INTRODUCTION

The northern High Plains of Colorado extend from the Colorado State line in the east to the edge of the Ogallala Formation in the north, south, and west, an area of about 9,500 mi² (index map showing location of study area). The Ogallala Formation, of late Tertiary age, is composed of unconsolidated or partly consolidated sand, gravel, clay, silt, and caliche.

The Ogallala aquifer consists of the Ogallala Formation and overlying Quaternary sediments and is the major source of irrigation, industrial, municipal, and domestic water for much of the northern High Plains. The aquifer will not be able to supply as much water in the future as it did in the past because of declining water levels. To examine the extent of this problem, this study developed a detailed digital model of the hydrologic system to simulate the effects of water-management practices on well yields.

Much of the information needed for the model development already existed; calculations of quantities of natural recharge and discharge are developed in this paper. Maps comparing model-simulated and measured water-table configurations are presented to enable users to evaluate the accuracy of the model. In order to translate model predictions into practical terms, results are presented in the form of maps showing the yields that might be expected in the future from an average well completed in the Ogallala aquifer.

HYDROLOGIC SYSTEM

Before ground water was withdrawn for irrigation and other uses in the northern High Plains, the hydrologic system in the Ogallala aquifer was in balance. The volume of water leaving the ground-water system was the same as the volume provided by recharge; therefore, the quantity of water in storage remained unchanged. Recharge was provided by precipitation, which averages from 14 to 18 in. per year. Most ground water discharging from the aquifer left as underflow eastward across the State line into Nebraska and Kansas. The north and south edges of the aquifer in the study area are overlain by sand dunes and the alluvium of the South Platte and the Arkansas Rivers. A small quantity of ground water discharged to this material. A quantity of water also was discharged to three streams—the North Fork and South Fork Republican River and the Arikaree River. The quantity of water lost to evapotranspiration probably was not significant because the water table was far below the land surface in most areas.

At present (1983), however, water is being withdrawn from the aquifer for irrigation and other uses. As a result, water levels are declining in much of the area.

RECHARGE

Before ground-water development occurred, the volume of water leaving the Ogallala aquifer through underflow and streamflow was balanced by the volume of water entering as recharge provided by infiltration of precipitation. For the purposes of estimating recharge, the study area was first divided into two subareas—one subarea of about 8,200 mi² covered by relatively impermeable loess, and a second subarea of about 1,300 mi², mostly in northern Yuma and southern Phillips Counties, covered by more permeable sandy soils. Because the predevelopment recharge could not be easily estimated for the entire area, two test areas were selected for which the hydraulic properties and gradients were known. The net outflow from these areas was calculated and assumed to be equal to the net recharge. The estimated recharge was about 0.4 in. of water per year through the loess, and about 1.7 in. per year through the sandy soils. If these estimates were applied to the entire 8,200 mi² of loess and 1,300 mi² of sandy soils in the northern High Plains, a total of about 400 ft³/s of recharge from precipitation would be estimated for the entire study area. This recharge value is somewhat larger than the estimated total discharge of 340 ft³/s discussed in the following section, so the estimated recharge was decreased by 15 percent to balance the two values. The resulting average recharge for the entire study area was estimated to be 0.48 in. per year. Estimates of recharge by other investigators range from less than 0.5 in. per year in eastern Kit Carson County and nearly 0.75 in. per year in Yuma County (Luckey and Hofstra, 1973) to 0.85 in. per year average over the entire study area (Boettcher, 1966).

The calibrated model indicated recharge rates that were lower than the initial estimates calculated from areal discharge discussed previously; 0.93 in. per year in the areas of sandy soils and 0.18 in. per year in the loess-covered areas, as well as a zone of intermediate recharge rates (0.24 to 0.48 in. per year) across much of the southern and western parts of the study area. This zone of intermediate recharge does not correlate with any particular soil type. However, it is hypothesized that a long period of dryland farming in his area may have increased infiltration rates (Ogilbee and Osborne, 1962). The recharge zones are delineated on the map which also indicates the unsaturated areas, nodes for which streamflow was calculated, and the finite-difference grid.

DISCHARGE

Underflow

To estimate ground-water flow east across the State line (underflow), the average saturated thickness, hydraulic gradient, and hydraulic conductivity of the aquifer were evaluated along the eastern boundary at sections approximately 2.5 mi wide. The resulting flow leaving each section was calculated according to Darcy's law (Lohman, 1972):

$$Q = \frac{KAI}{86{,}400},$$

where:

Q = discharge through section, in cubic feet per second;
K = hydraulic conductivity, in feet per day;
A = cross-sectional area, in square feet; and
I = hydraulic gradient, change in hydraulic head per unit length of flow path (dimensionless).

Flows leaving each section were summed for the length of the entire eastern boundary. Total underflow was estimated by this method to be 190 ft³/s, which is the value of underflow used in the model. Although this number is considerably less than an earlier published value of 540 ft³/s (Boettcher, 1966; McGovern and Coffin, 1963), the current study was based on additional data, which gave a lower value for hydraulic conductivity than that assumed by previous investigators.

Streamflow

Baseflow in streams under predevelopment conditions (before a significant quantity of water was pumped from the aquifer) was estimated from streamflow records for water years 1950–54 (U.S. Geological Survey, 1964). Streamflow data from October through January were used to minimize the effects of irrigation diversion and storm runoff. A value of 100 ft³/s was obtained for the combined baseflow of the North Fork and South Fork Republican River and for the Arikaree River, compared with a published baseflow estimate of 55 ft³/s (Boettcher, 1966). Baseflow in these streams was estimated by the calibrated model to be about 150 ft³/s, even higher than the estimate from the streamflow records. The higher estimate of baseflow in the final model probably includes water flowing in the alluvium adjacent to or beneath the stream (which is not included in the previously published values) and is the value used in later calculations. Model nodes for which streamflow was calculated are indicated on the map showing the finite-difference grid. Total predevelopment discharge was estimated to be 340 ft³/s, the sum of 190 ft³/s ground-water underflow and 150 ft³/s of stream baseflow.

MODELING PROCEDURES

Development of a model to simulate the water table in the northern High Plains was a two-step process. The first stage in the study was the development of a steady-state model which represented the aquifer under prepumping conditions. The second stage, referred to as the "transient case," consisted of trying to match the observed changes in the water levels due to pumping. When both of these steps were successfully accomplished, the model was ready to be used for predictive purposes.

Information needed for the model construction and calibration included a predevelopment water-table map (Borman, 1983), a map showing altitude of bedrock surface (Borman and Meredith, 1983), and maps showing the regional distribution of hydraulic conductivity (a measure of the ability of the aquifer material to transmit water) and specific yield (a measure of the quantity of usable water stored in the aquifer) (Borman and others, 1983). Pumpage was estimated for 5-year intervals from predevelopment to 1980 based on crop demand and irrigated acreage (Heimes and Luckey, 1982).

A rectangular grid of model blocks (map showing the finite-difference grid) was superimposed over each of these maps, and the average value of water-table altitude, altitude of bedrock, hydraulic conductivity, specific yield, and irrigation pumpage in each block then was determined. The model blocks ranged in size from 2.5 by 2.5 mi to 2.5 by 5 mi. The smaller blocks were located in areas where there were more irrigation wells and where more detailed information was desired. The process of assigning a single average value for the large area of a model block leads to some inaccuracy, particularly in areas where aquifer properties change rapidly.

Vertical-flow components in the study area are so much smaller than horizontal-flow components that ground-water flow was assumed to be horizontal (two-dimensional). A single average value was assigned to hydrologic properties over the entire thickness of the aquifer because there is no consistent vertical pattern of sediment distribution with depth (Gutentag and others, 1983). The base of the aquifer is almost impermeable (Cardwell and Jenkins, 1963; McGovern and Coffin, 1963), and no flow or leakage was considered to occur. For the steady-state simulation, the ground-water discharge to the east, north, and south was simulated as a line of wells, one per block, each well discharging at a constant rate calculated by Darcy's law as shown in the section on "Underflow." In the transient case, the discharge rate was simulated as varying in proportion to the saturated thickness, as the saturated thickness decreased. The underlying assumption for this treatment is that pumping on both sides of the model boundary is nearly equal. While this may not necessarily continue to be true in the future, in the past, development has occurred approximately equally on both sides of the boundary.

To minimize errors due to the presence of boundaries, particularly the eastern boundary, the aquifer area modeled extended beyond the eastern edge of the study area. However, only results for the northern High Plains of Colorado are discussed in the report. In a few areas, most noticeably along the northern and western edges of the study area, the model does not extend to the boundary of the Ogallala aquifer (map showing finite-difference grid). Data from Borman (1983), Borman and others (1983), and Borman and Meredith (1983) were used to extend model results into these areas for the water-table and potential-yield maps.

The model used was a two-dimensional finite-difference model (Trescott and others, 1976). The method by which iteration parameters for the strongly implicit procedure are calculated was modified slightly, and a subroutine was added to vary underflow along the boundary as a function of saturated thickness. The authors gratefully acknowledge the assistance of R. R. Luckey (U.S. Geological Survey, High Plains Regional Aquifer-System Analysis staff) in the development of this subroutine.

During the steady-state calibration, predicted water-levels were calculated by the model program based on initial estimates of aquifer parameters and stresses. Simulated water levels were compared with water levels measured before development. Where the simulated water levels did not agree with measured water levels, values of aquifer parameters and recharge rates were adjusted within limits based on the reliability of the data, and new modeled water levels were generated. The calibration process was repeated until simulated and measured water levels agreed within 25 ft. Hydraulic conductivity and recharge rate were known least accurately so it was primarily these values that were adjusted. Adjustments to estimated recharge rates were discussed in the "Recharge" section; hydraulic conductivity was varied by as much as 35 percent from the values reported in Borman and others (1983). Estimates of average bedrock-surface altitude were adjusted only slightly. The map of the water-table configuration shows both the resulting simulated water table and the measured water table for comparison.

In eastern Cheyenne County and at the extreme southern edge of the study area in Prowers County, it was impossible to simulate the measured water table with acceptable accuracy (±25 ft) using the available data. This may be due to:

1. Both these areas contain bedrock valleys in which the saturated thickness changes greatly in a short distance. Because of the size of the model blocks in those areas, the model lacks sufficient detail to depict these changes accurately.

2. An area of unsaturated material just east of the Cheyenne County-Kit Carson County line in Kansas could not be accurately represented in the model.

Irrigation development became significant beginning in the early 1960's. By 1975, water-level declines caused by pumping had occurred throughout most parts of the study area. The transient-case simulation consisted of trying to predict the 1975 water levels starting with the predevelopment water levels and pumpage for 1950–75, and comparing the simulated water levels with the measured 1975 water levels. Estimated values of specific yield of the aquifer were adjusted until the best possible agreement was achieved between the simulated and measured water-level changes. Best fit was obtained by multiplying the specific-yield values reported in Borman and others (1983) by a factor that varied areally between 75 and 85 percent. This change in the values of specific yield seemed reasonable because most of the data were obtained from irrigation wells, which probably were located in areas with large values of specific yield. Pumpage originally was defined as crop demand times irrigated acreage, as reported in Heimes and Luckey (1982). The simulated water levels matched the measured water levels best when pumpage was increased by 10 percent. The 10-percent increase may in part account for evaporative losses during application. Excess water applied to the land which probably would infiltrate and eventually recharge the aquifer is ignored in the pumpage estimates. The pumpage value used in the model, therefore, actually represents water withdrawn from the aquifer rather than total volume withdrawn and later partly replaced.

A comparison of the simulated water levels for 1980 with the measured water levels for 1980 appears on the map showing the simulated and measured 1980 water table.

POTENTIAL WELL YIELDS

The three probable well-yield maps show the well yields that might be expected from the Ogallala aquifer by the years 2000 and 2020 under two hypothetical water-management alternatives. The first alternative assumes that the present (1980) pumpage will continue to the year 2020 with no change. The second alternative is based on the assumption of improved efficiency of water application of 3 percent by 1990, 7 percent by 2000, and 12 percent by the year 2020. Pumpage used in the model then was correspondingly decreased. The projections of improved application efficiencies were made by the Colorado High Plains Advisory Committee (1981) as part of a study of the Ogallala aquifer funded by the U.S. Department of Commerce, Economic Development Administration.

Probable well yields were computed by solving the Theis equation with water-table corrections (Jacob, 1963). The hypothetical irrigation well used in the computation was assumed to have a 30-in. effective diameter (irrigation wells typically have a 16-in. screen or perforated casing and are gravel packed to 30-in. diameter) that penetrates and is open to the entire saturated thickness of the aquifer. It was further assumed that each well was pumped for 90 days and was pumped at 65 percent of the yield calculated above (E. D. Gutentag, U.S. Geological Survey, oral commun., 1983). It was further assumed that pumping water levels in the aquifer were drawn down to within 15 ft of the bottom of the aquifer. Drawdowns were calculated on an individual-well basis, but it was found that interference effects in most places were negligible on wells 0.25 mi away. The probable well-yield maps need to be used with caution because there may be areas too small to be mapped which will yield more or less water than that shown on the maps.

Probable well yields for predevelopment conditions and for 1980 were reported by Borman and others (1983). These authors state that well yields of more than 300 gal/min were likely in 45 percent (2.7 million acres) of the study area during 1980, and yields of more than 600 gal/min were likely in 34 percent of the area (2.1 million acres). The model developed in the current study indicates that by the year 2000, about 39 percent (2.4 million acres) of the Ogallala aquifer underlying the northern High Plains will yield more than 300 gal/min, and about 26 percent (1.6 million acres) will yield more than 600 gal/min. The areal distribution of these yields can be seen in the map showing potential well yields by the year 2000. This map was based on pumpage continuing for 20 years at 1980 rates; however, well yields by 2000 under the increased efficiency assumptions stated earlier are not significantly different from those discussed here.

If 1980 pumping rates are maintained, 18 percent (1.1 million acres) of the study area will yield more than 600 gal/min by the year 2020, and 29 percent (1.8 million acres) will have yields of greater than 300 gal/min. These areas can be seen on the map showing potential well yields by 2020 assuming pumpage continues at 1980 rates. Under the assumption of increased application efficiency used to produce the map showing potential well yields by 2020 assuming pumpage will decrease from the rate during 1980, the aquifer under about 20 percent (1.2 million acres) of the study area is likely to be able to produce 600 gal/min or more, and about 32 percent (1.9 million acres) will yield more than 300 gal/min. The difference between the area projected to yield more than 600 gal/min by the year 2020 under assumptions of continued pumpage at 1980 rates and the area projected to yield more than 600 gal/min under the reduced pumpage assumptions is only an increase of 100,000 acres—2 percent of the total study area. This small difference indicates that increased water-application efficiency and the associated decrease in pumpage is not enough to make a significant impact on declining water levels in the northern High Plains. These results are summarized in the following table.

About 500,000 acres that were able to yield 600 gal/min or more to wells during 1980 would yield less than 600 gal/min in the year 2000. An additional 500,000 acres would yield less than 600 gal/min by the year 2020 if pumping continues at 1980 rates. The locations of these areas are shown on the map showing changes in well yields from 1980 to 2000 and 2020.

Percentage and area of northern High Plains yielding more than 300 or more than 600 gallons per minute to wells

Year	Pumping condition	More than 300 gallons per minute: Percentage of study area	More than 300 gallons per minute: Millions of acres	More than 600 gallons per minute: Percentage of study area	More than 600 gallons per minute: Millions of acres
Predevelopment[1]	No pumping	51	3.1	39	2.4
1980[1]	1980 rate	45	2.7	34	2.1
2000	1980 rate	39	2.4	26	1.6
2020	1980 rate	29	1.8	18	1.1
2020	Less than 1980 rate	32	1.9	20	1.2

[1]Data from Borman and others (1983).

Well yields of less than 300 gal/min from individual wells generally are insufficient for irrigation, but multiple-well systems may yield enough to irrigate small fields. Flood irrigation can be done economically with single-well yields of 300 to 600 gal/min, provided that field sizes are compatible with the yields of the wells. Multiple-well systems may be required, however, to operate a quarter-section center-pivot sprinkler (irrigating about 130 acres). Single well yields greater than 600 gal/min are sufficient to operate a quarter-section center-pivot sprinkler.

In all the simulations, the most significant and widespread declines in yield were in eastern Kit Carson County. Water-level declines as much as 100 ft were simulated both there and in northern Yuma-southern Phillips Counties; however, the remaining saturated thickness in northern Yuma-southern Phillips Counties still would be sufficient to yield more than 1,200 gal/min, so the effects of the water-level declines on well yields are not as apparent there as they are in eastern Kit Carson County.

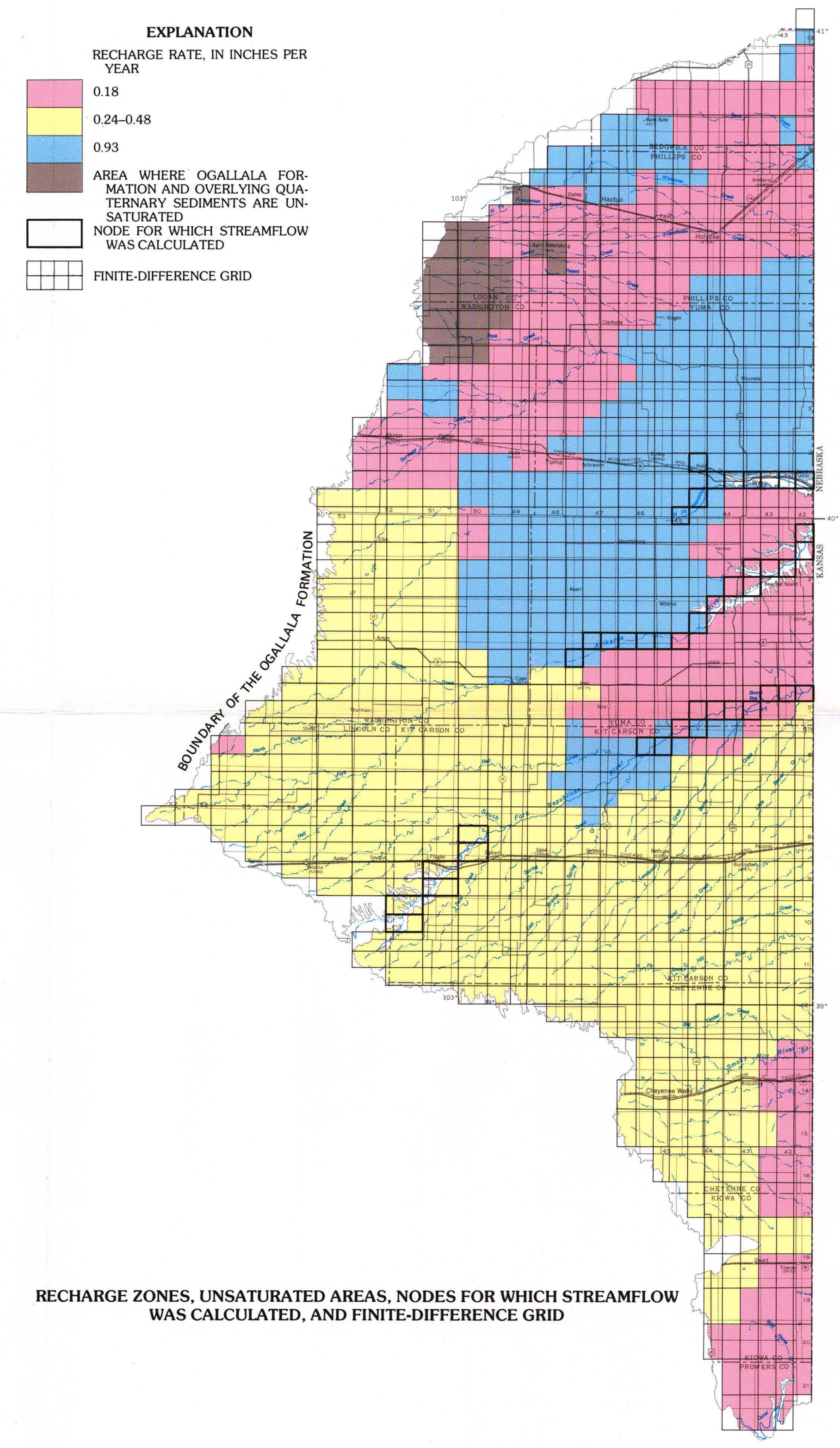
SUMMARY

The ground-water flow model of the Ogallala aquifer successfully simulated the water-table configuration in all parts of the study area except east-central Cheyenne County and Prowers and southern Kiowa Counties. In these areas, steep-sided bedrock valleys with large changes in saturated thickness over short distances may be the reason for the unsatisfactory simulation of the water levels.

The model predicts that in 26 percent (1.6 million acres) of the northern High Plains, the Ogallala aquifer still could yield 600 gal/min to wells by the year 2000 if pumping continues at the same rate as during 1980. However, 500,000 of the 2.1 million acres which yielded more than 600 gal/min during 1980 will yield less than 600 gal/min by the year 2000. (This is the approximate minimum pumping rate required to irrigate 130 acres with a center-pivot sprinkler system.) Simulations using the assumed increased irrigation efficiency and associated decrease in the use of irrigation water made almost no difference in water-level declines by the year 2000. By the year 2020, however, projected increases in irrigation efficiency made a slightly greater difference in water-level and well-yield projections. If pumping continues at 1980 rates, 1.1 million acres will be able to yield 600 gal/min or more to wells by 2020—a decrease of 1 million acres (16 percent of the total study area) from 1980. If irrigation efficiencies increase as projected, leading to a total of 12-percent decrease in pumpage by the year 2020, 1.2 million acres of the northern High Plains will be able to yield 600 gal/min or more to wells. This difference of about 100,000 acres is small when compared to the 1 million acres with decreased well yields in the northern High Plains.

EXPLANATION

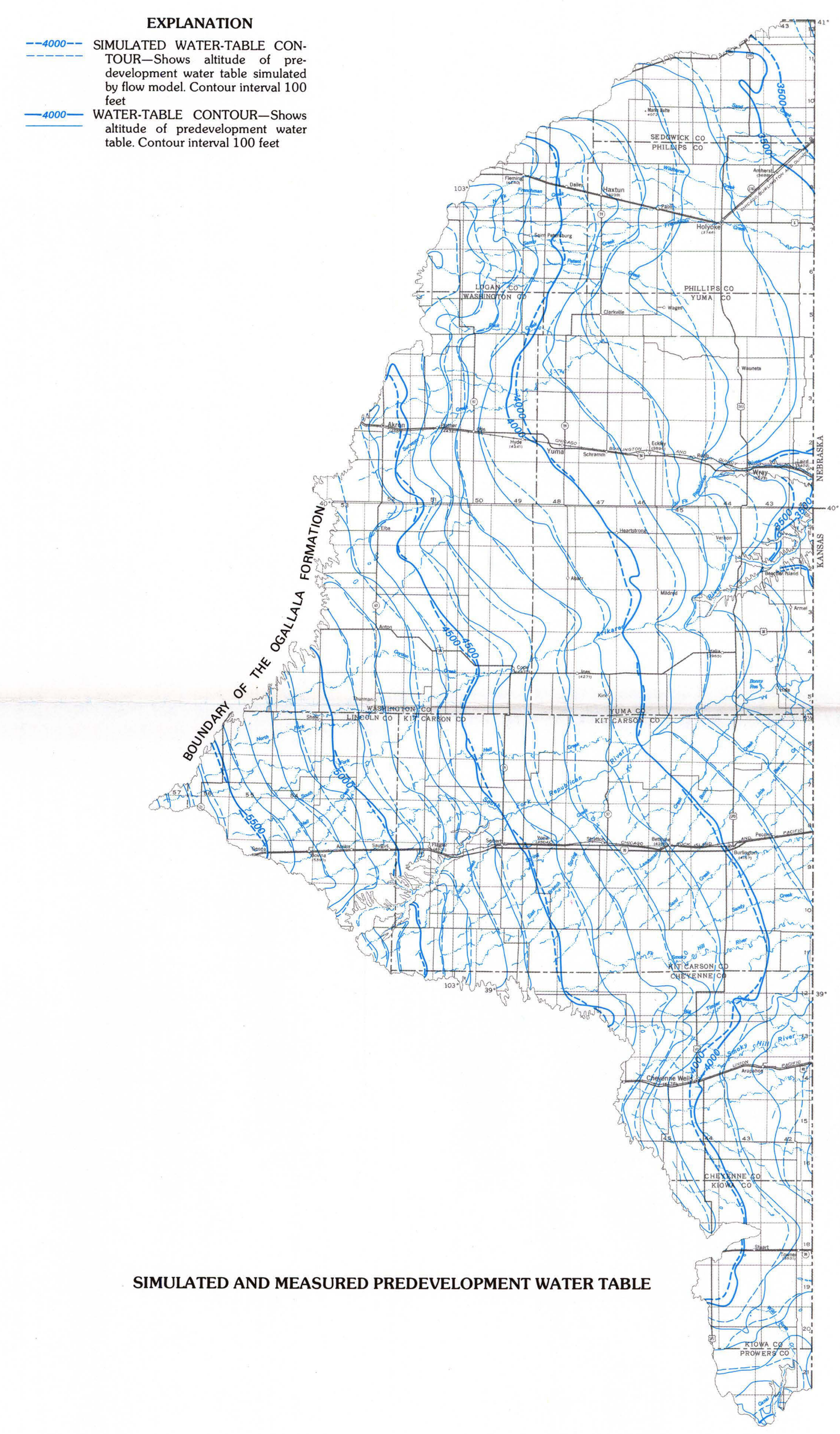
RECHARGE RATE, IN INCHES PER YEAR
- 0.18
- 0.24–0.48
- 0.93
- AREA WHERE OGALLALA FORMATION AND OVERLYING QUATERNARY SEDIMENTS ARE UNSATURATED
- NODE FOR WHICH STREAMFLOW WAS CALCULATED
- FINITE-DIFFERENCE GRID



RECHARGE ZONES, UNSATURATED AREAS, NODES FOR WHICH STREAMFLOW WAS CALCULATED, AND FINITE-DIFFERENCE GRID

EXPLANATION

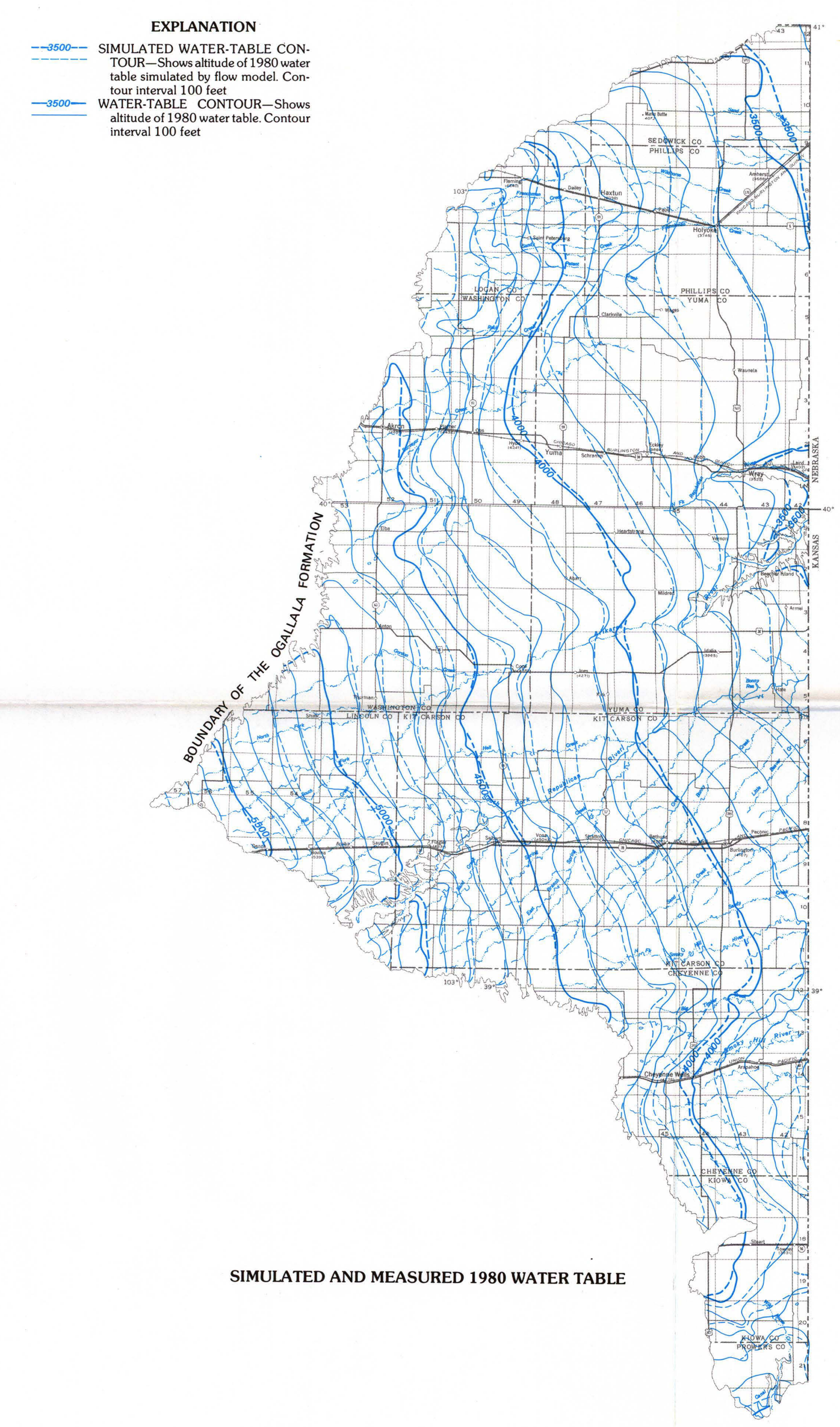
- 4000 SIMULATED WATER-TABLE CONTOUR—Shows altitude of predevelopment water table simulated by flow model. Contour interval 100 feet
- 4000 WATER-TABLE CONTOUR—Shows altitude of predevelopment water table. Contour interval 100 feet



SIMULATED AND MEASURED PREDEVELOPMENT WATER TABLE

EXPLANATION

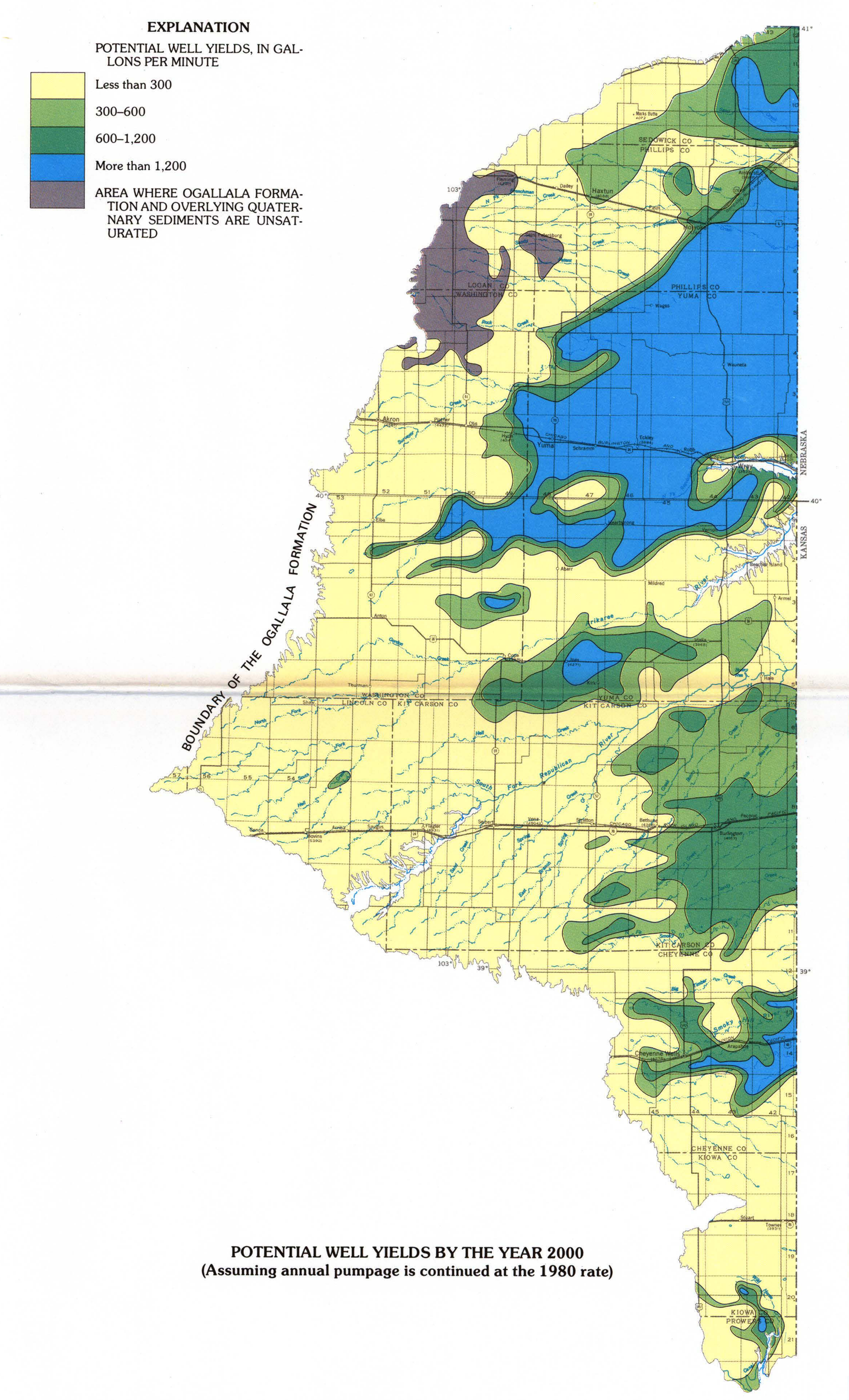
- 3500 SIMULATED WATER-TABLE CONTOUR—Shows altitude of 1980 water table simulated by flow model. Contour interval 100 feet
- 3500 WATER-TABLE CONTOUR—Shows altitude of 1980 water table. Contour interval 100 feet



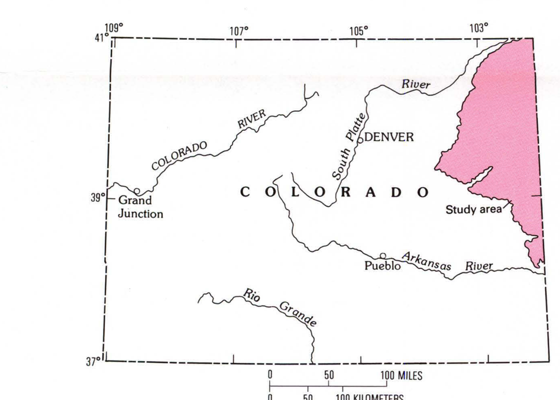
SIMULATED AND MEASURED 1980 WATER TABLE

EXPLANATION

POTENTIAL WELL YIELDS, IN GALLONS PER MINUTE
- Less than 300
- 300–600
- 600–1,200
- More than 1,200
- AREA WHERE OGALLALA FORMATION AND OVERLYING QUATERNARY SEDIMENTS ARE UNSATURATED



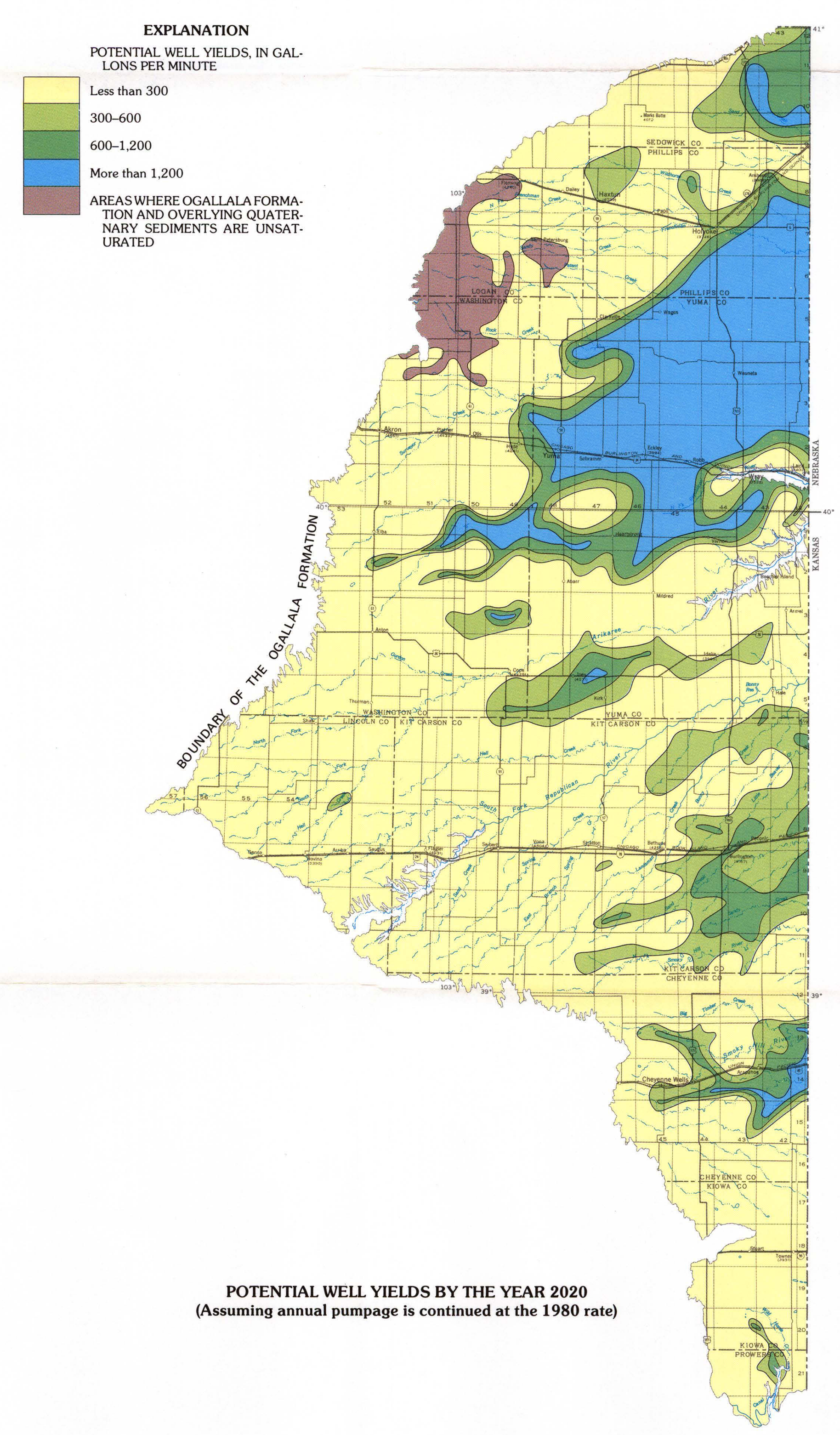
POTENTIAL WELL YIELDS BY THE YEAR 2000
(Assuming annual pumpage is continued at the 1980 rate)



INDEX MAP SHOWING LOCATION OF STUDY AREA

EXPLANATION

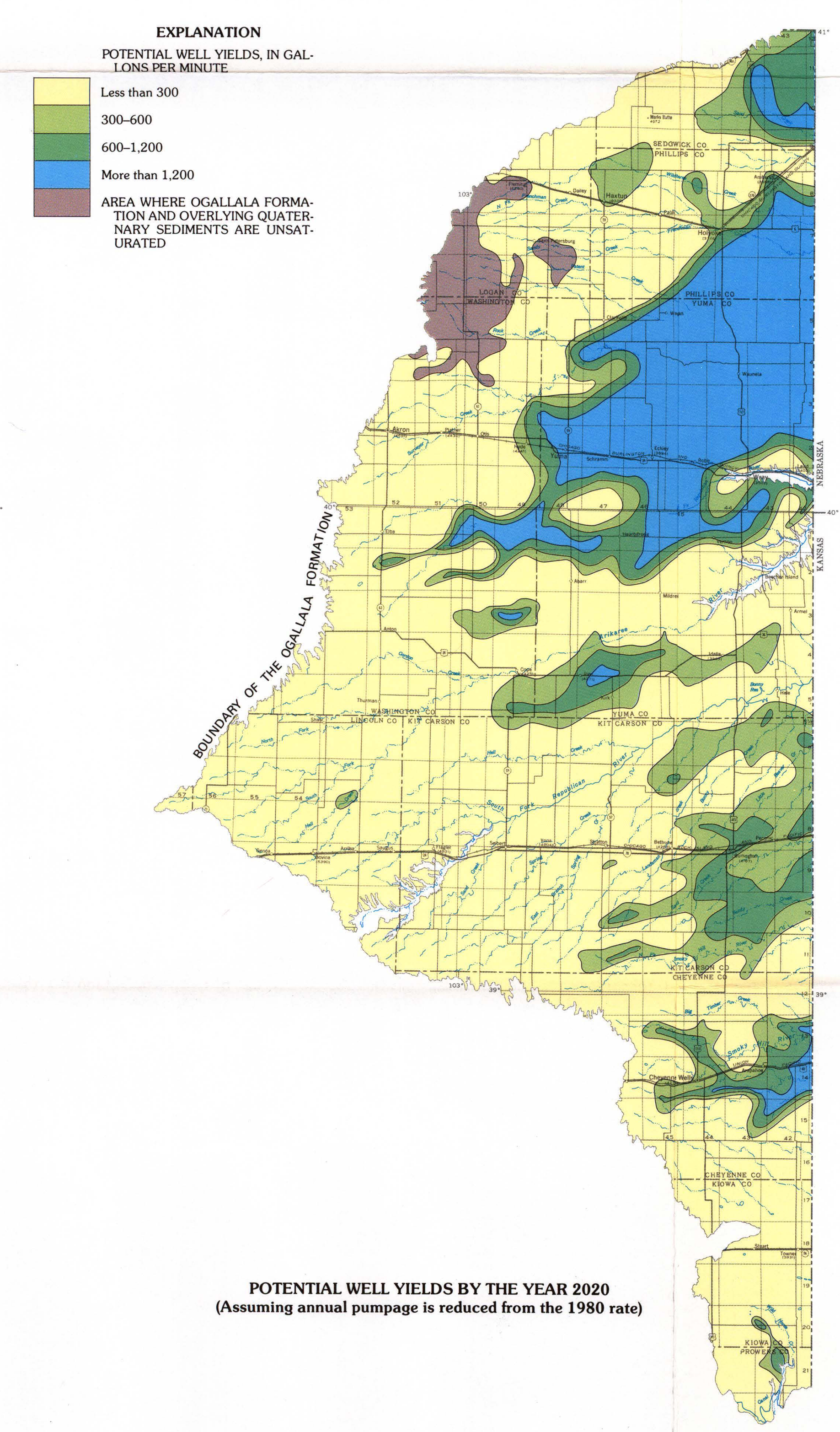
POTENTIAL WELL YIELDS, IN GALLONS PER MINUTE
- Less than 300
- 300–600
- 600–1,200
- More than 1,200
- AREAS WHERE OGALLALA FORMATION AND OVERLYING QUATERNARY SEDIMENTS ARE UNSATURATED



POTENTIAL WELL YIELDS BY THE YEAR 2020
(Assuming annual pumpage is continued at the 1980 rate)

EXPLANATION

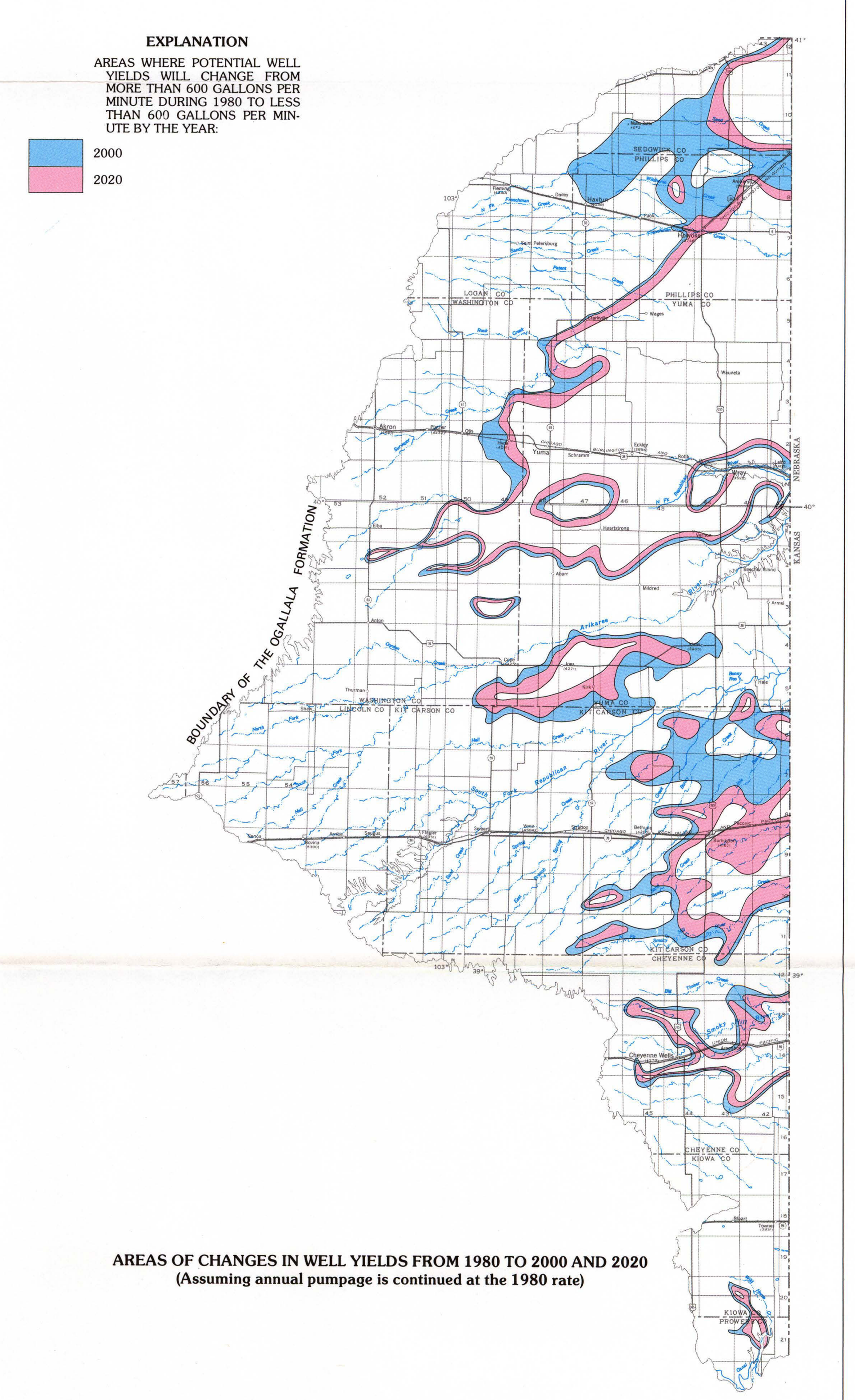
POTENTIAL WELL YIELDS, IN GALLONS PER MINUTE
- Less than 300
- 300–600
- 600–1,200
- More than 1,200
- AREA WHERE OGALLALA FORMATION AND OVERLYING QUATERNARY SEDIMENTS ARE UNSATURATED



POTENTIAL WELL YIELDS BY THE YEAR 2020
(Assuming annual pumpage is reduced from the 1980 rate)

EXPLANATION

AREAS WHERE POTENTIAL WELL YIELDS WILL CHANGE FROM MORE THAN 600 GALLONS PER MINUTE DURING 1980 TO LESS THAN 600 GALLONS PER MINUTE BY THE YEAR
- 2000
- 2020



AREAS OF CHANGES IN WELL YIELDS FROM 1980 TO 2000 AND 2020
(Assuming annual pumpage is continued at the 1980 rate)

CONVERSION FACTORS

Inch-pound units used in this report may be converted to SI (International System) units by the following conversion factors:

Multiply inch-pound unit	By	To obtain SI units
inch (in.)	25.40	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft²)	0.0929	square meter
acre	0.4047	hectare
square mile (mi²)	2.590	square kilometer
foot per day (ft/d)	0.3048	meter per day
gallon per minute (gal/min)	0.0631	liter per second
cubic foot per second (ft³/s)	0.0283	cubic meter per second

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

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Base from U.S. Geological Survey 1:500,000
State base map, 1969

SCALE 1:1 000 000
25 0 25 50 75 100 MILES
25 0 25 50 75 100 KILOMETERS

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POTENTIAL WELL YIELDS FROM THE OGALLALA AQUIFER IN THE NORTHERN HIGH PLAINS OF COLORADO

By
Juli B. Lindner-Lunsford and R. G. Borman
1985

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