

DIGITAL SIMULATION OF THE OGALLALA AQUIFER IN
SHERMAN COUNTY, NORTHWESTERN KANSAS

by 632

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INTRODUCTION

Irrigation, which is increasing at a rapid rate, is the largest use made of ground water in northwestern Kansas. It is becoming increasingly important to an area that receives a small amount of erratically distributed precipitation. This report is an outgrowth of an investigation of the geology and ground-water resources of six counties in northwestern Kansas, including Sherman County, which was begun in 1964 to determine the effects of irrigation on the hydrology of the area.

An area of 340 square miles (17 x 20 miles) in Sherman County (Fig. 1) was selected for study. The purpose of the study was to observe the effects on the aquifer of past pumpage and to predict, by digital computer simulation, the influence on the aquifer of future pumpage from wells. At the present time, 264 large-capacity wells are in the study area, including 253 for irrigation, four for industrial, and seven for municipal use. The well density averages 0.8 well per square mile but locally is as much as 5, and well yields range from 100 to 1,900 gpm (gallons per minute). In 1969 more water was pumped and more wells existed in Sherman County than in any of the other counties in northwestern Kansas.

Water in the area is being "mined"; that is, water is being pumped from the ground-water reservoir at a rate faster than it is being replaced by nature. To determine the nature of the response of the aquifer to past and predicted future irrigation development, it was necessary to:

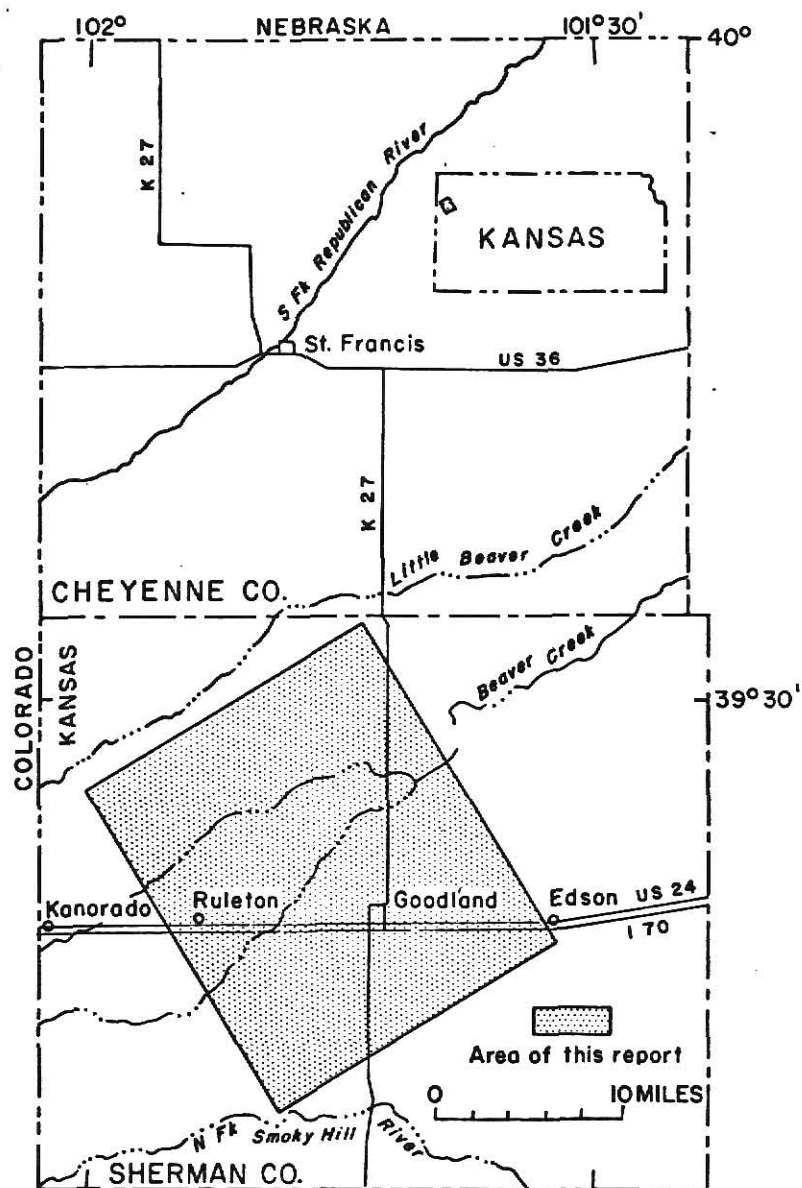


Fig. 1 Index map.

- 1) Establish an observation-well network;
- 2) Determine the location and annual discharge of all large-capacity wells;
- 3) Determine the aquifer coefficients;
- 4) Collect and tabulate hydrologic data from 1966 through 1969 that would be suitable for both manual and computer analysis;
- 5) Test and adjust the input data by use of the digital model to simulate actual field conditions during 1966 through 1969; and
- 6) Apply the model (a) to predict the effects of projected development for 20 years (1970 through 1989); and (b) to predict the effects of little or no further development for 20 years (1970 through 1989).

HYDROGEOLOGIC SETTING

The area is in the High Plains section of the Great Plains physiographic province and consists of nearly flat to gently rolling uplands dissected by several relatively shallow valleys. The streams are intermittent, flowing only for brief periods during and immediately after rains. The normal annual precipitation at Goodland is 16.5 inches (U.S. Department of Commerce, 1969).

The principal aquifer (water-bearing formation) is the Ogallala Formation of Pliocene age. It consists of sand, silt,

clay, gravel, caliche, and resistant "mortar beds" composed of sand and gravel cemented with calcium carbonate. The Ogallala is underlain by the Pierre Shale of Cretaceous age and is generally overlain by a thick deposit of windblown silt or loess of Pleistocene age.

The depth to the Pierre Shale in the study area ranges from 136 to 390 feet and the depth to water ranges from 23 to 185 feet. The saturated zone is 80 to 260 feet thick.

Recharge in the area is derived either directly or indirectly from precipitation within the area, or from nearby areas to the west and southwest. Recharge from nearby areas occurs as ground-water inflow and by seepage from intermittent streams that enter and cross the area from west to east. Although much of the water pumped for irrigation is used by vegetation, some is lost by evaporation and some percolates back to the water table. Ground water in the area is discharged by wells and by ground-water outflow to the east.

COLLECTION AND USE OF DATA

One important factor in data collection for the model was establishing a complete network of observation wells. All large-capacity industrial, irrigation, and municipal wells were inventoried, and selected wells were measured and tested to provide information on aquifer characteristics and pumping practices.

A network of observation wells, as shown on Fig. 2,

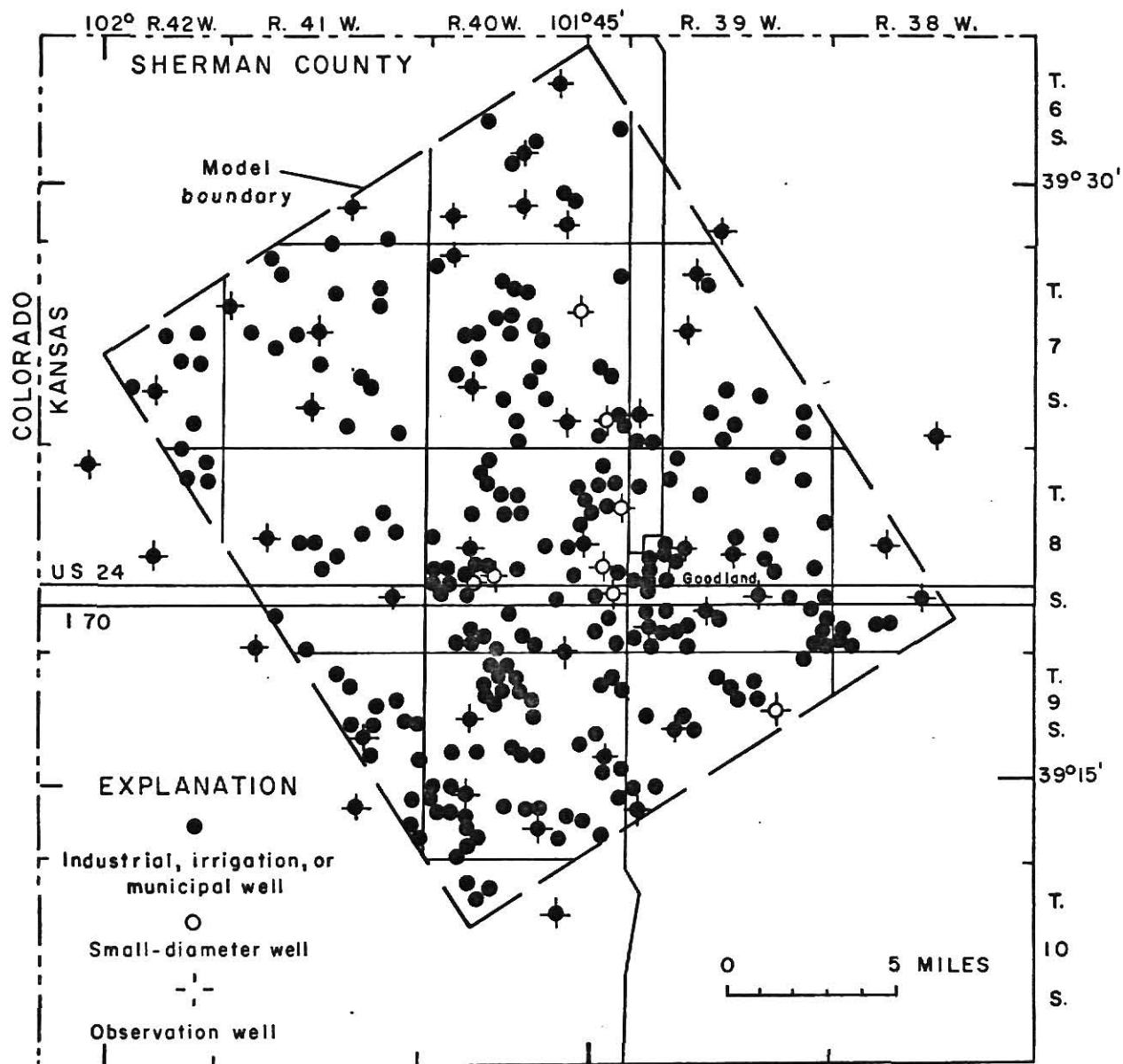


Fig. 2 Location of wells in 1969.

was established in 1966-67 to determine the seasonal and annual fluctuations in the water table. The configuration of the water table is shown by contours on Figs. 3 and 4 for January 1966 and January 1970, respectively. During this period, water levels declined throughout more than 90 percent of the area.

Where adequate power records are available, information concerning well locations and discharge can be obtained from power-company offices. A majority of the power units of the irrigation wells are industrial internal-combustion engines powered by natural gas, but a few are electric motors. The average amount of power required to pump 1 acre-foot of water was determined by sampling a number of wells. The discharge of a well was measured with a Jacuzzi (pitot-type) meter or an in-line (propeller-type) meter, the rate of natural gas use corresponding to the discharge was measured at the gas meter with a stop watch, and a pressure gage was attached to the meter to determine the pressure factor. The power input was determined by applying the equation:

$$K_g = \frac{325,851 \times 60 \ V \ P_g}{Q \ t_g} = \frac{1.955 \times 10^7 \ V \ P_g}{Q \ t_g} \quad (1)$$

where K_g = cubic feet of natural gas to pump 1 acre-foot of water;

V = cubic feet of natural gas consumed in t_g seconds;

P_g = pressure factor (See Table 1);

Q = pump discharge, in gallons per minute;

t_g = time, in seconds, to consume V volume of natural gas.

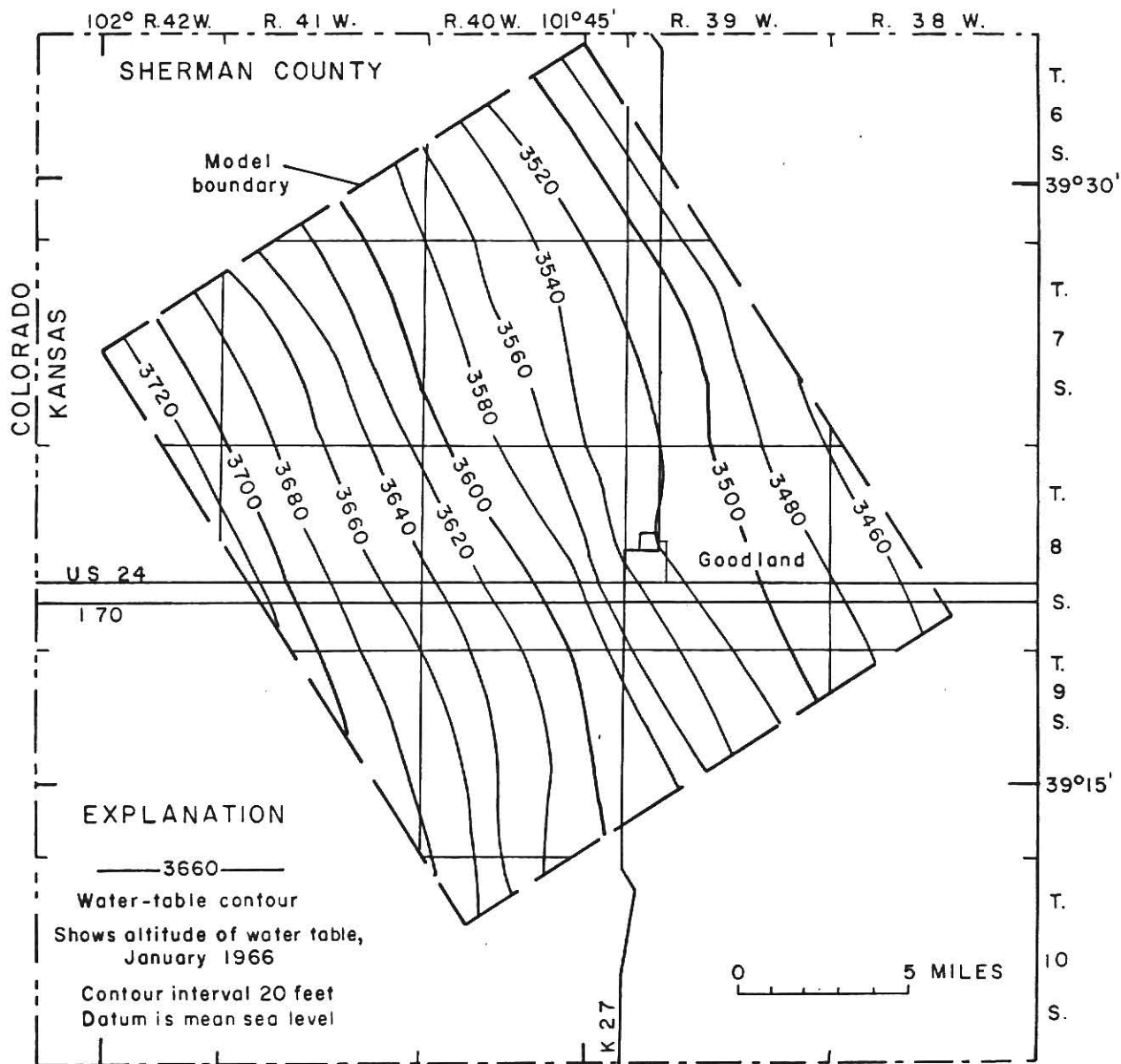


Fig. 3 Configuration of the water table, January 1966.

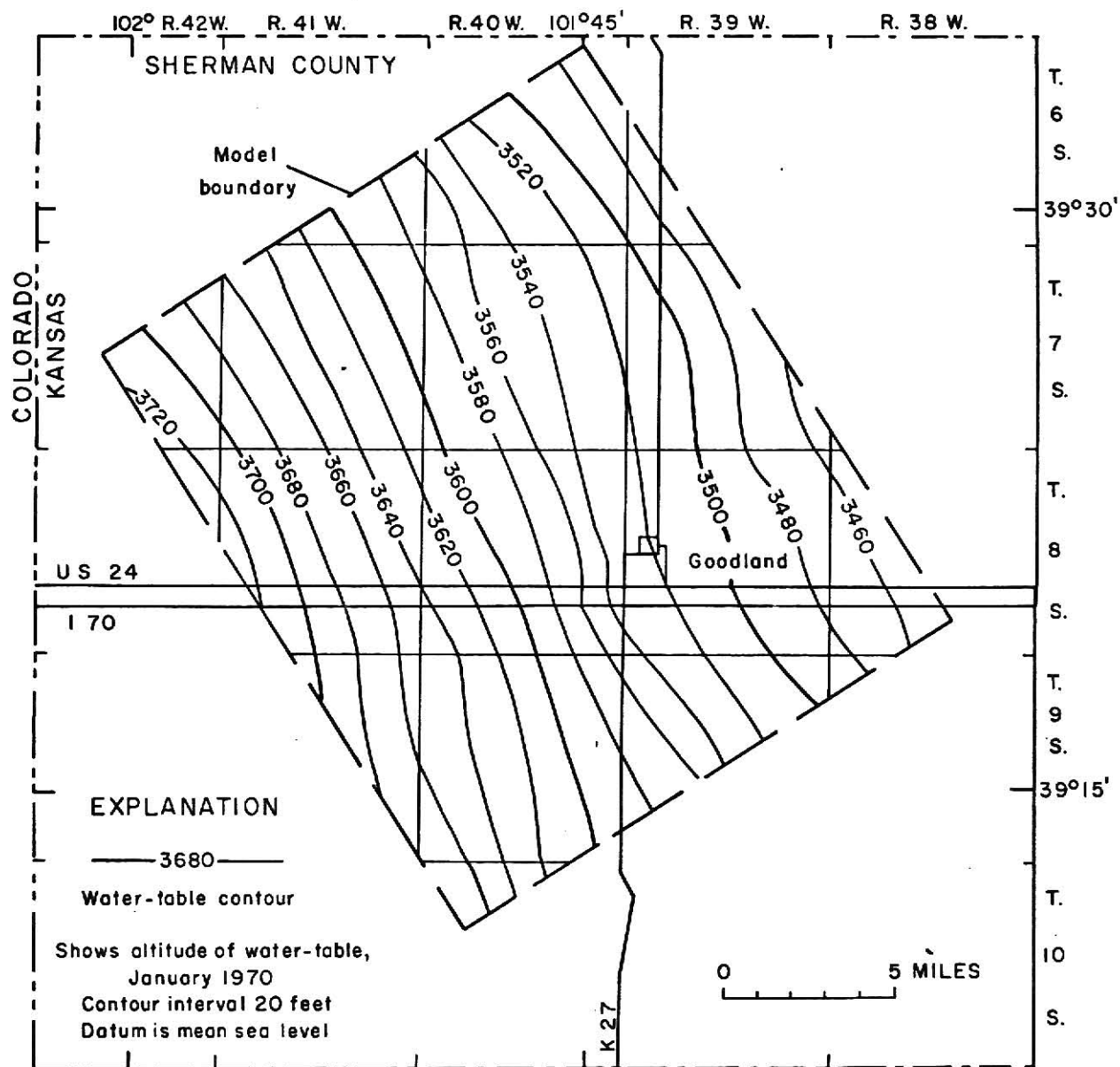


Fig. 4 Configuration of the water table, January 1970.

Table 1.--Natural gas pressure factors.

Line pressure (psi)	Pg	Line pressure (psi)	Pg
1	1.0573	9	1.6690
2	1.1338	10	1.7454
3	1.3103	11	1.8219
4	1.2867	12	1.8993
5	1.3631	13	1.9748
6	1.4396	14	2.0512
7	1.5160	15	2.1277
8	1.5925	16	2.2041

The pressure factor (Pg) is a function of atmospheric pressure, altitude above mean sea level, and line pressure. The factors in Table 1 are furnished by the Plateau Natural Gas Co. for use in the vicinity of Goodland, Kans. The Kansas-Nebraska Natural Gas Co., Inc., which serves only the southeastern part of the area, uses slightly different Pg factors (not shown) because of a difference in altitude of the area served.

Electrical input required to pump an acre-foot of water in the area was determined by applying the equation:

$$K_e = \frac{325,851 \times R \text{ Kh } 3.6}{60 Q t_e} = \frac{1.955 \times 10^4 R \text{ Kh}}{Q t_e} \quad (2)$$

where K_e = kilowatt-hours to pump 1 acre-foot of water;

R = revolutions of meter disc in t_e seconds;

Kh = constant for each meter (generally stamped on the

nameplate of the instrument) giving the number of watt-hours represented by one revolution of the meter disc;

Q = pump discharge, in gallons per minute;

t_e = time, in seconds, for the meter disc to make R revolutions.

The quantity of water pumped from irrigation wells, for which power-consumption and pump-discharge data were available, was computed from the equation:

$$A = \frac{K_v}{K_g} = \frac{K_{whr}}{K_e} \quad (3)$$

in which

A = water pumped from each well during the year, in acre-feet;

K_v = cubic feet of natural gas consumed during the year;

K_{whr} = kilowatt-hours consumed during the year.

Average K_g or K_e values were used in computing the discharges for wells, in areas of similar lift and type of irrigation, that had not been sampled. Power consumption varies with differences in pump and well efficiency, discharge pressure, and depth to water level. Values of K_g for the area range from 4,800 to 12,500 cubic feet per acre-foot but average 7,600. Values for K_e range from 326 to 349 kilowatt-hours per acre-foot but average 340.

The amount of ground water pumped annually by wells was determined from several sources. Records of pumpage for

municipal use were obtained from the city of Goodland; for industrial use, from the Great Western Sugar Co.; and for irrigation use, from Plateau Natural Gas Co. and Kansas-Nebraska Natural Gas Co. Total pumpage has increased considerably in the past few years (Table 2). The difference in pumpage between 1968 and 1969 resulted from a year of below-normal precipitation in 1968 (13.70 inches) and a year of above-normal precipitation in 1969 (18.67 inches). Compared to 1968, more wells existed in 1969 but they pumped less water.

Table 2.--Pumpage from large-capacity industrial, irrigation, and municipal wells.

Year	Ground-water pumpage, in acre-feet
1966	26,000
1967	38,000
1968	59,000
1969	54,000

Aquifer tests were made at selected well sites to determine the hydraulic coefficients of the aquifer. Hydraulic conductivities¹ determined for various zones in the aquifer

¹Hydraulic conductivity is the rate at which an isotropic porous medium will transmit a unit volume of homogeneous fluid in unit time at the prevailing kinematic viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head over unit length of flow path (Lohman and others, 1970, p. 9).

from the samples collected during test drilling also were applied to approximate the transmissivity² for the area as described by R. H. Pearl (written commun., 1970). Using multiple regression, Pearl found a correlation between average hydraulic conductivity and the amount of fine and very fine gravel (2-8 millimeters) present in the Ogallala Formation. Therefore, by determining the particle-size distribution of sets of samples, transmissivities can be assigned. Transmissivities, shown by lines on Fig. 5, ranged from 40,000 to 130,000 gallons per day per foot.

Storage coefficients³ from field tests ranged from 0.01 for tests of a day or two to 0.12 for longer tests. A coefficient of 0.15 was used in the digital model because complete drainage of sediments above the cone of depression⁴ probably did not occur during most field tests. Model trial runs were made using storage coefficients of 0.10 and 0.20; a coefficient of 0.15 gave results that matched most closely the measured levels. The volume of water pumped for the period 1966 through 1969 was 177,000 acre-feet, whereas the volume

²Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman and others, 1970, p. 41).

³Storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Lohman and others, 1970, p. 38).

⁴Cone of depression is the depression produced in a potentiometric surface by pumping.

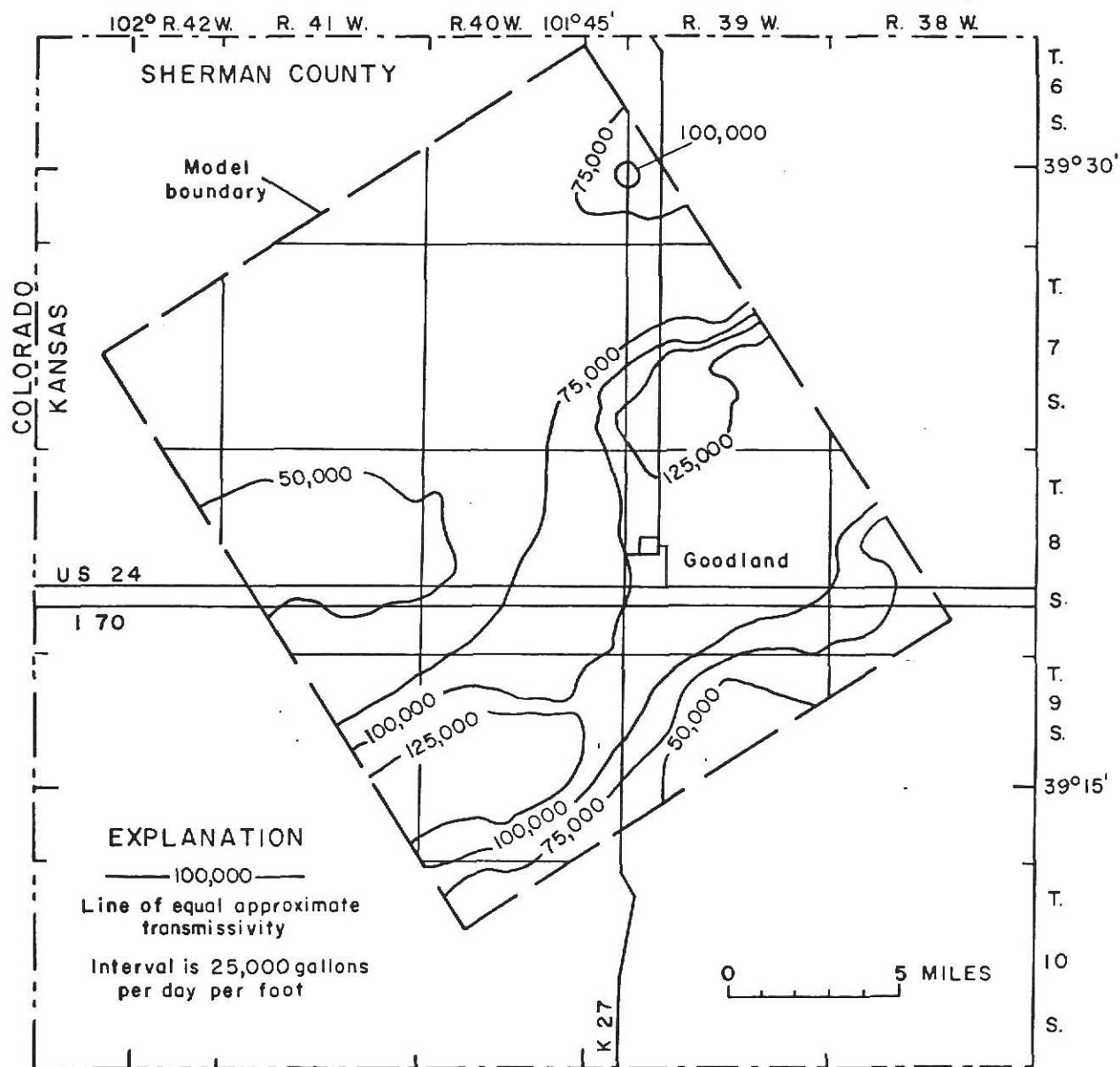


Fig. 5 Transmissivity in 1966.

of sediments dewatered was about 1,130,000 acre-feet. The volume of water pumped, including return flow from irrigation, was about 16 percent of the volume of dewatered sediments, hence the apparent storage coefficient (specific yield) could be as much as 0.16.

The thickness of the saturated zone in 1966, as determined from test-hole and well logs, is shown on Fig. 6.

The water-level change for the period January 1966 to January 1970 (Fig. 7) was prepared by superimposing the water-table contour maps (Figs. 3 and 4) and connecting points of equal change in water level.

DIGITAL MODEL

The theoretical model used in this study was originally developed by Douglas, Peaceman, and Rachford (1960). A digital computer model based on the theoretical model was developed by Pinder and Bredehoeft (1968) and modified by Dabiri, Green, and Winslow (1970).

The model used a numerical form of the following differential equation to simulate nonsteady two-dimensional flow in a nonhomogeneous aquifer:

$$\frac{\partial}{\partial x} [T_x(x,y) \frac{\partial h}{\partial x}] + \frac{\partial}{\partial y} [T_y(x,y) \frac{\partial h}{\partial y}] = S(x,y) \frac{\partial h}{\partial t} + W(x,y,t)$$

where h is hydraulic head (L) (ft);

t is time (T) (hr);

x,y are space coordinates (L) (ft);

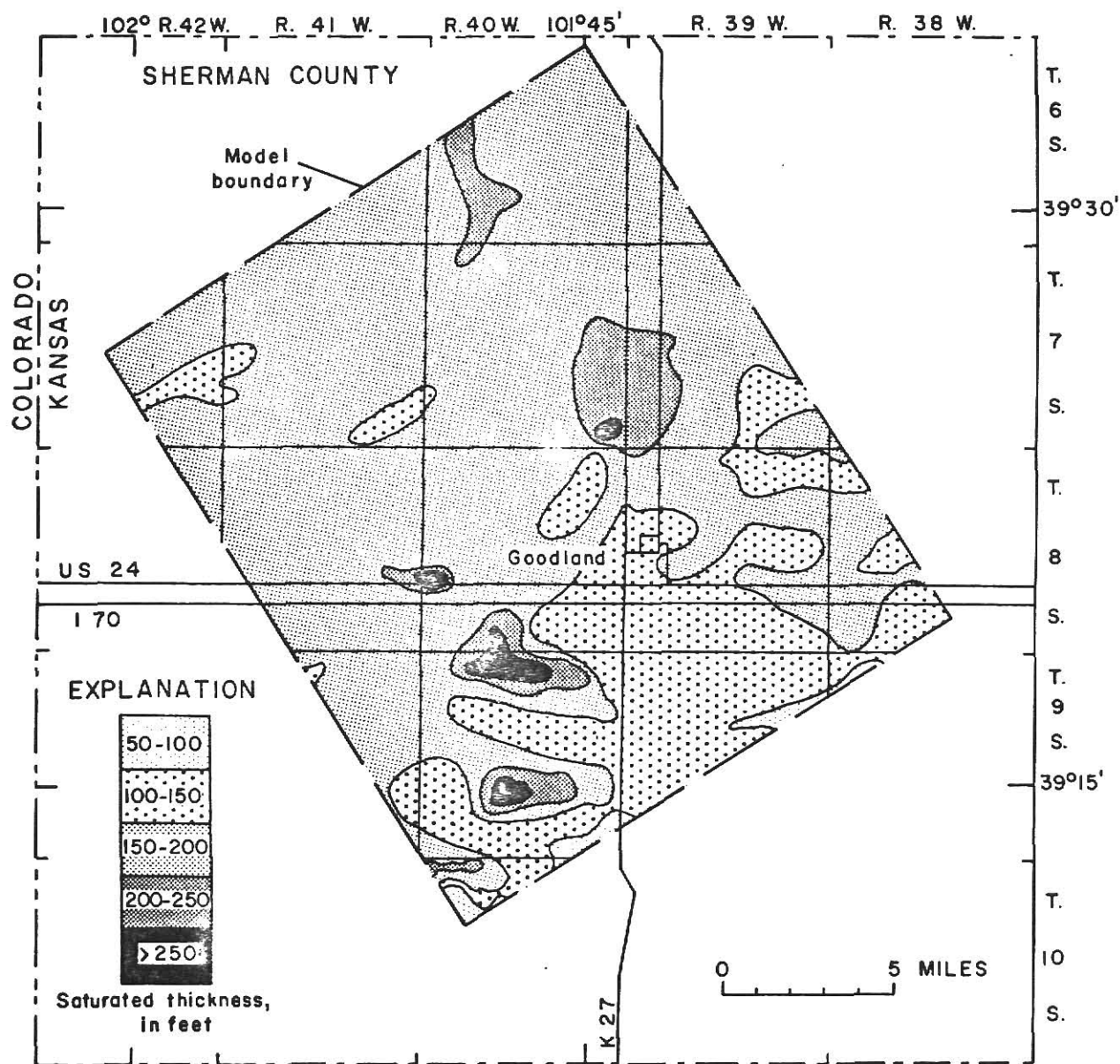


Fig. 6 Saturated thickness in 1966.

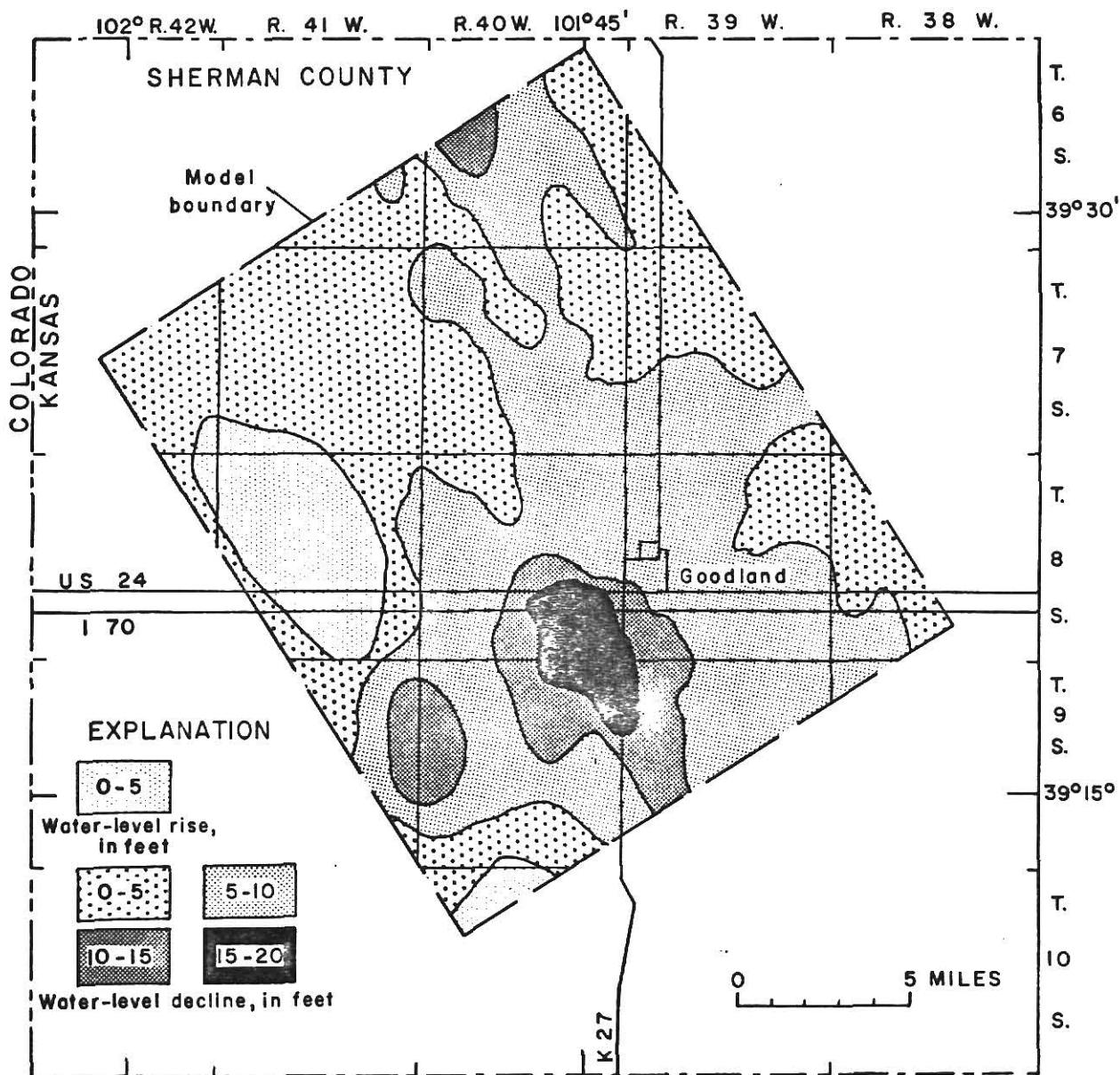


Fig. 7 Changes in water level, January 1966 to January 1970.

$T(x,y)$ is transmissivity (L^2/T) (ft^2 per hr);

$S(x,y)$ is storage coefficient (dimensionless); and

$W(x,y,t)$ is a source/sink term, volume flux per unit area (L/T) (ft per hr).

The source/sink term, $W(x,y,t)$, may be used to represent pumpage, recharge from precipitation, and flow between the aquifer and streams or lakes.

The differential equation applies to a confined aquifer; however, a correction for change in transmissivity due to variation in the saturated thickness was inserted in the computer program. Thus, the resulting solution of the equation, though not exact, is assumed to approximate closely the solution of the equation for an unconfined aquifer.

A grid normal and parallel to the general direction of ground-water flow in the area, to simplify the model by having flow across only two boundaries, was superimposed on the plan view of the study area. The node spacing represented a distance of 1 mile. Data from those well locations that did not coincide with the node locations of the grid were transferred to the nearest node. In a number of instances, the discharge values for several wells were transferred to the same node. Values for inflow and outflow across the boundaries of the model are the product of transmissivity, gradient of the water table, and length of boundary. Inflow and outflow were maintained constant for the simulations.

Input data

Data for each node location were transferred from the maps showing location of wells (Fig. 2), initial water-table altitude or head (Fig. 3), transmissivity (Fig. 5), and initial saturated thickness (Fig. 6) to punch cards for use with the model. Data representing storage coefficient, actual pumpage per year (1966 through 1969), and assumed pumpage per year (1970 through 1989) also were punched on cards. Other data required were total length of simulation period, nodal dimensions of the area, initial time step, and recharge. Total length of the period simulated was 24 years; nodal dimensions of columns and rows were 18 by 21, respectively, that represent the 17- by 20-mile area; and the initial time step was 500 seconds. A value for recharge of 3 percent of actual annual precipitation (1966 through 1969) and 3 percent of normal annual precipitation (1970 through 1989), about 1/2 inch, was uniformly distributed in the model to simulate recharge from precipitation and excess irrigation (Cardwell and Jenkins, 1963; White and others, 1946; Reddell, 1967). Rates of pumpage were converted from acre-feet per year to gallons per year for use in the model.

Output data

Computed drawdowns for each of the 378 nodes on the grid pattern are printed in columns and rows for each of the

24 years of simulation. Also tabulated are time period, net boundary effect, and cumulative recharge. Actual and assumed pumpage is compared with pumpage as computed from the volume of the cone of depression and the difference is shown as a percentage.

RESULTS

Field data were entered in the model and then were adjusted to approximate the measured changes in water level from January 1966 to January 1970. Measured and computed changes in water levels show general agreement. Measured water levels from January 1966 to January 1970 (Fig. 7) ranged from a 5-foot rise to a 20-foot decline but averaged a 5.2-foot decline; computed changes in water level (Fig. 8) ranged from a 5-foot rise to an 18-foot decline. The average change for all 378 nodes was a 5.5-foot decline.

A computer run was made to simulate the effects of continued development by increasing the pumpage at 5-year intervals for 1970 through 1989 as given in Table 3(a). The pumpage from Table 2 was used for 1966 through 1969. An increase of 27,000 acre-feet was distributed over the entire area in 1975, 1980, and 1985, as given in Table 3(a). By 1985, the well density is assumed to be about two wells per square mile, each with an annual discharge of about 200 acre-feet; therefore, the total annual pumpage would be about 135,000 acre-feet. The results of the simulation are shown on the

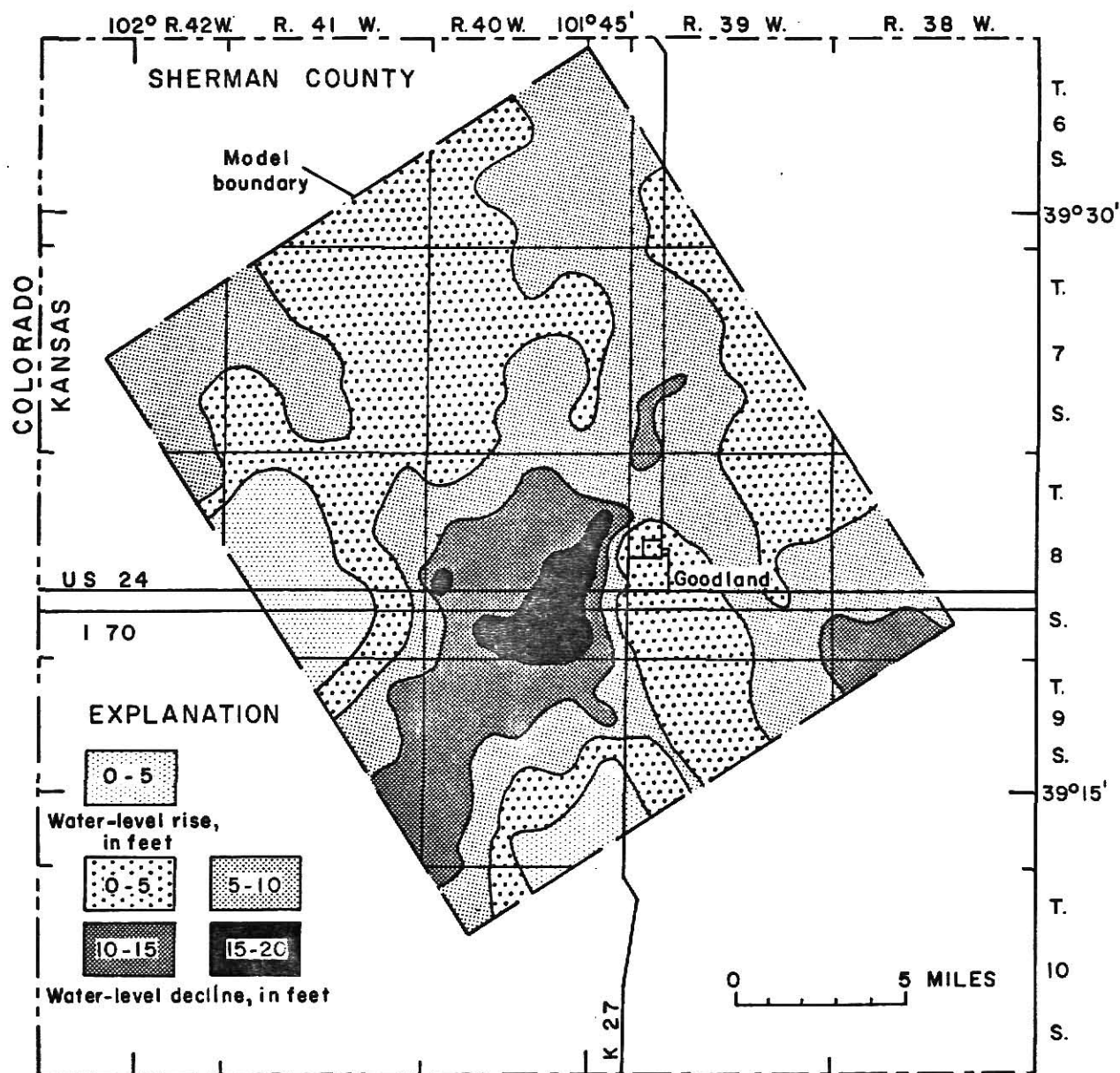


Fig. 8 Computed changes in water level, January 1966 to January 1970.

15-year (1966 through 1980) decline map (Fig. 9) and the 24-year (1966 through 1989) decline map (Fig. 10). Computations indicate that declines of about 48 feet by 1981 and 88 feet by 1990 may be expected in some local areas. The average declines by 1981 and 1990, as computed for all nodes, are 31 feet and 66 feet, respectively. The average saturated thickness for the model area was 165 feet in 1966. Digital model computations indicate that the aquifer could be depleted by 19 percent in 15 years and by 40 percent in 24 years. Therefore, where the saturated thickness is small, as in the area south and east of Goodland, the drop in water levels would be more rapid than in areas where the saturation is large.

Table 3.--Assumed pumpage from large-capacity wells, 1970 through 1989. (a) with continued development, (b) with no increase in development.

	Years	Ground-water pumpage, in acre-feet per year
(a)	1970 through 1974	54,000
	1975 through 1979	81,000
	1980 through 1984	108,000
	1985 through 1989	135,000
(b)	1970 through 1989	59,000

Another computer run was made to simulate the effects of present (1966 through 1969) pumpage with no increase in development or annual pumpage from 1970 through 1989. The

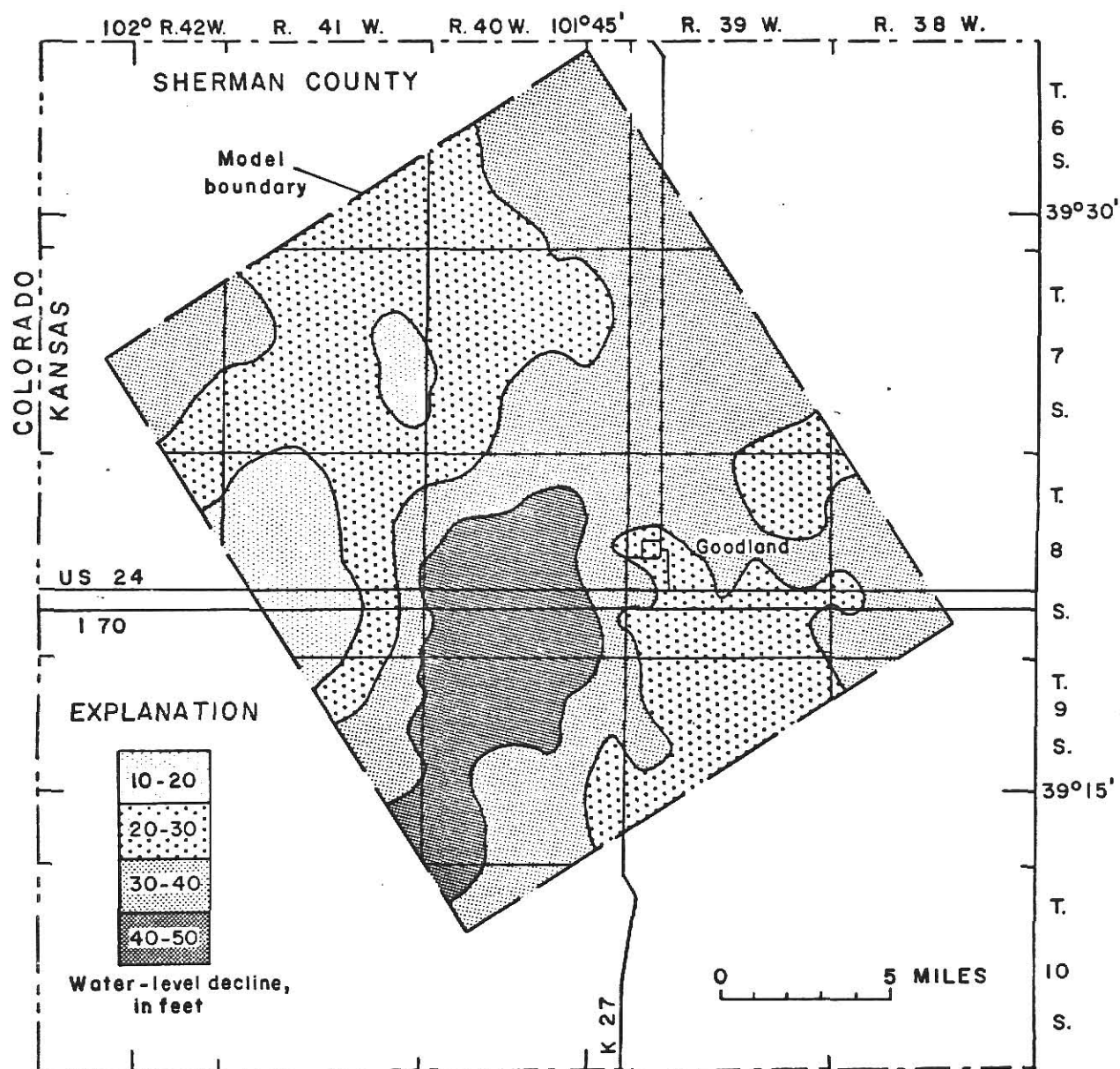


Fig. 9 Computed changes in water level, January 1966 to January 1981, assuming an increase in pumpage from 54,000 acre-feet in 1970 to 108,000 acre-feet in 1980.

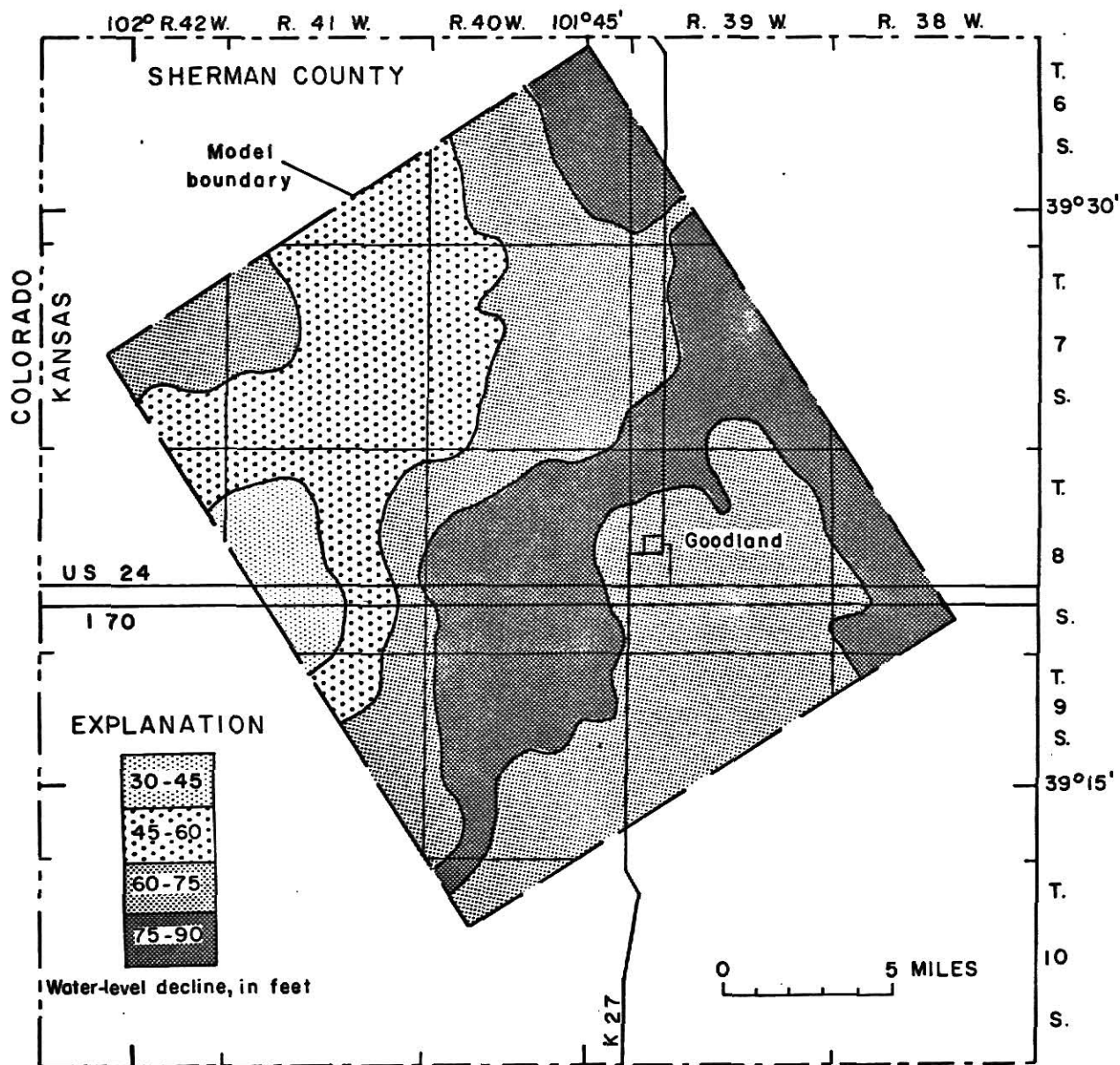


Fig 10 Computed changes in water level, January 1966 to January 1990, assuming an increase in pumpage from 54,000 acre-feet in 1970 to 135,000 acre-feet in 1989.

pumpage, as given in Table 2, was used for 1966 through 1969 but the annual pumpage was maintained constant at 59,000 acre-feet for 1970 through 1989, as given in Table 3(b). The 1968 pumpage of 59,000 acre-feet was used because it occurred in a year of less than normal precipitation and is more representative of present pumpage than the pumpage during 1969. The average decline by 1990, as computed for all nodes, is 43 feet. Computations indicate that the aquifer could be depleted by 26 percent in the 24-year period, 1966 through 1989.

The average volume of aquifer dewatered was determined and then was compared with the decline computed by the model for continued development. The volume of dewatered aquifer, after discharging 2,070,000 acre-feet of water (1966 through 1989), would be about 12,940,000 acre-feet using the apparent storage coefficient (specific yield) of 0.16 that was manually computed from Fig. 7. The average decline for the 340-square-mile area, therefore, would be 59 feet ($12,940,000 \text{ acre-feet} \div 217,600 \text{ acres}$) as compared with the digital model computation of 66 feet. The fact that the model predicted a larger drawdown than that calculated manually also is indicated by the output data. The quantity of water pumped, as input to the model, was 20 percent less than that calculated from the cone of depression. Assuming that the drawdown or cone of depression developed by the model is larger than it should be, perhaps a storage coefficient of 0.16 or 0.17 should be used instead of

0.15. The storage coefficient appears to increase slowly with time as water drains from fine-grained sediments above the cone of depression.

The maps showing water-level changes give an indication as to what may be expected, provided the assumptions of pumping rates, distribution of pumping, and aquifer characteristics are correct. Different patterns of well development will change the amounts and areas of decline. In this model, values for different parameters were adjusted individually for each node so that the computed water-level-change maps agreed with observed data. Other combinations of the data may provide similar results; therefore, no conclusions can be reached regarding the uniqueness of the final results.

SUMMARY AND CONCLUSIONS

A complete network of observation wells with records of past water levels provides a sound base for the model. In this study, all irrigation wells were inventoried; however, in future studies of this kind, an inventory of selected wells probably would provide the information necessary to run the model.

Discharge measurements and fuel usage tests were made on selected wells to determine an average fuel usage for wells in the area. The method of determining annual discharge from irrigation wells by total fuel usage worked well in this area, principally because all but a very few of the power units were

industrial engines that used natural gas fuel. Accurate records of fuel use supplied by power companies were the major factor in determining the amount of water pumped.

Comparisons between observed and model-computed data showed general agreement. The model simulation indicates that present pumping conditions in the study area could reduce the volume of ground water in storage by about 26 percent by the year 1990. With assumed continued development, water in storage could be reduced by 19 percent by 1981 and by about 40 percent by the year 1990. Decline in water levels could be expected to average 66 feet by 1990. The greatest decline (about 88 feet) would be in an area about 5 miles west of Goodland and the least decline (about 35 feet) would be near the intersection of Highway I-70 and the west edge of the model boundary.

The maps showing water-level changes give an indication as to what may be expected, provided the assumptions of distribution and rate of pumping are correct. Different patterns and densities of well development may change the areas and amounts of decline.

The results of this model were achieved by adjusting the values for individual parameters. As other combinations of the data may give a similar solution, no conclusions can be reached regarding the uniqueness of the results. A continuation of data collection would aid in making refinements in the model.

The digital model can be used by the hydrologist and those interested in the management of our water resources as an aid in checking aquifer constants, and in making predictions under assumed conditions to provide a basis for administration of ground water.

ACKNOWLEDGMENTS

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An area of 340 square miles was selected for developing a digital computer model of the Ogallala aquifer. The digital model was adapted to simulate inflow, outflow, water levels, recharge, transmissivities, storage coefficients, saturated thickness, and discharge.

The model was tested and found to be compatible with actual field conditions during the period 1966 through 1969. It was then programmed to define the effects on water levels of future development (1970 through 1989). With the continued ground-water development and annual pumpage assumed, digital model computations indicate a depletion of the aquifer in the area studied by 19 percent by 1981 and 40 percent by 1990. With no increase in development or annual pumpage from 1970 through 1989, model computations indicate that the aquifer could be depleted by 26 percent. A storage coefficient of 0.15 was used in this study but computations indicate that a slightly larger storage coefficient of 0.16 or 0.17 could have been used.