBLIC UTILITIES	30,062.5
ORANGE COUNTY PUBLIC UTILITIES	76,867.3
UTILITIES INC. OF FLORIDA	1,702.9
ORLANDO UTILITIES COMMISSION WATER UTILITIES	719,911.7
ORLANDO UTILITIES COMMISSION WATER UTILITIES	846,221.1
ORLANDO UTILITIES COMMISSION WATER UTILITIES	1,239,808.9
ORANGE COUNTY PUBLIC UTILITIES	27,069.9

cfd - cubic feet per day

Owner	Pumpage (cfd) Total
ORANGE COUNTY PUBLIC UTILITIES	25,800.5
ORANGE COUNTY PUBLIC UTILITIES	2,710.9
UTILITIES INC. OF FLORIDA	13,363.9
ZELLWOOD STATION	64,487.4
CITY OF MAITLAND	388,627.2
ROCK SPRINGS MOBILE HOME PARK	26,764.9
ORLANDO UTILITIES COMMISSION WATER UTILITIES	1,349,792.9
ORLANDO UTILITIES COMMISSION WATER UTILITIES	1,085,253.9
ORLANDO UTILITIES COMMISSION WATER UTILITIES	188,390.5
ORLANDO UTILITIES COMMISSION WATER UTILITIES	1,134,563.4
ORLANDO UTILITIES COMMISSION WATER UTILITIES	1,091,102.9
ORLANDO UTILITIES COMMISSION WATER UTILITIES	1,512,936.3
CITY OF EATONVILLE	81,701.3
WINTER PARK UTILITIES DEPT.	334,357.1
WINTER PARK UTILITIES DEPT.	267,315.4

cfd - cubic feet per day

Owner	Pumpage (cfd) Total
WINTER PARK UTILITIES DEPT.	686,039.2
ORANGE COUNTY PUBLIC UTILITIES	100,218.7
ORANGE COUNTY PUBLIC UTILITIES	482,969.8
SHADOW HILLS MHP	26,394.7
SOUTHERN STATES UTILITIES INC.	70,854.7
SOUTHERN STATES UTILITIES INC.	17,991.3
ORANGE COUNTY PUBLIC UTILITIES	14,245.0
ORANGE COUNTY PUBLIC UTILITIES	206.6
ORANGE COUNTY PUBLIC UTILITIES	5,170.5
TOWN OF OAKLAND	19,990.4
TANGERINE WATER CO.	18,139.4
ORANGE COUNTY PUBLIC UTILITIES	177,906.3
CITY OF OCOEE	89,882.5
CITY OF OCOEE	120,608.4
CITY OF WINTER GARDEN	118,757.5
CITY OF WINTER GARDEN	75,926.3
ZELLWOOD WATER USERS ZELLWOOD	23,322.1

cfd - cubic feet per day

Owner	Pumpage (cfd) Total
CITY OF OCOEE	77,333.0
OVIEDO	105,578.7
OVIEDO	50,642.2
SANFORD	434,308.9
SANFORD	245,511.1
CITY OF CASSELBERRY	104,616.2
CITY OF CASSELBERRY	294,746.6
CITY OF CASSELBERRY	252,359.7
SEMINOLE CO EENVIROMENTAL SER	169,955.0
SEMINOLE UTILITIES TUSCAWILLA COUNTRY CLUB	238,033.2
NORTH ORLANDO WATER & SEWER	79,110.0
NORTH ORLANDO WATER & SEWER	83,996.5
SUNLANDO UTILITIES	760,888.2
SUNLANDO UTILITIES	447,502.5
SUNLANDO UTILITIES	11,798.0
UTILTIES INC. OF FLORIDA	18,250.4

cfd - cubic feet per day

Owner	Pumpage (cfd) Total
UTILTIES INC. OF FLORIDA	16,325.5
UTILTIES INC. OF FLORIDA	56,084.0
SOUTHERN STATES UTILITIES INC.	2,850.5
SOUTHERN STATES UTILITIES INC.	3,776.0
SOUTHERN STATES UTILITIES INC.	19,657.2
SOUTHERN STATES UTILITIES INC.	5,849.0
SOUTHERN STATES UTILITIES INC.	11,031.7
SOUTHERN STATES UTILITIES INC.	34,872.1
SEMINOLE CO EENVIROMENTAL SER	20,730.7
SEMINOLE CO EENVIROMENTAL SER	3,516.8
SEMINOLE CO EENVIROMENTAL SER	360,677.7
SEMINOLE CO EENVIROMENTAL SER	172,213.2
SEMINOLE CO EENVIROMENTAL SER	1,962.0
SOUTHERN STATES UTILITIES INC.	59,415.8
SEMINOLE CO EENVIROMENTAL SER	42,238.9
UTILTIES INC. OF FLORIDA	8,995.7
UTILTIES INC. OF FLORIDA	8,403.4

cfd - cubic feet per day

Owner	Pumpage (cfd) Total
UTILTIES INC. OF FLORIDA	3,183.6
UTILTIES INC. OF FLORIDA	3,479.8
UTILTIES INC. OF FLORIDA	5,071.6
CITY OF LONGWOOD 1 & 2	105,393.6
CITY OF ALTAMONTE SPRINGS	26,061.5
CITY OF ALTAMONTE SPRINGS	413,800.2
CITY OF ALTAMONTE SPRINGS	87,365.2
CITY OF ALTAMONTE SPRINGS	58,440.9
CITY OF ALTAMONTE SPRINGS	516,750.5
SOUTHERN STATES UTILITIES INC.	26,431.7
PALM VENTURES INC PALM VALLY MHP	21,137.9
SEMINOLE CO EENVIROMENTAL SER	29,245.1
ORANGE CITY WATER CO.	68,707.6
VOLUSIA COUNTY WATER DEPT.	18,916.8
VOLUSIA COUNTY WATER DEPT.	53,566.7
VOLUSIA COUNTY WATER DEPT.	19,235.2

cfd - cubic feet per day

Owner	Pumpage (cfd) Total
SUNDOR BRANDS INC. (USED TO BE DORIC FOODS)	3,045.0
B & W CANNING CO. INC.	131,195.9
GOLDEN GEM GROWERS INC.	579,831.2
FLORIDA CRUSHED STONE TULLEY SAND MINE	295,153.8
THE COCA COLA COMPANY FOODS DIVISION	241,142.9
SILVER SPRINGS CITRUS COOP HOWEY CITRUS PROC PLANT	95,398.4
FLORIDA ROCK INDUSTRIES LAKE SAND MINE	117,410.0
SILVER SAND CO. OF CLERMONT	167,178.6
THE COCA COLA CO. FOODS DIVISION	14,252.4
ZELLWOOD FARMS INC.	20,471.6
WINTER GARDEN CITRUS PRODUCTS COOPERATIVE	253,063.0
DEEP SOUTH PRODUCTS	46,236.9
LAKE MONROE UTILITIES I-4 INDUSTRIAL PARK	17,658.1
VOLUSIA COUNTY WATER DEPT.	19,101.9

cfd - cubic feet per day

Owner	Pumpage (cfd) Total
FLA. DEPT. OF CORRECTIONS LAKE COUNTY FACILITY	15,140.8
SUN RESORT INC YOGI BEAR CAMPGROUND N.	13,438.0
UNIVERSITY OF CENTRAL FLORIDA	99,433.5
FLORIDA POWER & LIGHT CO. SANFORD PLANT	42,757.1
FLORIDA POWER CORP. GEORGE E. TURNER	12,864.2

cfd - cubic feet per day