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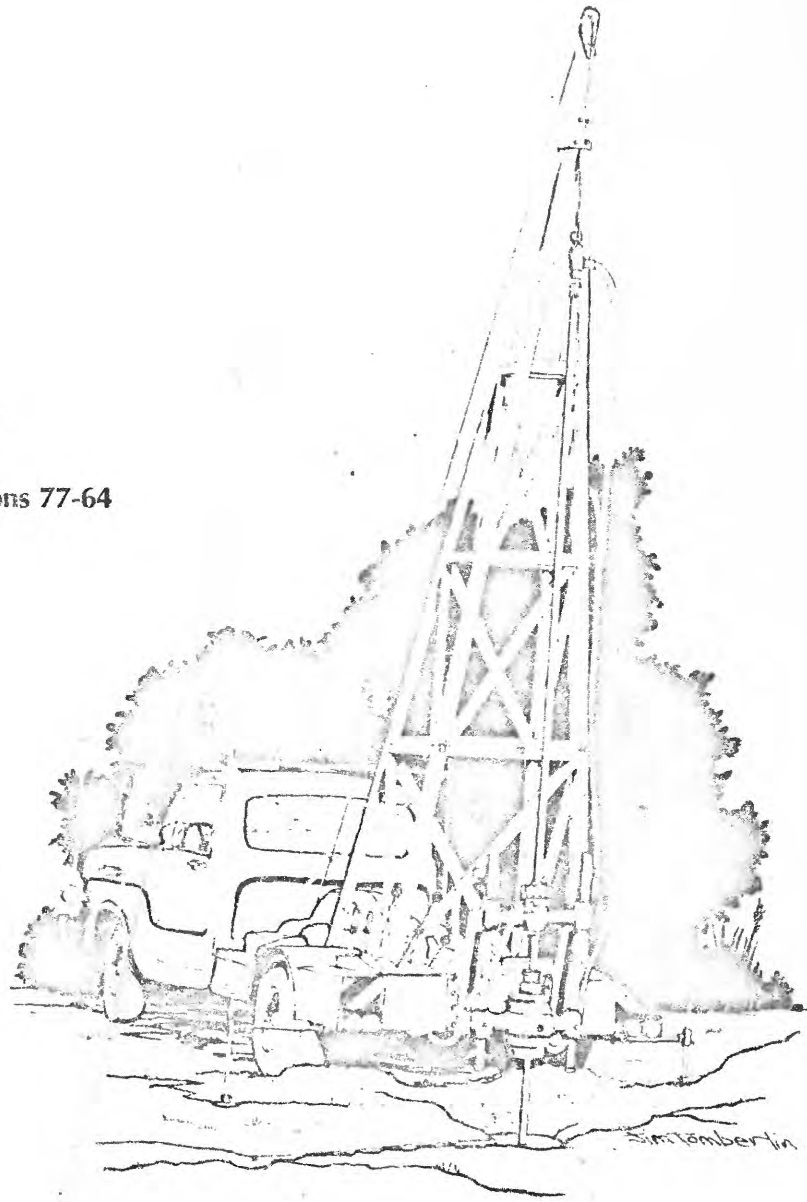
A DIGITAL MODEL OF THE FLORIDAN AQUIFER, NORTH OF TAMPA, FLORIDA



U.S. GEOLOGICAL SURVEY

Water Resources Investigations 77-64

Prepared in cooperation with the
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

WRI 77-64 A DIGITAL MODEL OF THE FLORIDAN AQUIFER, NORTH OF TAMPA, FLORIDA

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By Alton F. Robertson and Michael J. Mallory

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October 1977

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ABSTRACT

West-central Florida has had considerable growth in population with resultant commercial and industrial development in the last two decades. A method to evaluate the effects of proposed ground-water withdrawals upon the Floridan aquifer is needed to help ensure orderly and safe development of the ground-water resource. A regional ground-water model of the aquifer was constructed for an 875-square-mile part of the rapidly developing area north of Tampa Bay.

The digital model was calibrated by comparing observed (March 1974 and May 1975) and computed potentiometric heads. A good comparison was obtained by adjusting leakance and transmissivity. Differences between the computed and measured potentiometric surface were generally less than 3 feet with a maximum error of 15 feet. The calibrated model may be used as a predictive tool. For example, the model could be used to evaluate the regional effects of increased ground-water withdrawal on the Floridan aquifer.

The process of calibration of the model resulted in an improved understanding of the functioning of the Flotidan aquifer in the study area. It was noted that the transmissivity distribution obtained from aquifer pumping tests is reasonable, that leakage is more variable than pumping tests generally indicate, and that direct connection of rivers and lakes with the Floridan aquifer cannot be assumed on the scale of a regional model.

INTRODUCTION

West-central Florida has had considerable growth in population with resultant commercial and industrial development in the past two decades. The coastal area north of Tampa Bay has developed rapidly, and numerous urban developments now exist. The need for freshwater to supply this area has increased accordingly. Historically, the major source of supply of freshwater to the area has been ground water. As the area developed, well fields, consisting initially of only a few wells, were located near the coast where water was needed. As water demand increased, these well fields could not supply freshwater without inducing saltwater encroachment in the aquifer. Consequently, well fields were located further inland and--because of demand--each contained a greater number of wells than did the coastal fields.

Analytical methods to evaluate the effects of pumping from the various well fields are complex and their application is generally impractical on a regional basis. These methods are also impractical for evaluating the probable regional effects of proposed well fields. With the advent of high-speed digital computers and digital-modeling techniques to solve the finite-difference equations for simulating ground-water flow, it became economically feasible to evaluate the effects of pumping on a regional basis.

For those readers who may prefer to use metric units rather than English units, the conversion factors for terms used in this report are as follows:

English	Multiply by	Metric
inches (in)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
acres	.4047	hectares (ha)
square miles (mi^2)	2.59	square kilometers (km^2)
feet squared per day (ft^2/d)	0.093	meters squared per day (m^2/d)
feet squared per second (ft^2/s)	0.093	meters squared per second (m^2/s)
million gallons per day (Mgal/d)	.04381	cubic meters per second (m^3/s)
feet per day per foot [(ft/d)/ft]	1.0	meters per day per meter [(m/d)/m]

Purpose and Scope

The purpose of this report is to describe the development and calibration of a regional digital model of the Floridan aquifer in the Tampa Bay area. This model can be used to provide regional analyses of the effects of present and proposed pumping from the Floridan aquifer.

The study, in cooperation with the Southwest Florida Water Management District, began in 1972 and was completed in October 1975. The study area includes about 875 mi^2 (fig. 1). Since the aquifer in this area is considered infinite, for the purpose of modeling, the modeled area was made larger than the study area to minimize the effects of boundary conditions.

Description of the Area

The area modeled is relatively flat (figs. 2 and 3), altitudes generally are less than 75 ft. A ridge from Brooksville (north of the modeled area) southeast to Zephyrhills is higher: these altitudes exceed 150 ft. Numerous lakes are along this ridge and also in a large area extending from north of Tampa to Massaryktown. The flat, western part of the area supports grasslands and cypress swamps. The area has a subtropical climate and an average rainfall of about 52 in per year. Deviations from this average are as great as 25 in per year (Tampa Bay Regional Planning Council, 1974).

Urban development is greatest along the coast. Residential and commercial developments extend northward from the Pinellas-Pasco County line nearly to the Pasco-Hernando County line. That part of the area west of U. S. Highway 19 was developed first, but in the last 5 years development has extended, particularly inland, north, and northwest of Tampa. Most of the remaining parts of the area are agricultural.

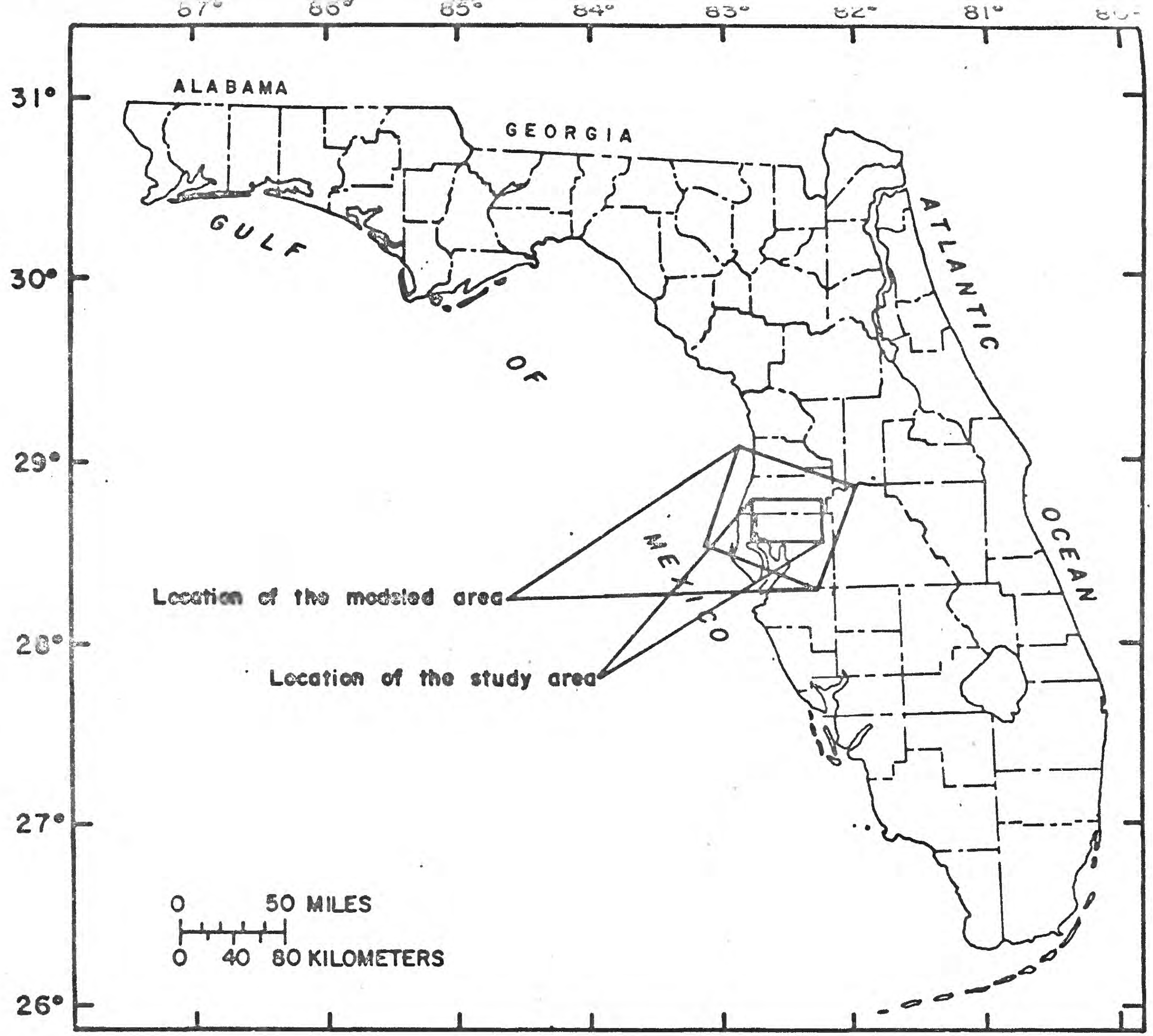


FIGURE 1.--LOCATION OF THE STUDY AREA AND MODELED AREA.

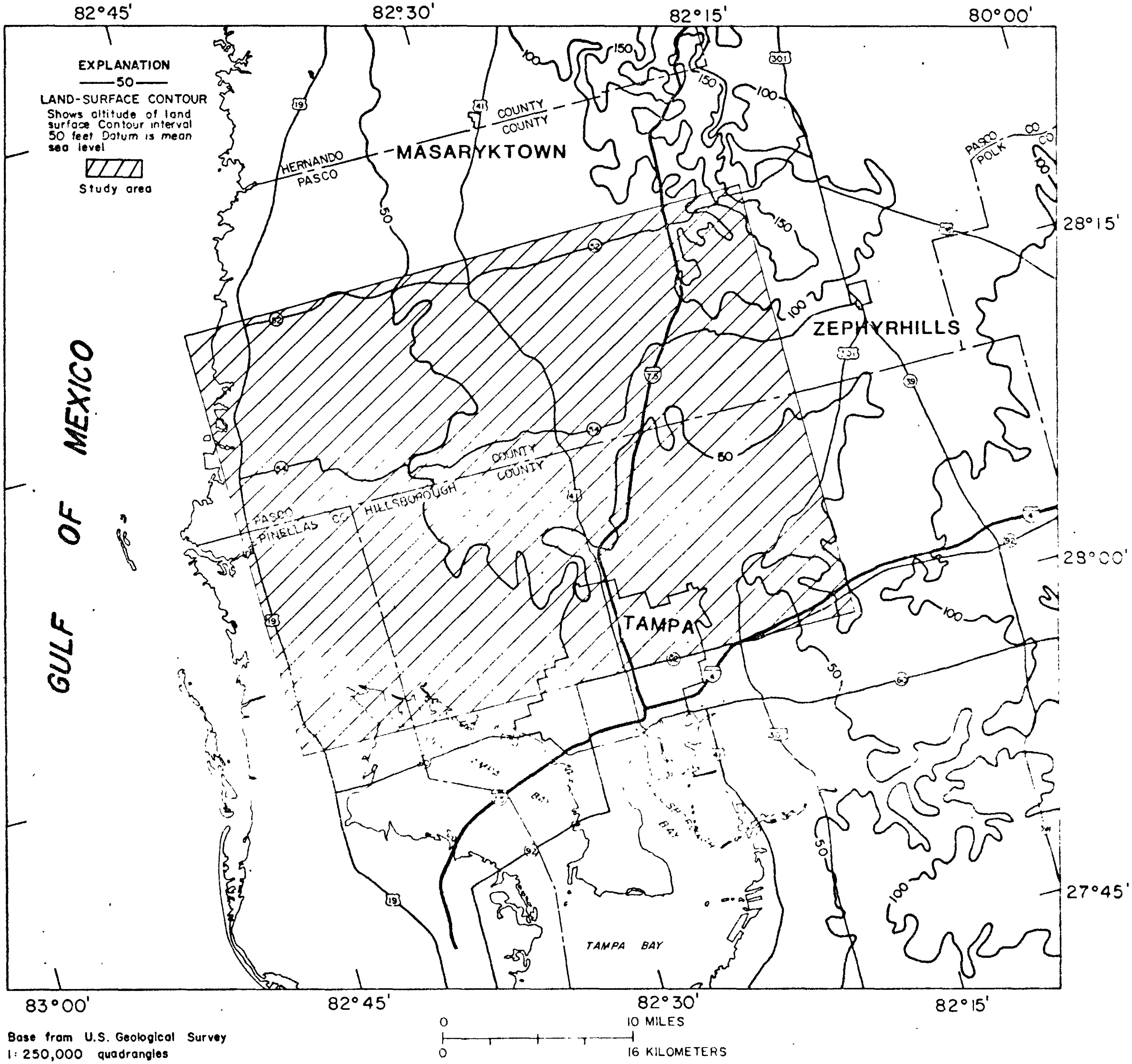
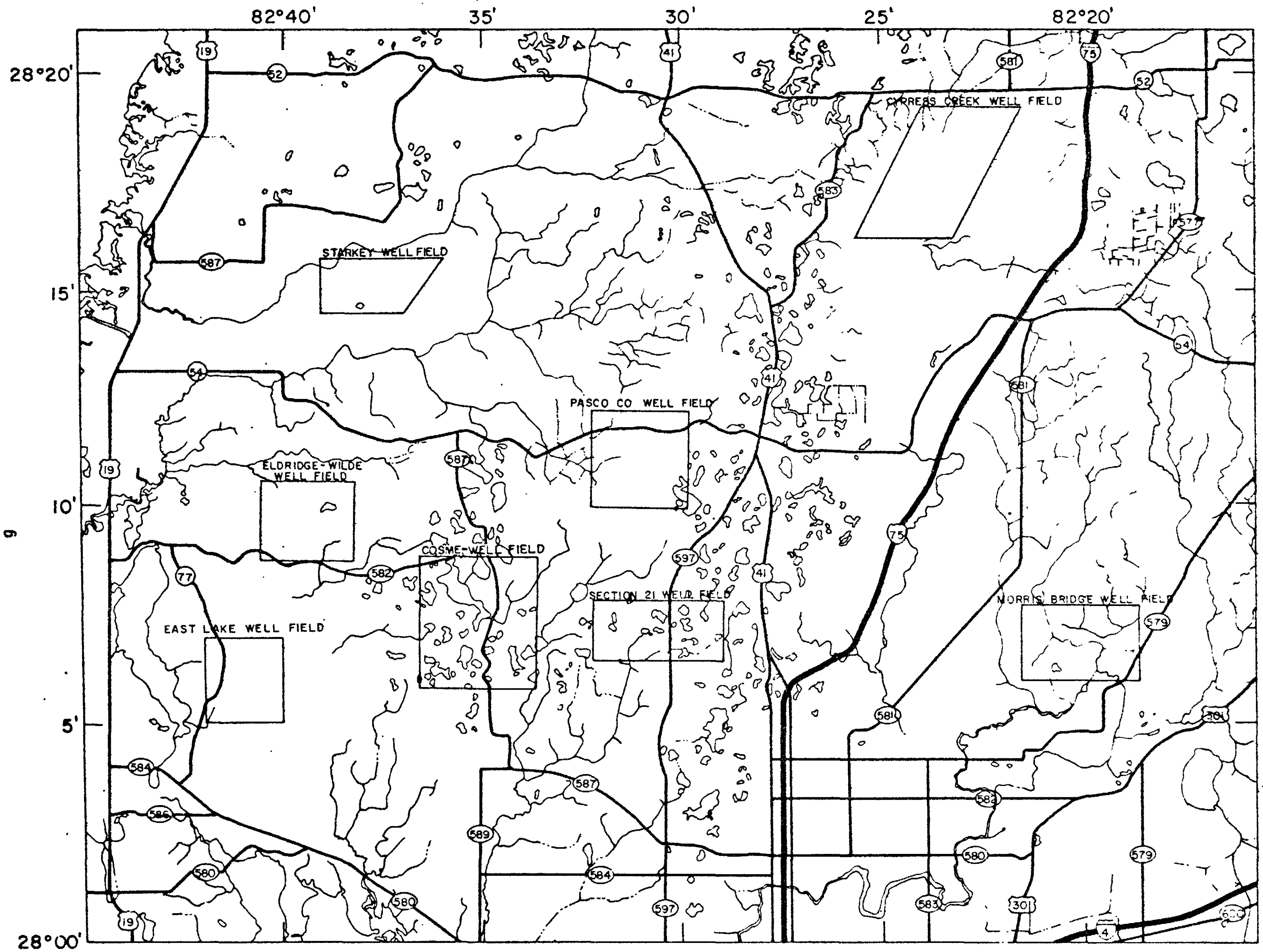


FIGURE 2.--MODELED AREA SHOWING LOCATION OF STUDY AREA.



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0 5 MILES
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FIGURE 3.--Study area showing municipal well fields and surface-water features.

Water Use

Public water supply is the largest use of water in the area (Healy, 1972). Total withdrawals from municipal well fields have increased from 50 Mgal/d in 1950 to 110 Mgal/d in 1974. Monthly variations in well-field production are considerable. About 40 percent of the total annual pumpage is withdrawn in May, June and July.

Little data are available to accurately define industrial and agricultural ground-water withdrawal in the area. Uses that require sizeable quantities of freshwater are irrigation, dairies, poultry production, and citrus processing plants. The combined water-use estimates for these uses were about 170 Mgal/d in 1965 and 159 Mgal/d in 1970 (Pride, 1970 and 1973) for Hillsborough, Pasco, and Pinellas Counties. It should be noted, however, that between 1965 and 1970, industrial pumpage in the area declined 20 Mgal/d due mainly to the cessation of phosphate mining in southwest Hillsborough County.

The acreage of land devoted to citrus production can be used to estimate water withdrawals for irrigation. In Hillsborough, Pasco and Pinellas Counties this area was about 106,000 acres in 1965, but decreased to about 80,000 acres in 1973 (Florida Department of Agriculture, 1974). Estimates of the water requirements for irrigation and percentage of total acreage irrigated have been made in another similar area in Florida (Robertson and Mills, 1974). These estimates were applied to the figures for the total citrus acreage in Pasco, Pinellas, and Hillsborough Counties to arrive at estimated irrigation requirements of 34 Mgal/d and 26 Mgal/d in 1965 and 1974, respectively.

Acknowledgments

The writers gratefully acknowledge assistance rendered by members of the Southwest Florida Water Management District staff as well as by the many public officials who provided water-use data. They are also grateful to the many citizens who permitted access to their wells for measurements of water levels.

HYDROGEOLOGY

The modeled area is underlain by carbonate rocks that form a highly productive artesian aquifer referred to as the Floridan aquifer (Parker and others, 1955) (fig. 4). The aquifer is Eocene to Miocene in age and is several thousand feet thick. In the northeast part of the area, most water wells drilled into the aquifer are no more than 1000 ft deep and near the coast, no more than 300 ft deep. The Floridan aquifer is characterized by zones where solution openings have formed in the limestone. These zones generally are more productive than the rest of the aquifer. The base of the Floridan aquifer has not been defined. There is evidence that very little freshwater circulates below about 1000 ft below msl.

The top of the limestone forms an irregular surface (fig. 5) that is overlain by sand and clay deposits as much as 80 ft thick (figs. 6 and 7). Overlying the Floridan aquifer is a clay or sandy clay layer that exhibits confining bed characteristics. Above this layer is a water-table aquifer comprised mainly of sand. To obtain data that would permit improving the estimate of vertical hydraulic conductivity of the semiconfining clay and to determine its areal thickness, 29 test holes were drilled to the top of the limestone using a hollow-stemmed auger. The locations of the test holes, all drilled in 1973, are shown on figure 7. The clay deposits and surficial sands are generally thicker along an elongated north-south band near the center of the area.

The numerous sinkholes in the area constitute an important aspect of the hydrogeologic system. These sinkholes result from the collapse of the rock and unconsolidated material that overlaid solution cavities in the limestone. The semiconfining layers are displaced vertically and the effect is a "short-circuit" of the connection between the water-table aquifer and the Floridan aquifer than is generally indicated by determination of the vertical hydraulic conductivity of the semiconfining layers.

An understanding of the hydrologic conditions in the area is, of course, necessary for calibration and use of the digital model. Recharge to the Floridan aquifer in the area is by regional ground-water inflow from upgradient, and vertical leakage through the confining layer. Discharge from the aquifer is by upward vertical leakage, regional ground-water outflow downgradient, and ground-water withdrawal. The response of the system to recharge and discharge is a change in aquifer head or in storage.

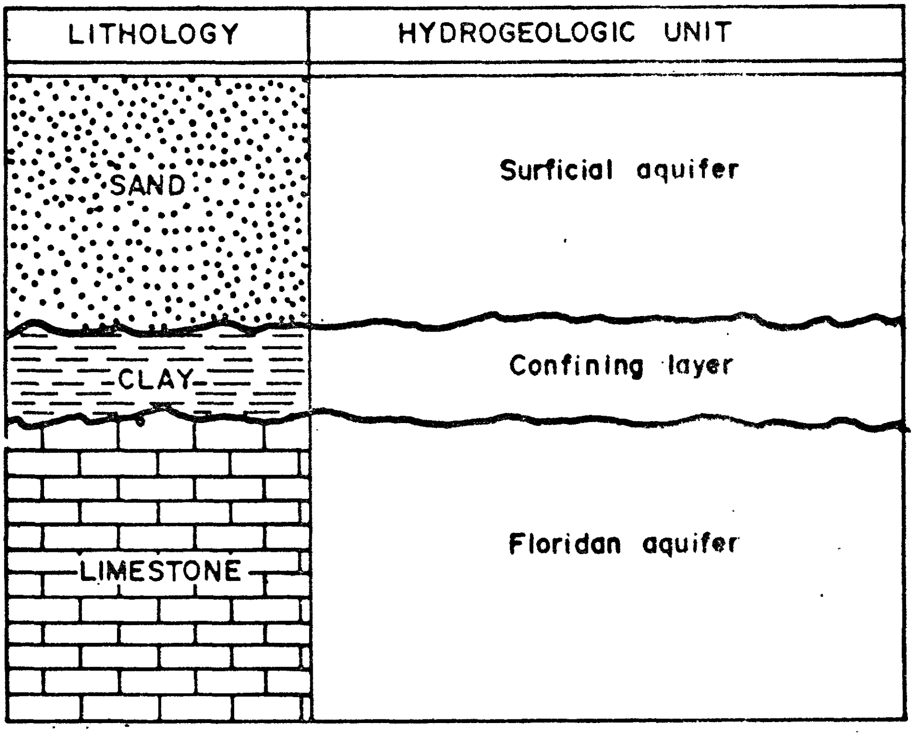

FIGURE 4.--GENERALIZED HYDROGEOLOGICAL SECTION

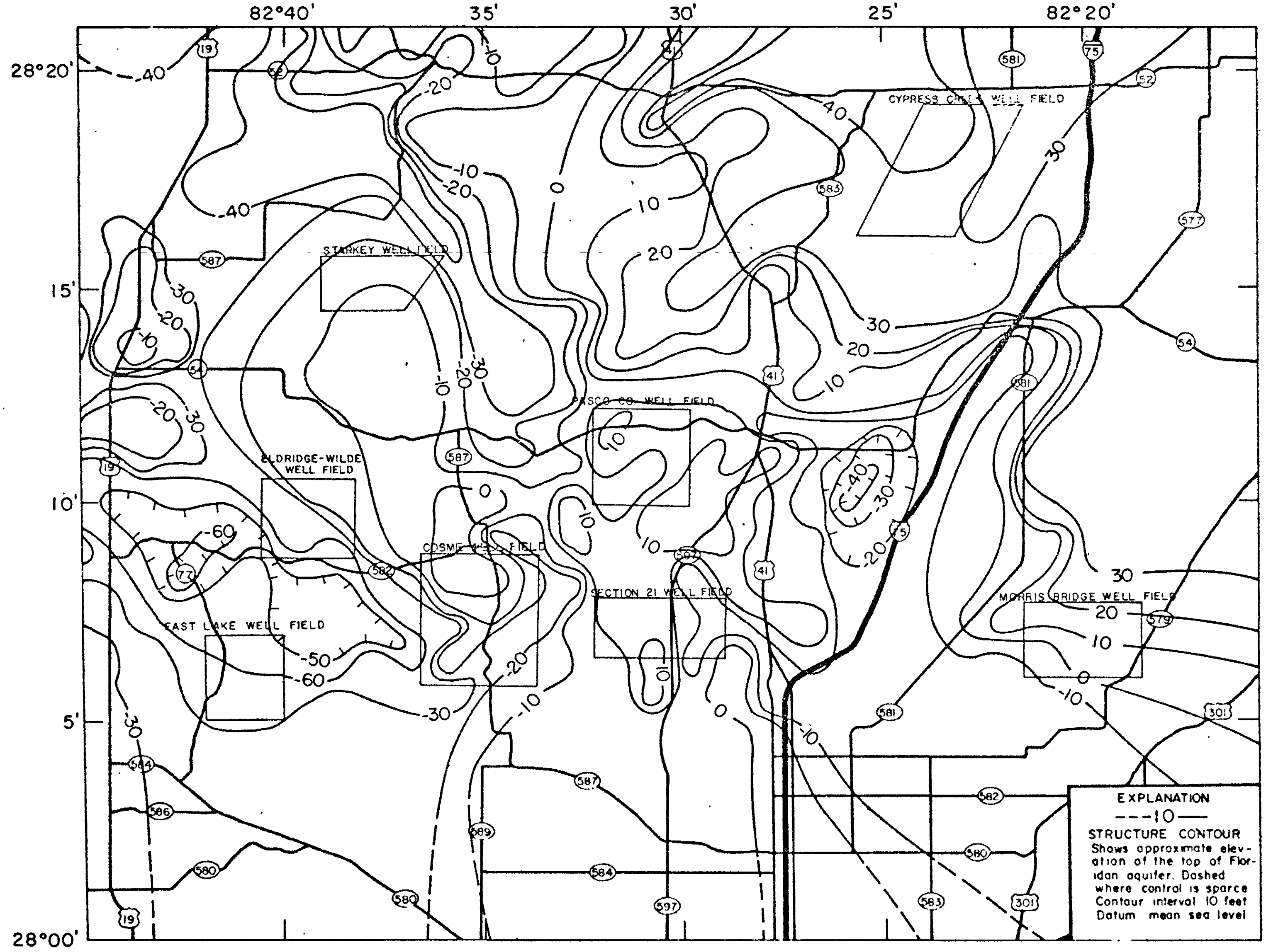

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FIGURE 5.--Contours of the top of the Floridan aquifer.

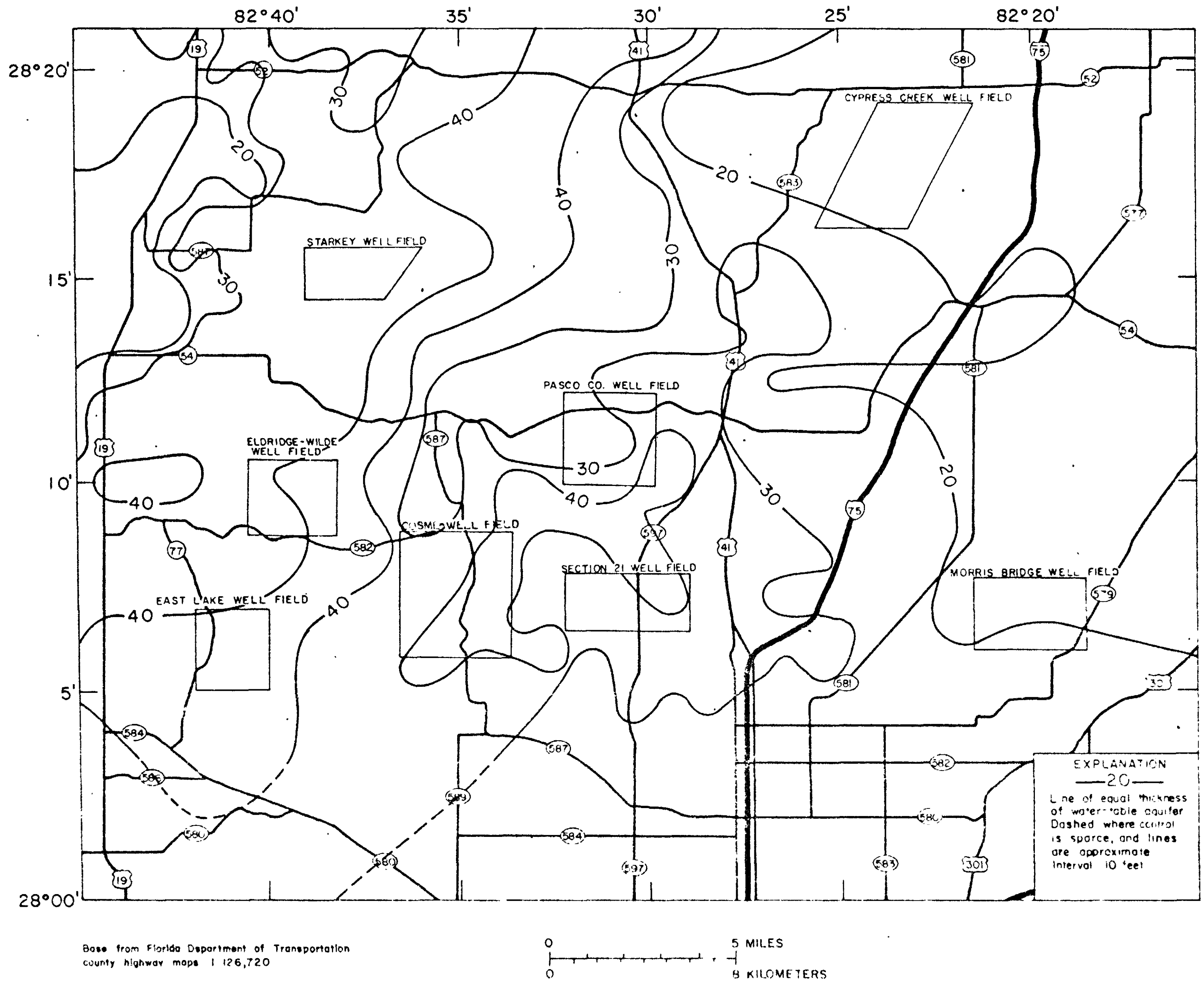

FIGURE 6.--Thickness of surficial aquifer

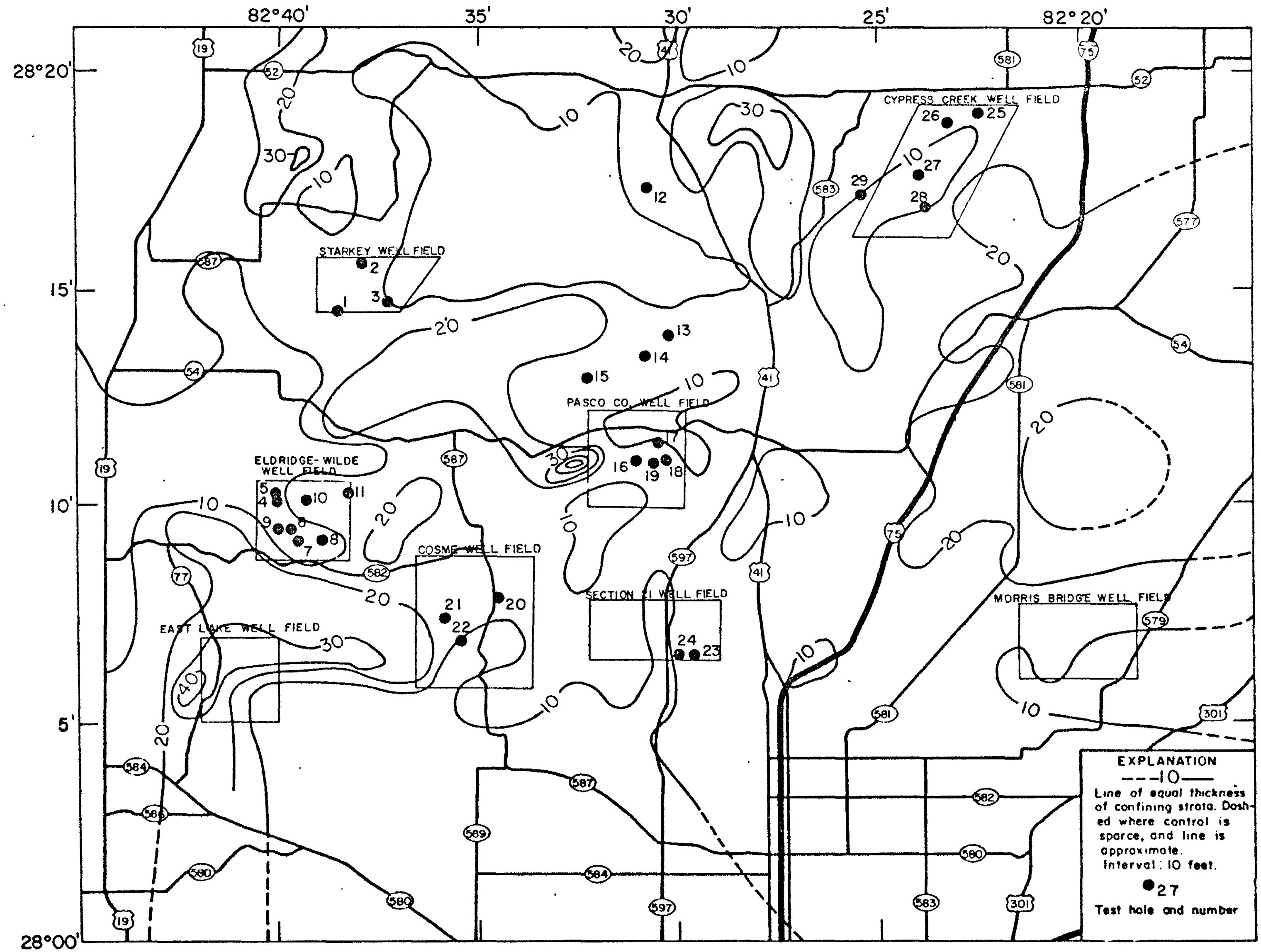

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FIGURE 7.--THICKNESS OF CONFINING STRATA AND LOCATIONS OF TEST HOLES IN STUDY AREA.

Data to define these hydrologic conditions have been gathered from about 150 monitor wells that penetrate the Floridan aquifer and 100 wells that penetrate only the surficial water-table aquifer (Stewart and others, 1971). Streamflow was measured at 34 sites and observations were made at 54 lake-stage stations (U. S. Geol. Survey, 1974). These data provide information necessary for constructing a two-dimensional ground-water flow model which is described in the following section.

DIGITAL MODEL DESCRIPTION

Theory

The partial differential equation (Trescott and Pinder, 1975) which describes ground-water flow in two dimensions in a confined aquifer may be written as:

$$\frac{\partial}{\partial x}\left(Txx\,\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial x}\left(Txy\,\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial y}\left(Tyx\,\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Tyy\,\frac{\partial h}{\partial y}\right) =$$

$$S\,\frac{\partial h}{\partial t} + W(x,y,t) \qquad (1)$$

in which:

Txx, Txy, Tyx, Tyy	are the components of the transmissivity tensor (L^2t^{-1})
h	is the hydraulic head (L)
S	is the storage coefficient (dimensionless)
W(x,y,t)	is the volumetric flux of recharge or withdrawal per unit surface area of the aquifer (Lt^{-1})

If the Cartesian coordinate axes x and y are alined with the principle components of the transmissivity tensor Txx and Tyy, equation (1) may be written as:

$$\frac{\partial}{\partial x}\left(Txx\,\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Tyy\,\frac{\partial h}{\partial y}\right) = S\,\frac{\partial h}{\partial t} + W(x,y,t) \qquad (2)$$

Because there is no general analytical solution to equation (2), numerical methods are employed to arrive at a finite-difference approximation (Pinder and Bredehoeft, 1968).

The finite-difference equation is solved at each node of the rectangular grid on a digital computer. This results in a set of algebraic equations that are solved using matrix techniques. Two matrix techniques were used in this study: the iterative alternating-direction implicit (ADI) procedure and the strongly implicit procedure (SIP).

The iterative alternating-direction implicit procedure (Peaceman and Rachford, 1955) was used for the early calibration runs of the model. At the time these runs were made, ADI was the only numerical method for solution of the ground-water flow equations available with the Pinder-Trescott model. In the 1975 version of the Pinder-Trescott model, however, the strongly implicit procedure (Stone, 1968) was introduced, and because of the reduced cost of this numerical method over ADI, it was used in all later runs of the model.

Assumptions

The model used in this study is areally two-dimensional. The assumptions used in the model formulation are:

1. The movement of water in the Floridan aquifer is assumed to occur only in the horizontal plane. In nature, this assumption will be invalid where appreciable vertical gradients exist. On a regional basis, however, the vertical gradient is sufficiently small that model results probably are not significantly affected by this assumption.

2. The movement of water leaking through the confining bed into the Floridan aquifer is vertical. This assumption is less likely to be valid if there are steep gradients in the overlying water-table aquifer and a relatively high hydraulic conductivity in the confining bed. Again, however, on a regional basis, model results probably are not affected by nonvertical flow through the confining bed.

3. Within each cell of the finite-difference grid, the hydrologic properties are constant over the area of that cell. This assumption may result in some degree of error especially in regard to leakage through the confining layer. For example, the existence of sinkholes within an area modeled by a grid cell will result in variations in vertical hydraulic conductivity across the cell area. However, for the purpose of regional modeling, the varying values for vertical hydraulic conductivity can be averaged over a cell.

4. The simulations presented in this investigation are based on a hydrogeologic framework that is idealized as a single confined aquifer overlain by a semi-permeable confining layer which, in turn, is overlain by an unconfined aquifer. Leakage across the bottom of the confined aquifer is negligible. During simulation, the water levels in the unconfined aquifer are assumed to be constant. The modeled area was divided into discrete segments by a grid network. The grid network for the modeled area in this report has 49 rows and 47 columns (fig. 8). The grid spacing ranges from 2,000 ft to 30,000 ft. The close spacings are in the areas of the major well fields (fig. 9) and the wide spacings are near the boundary of the modeled area.

5. The potentiometric heads in the model are simulated at the node or center of the grid cells. Stress is applied to the grid cells representing areas of the aquifer in the form of withdrawal or recharge, which is assumed to be evenly distributed throughout the area corresponding to the grid cell.

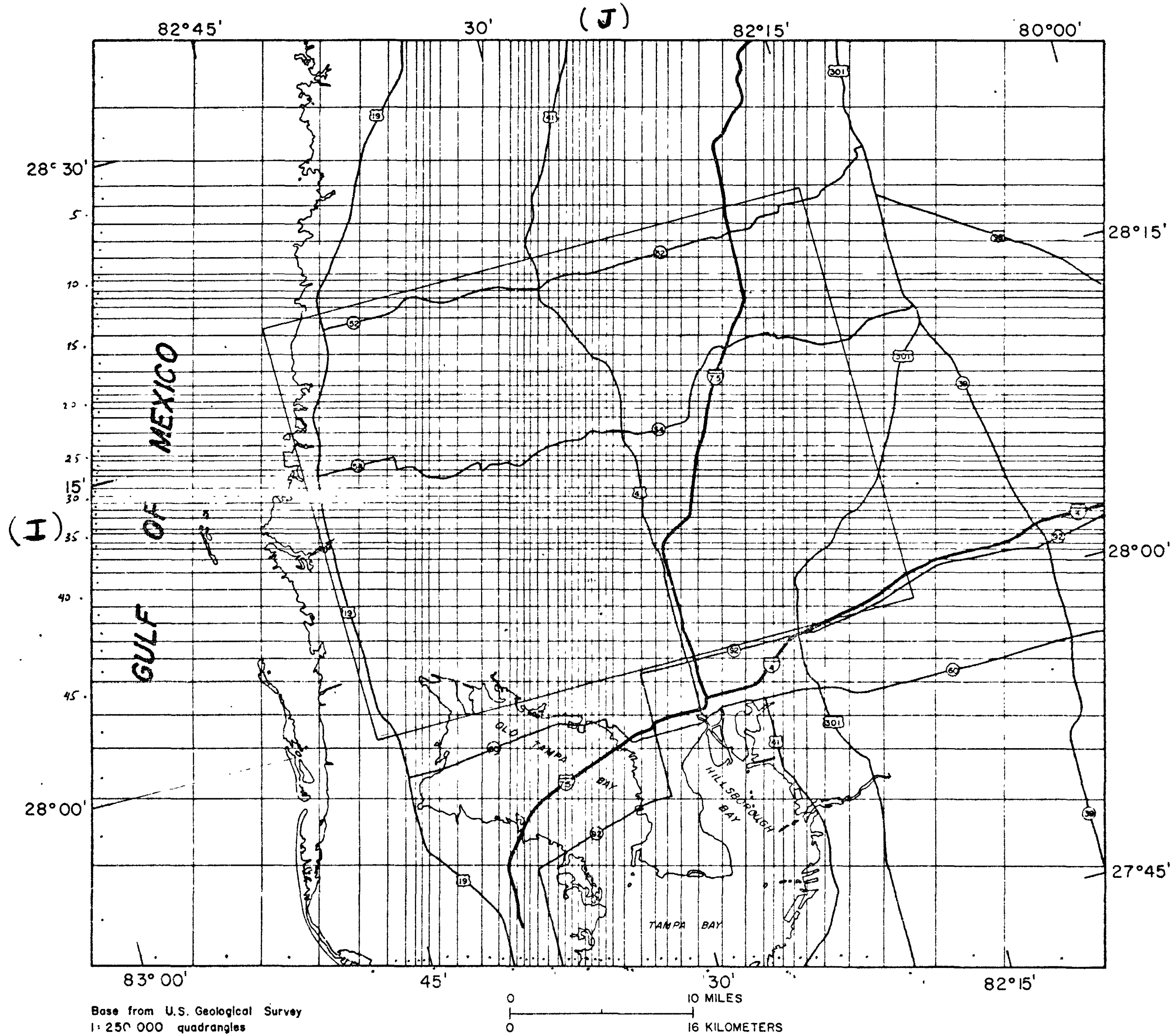

FIGURE 8.--GRID NETWORK OF MODELED AREA.

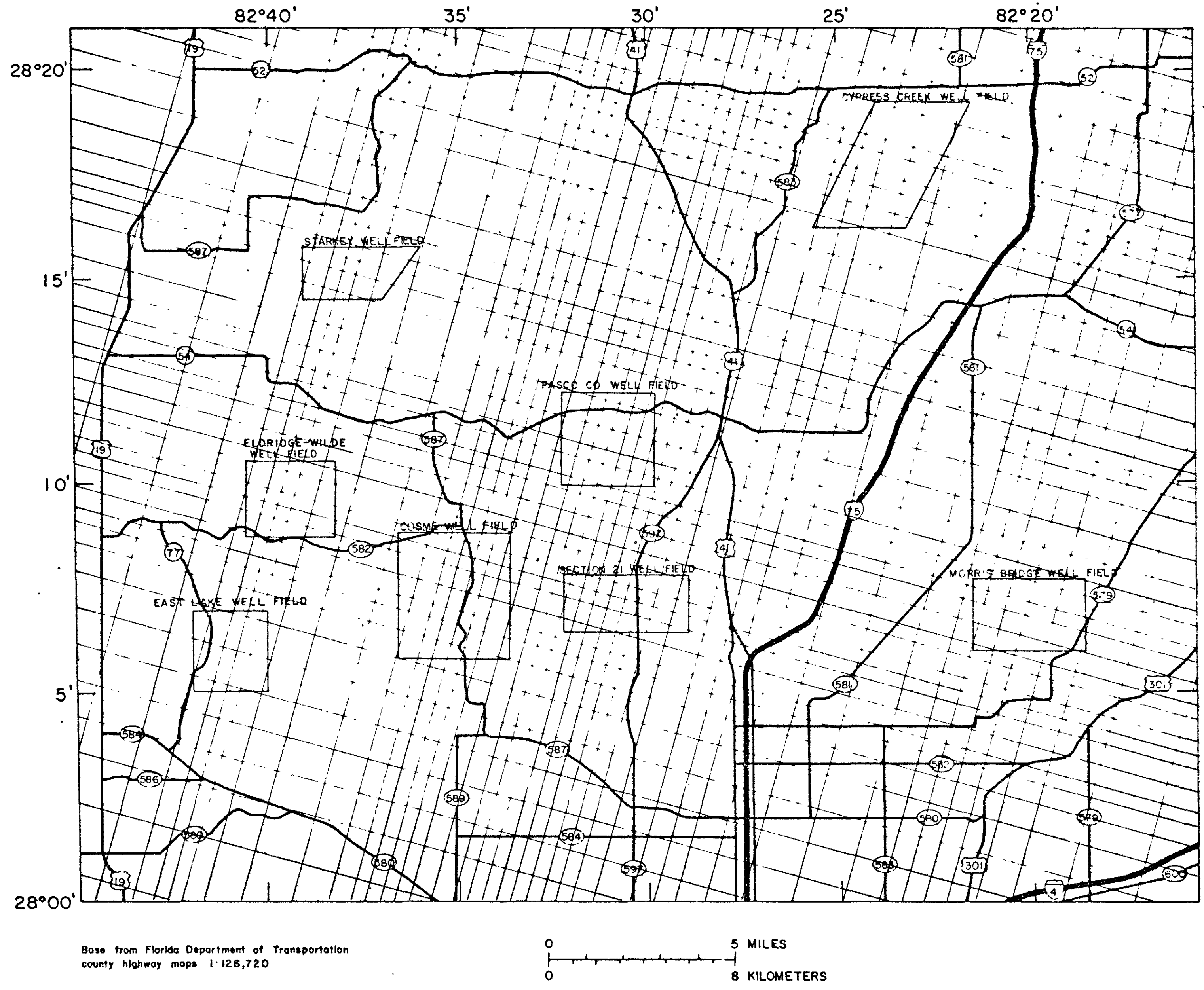

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FIGURE 9.--GRID NETWORK OF THE STUDY AREA.

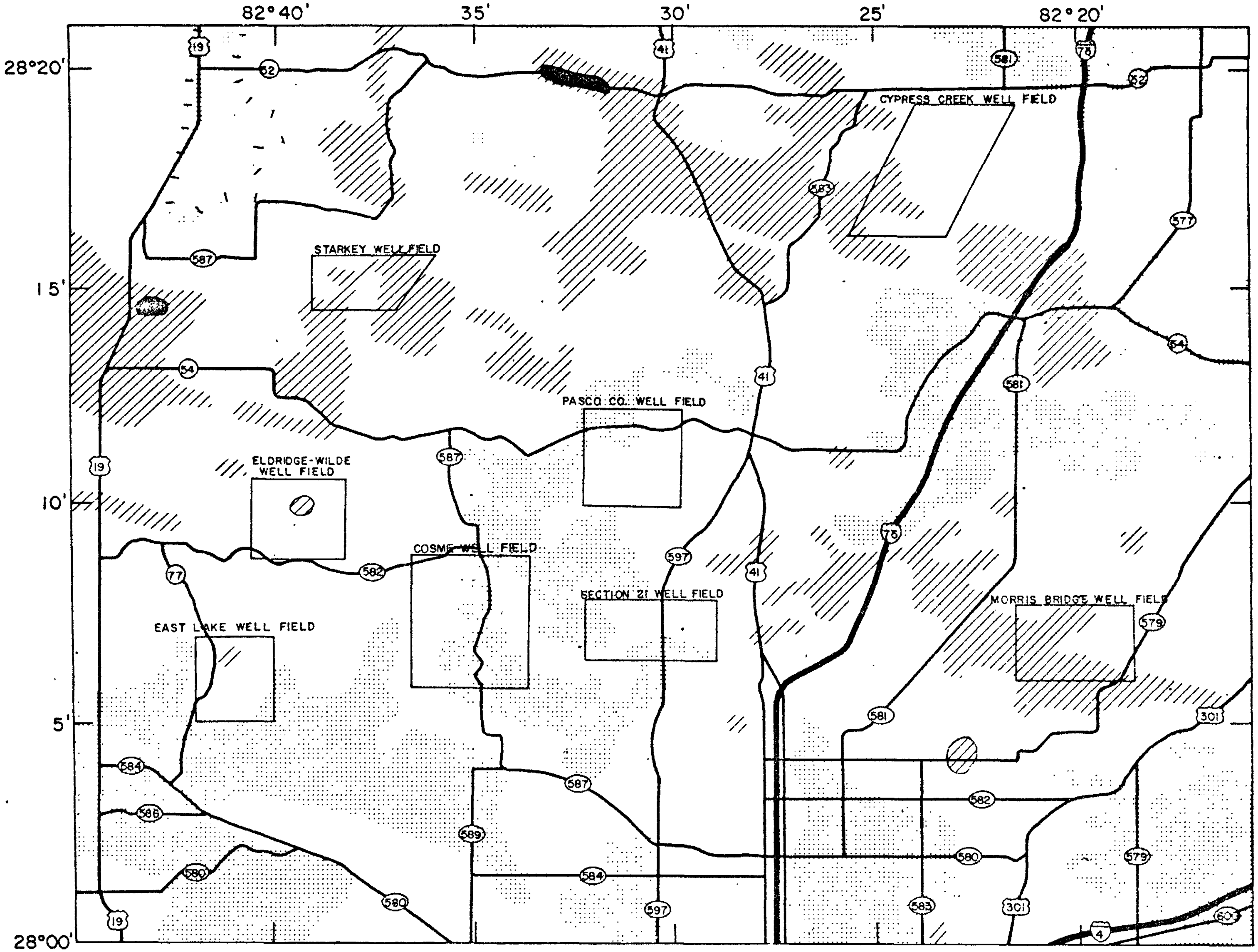
Boundary Conditions

The types of boundaries allowed by the model are constant head or constant flux boundaries. The boundary conditions for the modeled area were first simulated as constant head, that is, the potentiometric head was held constant. Constant head boundaries were selected in order to simulate the regional flow entering the ground-water system from upgradient and leaving it downgradient, a process which no-flow boundaries would clearly not simulate. Constant flux values would simulate this ground-water flow but the volumetric flux rates are not accurately known. The boundaries are located a sufficient distance from the well fields so that the effects of well-field pumping do not reach them. This supposition was confirmed by test runs of the model. The possibility of using constant-head boundaries to represent rivers and sinkholes where a high degree of interconnection exists was explored. Those simulations in which rivers were represented by a constant head gave unsatisfactory results. A more reasonable simulation was obtained by adjusting the values of vertical hydraulic conductivity. These results indicate that the connection between rivers and sinkholes and the Floridan aquifer, although locally significant, cannot be treated as direct connections on a regional scale.

Input Data Requirements

The digital model requires the following input data: 1. Head distribution of the water table (assumed static for the duration of the simulation); 2. Areal distribution of the leakance coefficient based on vertical hydraulic conductivity and thickness of the semi-confining bed between the surficial aquifer and the Floridan aquifer (fig. 10); 3. Head distribution in the Floridan aquifer at the start of simulation (fig. 11); 4. Areal distribution of the storage coefficient and transmissivity of the Floridan aquifer (fig. 12); 5. Spacing of the grid network; 6. Locations and discharge rates of the wells; and 7. Duration of pumping periods and time descretizations used to represent each period.

The starting input values for transmissivity, storage coefficient and vertical coefficient of leakage were determined from aquifer tests made in municipal well fields (table 1).



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EXPLANATION

Estimated leakance coefficients in [(ft³/d)/ft³]

- Less than 1.3×10^{-4}
- 1.3×10^{-4} to 1.3×10^{-3}
- 1.3×10^{-3} to 1.3×10^{-2}
- Greater than 1.3×10^{-2}

FIGURE 10.--LEAKANCE COEFFICIENTS USED IN MODEL.

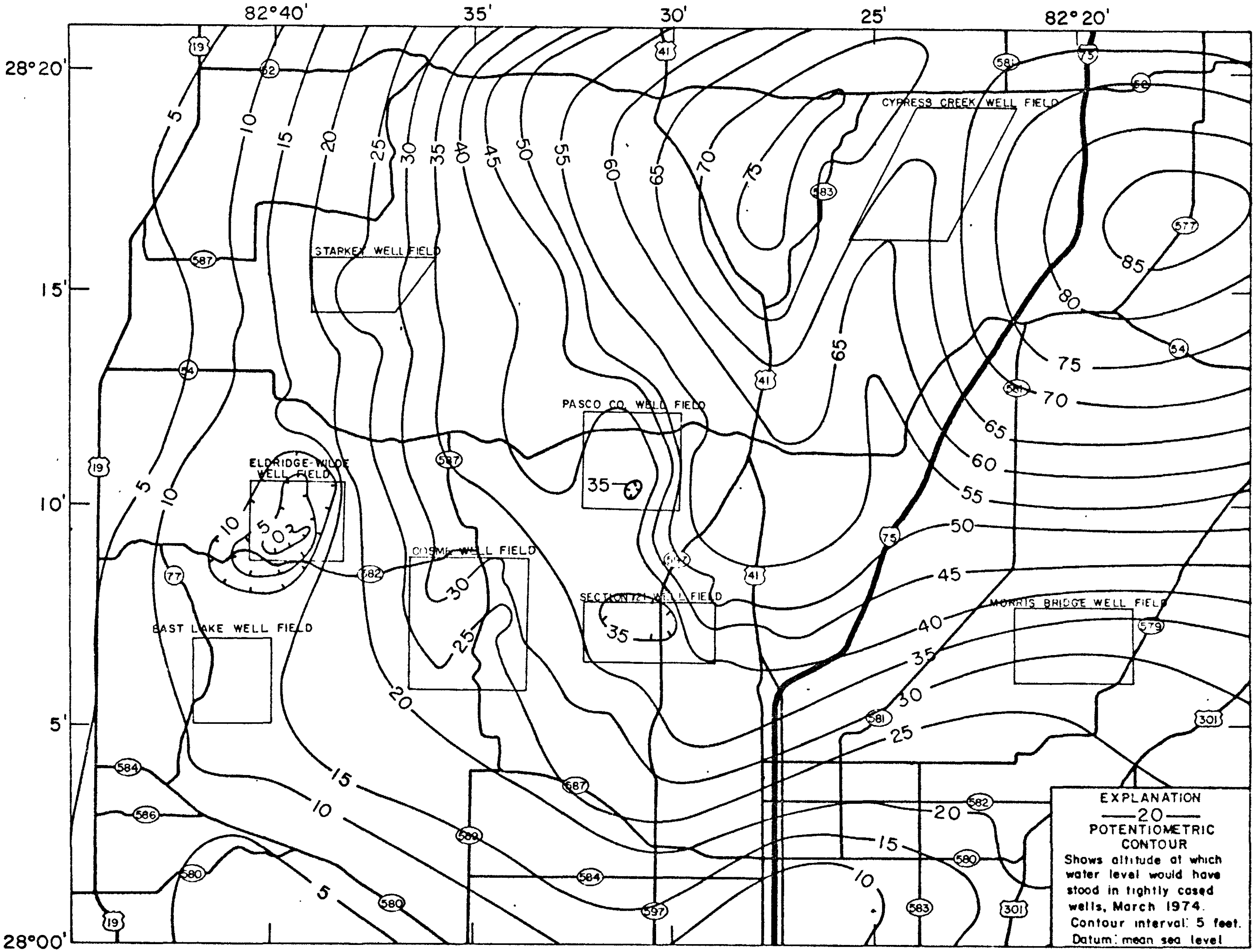

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FIGURE 11.--POTENTIOMETRIC SURFACE OF FLORIDAN AQUIFER, MAY 1974.

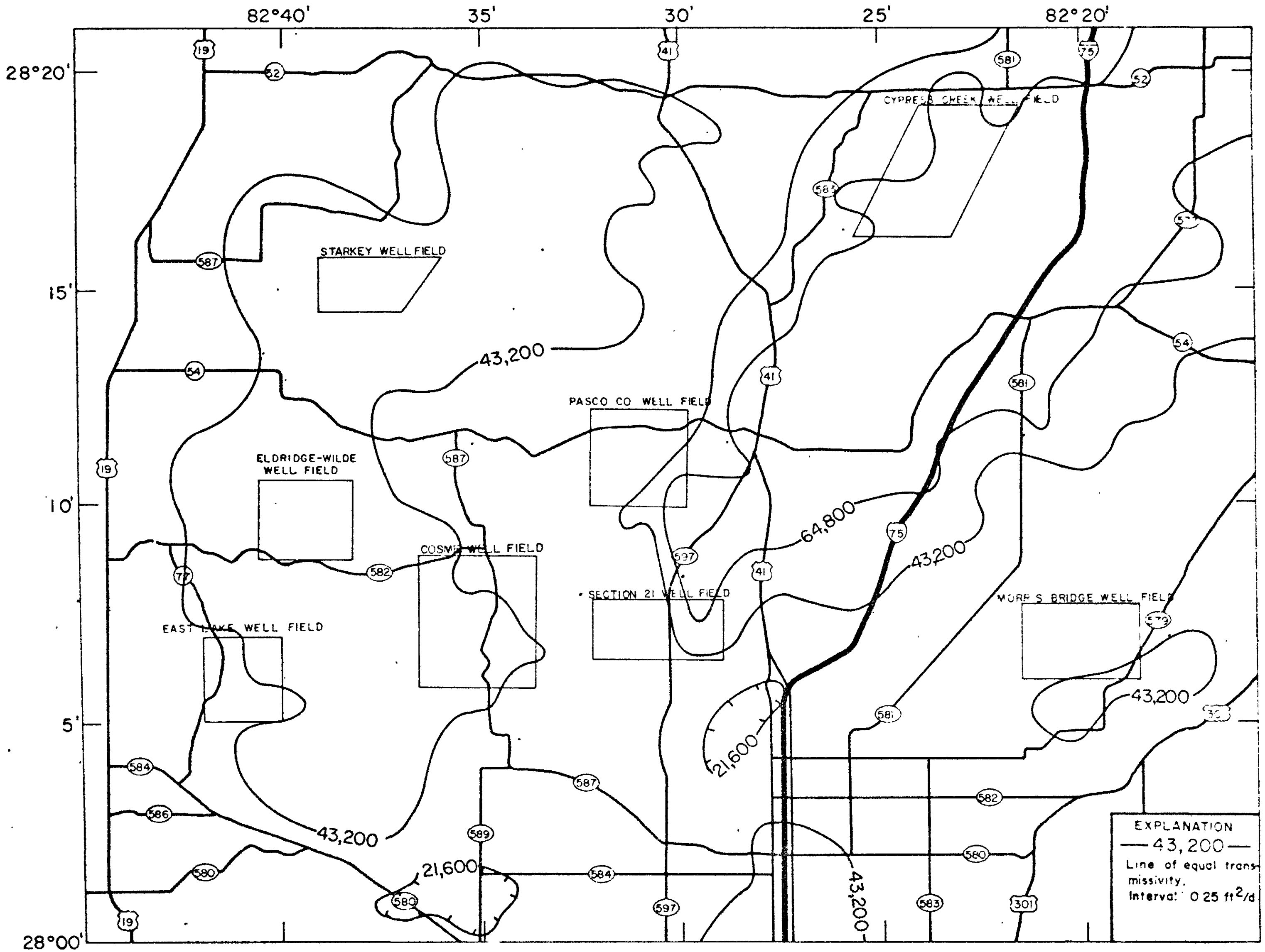

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FIGURE 12.--Transmissivity of Floridan aquifer used in model.

Table 1. -- Values of hydraulic parameters determined from aquifer pumping tests.

Well field	Transmissivity* (T) (ft^2/d)	Storage coefficient (S)	Vertical coefficient of leakance* (K'/b') [$(ft^3/d)/ft$]
Eldridge Wilde	33,000	5.0×10^{-4}	2.7×10^{-4}
East Lake Road	40,000	9.0×10^{-4}	1.1×10^{-3}
Pasco County	53,000	8.0×10^{-4}	2.7×10^{-4}
Cypress Creek	47,000	8.0×10^{-4}	2.7×10^{-4}
Starky	40,000	2.0×10^{-4}	2.7×10^{-3}
Morris Bridge	130,000	3.0×10^{-4}	4.0×10^{-3}

* For those readers who prefer to use T in (gal/d)/ft and K'/b' in $(gal/d)/ft^3$, multiply T presented in (ft^2/d) and K'/b" in $[(ft^3/d)/ft]$ by 7.48.

Data describing aquifer and confining-bed properties are entered by rows; each entry represents the value of the parameter at each grid center. These values are determined by superimposing an overlay of the grid network on a contour map of the parameter to be digitized and visually assigning the value of the parameter at the center of each grid cell.

MODEL DEVELOPMENT

Model simulations of the aquifer response to an applied stress provide the potentiometric head values at each grid cell of the model. The model is calibrated by comparing computed and field-measured potentiometric heads. In the model used in this study, a mass balance is computed at each time interval of a model run. This provides a means to check the relative magnitudes of accumulated sources and discharges and insures that the difference between them is acceptably small.

The aquifer model was developed in two phases. Initially, a coarse grid network composed of 16 rows and 17 columns was selected. Several boundary-condition configurations were investigated with this version. It was concluded that constant-head boundaries around the entire grid gave results that most closely simulated observed water levels. In addition, the mass balance calculated by the model accounted for inflow to the modeled area and outflow from the area comparing favorably with the empirical mass balance for a similar area (Cherry, Stewart, and Mann, 1970). The hydraulic parameters for this model were taken from published information (Cherry, Stewart, and Mann, 1970). This coarse grid network required the averaging of initial head values in the confined and surficial aquifers for the large area represented by each grid cell. Likewise, the thickness of clay was, of necessity, averaged over a large area.

Simulations made with the coarse grid network model approximated the observed potentiometric surface but did not provide sufficient detail to model localized features in many areas. These simulations were used to make some areal adjustments. A larger grid network was then adapted to the project area. This network allowed closer node spacings and was composed of 49 rows and 47 columns. The closest of the grid spacings was 2000 ft within the area of the well fields where greater detail was required. Near the boundary of the network, well outside the project area, the grid spacing was 30,000 ft.

The relative effects of changing the values of individual hydrologic parameters were measured by changing one parameter and holding the others constant. The effect of changing that parameter was then compared with the effect of changing other parameters. Through this process it was possible to identify the parameters that caused the greatest variation in simulated head values. Withdrawal and leakage had the most pronounced effect on simulated results. Withdrawal rates were reasonably well defined, particularly in the well fields. Therefore, leakance was the parameter that was adjusted to achieve simulation results corresponding well with observed data.

Although changes in the values of transmissivity generally did not affect the model as much as leakance, changes of transmissivity were effective in achieving a more accurate simulation of localized variations in the potentiometric surface (fig. 13).

The potentiometric surface for March 1974 was selected for simulation and final calibration of the model. This period was selected because the number of observation wells sampled allowed an accurate definition of the potentiometric surface. The withdrawal rates from well fields in the area were accurately known. In the spring, the dry season has become well established, as has increased pumpage to meet an increased water demand. Because these situations have existed for several weeks by the beginning of March, and because the Floridan aquifer, with its high transmissivity, reaches steady-state quickly, the potentiometric surface which existed in March can be regarded as quasi-steady state.

Differences between the simulated potentiometric surface and that observed in the field are generally less than 3 ft and in all cases, less than 15 ft (fig. 13). In well-field areas the relatively large differences were expected because field measurements can change markedly with variations of pumpage in the field.

The small difference between the observed and the simulated potentiometric surfaces suggested that the model has been successfully calibrated. To verify this, the model was used to simulate a different condition of stress than for which it was calibrated, using the same values for aquifer parameters that were determined in the calibration procedure. Verification, for this model, consisted of attempting to duplicate the May 1975 potentiometric surface (fig. 14) using the withdrawal rates reported for May 1975. The similarity between the observed and simulated potentiometric surfaces are close and this simulation is considered to constitute a verification of the model.

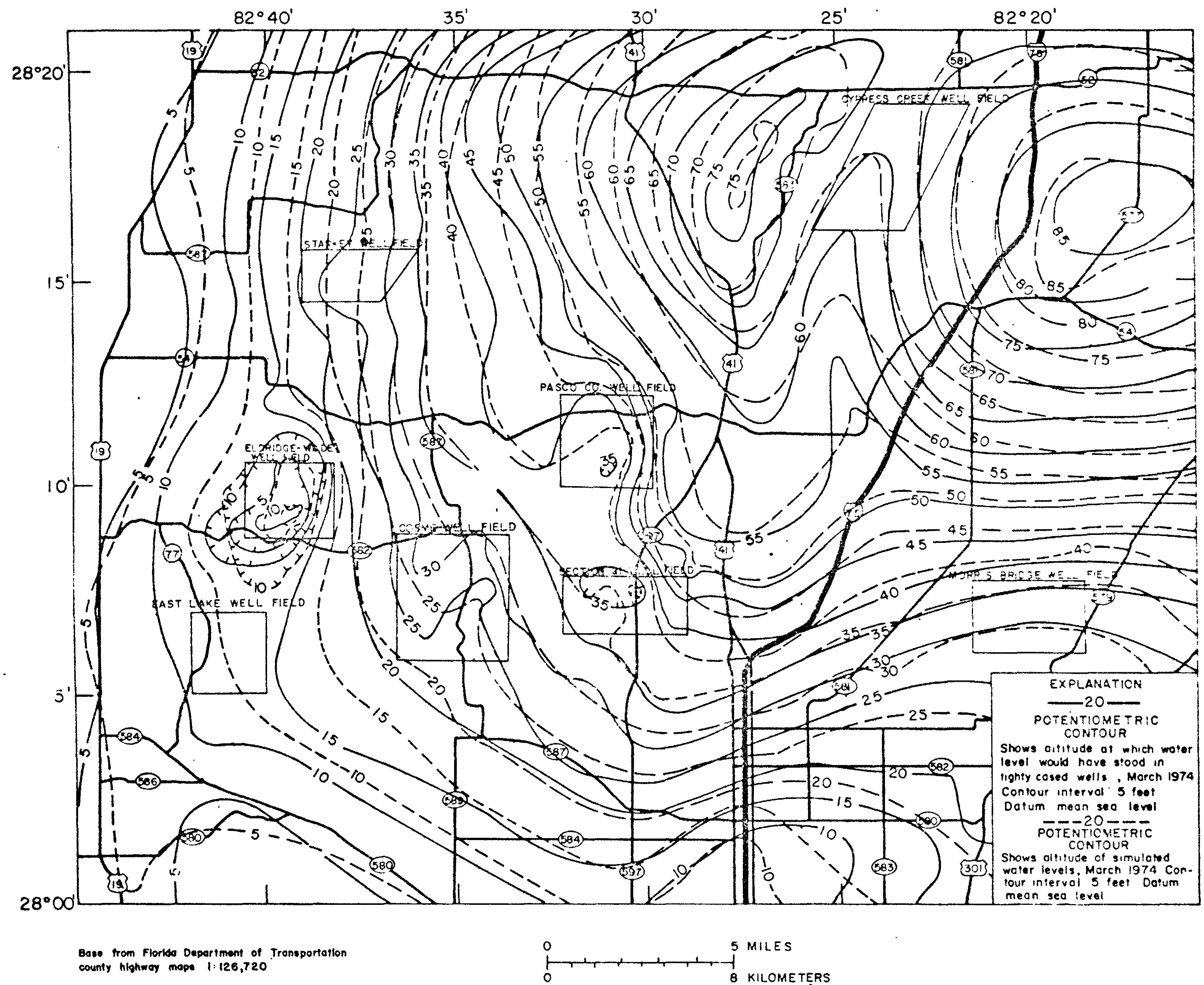

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FIGURE 13.--Contours of observed and simulated potentiometric surface, March 1974.

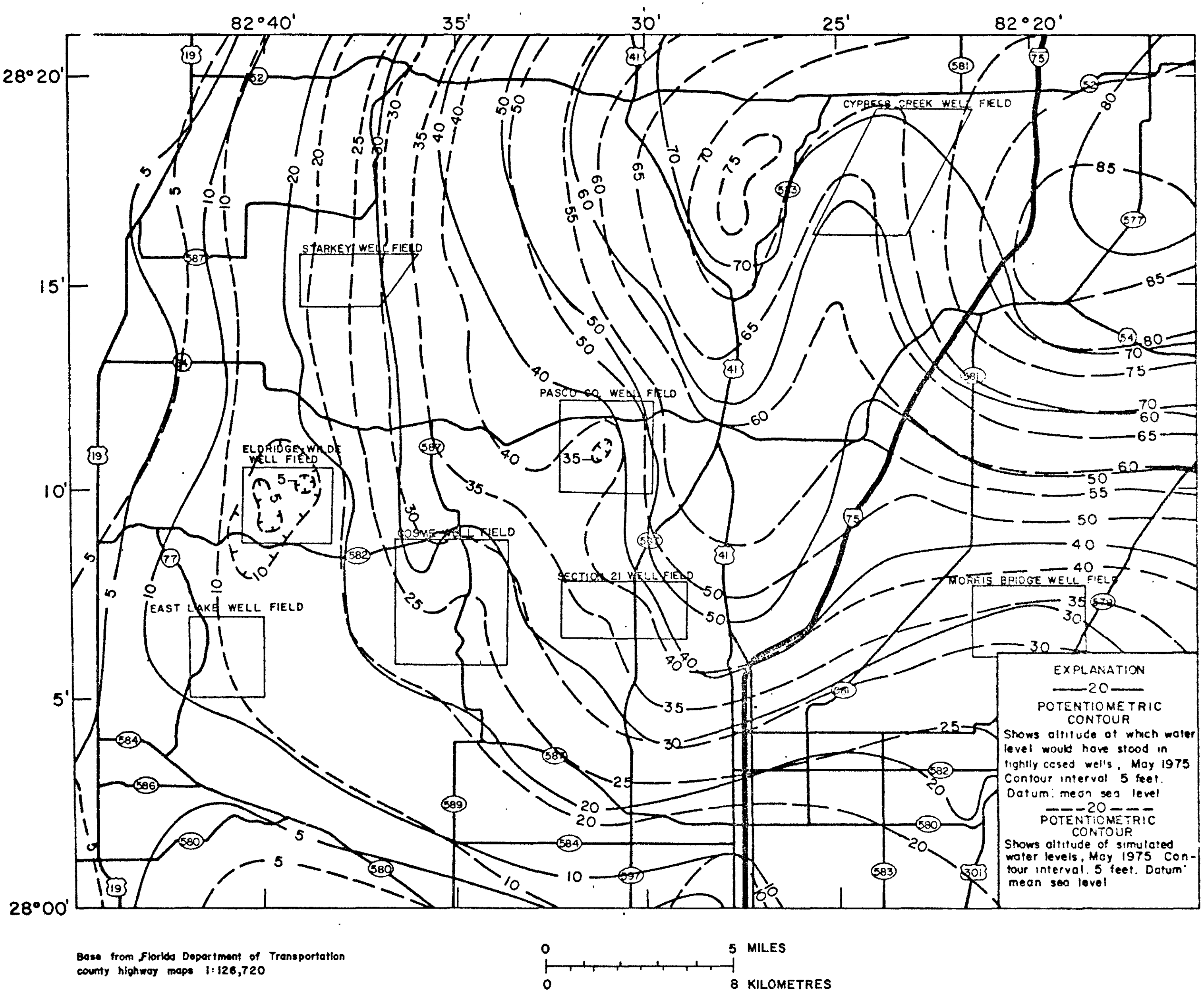

FIGURE 14.--CONTOURS OF OBSERVED AND SIMULATED POTENTIOMETRIC SURFACE, MAY 1975.

The purpose in developing the model is to predict the effects of changes in rates of pumping. That this could be done is evidenced by the simulation of water levels for May 1975. Calibration of the model was made for the season when withdrawals were highest and potentiometric levels in the water-table aquifer as well as in the artesian aquifer were lowest. Predictions for autumn, when water levels have risen, would require the construction of an additional matrix to reflect the higher surface of the water table then prevalent.

SUMMARY AND CONCLUSIONS

Rapid population and economic growth in west-central Florida has resulted in an accompanying increase in water demand and consequent water-quality and water-supply problems. A model of the ground-water system was constructed to aid in the comprehensive planning for utilization of the resource.

The study area covers about 875 mi^2. In order to minimize boundary effects, an area larger than the study area was modeled. A finite-difference approximation of the ground-water flow equation was solved on a digital computer using a program developed by Trescott and Pinder (1975). Aquifer properties, boundaries, and hydrologic stresses were incorporated into a finite-difference grid with cell dimensions that vary from 2,000 ft to 30,000 ft spacing.

The model may be used as a predictive and analytical tool. Calibration was achieved by matching observed and calculated potentiometric heads for March 1974. A good agreement was obtained between observed and calculated heads by adjusting leakance and transmissivity. As further verification, the potentiometric surface for May 1975 was reproduced by the model using the known withdrawal rates for that month. This calculation yielded good agreement between observed and computed potentiometric heads. Were the model to be used to represent other hydrologic conditions, the water-table head matrix would have to be changed to represent those conditions.

The process of calibration of a computer model often can be of value in improving the hydrologist's understanding of the functioning of the system being modeled. In this study it was noted that: (1) Calibration of the model was achieved with very little manipulation of the transmissivity distribution obtained from pumping tests. This indicates that the values from these tests reasonably define transmissivity in the physical system. (2) Leakage in the area is quite variable, perhaps more variable than is indicated by pumping test results which integrate the leakage effects of a large area. (3) The simulation, assuming a constant head in lakes and rivers, generally gave unsatisfactory results. This indicates that the connection between these features and the Floridan aquifer, while significant in places, cannot be considered direct on a regional scale. (4) The mass balance of the calibrated model agrees well with an empirical mass balance calculated for the similar but larger Mid-Gulf area (Cherry, Stewart, and Mann, 1970), indicating that the conceptual model of the area is in good agreement with the real physical system.

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