ESTIMATION OF VERTICAL HYDRAULIC CONDUCTIVITY OF THE CLAY LAYER BETWEEN THE EUTAW AND GORDO AQUIFERS IN THE VICINITY OF FAUNSDALE, MARENGO COUNTY, ALABAMA

By Michael Planert and Sydney L. Sparkes

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METRIC CONVERSION FACTORS

The following factors may be used to convert the Inch-Pound units published herein to International System of units (SI).

Multiply Inch-Pound units	by	To obtain SI units
Length		
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)
Flow		
gallons per minute (gal/min)	0.06308	liters per second (L/s)
Transmissivity		
feet squared per day (ft^2/d)	0.09290	meters squared per day (m^2/d)
Vertical Hydraulic Conductivity		
feet per day (ft/d)	0.3048	meters per day (m/d)

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ESTIMATION OF VERTICAL HYDRAULIC CONDUCTIVITY OF THE CLAY LAYER BETWEEN THE EUTAW AND GORDO AQUIFERS IN THE VICINITY OF FAUNSDALE, MARENGO COUNTY, ALABAMA

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ABSTRACT

The vertical hydraulic conductivity of the confining bed between the Eutaw and Gordo aquifers in the vicinity of Faunsdale, in northeast Marengo County, Alabama, is 1×10^{-5} foot per day or less. A conductivity of 1×10^{-5} foot per day in a 48-hour simulation reproduced the drawdown in the well from the 48-hour pumping test, but the conductivity may be as small as an untested 1×10^{-6} foot per day. Modeling vertical conductivities larger than 1×10^{-5} foot per day produced drawdowns in the Eutaw aquifer greater than those observed in an aquifer test that pumped 750 gallons per minute from the Gordo aquifer. Modeling has shown that vertical hydraulic conductivity of the confining bed is the controlling factor on the drawdown in the Eutaw aquifer. At equilibrium (steady-state) pumping 750 gallons per minute there was 3 feet of drawdown in the Eutaw aquifer with a confining bed conductivity of 1×10^{-5} foot per day. When the conductivity was decreased to 1×10^{-6} foot per day drawdown in the Eutaw aquifer was only 0.35 foot.

INTRODUCTION

The U.S. Geological Survey is conducting a regional aquifer study of the Southeast Coastal Plain aquifer system. To supplement the hydrogeologic data available to that study, the Survey is interested in obtaining data on the hydraulic properties of the Eutaw and Gordo aquifers and in determining a reasonable value for vertical hydraulic conductivity of the clay layer that separates the Gordo aquifer from the overlying Eutaw aquifer. The city of Linden drilled a test well penetrating the Gordo aquifer 5 miles south of Faunsdale in northeast Marengo County, Alabama, (fig. 1) providing the Survey an opportunity to collect heretofore unavailable data in that vicinity. This report addresses the modeling of the Eutaw and Gordo aquifers to determine the vertical hydraulic conductivity of the clay layer locally and to determine the long range effects pumping the Gordo aquifer would have on the Eutaw aquifer.

Geophysical logging and drill cuttings at the test site identified chalk from land surface to 700 ft below land surface; below the chalk was sand with clay streaks of the Eutaw Formation to 1,110 ft; then 90 ft of clay, 40 ft of sand, 60 ft of clay, 100 ft of sand, 10 ft of clay, and 60 ft of sand of the Gordo Formation, in the Tuscaloosa Group, to 1,470 ft. The test well was screened from 1,345 to 1,395 ft and from 1,410 to 1,455 ft in the Gordo Formation.

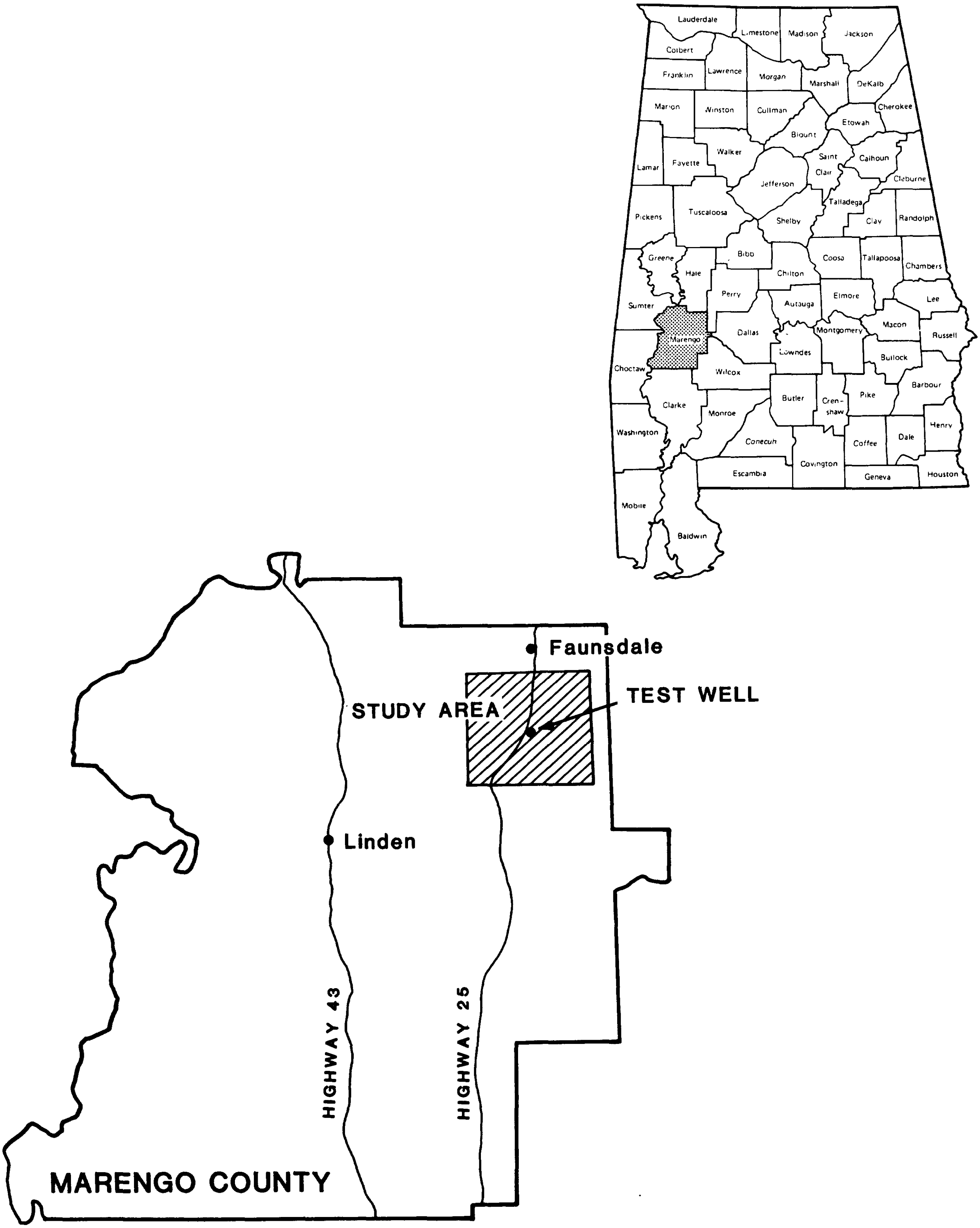


Figure 1.--Location of study area.

The test well was pumped continuously for 48 hours at 750 gal/min. Water-level measurements were made in three observation wells in the Eutaw Formation during the test. The wells were also measured periodically for 48 hours prior to the test to determine any water-level trends that might have been present. The water-level measurements indicated that pumping the Gordo aquifer at 750 gal/min for 48 hours had no measurable effect (less than 0.01 ft of drawdown) on water levels in the Eutaw aquifer. The closest observation well known to tap the Eutaw aquifer was about 1,300 ft from the pumping well in the Gordo aquifer. Thus, drawdown in the Gordo should have been small at that distance and drawdown in the Eutaw, if it existed at all, would be very small--perhaps unmeasurable. Because of the thickness of clay separating the Eutaw and Gordo, a very long time would be required for the effects of pumping to be transmitted through the clay layer. Possibly several months would be needed to ascertain whether or not pumping from the Gordo would affect water levels in the Eutaw aquifer. Because of the time and financial restrictions of performing such a test, a computer simulation of the system was used to determine the long range effects.

Hydrogeologic Setting

The Gordo Formation of the Tuscaloosa Group and the younger Eutaw Formation both of Cretaceous Age crop out in a broad northwestward arc in west-central Alabama. Both formations dip south and southwest about 40 ft per mile (fig. 2). The McShan Formation is recognized between the Eutaw and Gordo Formations in its type area north in Pickens County, but the McShan is not distinguishable from the Eutaw in this study area. For the purpose of this report, the term Eutaw Formation is used which includes the Eutaw aquifer. The Gordo has an average thickness of about 350 ft with sand and gravel in the lower part of the formation and clay in the upper part of the formation. The Eutaw has an average thickness of about 400 ft with the most productive part of the formation in the lower 100 ft, referred to as the basal sand of the Eutaw Formation. The Eutaw Formation is overlain by the Mooreville Chalk of the Selma Group. The chalk is an effective confining layer for the aquifers and the chalk must be penetrated to obtain adequate water supplies. A more detailed discussion of the geology of the Upper Cretaceous rocks in west-central Alabama is presented in Drennen (1953) and Monroe (1941).

The regional flow for the aquifers can be determined from the potentiometric surface maps compiled by Gardner (1981) in figures 3 and 4. Generally, regional flow conforms to a set pattern where, in the outcrop area (recharge area) for each aquifer, flow is toward the major rivers and, once the aquifer becomes confined, flow continues approximately down the dip of the aquifer. In most cases, the ultimate natural discharge route for water flowing downdip in aquifers is diffuse vertical flow to overlying aquifers. However, below the lower outcrop limit of the Eutaw, the flow in the aquifer is altered by the occurrence of highly impermeable chalk overlying the aquifers. The chalk prohibits the diffuse vertical flow and, although water does move downdip in areas distant from the major rivers, it is necessary for water to flow updip near the major rivers.

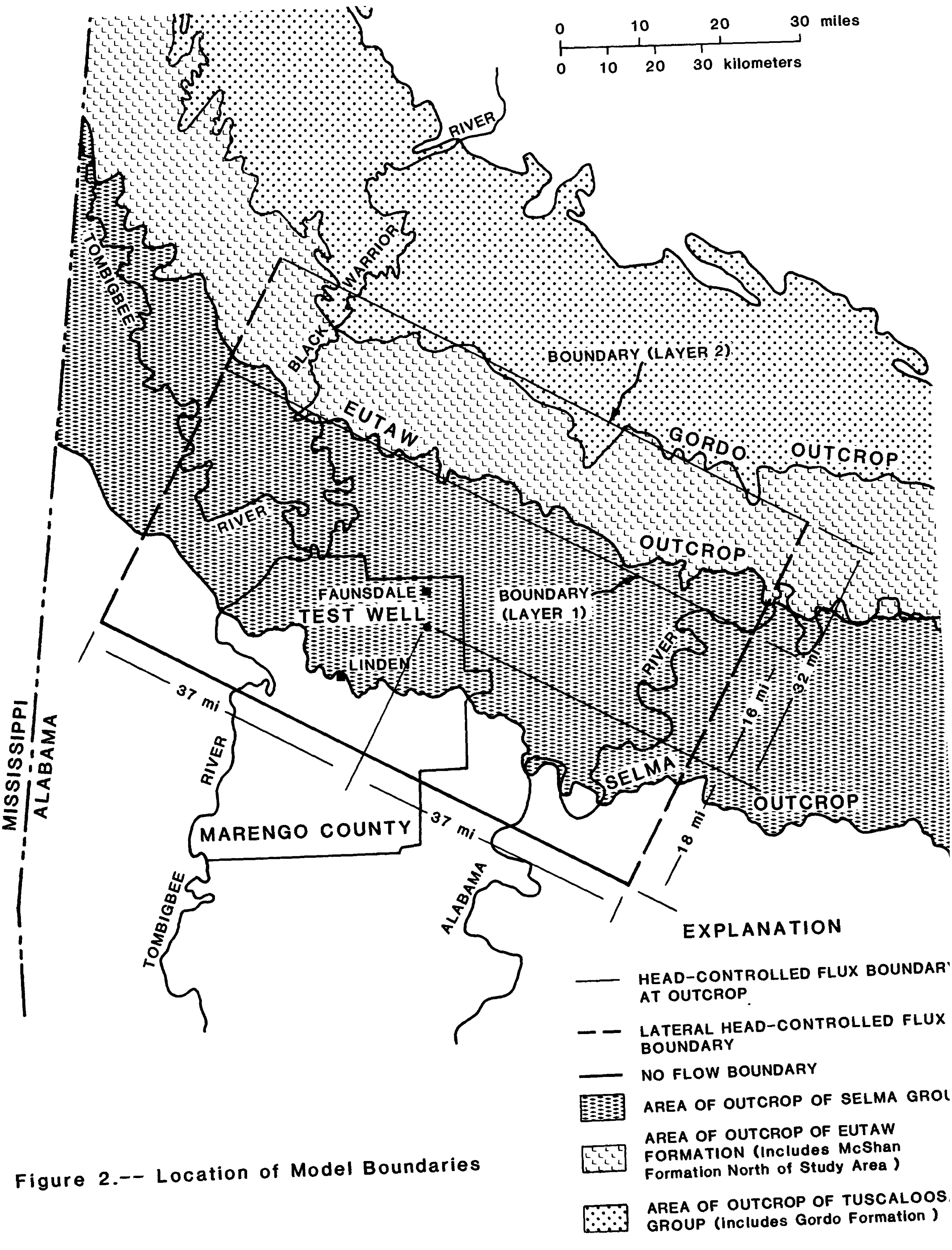
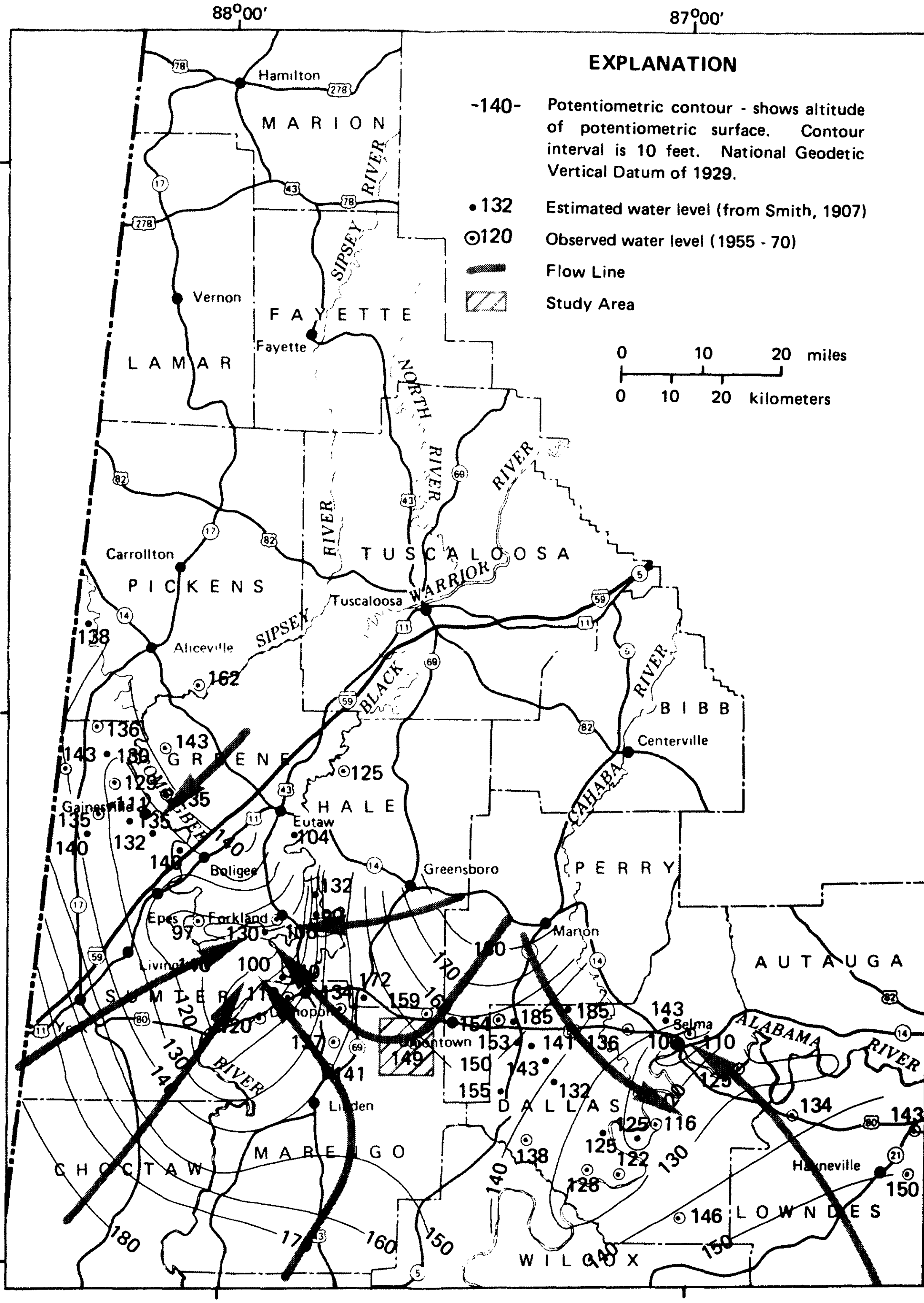


Figure 2.-- Location of Model Boundaries



Modified from Gardner (1981)

Figure 3.--Potentiometric surface in the Eutaw aquifer 1955-70.

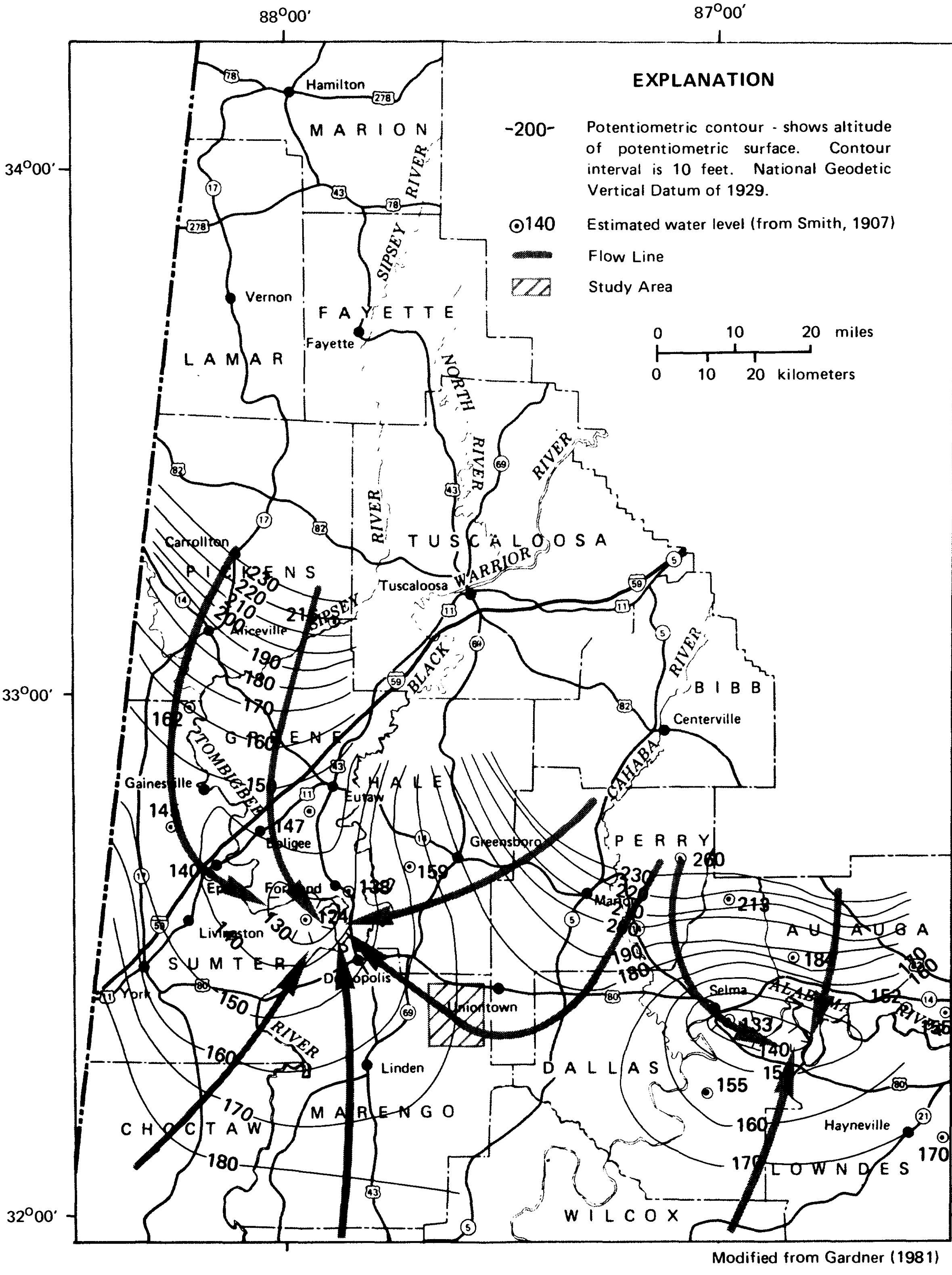


Figure 4.--Potentiometric surface in the Gordo aquifer 1955-70.

Purpose and Scope

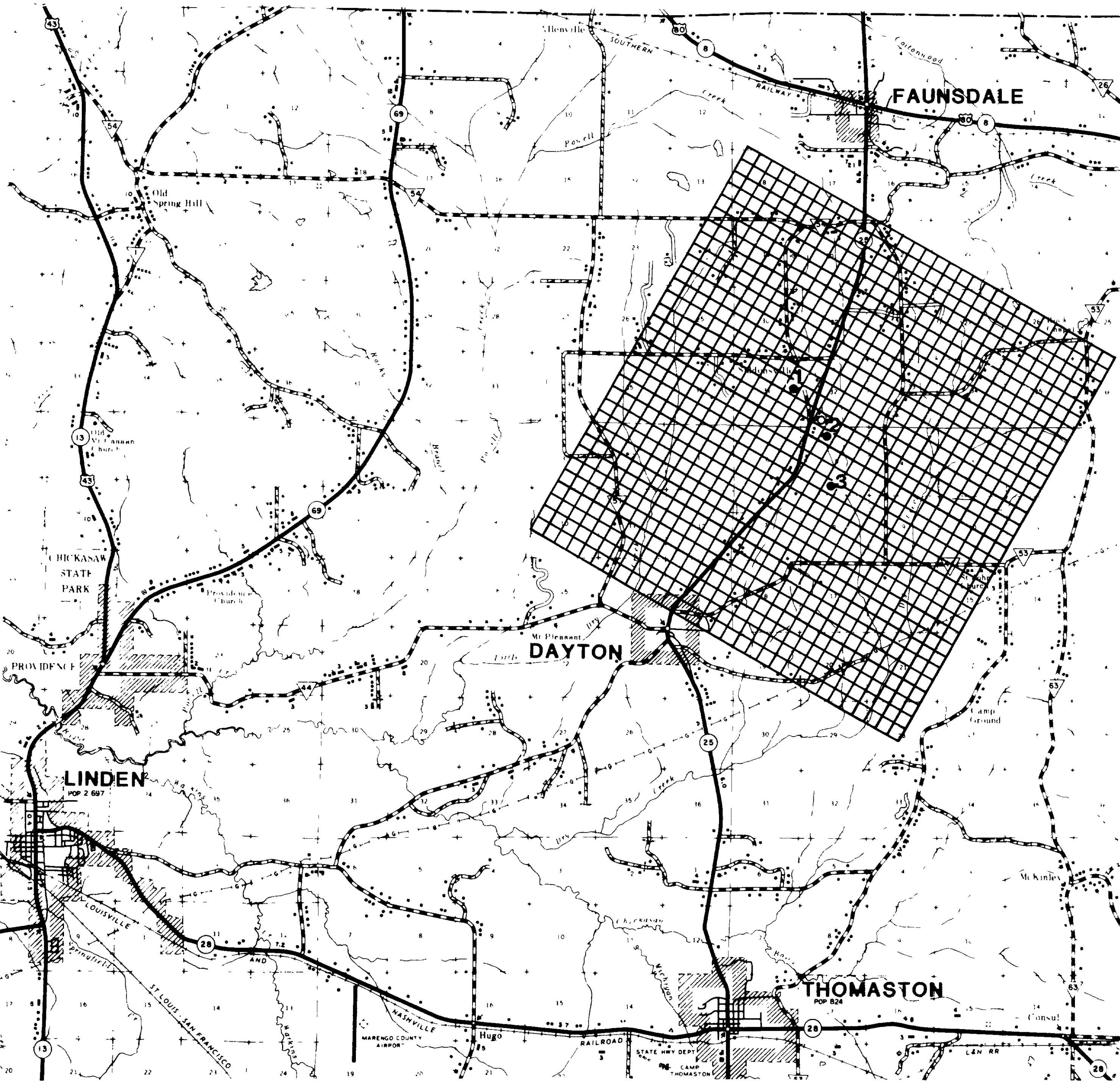
The purpose of this report is (1) to estimate vertical hydraulic conductivity for the confining bed between the Gordo aquifer and the overlying Eutaw aquifer by modeling an area in northeast Marengo County, Alabama (figs. 1 and 2) and (2) to estimate the effect in the Eutaw aquifer caused by pumping from the Gordo aquifer. Information collected by the U.S. Geological Survey during an aquifer test of the well 5 miles south of Faunsdale was used to determine a value for transmissivity of the Gordo aquifer in the area, which in turn was used in a computer simulation of the aquifers to determine the vertical hydraulic conductivity of the confining bed between the Gordo and Eutaw aquifers.

Approach

Information gained from the pumping test included a value for the transmissivity of the Gordo aquifer based on the drawdown in the pumped well at the end of the test and water-level data for three wells in the Eutaw aquifer collected during the test. All data from the pumping test were used in a finite-difference ground-water flow model (McDonald and Harbaugh, 1984) to determine the vertical hydraulic conductivity of the clay layer separating the Gordo and Eutaw aquifers. The type of simulation used for the analysis is termed quasi-three dimensional where lateral flows in the aquifers are modeled and heads are computed (active layer), but only vertical flow through the confining layer is modeled (inactive layer).

The exchange of water between the Eutaw and the Gordo aquifers is controlled by the confining layer. Because the confining layer is composed mostly of clay and clayey materials, the amount of horizontal ground-water flow is thought to be negligible so the unit was not modeled as an active layer. The thickness (b) of the unit and the vertical hydraulic conductivity (K') were used to calculate a leakance value (K'/b) for each model block. Leakance values were input as a data matrix and the value plus the difference in head values between the Eutaw and Gordo aquifers were used by the program to compute the amount of water exchanged between the units.

The modeled area, equivalent to 3,700 square miles, was designed so that the edges of the model were far enough away from the production well to assure that the simulated response of the well would be the same as in the actual aquifer system. The model was composed of two layers where water levels were calculated. Water levels for each layer were calculated for a 40 mi^2 area surrounding the production well (fig. 5). Boundary conditions were chosen that approximate a continuance of the aquifer system to a point of recharge or discharge or to a point beyond the influence of the proposed pumping. Boundary conditions used for the east-west and outcrop borders were head-controlled flux where flow across the border is determined from a point outside the model that can be assumed to remain constant throughout the simulations (fig. 2). Information needed to determine the flow at a head-controlled flux boundary includes transmissivity of the aquifer beyond the boundary, distance to the controlling head, and the controlling head.



Base from Alabama State Highway Departme
General Highway Map, Marengo County,
Alabama (1970)

EXPLANATION

○ PUMPING WELL IN GORDO AQUIFER

•2 OBSERVATION WELL AND NUMBER IN EUTAW AQUIFER

0 1 2 3 4 miles

0 1 2 3 4 kilometers

Figure 5.--Orientation of Model Grid and Location of Wells.

The northern boundaries for each layer were numerically extended to the outcrop of each aquifer unit (fig. 2). Water levels were assumed to remain constant in the outcrop area because of the greater storage properties that are associated with water-table conditions. The Eutaw aquifer boundary was simulated at 16 miles from the production well and the Gordo aquifer boundary was simulated at 32 miles from the production well. The east-west boundaries were chosen to be 37 miles from the production well for both aquifer layers to extend beyond major rivers on both sides (fig. 2). Discharge to the major rivers should be a source for the pumping well and considering the amount of pumpage, heads at that distance were assumed to remain constant. This distance is rather conservative as the boundaries could be appropriately ended at the rivers. However, the uncertainty of the connection between the aquifers and the rivers through the chalk necessitates some conservatism in the analysis. The southern boundaries were simulated at 18 miles from the production well to coincide with the location of water with greater than 10,000 mg/L total dissolved solids in both aquifers. The 10,000 total dissolved solids value has been defined as the limit of the freshwater flow system for the Southeast Coastal Plain RASA study. The northern and east-west boundaries were simulated as head-controlled flux boundaries where an amount of water is calculated as passing across the boundary as the water levels next to the boundary change. The southern boundaries were simulated as impermeable boundaries where no additional water can pass across the boundary.

The actual grid where heads are computed has a uniform grid spacing of 1,000 ft on a side for a radius of about 3 miles in the northern, eastern and western directions (the area is not oriented to true north, but to simplify the explanation reference will be made as if it were). In the southern direction, the actual grid had to be extended to the theoretical impermeable boundary. This meant beyond the 3 mile radius succeeding nodal spacings were increased until the correct distance of 18 miles was reached. The dimensions of the grid were thirty-three 1,000-ft nodes in the east-west direction and thirty-three 1,000-ft nodes in the north-south direction followed by six nodes with lengths of 2,000 ft, 4,000 ft, 8,000 ft, 16,000 ft, 20,000 ft, and 30,000 ft towards the southern direction.

The transmissivity of the Gordo aquifer was estimated as 10,000 ft^2/d using a specific capacity derived from the 48-hour pumping test and the equation from R. H. Brown in Bentall (1963, p. 336):

$$T = \frac{Q}{s}\,[K - 264 \log_{10} (5S \cdot 10^3) + 264 \log_{10} t],$$

where: T = transmissivity,
Q = pumping rate in gallons per minute (750 gal/min),
s = drawdown in feet (25 ft),
$K = -66 - 264 \log_{10} (3.74\, r^2 . 10^{-9})$, (2,477),
S = storage coefficient (1×10^{-4}),
t = time in days (2),
and r = radius of well in feet (0.25 ft).

A specific capacity of 30 was used, based on a pumping rate of 750 gal/min, and a drawdown of 25 ft taken after one minute of recovery which eliminates the inefficiency of the well. (The water level in the test well rose from 91 ft to 25 ft after one minute of recovery which meant the test well was highly inefficient and that the 25-ft water level would be a better figure in estimating the transmissivity of the aquifer.) Other parameters used in the equations are a storage coefficient of $1x10^{-4}$, a radius of 3 inches (0.25 ft) which gives a K value of 2,477 (Brown, 1963, p. 337).

The transmissivity of the Eutaw aquifer was calculated as 2,000 ft^2/d using specific capacity data in a report by Newton and others (1971) and the equation above. The storage coefficient for both aquifers was assumed to be $1x10^{-4}$. The model cannot calculate water derived from storage in the clay layer without calculating the heads in that layer. The vertical hydraulic conductivity of the clay was simulated as $1x10^{-4}$, $1x10^{-5}$, or $1x10^{-6}$ ft/d depending on the particular simulation. The vertical hydraulic conductivity is the least certain variable in the simulation but exerts the greatest control on the water level response in the Eutaw aquifer to pumping in the Gordo aquifer, hence a range of values was tested. No field data are available for the immediate area but vertical hydraulic conductivity values of $1.2x10^{-5}$ to $1.5x10^{-6}$ ft/d for clays of the Coastal Plain in Maryland were reported by Trapp and others (1984). The thickness of the clay layer was assumed to be a constant 90 ft as at the test site.

Transient simulations of 48 hours and 5 years were run. Steady-state simulations were run combining variations of the model variables. Results of the simulations are reported for three locations for comparison. The model calculates the drawdown for a well of a finite radius, so the value referred to as drawdown in the pumping well in table 1 and in the discussion that follows is drawdown for a 12-inch diameter well. The value referred to as drawdown in the Gordo aquifer is the drawdown in the node where the well is located. This value relates to a radius from the well of one-fifth the length of the node or 200 ft. The value for drawdown in the Eutaw aquifer is the approximate drawdown for the observation well in the Eutaw located 1,300 ft south of the pumping well. The value relates to a radius of about 1,400 ft; a diagonal distance of one model block from the pumping well (see figure 5, observation well 2). Results of these simulations are shown in table 1.

FORTY-EIGHT-HOUR TRANSIENT SIMULATIONS

Four model simulations were run using a 48-hour total time in five time steps in an effort to duplicate the results of the 48-hour pumping test. In simulation T1, the vertical hydraulic conductivity of the confining bed between the two aquifers was set at $1x10^{-4}$ ft/d. This was considered the highest value of the range of probable values for this parameter. This simulation produced 24.89 ft of drawdown in the pumping well, 11.0 ft of drawdown in the pumping well node in Layer 2 (Gordo aquifer), and 0.06 ft of drawdown at observation well 2 Layer 1 (Eutaw aquifer).

Table 1.--Simulation results for the Eutaw and Gordo aquifers

Simulation number	Length of simulation	Pumping rate gal/min	Vertical hydrauli conduc-tivity (ft/d)	Transmissivity (ft^2/d) Eutaw	Transmissivity (ft^2/d) Gordo	Storage coefficient Eutaw	Storage coefficient Gordo	East-west boundaries	Drawdown in pumping well (ft) r=0.25 ft	Drawdown Gordo (ft) r=200 ft	Drawdown Eutaw (ft) r=1,400 ft
T1	48 hours	750	$1x10^{-4}$	2000	10,000	$1x10^{-4}$	$1x10^{-4}$		24.89	11.0	0.06
T2	48 hours	750	$1x10^{-5}$	2000	10,000	$1x10^{-4}$	$1x10^{-4}$		24.92	11.0	.006
T3	48 hours	750	$1x10^{-4}$	2000	10,000	$1x10^{-3}$	$1x10^{-4}$		24.89	11.0	.01
T4	48 hours	750	$1x10^{-5}$	2000	10,000	$1x10^{-4}$	$1x10^{-4}$	extended	24.94	11.08	.01
T5	5 years	750	$1x10^{-4}$	2000	10,000	$1x10^{-4}$	$1x10^{-4}$		37.24	23.3	6.79
T6	5 years	750	$1x10^{-5}$	2000	10,000	$1x10^{-4}$	$1x10^{-4}$		38.48	24.62	1.50
T7	5 years	750	$1x10^{-4}$	2000	5,000	$1x10^{-4}$	$1x10^{-4}$		71.86	44.14	12.17
T8	5 years	750	$1x10^{-5}$	2000	5,000	$1x10^{-4}$	$1x10^{-4}$		76.27	48.56	2.86
SS1	--	200	$1x10^{-4}$	2000	10,000	--	--		9.65	6.06	1.75
SS2	--	200	$1x10^{-5}$	2000	10,000	--	--		9.97	6.38	.39
SS3	--	200	$1x10^{-6}$	2000	10,000	--	--		10.06	6.46	.05
SS4	--	750	$1x10^{-4}$	2000	10,000	--	--		36.98	23.12	6.56
SS5	--	750	$1x10^{-5}$	2000	10,000	--	--		38.39	24.53	1.49
SS6	--	750	$1x10^{-6}$	2000	10,000	--	--		38.78	24.92	.17
SS7	--	750	$1x10^{-4}$	2000	10,000	--	--	extended	43.00	29.14	11.59
SS8	--	750	$1x10^{-6}$	2000	10,000	--	--	extended	46.15	32.29	.45
SS9	--	750	$1x10^{-4}$	2000	5,000	--	--		71.92	44.21	12.26
SS10	--	750	$1x10^{-5}$	2000	5,000	--	--		76.30	48.59	2.92
SS11	--	750	$1x10^{-6}$	2000	5,000	--	--		77.50	49.78	.35
SS12	--	750	$1x10^{-5}$	1000	10,000	--	--		38.52	24.66	2.67

In simulation T2, the vertical hydraulic conductivity was changed to $1x10^{-5}$ ft/d. After 48 hours, the drawdown in the pumping well was only 0.03 ft greater than in the previous simulation (24.92 ft) and the drawdown in the Gordo aquifer remained the same, 11 ft, as in T1. A map of the drawdown in the Gordo aquifer is shown in figure 6. The drawdown in the Eutaw aquifer decreased an order of magnitude to 0.006 ft at observation well 2, in the range that would not be measurable in the field using the methods employed for the pumping test.

In simulation T3, the storage coefficient for the Eutaw aquifer was increased from $1x10^{-4}$ to $1x10^{-3}$ to test the possible effects of storage of water in the clay layer (by assuming that the additional storage in the Eutaw was water from the clay). The confining bed conductivity was the same as in simulation T1. There was no change in drawdown from that of simulation T1 in the pumping well or in the Gordo aquifer. In the Eutaw, drawdown was 0.012 ft at observation well 2, 0.05 ft less than in simulation T1, indicating that storage in the clay layer would slightly affect drawdown in the Eutaw. Consequently, even with a value of vertical hydraulic conductivity of $1x10^{-4}$ ft/d modeling indicates the drawdown in the Eutaw should still be measurable. From these simulations, it can be inferred that even when storage in the clay layer is taken into account, a vertical hydraulic conductivity for the clay layer of $1x10^{-4}$ ft/d is too large because this value would have produced a measurable drawdown in the Eutaw aquifer for the 48-hour test.

In simulation T4, the east-west boundaries of the model were extended twice their original distance from the pumping well to determine if artificially narrow boundaries had any effects on the simulations. Moving the boundaries farther from the pumping well would result in greater drawdowns because the source of water would be at a greater distance. Vertical hydraulic conductivity of the confining bed was set at $1x10^{-5}$ ft/d so that this test can be compared directly with simulation T2. The effect in the pumping well was 0.02 ft greater drawdown than in T2. The Gordo aquifer had 0.08 ft greater drawdown and the Eutaw had only 0.004 ft greater drawdown. The effect of moving the lateral boundaries in the 48-hour simulations was very small, and thus boundaries had no bearing on the conclusion reached above.

The data from these 48-hour simulations can be compared to actual water-level measurements during the pumping test. The drawdowns in the pumping well from the simulations are comparable to the drawdown in the well from the pumping test after one minute of recovery (25 ft). The maximum drawdown in the well from the test (91 ft) is not representative of drawdown in the aquifer due to the inefficiency of the well (a factor not taken into account by the model). Actual and predicted drawdowns elsewhere in the Gordo cannot be compared because there were no other wells in the aquifer for the test. The response of the Eutaw is a key to estimating more accurately the vertical hydraulic conductivity of the confining bed. The smaller simulated value for confining bed vertical hydraulic conductivity ($1x10^{-5}$ ft/d) produced drawdown in the Eutaw too slight to have been detected in the field, as was the result during the actual test. Consequently, the value for confining bed conductivity is $1x10^{-5}$ ft/d or smaller. The results thus far are based on only 48 hours of pumping and simulation. The following discussion extrapolates the short term results by simulating a 5-year pumping period.

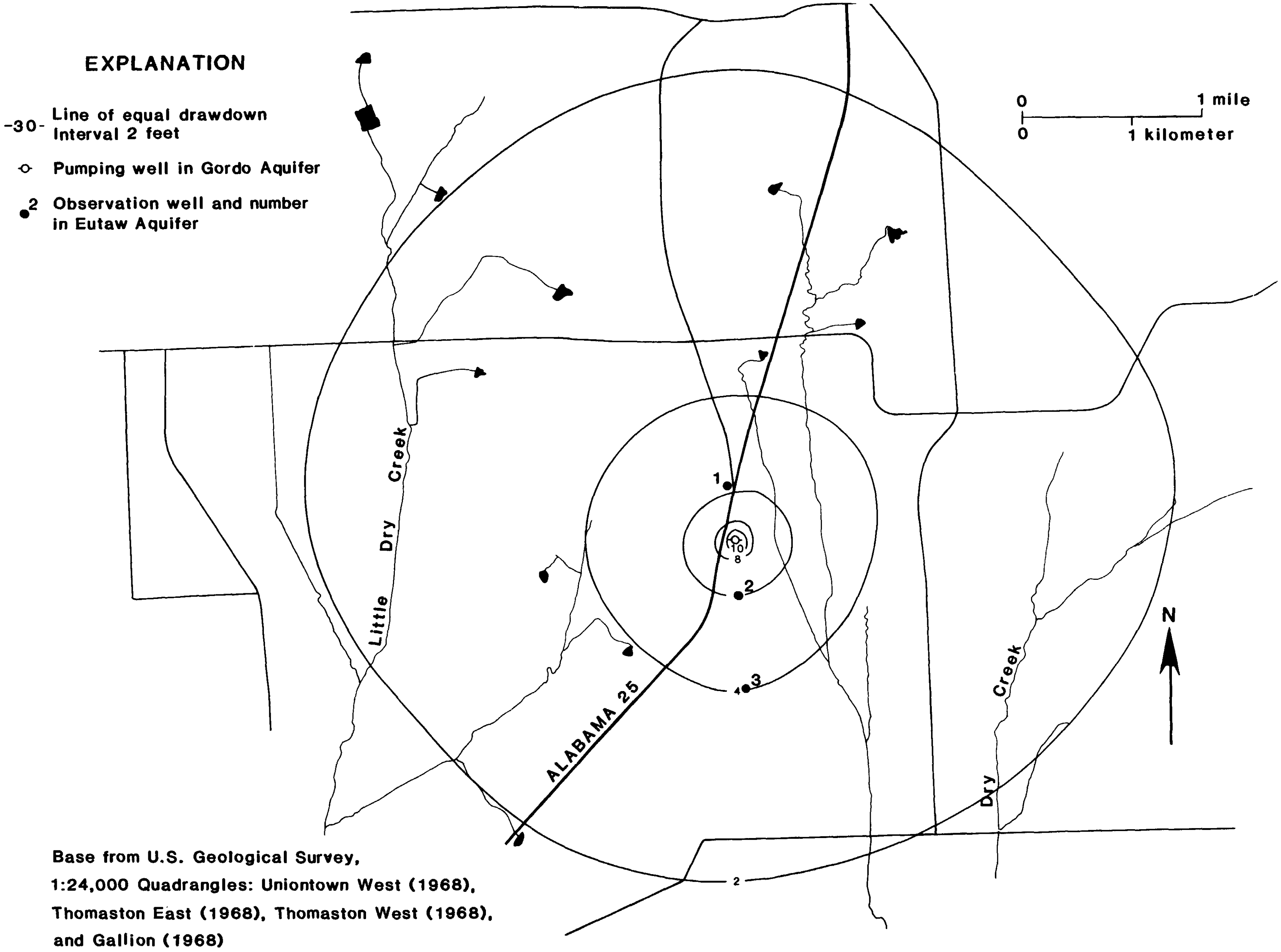


Figure 6.--Drawdown in the Gordo aquifer after 48 hours pumping at 750 gallons per minute with vertical hydraulic conductivity of the confining bed of 1 x 10^{-5} feet per day. Simulation T2.

FIVE-YEAR TRANSIENT SIMULATIONS

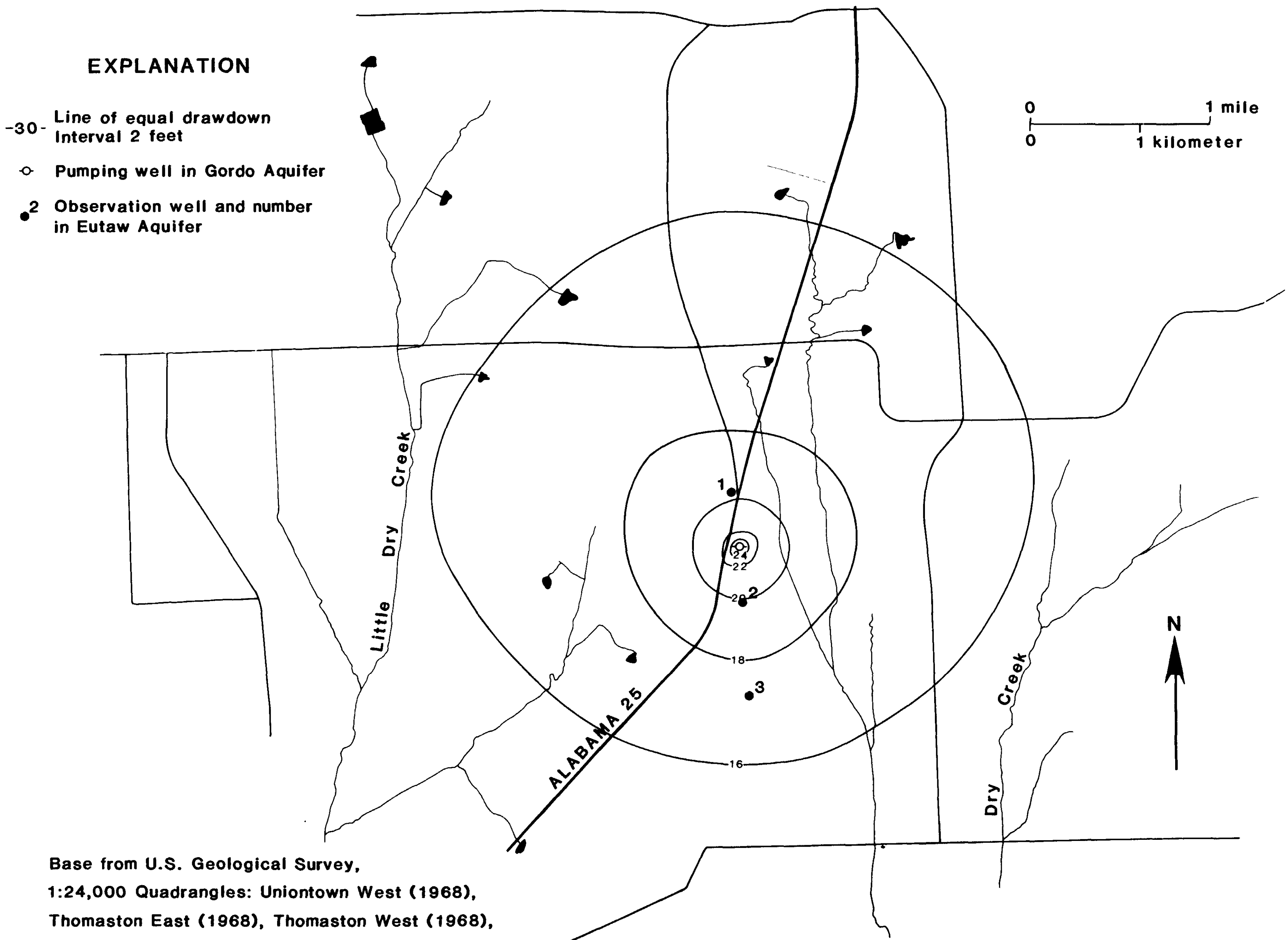
Two 5-year simulations (T5 and T6) were run, using confining bed conductivities of 1×10^{-4} ft/d and 1×10^{-5} ft/d, respectively, to examine the long-term effect of the difference in conductivity. Drawdown in the pumping well in T5 was 37.24 ft compared to 38.48 ft in T6. Drawdown in the Gordo in T5 was 23.3 ft compared to 24.62 ft in T6 (fig. 7). In the Eutaw at observation well 2 the maximum drawdown in T5 was 6.8 ft, but in T6 it was only 1.5 ft. The drawdown was less in the pumping well and in the Gordo in T5 because the relatively leaky confining bed allowed water to be drawn from the Eutaw.

Two additional 5-year simulations (T7 and T8) were run using a transmissivity of 5,000 ft^2/d for the Gordo aquifer, 50 percent of the estimated transmissivity. Vertical hydraulic conductivity of the confining bed in T7 was simulated as 1×10^{-4} ft/d. The drawdown in the pumping well and in both layers nearly doubled from simulation T5 (pumping well drawdown in T7 was 71.86 ft, in the Gordo drawdown was 44.14 ft, and in the Eutaw drawdown at observation well 2 was 12.17 ft). Simulation T7 would represent the worst possible circumstance--an extremely leaky confining bed and a low transmissivity for the Gordo aquifer. The drawdowns produced by this simulation would represent a maximum for the 5-year period. In simulation T8, vertical hydraulic conductivity was set at the more realistic value of 1×10^{-5} ft/d. Drawdown in the well was 76.27 ft. Drawdown in the Gordo was 48.56 ft (fig. 8) and in the Eutaw at observation well 2 was 2.86 ft.

The 5-year runs have shown that changing the vertical hydraulic conductivity of the confining layer has very little effect on the heads in the Gordo aquifer but reduces the drawdown in the Eutaw aquifer over 4.5 times. The runs using half the value of transmissivity for the Gordo aquifer show that the Gordo transmissivity controls the entire simulation as drawdowns in both aquifers were nearly doubled, precisely as the flow equation would dictate. The probable reason the drawdowns were not exactly doubled was the influence of the boundaries that supplied some water to the pumping.

STEADY-STATE SIMULATIONS

Steady-state simulations were run to determine the drawdowns expected when the system reached a new equilibrium. Simulations would represent the maximum drawdowns for the system under the given stresses (pumping rates). The steady-state simulations were also used to further test the variables input to the model. Discharge rate, vertical hydraulic conductivity of the confining bed, transmissivity of the Gordo aquifer, distance to the lateral boundaries of the model, and transmissivity of the Eutaw aquifer were systematically varied to test their individual effect on the drawdown in the well and in each layer under steady-state (equilibrium) conditions. The values for drawdown in each layer and in the well are shown for the various steady-state simulations in Table 1.



Base from U.S. Geological Survey, 1:24,000 Quadrangles: Uniontown West (1968), Thomaston East (1968), Thomaston West (1968), and Gallion (1968)

Figure 7.--Drawdown in the Gordo aquifer after 5 years pumping at 750 gallons per minute with vertical hydraulic conductivity of the confining bed of 1×10^{-5} feet per day. Simulation T6.

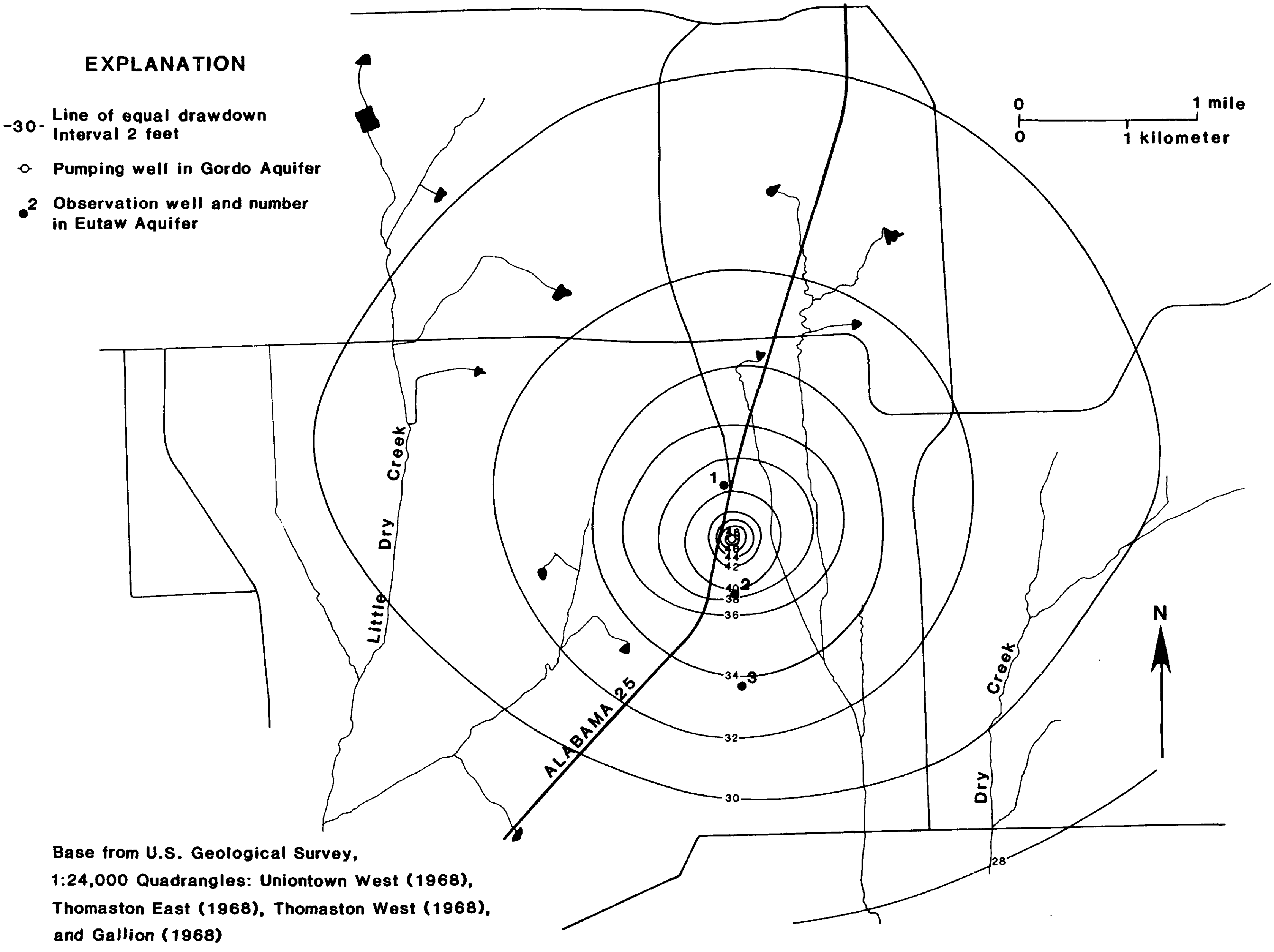


Figure 8.--Drawdown in the Gordo aquifer after 5 years pumping at 750 gallons per minute with vertical hydraulic conductivity of the confining bed of 1 x 10^{-5} feet per day and transmissivity of the Gordo aquifer of 5000 $feet^2$ per day. Simulation T8.

The first three steady-state simulations were run using a discharge rate of 200 gal/min. This rate is considerably less than the 750 gal/min pumped during the 48-hour pumping test and used in the transient simulations. Vertical hydraulic conductivity of the confining bed was set at 1×10^{-4} ft/d in simulation SS1, at 1×10^{-5} ft/d in simulation SS2, and at 1×10^{-6} ft/d for SS3. These simulations cannot be compared with the transient simulations due to the difference in discharge. The effect of changing the vertical hydraulic conductivity can be seen in comparing the three simulations (table 1). Drawdown in the pumping well ranged from a maximum of 10.06 ft in simulation SS3 (vertical hydraulic conductivity of 1×10^{-6} ft/d) to a minimum of 9.65 ft in SS1 (vertical hydraulic conductivity of 1×10^{-4} ft/d). Drawdown in the Gordo aquifer was at a maximum of 6.46 ft in SS3 and at a minimum of 6.06 ft in SS1. Drawdown in the Eutaw aquifer was at a maximum of 1.75 ft in SS1 and at a minimum of 0.046 ft in simulation SS3. As in the transient simulations, the effect of increasing the vertical hydraulic conductivity is to reduce drawdown in the pumping well and in the Gordo aquifer, but to increase drawdown in the Eutaw aquifer as water leaks through the confining bed from the Eutaw into the Gordo.

The remaining steady-state simulations were run using a discharge of 750 gal/min. In simulations SS4, SS5, and SS6, the vertical hydraulic conductivity was varied as before (from 1×10^{-4} to 1×10^{-6} ft/d). The maximum drawdown in the pumping well (38.78 ft) and in the Gordo aquifer (24.92 ft) was produced by the smallest value for vertical hydraulic conductivity (1×10^{-6} ft/d) in simulation SS6 (fig. 9). This simulation produced the least drawdown in the Eutaw aquifer (0.17 ft). The greatest drawdown in the Eutaw aquifer (6.56 ft) was produced in SS4 by the largest value for vertical hydraulic conductivity (1×10^{-4} ft/d). This simulation produced 36.98 ft of drawdown in the pumping well and 23.12 ft of drawdown in the Gordo aquifer. In simulations SS7 and SS8, the east-west boundaries were extended as they were in transient simulation T4. Extending the east-west boundaries increased the drawdown in the pumping well to 43.00 ft in SS7 (vertical hydraulic conductivity = 1×10^{-4} ft/d) and to 46.15 ft in SS8 (vertical hydraulic conductivity = 1×10^{-6} ft/d). In simulation SS7, the drawdown in the Gordo aquifer was 29.14 ft and in the Eutaw aquifer was 11.59 ft. In simulation SS8, the drawdown in the Gordo aquifer was 32.29 ft (fig. 10) and in the Eutaw aquifer was 0.45 ft. In simulations SS9, SS10, and SS11, the transmissivity of the Gordo aquifer was changed to 5,000 ft^2/d (half of what is expected for the Gordo aquifer) and the vertical hydraulic conductivity was varied as before. Results were similar to those produced by these variations in the transient simulations. Reducing the transmissivity of the Gordo aquifer greatly increases the drawdown in the pumping well. Drawdown in the well in SS9 was 71.92 ft, in SS10 was 76.30 ft, and in SS11 was 77.50 ft. The effect of the lower vertical hydraulic conductivity is to reduce drawdown in the Eutaw aquifer and increase drawdown in the pumping well and in the Gordo aquifer (fig. 11). The drawdown in the Eutaw aquifer decreased to 0.35 ft in simulation SS11 (vertical hydraulic conductivity = 1×10^{-6} ft/d) compared to 12.26 ft in simulation SS9 (vertical hydraulic conductivity = 1×10^{-4} ft/d).

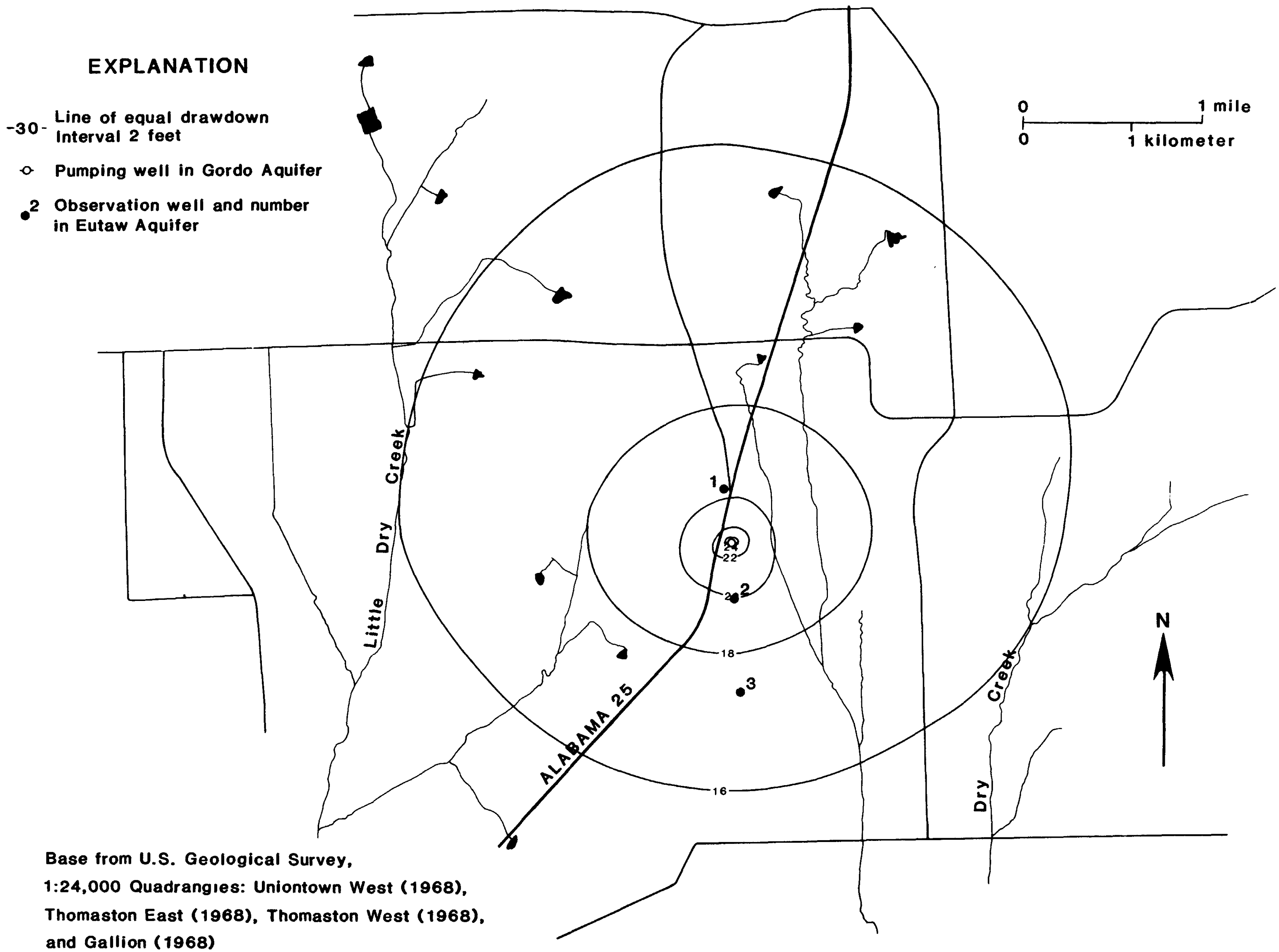


Figure 9.--Drawdown in the Gordo aquifer (steady-state simulation) pumping at 750 gallons per minute with vertical hydraulic conductivity of the confining bed at 1 x 10^{-6} feet per day. Simulation SS6.

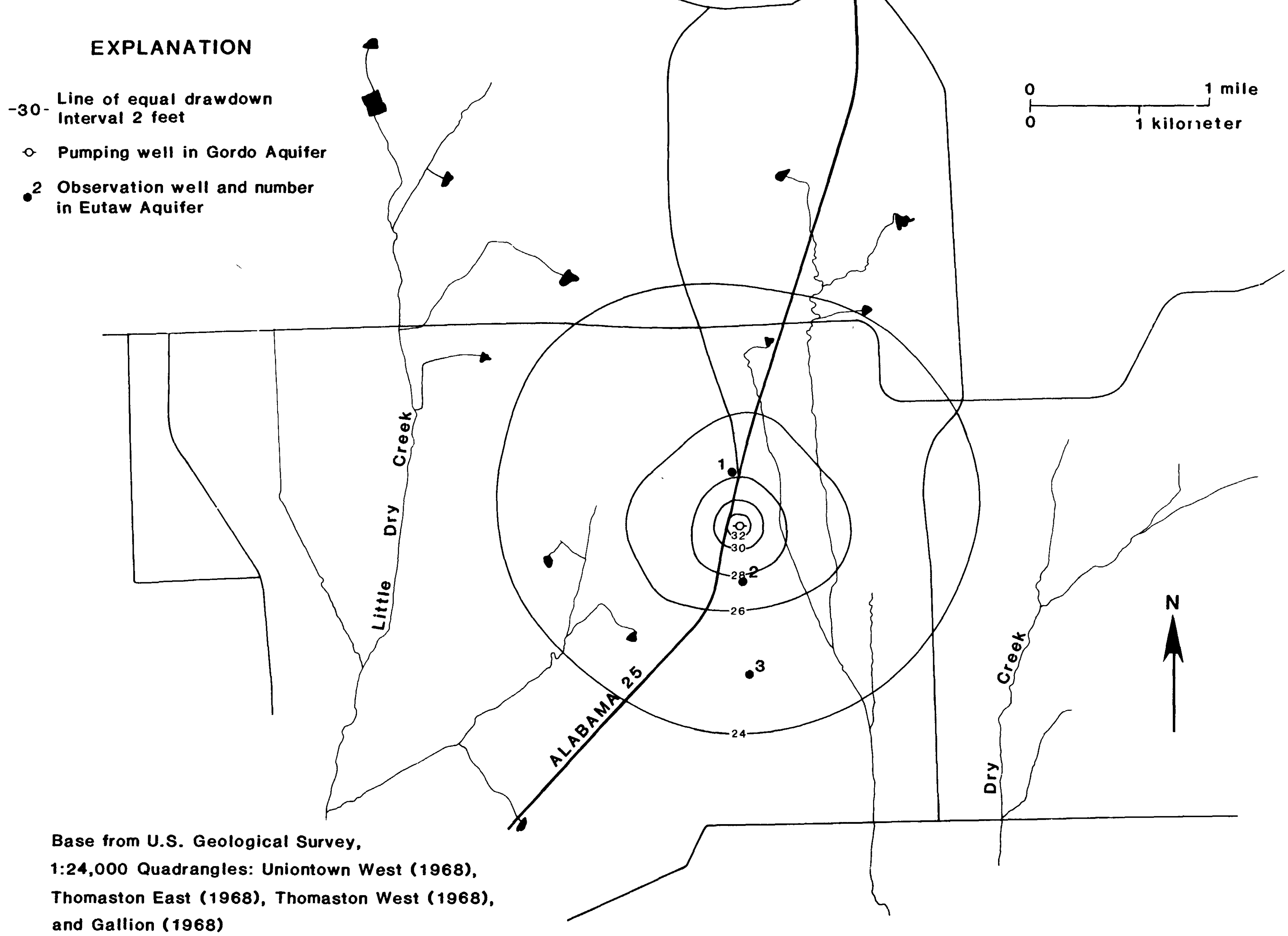
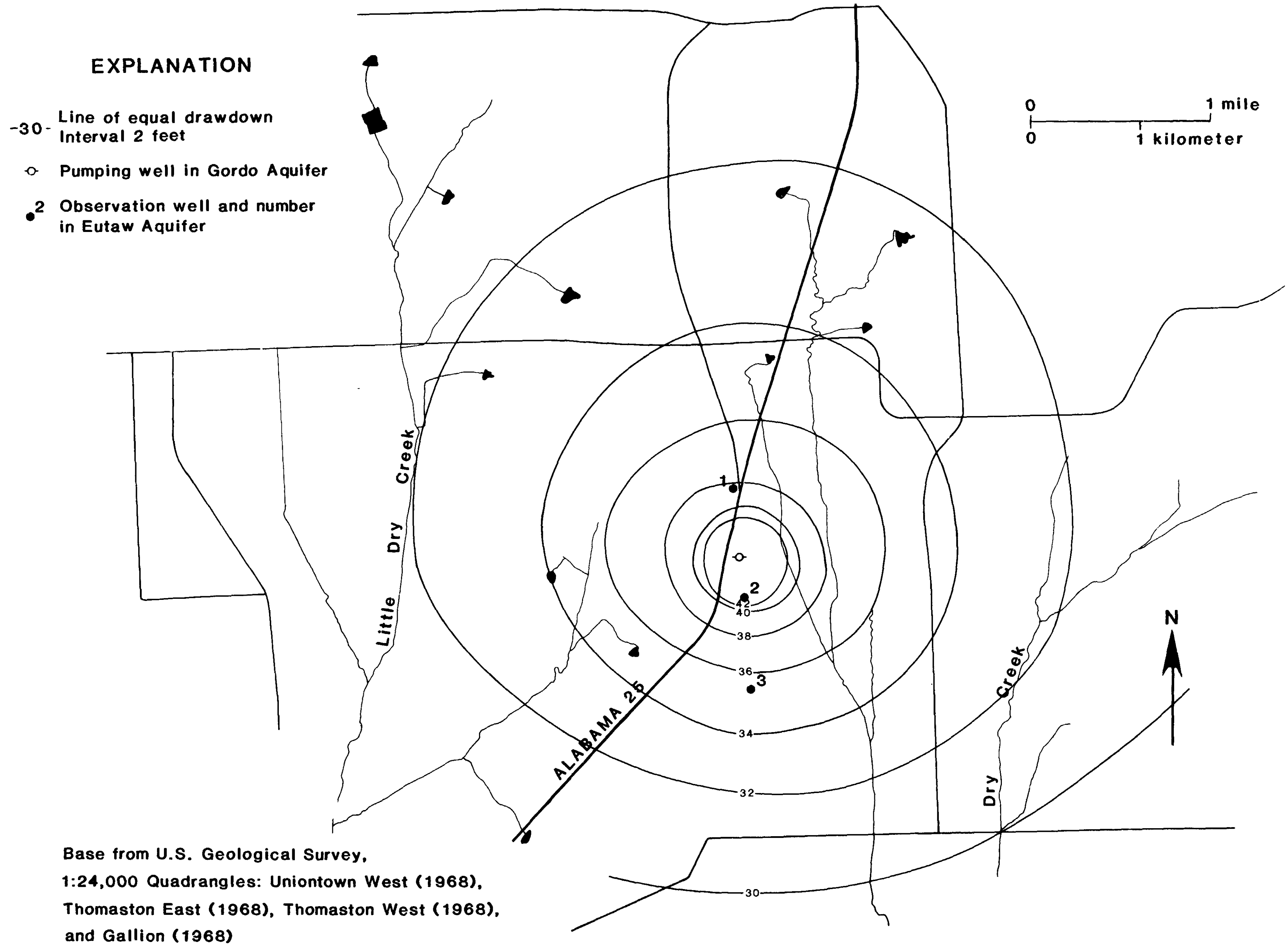


Figure 10.--Drawdown in the Gordo aquifer (steady-state simulation) pumping at 750 gallons per minute with vertical hydraulic conductivity of the confining bed at 1×10^{-6} feet per day with lateral boundaries extended. Simulation SS8.



Base from U.S. Geological Survey,
1:24,000 Quadrangles: Uniontown West (1968),
Thomaston East (1968), Thomaston West (1968),
and Gallion (1968)

Figure 11.--Drawdown in the Gordo aquifer (steady-state simulation) pumping at 750 gallons per minute with vertical hydraulic conductivity of the confining bed at 1×10^{-6} feet per day and transmissivity of the Gordo aquifer at 5000 $feet^2$ per day. Simulation SS11.

In simulation SS12 (table 1) the transmissivity of the Eutaw aquifer was decreased to 1,000 ft^2/d. Confining bed conductivity was set at $1x10^{-5}$. The drawdown in the pumping well was 38.52 ft. Drawdown in the Gordo aquifer was 24.66 ft and in the Eutaw aquifer was 2.67 ft. These results can be compared to simulation SS5 with the same variables except for the transmissivity of the Eutaw. Drawdown in the pumping well and in the Gordo aquifer was almost unchanged while drawdown in the Eutaw aquifer was about 1 ft greater in SS12 with the reduced value of transmissivity for the Eutaw.

Relations determined from the steady-state simulations follow those prescribed by the general flow equation:

$$Q = T\, dh/dl\, W,$$

where Q = quantity of flow,
T = transmissivity,
dh/dl = hydraulic gradient in the aquifer,
and W = width of aquifer for which the flow is computed.

The relations are:

(1) changing the pumping rate changes the amount of drawdown in both aquifers proportionally to the rate change,
(2) extending the east-west boundaries of the model has a greater effect proportionally on the Eutaw aquifer because the Eutaw's lower transmissivity requires a greater head gradient to transmit a given amount of water,
(3) reducing the transmissivity of the Gordo aquifer increases the gradient proportionally in both aquifers because the Gordo is the source aquifer for the pumping and the gradient in the Gordo controls flow in both aquifers, and
(4) reducing the transmissivity in the Eutaw aquifer increases the gradient proportionally in the Eutaw aquifer but has virtually no effect on the Gordo aquifer. The reason for this is that the Eutaw is not the source aquifer for the pumping well and the change in transmissivity controls only the gradient necessary to move water in the Eutaw.

CONCLUSION

The vertical hydraulic conductivity of the confining bed between the Eutaw and Gordo aquifers in the vicinity of Faunsdale, in northeast Marengo County, Alabama, is 1×10^{-5} ft/d or less. A conductivity of 1×10^{-5} ft/d in the 48-hour simulation pumping 750 gal/min reproduced the appropriate drawdown response in the pumping well and observation wells in the Eutaw aquifer from a 48-hour pumping test, but the conductivity may be as small as 1×10^{-6} ft/d. Larger vertical hydraulic conductivities produced a drawdown in the Eutaw aquifer that did not match the results of a 48-hour aquifer test. Modeling has shown that vertical hydraulic conductivity of the confining bed is the controlling factor on the drawdown in the Eutaw aquifer. At equilibrium (steady-state) pumping 750 gal/min there was a maximum 3 ft of drawdown in the Eutaw aquifer with a confining bed conductivity of 1×10^{-5} ft/d. When the conductivity was decreased to 1×10^{-6} ft/d drawdown in the Eutaw aquifer was only 0.35 ft. For a worst-case study, the transmissivity of the Gordo aquifer was halved and a vertical hydraulic conductivity for the confining bed was simulated as 1×10^{-4} ft/d. The result of this simulation was a drawdown of about 12 ft in the Eutaw aquifer under steady-state conditions. This 12 ft of drawdown is probably the maximum effect pumping 750 gal/min from the Gordo aquifer would have on the Eutaw aquifer.

From the modeling analysis using 1×10^{-5} ft/d for vertical hydraulic conductivity for the clay, the maximum drawdown predicted in the Eutaw aquifer from pumping the Gordo aquifer at 750 gal/min is about 3 ft. Actual drawdown in the Eutaw aquifer would likely be even less because the 3-ft value is based on a transmissivity of 5,000 ft^2/d, as opposed to the more probable value of 10,000 ft^2/d for the Gordo aquifer.

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