COMPARISON OF IRRIGATION PUMPAGE WITH CHANGE IN GROUND-WATER STORAGE IN THE HIGH PLAINS AQUIFER IN CHASE, DUNDY, AND PERKINS COUNTIES, NEBRASKA, 1975-83

By Frederick J. Heimes, Carmelo F. Ferrigno, Edwin D. Gutentag,
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CONVERSION FACTORS AND ABBREVIATIONS

For the benefit of readers who prefer metric (International System) units rather than the inch-pound units used in this report, the following conversion factors may be used:

Multiply inch-pound unit	*By*	*To obtain metric unit*
inch	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot	0.3048	meter
acre	0.4047	hectare
acre-foot	1,233	cubic meter
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year

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ABSTRACT

An evaluation of the relation between pumpage and change in storage was conducted for most of a three-county area in southwestern Nebraska from 1975 through 1983. Initial comparison of the 1975-83 pumpage with change in storage in the study area indicated that the 1,042,300 acre-feet of change in storage was only about 30 percent of the 3,425,000 acre-feet of pumpage.

An evaluation of the data used to calculate pumpage and change in storage indicated that there was a relatively large potential for error in estimates of specific yield. As a result, minimum and maximum values of specific yield were estimated and used to recalculate change in storage. Estimates also were derived for the minimum and maximum amounts of recharge that could occur as a result of cultivation practices.

The minimum and maximum estimates for specific yield and for recharge from cultivation practices were used to compute a range of values for the potential amount of additional recharge that occurred as a result of irrigation. The minimum and maximum amounts of recharge that could be caused by irrigation in the study area were 953,200 acre-feet (28 percent of pumpage) and 2,611,200 acre-feet (76 percent of pumpage), respectively. These values indicate that a substantial percentage of the water pumped from the aquifer is resupplied to storage in the aquifer as a result of a combination of irrigation returnflow and enhanced recharge from precipitation that results from cultivation and irrigation practices.

INTRODUCTION

The U.S. Geological Survey began a study of the High Plains aquifer (fig. 1) in 1978 as part of the Regional Aquifer-System Analysis (RASA) program. The purposes of the High Plains RASA were to provide hydrologic information needed to evaluate the effects of continued ground-water development, and to develop computer models to predict aquifer response to changes in ground-water development. During the study, the volume of ground water pumped (pumpage) and the change in the volume of water stored in the aquifer (change in storage) were determined for the period from predevelopment through 1980 (Heimes and Luckey, 1982, and Gutentag and others, 1984). A comparison of the values determined from predevelopment through 1980 indicated that the estimated change in volume in storage amounted to only about 37 percent of the volume pumped. The large difference between pumpage and change in storage indicated that additional study was required to define the factors affecting the water budget for irrigated areas of the High Plains.

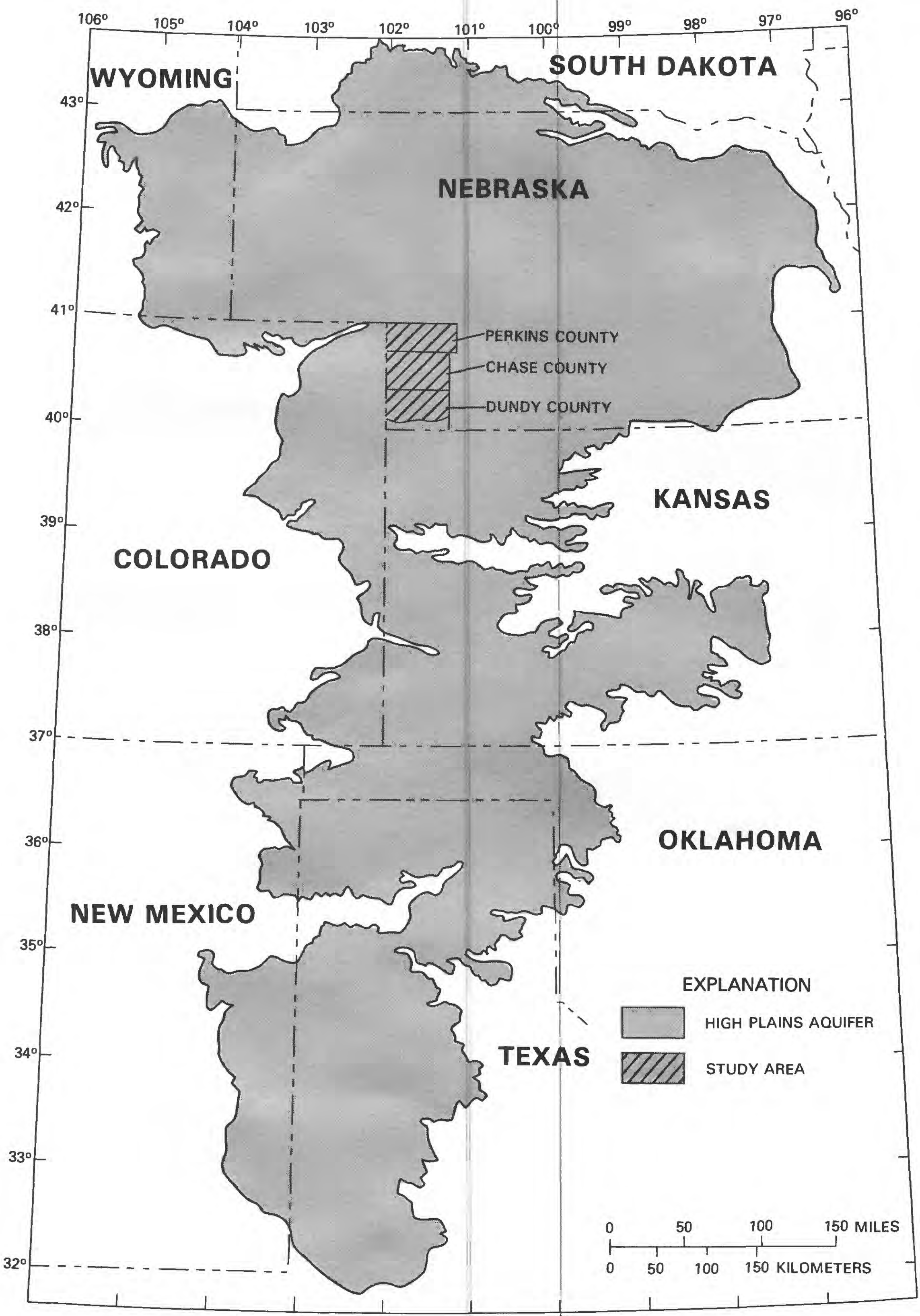

Figure 1.--Location of study area in the High Plains.

A second phase of the High Plains RASA was begun in 1983 to address the need for additional information on the factors affecting the relation between pumpage and change in storage. Two discrete areas were selected for the study, one in Nebraska and one in Texas. The results of the study conducted in Nebraska are the subject of this report. The results from the study in Texas are presented in a separate report (Mackey, 1987).

Purpose and Scope

The purpose of this study was to compare pumpage from the High Plains aquifer with change in storage and analyze the relations between them for a three-county area in southwestern Nebraska (fig. 2). The study is based on detailed information on pumpage and water-level change collected during 1975-83, and on characteristics of the High Plains aquifer. Regional metering of irrigation wells provided data on measured pumpage beginning in 1978. The availability of these data, combined with estimates of irrigated acreage, numerous water-level measurements, and detailed lithologic logs, made this an ideal area for the study.

Description of Study Area

The study area includes Chase and Perkins Counties, and the area north of the Republican River in Dundy County, Nebraska. The area is located in the High Plains section of the Great Plains physiographic province. Most of the study area consists of gently rolling uplands with many small flat areas (Lappala, 1978, p. 4-5). The southwestern and north-central parts of the area contain sandhills and some small, interdune lakes and marshes. The Republican River and Frenchman, Spring, and Stinking Water Creeks provide the majority of the surface drainage (fig. 2). These streams flow generally eastward across the study area.

The study area is characterized by a simiarid climate with an average annual precipitation of about 19 inches. However, large variations can occur from year to year. About 80 percent of the annual precipitation occurs during the growing season, April through September. Most of the growing-season precipitation is derived from local thunderstorms which cause large variations in rainfall from place to place. Mean Class-A-pan evaporation in the study area averages about 75 inches per year -- almost four times the average annual precipitation. Most soils in the area are ideally suited to agriculture, but the low precipitation and rapid rate of evaporation limit agricultural production in the absence of irrigation.

About 55 percent of the three-county area is under cultivation. In 1985, irrigated acreage accounted for about 19 percent of the area in the three counties. About 2,900 wells supply virtually all of the irrigation water to the area. Approximately 45 percent of these wells are in Chase County, 26 percent are in Dundy County, and 29 percent are in Perkins County. Most of the irrigation is done using center-pivot sprinklers. Corn is the principal irrigated crop in the area and represents about 70 percent of the total irrigated acreage. Wheat is the second most commonly irrigated crop and

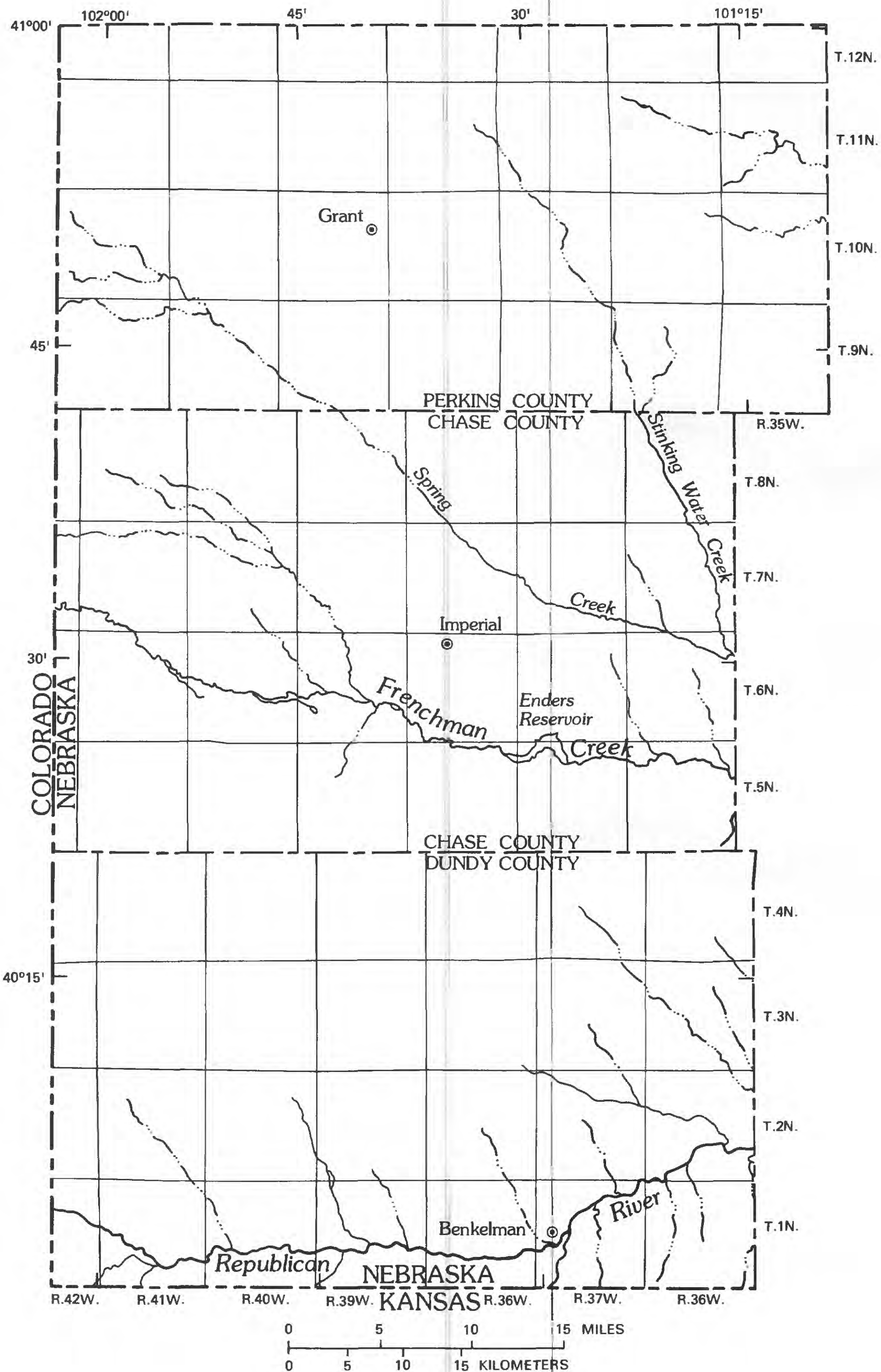

Figure 2.--The study area.

represents about 16 percent of the total irrigated acreage in the area. Dry beans, sorghum, alfalfa, and other crops account for the remainder of the irrigated acreage in the study area.

Chase, Dundy, and Perkins Counties comprise the Upper Republican Natural Resources District (NRD). In 1969, the State of Nebraska authorized the establishment of 24 NRD's (Chapter 2, Article 32, Revised Statutes of Nebraska, 1943) that cover the State. The NRD's became effective on July 1, 1972. The Ground Water Management Act, LB577, enacted in 1975 gave the NRD's authority and responsibilities to establish management practices to conserve ground water for beneficial use. Because of water-level declines north of the Republican River (fig. 2), the Upper Republican NRD designated the area a control area in 1977. The designation required that measures be adopted to control ground-water withdrawal and use. As part of these control measures, the Upper Republican NRD required that, beginning in 1980, all irrigation wells were to be metered using approved inline flowmeters. Irrigators are required annually to report the volume of water pumped from each irrigation well.

The amount and detail of the data available made this an ideal area to study the relation between pumpage and change in storage. Installation of inline flowmeters on irrigation wells in the NRD began in 1977, and, by 1980, meters were installed on all approved irrigation wells in the District. The installation of flowmeters and the reporting requirements provided a partial pumpage data set for 1978 and 1979 and a complete pumpage data set for 1980-83 for use in this study. Additionally, because of the large number of wells monitored in the area, adequate water-level data were available to construct maps of water-level change. Many of the wells (532 of 2,900) also had detailed lithologic logs that could be used to estimate specific yield.

Geohydrologic Setting

In the study area, the High Plains aquifer consists primarily of the Miocene Ogallala Formation and part of the Oligocene White River Group. The White River Group underlies the Ogallala in most of Perkins County and the northernmost township in Chase County (Lappala, 1978). The Pierre Shale, of Late Cretaceous age, underlies the rest of the study area (Lappala, 1978).

The base of the High Plains aquifer is defined by Lappala (1978) as the bottom of the lowermost coarse-grained sediments (sand and/or gravel) that lie on (1) fine-grained sediments (silts and clays) of the White River Group, or (2) weathered clays and unweathered black shale of the Pierre Shale of Cretaceous age, where the White River Group is absent. The major lithologic types of the High Plains aquifer are gravel, sand, silt, clay, and caliche (calcium carbonate-cemented beds locally known as magnesia or "mag").

The sediments that comprise the High Plains aquifer were deposited by eastward-flowing streams that transported rock debris from the Rocky Mountains. In the study area, these streams underwent many cycles of erosion and deposition that eventually overtopped stream divides and formed a vast alluvial plain. The distribution of rock types in the vertical section of the aquifer typically is random -- a characteristic of deposition by braided streams.

Soil texture in the study area generally ranges from silty clay loam to fine sand. Large areas of sandy soils (sandhills), interspersed with silt loam and sandy loam soils, predominate in the southwestern and north-central parts of the study area. The remainder of the study area consists principally of silty clay loam and loam soils. Most of the parent material upon which soils developed in the study area consists of loess (windblown silt) and dune sand. Deposition of the parent material was by eolian processes (duststorms and sandstorms) during Quaternary time (the last 2 million years). The sand soils have developed on the dune areas. In areas where sand and silt deposition have occurred at the same time and place, sandy-loam soils predominate. Loam and silt-loam soils generally developed on the loess parent materials. Clay-loam soils tend to predominate in areas where the parent material is composed primarily of clay.

The depth to the water table below land surface ranges from about 5 feet in the Republican River, and Frenchman, Spring, and Stinking Water Creek valleys to more than 293 feet in the upland of southeastern Chase County and averages about 90 feet in the study area. Water in the aquifer is stored in the pore spaces between the rock particles. The thickness of the saturated material between the water table and the aquifer base ranges from 25 to more than 400 feet and averages 230 feet. The distribution of the saturated thickness of the aquifer underlying the study area in 1980 is shown in figure 3.

The amount of water that can be drained from the aquifer is related to its specific yield. The specific yield of the aquifer is defined as the ratio of (1) the volume of water that the saturated material will yield by gravity drainage to (2) the total volume of the saturated material. Specific yield is greatest in coarse-grained sediments and least in fine-grained sediments. The specific yield in the study area averages about 0.13 and ranges from 0.06 to 0.25.

Ground-water flow in the study area is generally to the east-southeast. The rate of flow of ground water is controlled by the hydraulic conductivity of the aquifer material. Hydraulic conductivity is defined as the volume of water that will move through a unit cross-sectional area, in unit time, under a unit hydraulic gradient. In the study area, the hydraulic conductivities range from about 20 to 150 ft/d (see Table of Conversion Factors and Abbreviations) and average about 54 ft/d. Hydraulic conductivity is directly related to average grain-size in well-sorted materials.

Approach

The estimation of historical pumpage and the calculation of change in storage required a variety of data. Annual water-level data were available for many wells in the area beginning in 1975. Additionally, metered pumpage was available beginning in 1978, and Landsat (Land Satellite) data could be used in conjunction with available data to estimate pumpage for 1975 through 1977. As a result, a 9-year period (1975-83) was selected for the analysis of the relations between pumpage and change in storage.

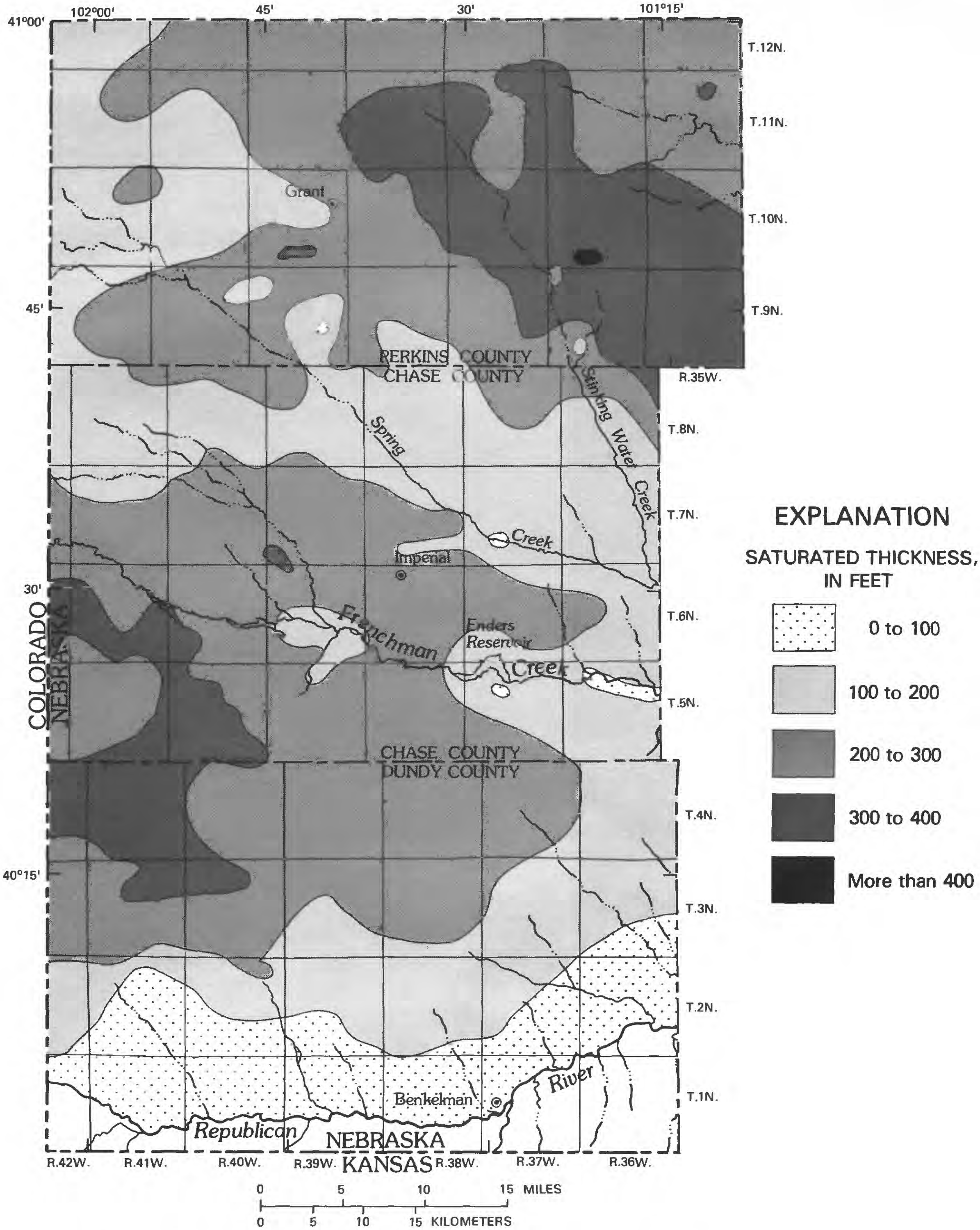

Figure 3.--Saturated thickness of the High Plains aquifer, 1980.

The data compiled for analysis were aggregated into cells of 1-minute of latitude by 1-minute of longitude (1-minute cells). An average cell size of 634.8 acres was used for all cells in the study area in order to simplify calculations of change in storage. The actual cell size ranges from about 630 acres in the north part of the study area to about 640 acres in the south part of the study area. The actual cell size is less than 0.8 percent different from the average cell size, so any error induced by using a constant cell size of 634.8 acres for calculations would be negligible. One-minute cells were selected so that the existing structure of the High Plains data base (Ferrigno, 1986a, Ferrigno, 1986b) could be used for data storage and retrieval. This also allowed the use of data manipulation and analysis programs that had been developed previously for the High Plains data-management system (Luckey and Ferrigno, 1982).

The following summarizes the approaches used to calculate and compare pumpage with change in storage for the 9-year period (1975-83). Detailed discussions of the approaches used to calculate pumpage and change in storage are presented in subsequent sections of this report entitled "Pumpage" and "Change in storage." The evaluation of the relation between pumpage and change in storage is presented in the section entitled "Evaluation of differences between pumpage and change in storage."

The development of pumpage for 1975-83 required several different approaches. Complete metered pumpage data were available from the Upper Republican NRD for 1980-83 and partial metered pumpage data were available for 1978 and 1979, and no metered data were available for 1975-77. The 1978 and 1979 partial metered pumpage data were extended using an interpolation technique and then combined with irrigated acreage measured from Landsat data to estimate pumpage for 1978 and 1979. For 1975-77, application (average inches of water applied per acre) was estimated using a linear regression based on 1973 (Leonard and Huntoon, 1974) and 1978-82 (Upper Republican NRD data) measured application and growing-season precipitation. Estimates of application subsequently were combined with irrigated acreage compiled from Landsat data to estimate pumpage for 1975-77. The total pumpage for 1975-83 was computed by summing the 1-minute cells of pumpage for each of the 9 years.

Change in storage for 1975-83 was calculated from water-level-change data and the specific yield of the aquifer material. The 9-year water-level change was determined for selected wells in the study area and then contoured. The contour map was interpolated to estimate a 1-minute-cell matrix of water-level change. Specific yield was estimated using logs from selected wells in the study area. The specific-yield estimates were used with a smoothing and interpolation program to develop a 1-minute-cell matrix of specific yield for the study area. Change in storage for 1975-83 was calculated by multiplying the water-level change by the specific yield by the average area of a 1-minute cell.

The relation between pumpage and change in storage was evaluated in two parts. First, pumpage was compared directly with change in storage and the results evaluated. These initial comparisons showed large differences between pumpage and change in storage and led to the second part of the evaluation. Change in storage was recalculated using a range of values for specific yield and recharge caused by cultivation practices. This part of the analysis resulted in a range in volume of change in storage. The minimum and maximum values of change in storage were subtracted from estimates of pumpage to calculate the probable range of values for recharge caused by irrigation.

Several other components of the water budget were evaluated but are not discussed in detail in this report. Underflow (ground-water flow into and out of the study area) was calculated for two dates [prior to extensive irrigation development (1950s) and at the end of the study (1983)] to determine if any changes had occurred that would affect the comparison of pumpage with change in storage. No significant change in underflow was indicated, so this component was not considered in subsequent calculations. Also, no attempt was made to include evapotranspiration estimates in this study because this component was not required for conducting an evaluation of the relations between pumpage and change in storage. The effects of precipitation are discussed in the "Evaluation of differences between pumpage and change in storage" section of this report.

PUMPAGE

The approaches used to develop pumpage data for 1975-83 are discussed in two subsections -- estimated pumpage and metered pumpage. Metered pumpage will be discussed first because the metered data were used in generating estimated pumpage for those years in which no measured data were available.

Metered Pumpage

The Upper Republican NRD began metering pumpage in the study area in 1978. The regulation establishing the metering requirement for the study area was passed in 1977, and installation of inline flowmeters began that year. Because of the large number of meters required, installation was not completed until after the end of the 1979 irrigation season. Consequently, a partial set of pumpage data was available from NRD records for 1978 (about 950 wells) and 1979 (about 1,300 wells) and a complete pumpage data set (about 2,900 wells) was available from 1980 to 1983.

The well records maintained by the Upper Republican NRD include a variety of information. The location of the well, acres irrigated, and annual pumpage were the recorded items used in this study. The well data for each year (1978-83) were aggregated by 1-minute cells and stored in the High Plains data base. Following the aggregation procedure, the data base contained a complete 1-minute-cell matrix of pumpage for 1980-83 and a partial 1-minute-cell matrix of pumpage for 1978 and 1979. The next steps in developing the 9-year pumpage history were to fill in the missing pumpage data for 1978-79, and develop estimates of pumpage for 1975-77 for which no measured data were available.

Estimated Pumpage

Separate procedures were followed for estimating the missing pumpage data for 1978 and 1979, and creating pumpage data sets for 1975-77. In both procedures, available metered data were used in conjunction with Landsat-derived irrigated acreage to develop the pumpage estimates. Because irrigated-acreage data were used in calculating all of the pumpage estimates for 1975-79, the procedures used to develop these data for the study area are discussed prior to the discussion of the actual steps used to estimate pumpage.

Landsat digital data for 1974, 1976, 1978, and 1980 were analyzed using a band-ratio technique. This analysis provided maps and tabular estimates of irrigated acreage for all 1-minute cells in the study area. The distribution of irrigated acreage for the study area, compiled from 1980 Landsat data, is shown in figure 4. The 1980 irrigated acreage in figure 4 was aggregated by 5-minute blocks (25 1-minute cells). Because of a lack of suitable Landsat data, irrigated acreage for 1975, 1977, and 1979 was estimated by averaging the acreage for adjacent years.

Analysis of the Landsat data was conducted by personnel from the U.S. Geological Survey at Ames Research Center, Moffett Field, California. The procedures used to analyze the Landsat data and to aggregate the acreage into 1-minute cells were the same as those used to map irrigated acreage for the entire High Plains in 1980 (Thelin and Heimes, in press).

The steps listed below provide a summary of the procedures used to extend metered-pumpage data and to estimate the missing pumpage data for 1978 and 1979. A detailed discussion of each of the steps follows the listing.

1. Calculate the average measured application (measured pumpage divided by acres irrigated) for 1-minute cells containing data.
2. Estimate application for cells without data using a weighted interpolation and smoothing algorithm.
3. Multiply the 1-minute cell application (step 1) by the corresponding irrigated acreage determined from Landsat data to calculate estimated pumpage.

The 1978 and 1979 NRD metered-pumpage and irrigated-acreage data were allocated to 1-minute cells. The measured application (inches of water applied per acre) was calculated for each cell by dividing the total metered pumpage for the cell by the acres irrigated by the metered wells in that cell. This resulted in partially filled matrices of measured application for 1978 and 1979.

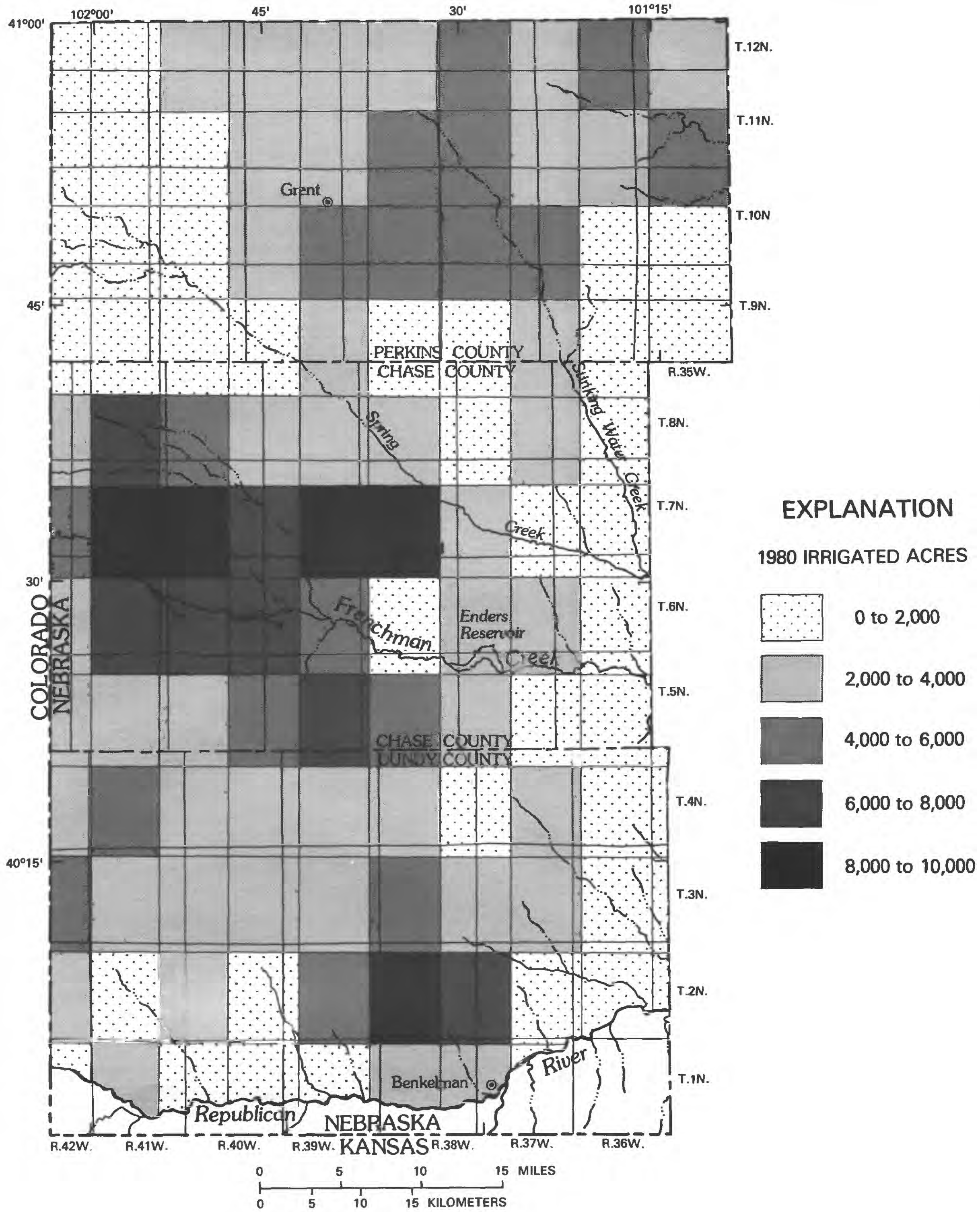

Figure 4.--Irrigated acres determined from 1980 Landsat data.

Next, application for 1-minute cells without data was estimated from cells with measured application values, which were distributed throughout the irrigated regions of the study-area matrix. Also, application primarily is a function of crop type, precipitation, and soils, all of which change gradually from cell to cell. Based on these factors, a smoothing and interpolation algorithm was used to estimate application values for cells with missing data. The formula for the smoothing and interpolation algorithm is:

$$V = \frac{\sum_{i=1}^{n} (w_i v_i)}{\sum_{i=1}^{n} w_i},$$

where

$$w_i = \frac{r^2-d^2}{s^2+d^2}$$

and

V = the interpolated value for a given grid-cell location;
v_i = the value of each input data point located within the specified effective radius of the grid cell for which V is being calculated;
w_i = the weight assigned to the input data point;
d = the distance between the input data point and the center of the grid cell for which V is being calculated (in feet);
r = a selected effective radius about the center of the grid cell at which V is being calculated for inclusion of input data points (in feet);
s = a selected smoothing factor (in feet); and
n = the number of data points within the specified effective radius.

An effective radius of 80,000 feet and a smoothing factor of 8,000 feet were used to calculate application values for cells with missing data. An effective radius of 80,000 feet used cell values from a radius of approximately 15 grid cells for calculating each interpolated value. The smoothing factor of 8,000 feet gave a much greater weight to input values close to the grid cell for which the interpolated value was being calculated. Estimated pumpage for 1978 and 1979 was calculated by multiplying the matrix of application by the corresponding matrix of Landsat-derived irrigated acreage.

A relatively complex procedure was required to estimate pumpage for 1975-77 because there were no metered data. The steps listed below summarize the procedure. A detailed discussion of each of the steps follows the listing.

1. Calculate the average annual application for the study area for each year from 1978 through 1982.
2. Calculate the average application for the study area for 1973 using data obtained from a study by Leonard and Huntoon (1974).
3. Calculate the average total inches of water applied each year for 1973 and 1978-82 by summing the average application and growing-season precipitation for the study area for each of those years.
4. Develop a linear-regression equation to estimate the average total inches of water applied for the 1975-77 growing seasons using the information from step 3.
5. Estimate average study-area application for 1975, 1976, and 1977 by subtracting the growing-season precipitation from the regression estimates of average total inches of water applied.
6. Multiply the average study-area application value for each year (from step 5) by a scaled average matrix of 1978-82 application values to compute a matrix of 1-minute cell values of application for 1975, 1976, and 1977.
7. Calculate estimated pumpage by multiplying the application matrices for 1975, 1976, and 1977 (from step 6) by the corresponding matrix of irrigated acreage determined from analysis of Landsat data.

The first step in developing pumpage estimates for 1975-77 was to calculate application matrices for the study area for each year from 1978 through 1982 by dividing the NRD metered-pumpage matrix by the corresponding NRD irrigated-acreage matrix. A single mean application for the study area for each year (1978-82) was calculated. A limited amount of measured-pumpage and irrigated-acreage data for the study area also were available for 1973. Leonard and Huntoon (1974) reported data collected at 37 irrigation sites in the area during the 1973 growing season. A mean application was computed for 1973 from the data for the 37 sites.

To estimate the total inches of water applied to irrigated crops, the growing-season (April through September) precipitation was added to the average application for each year from 1973-82. At the time these calculations were made, precipitation data for the 1983 growing season were not available. Growing-season precipitation was compiled for four stations located in the study area and three stations in adjacent counties in Colorado for 1973-82 (table 1). The growing-season precipitation was added to the average application to compute the total water applied each year.

The annual variability of total applied water was relatively small because most of the variation in growing-season precipitation was offset by changes in application; therefore, a linear regression was used to estimate total applied water for 1975-77. The year was the independent variable, and total inches of water applied was the dependent variable in the regression. The slope of the computed regression was -0.039, indicating a slight decline in the average total inches of water applied from 1973 through 1982. Most studies support this trend, indicating that improvements in irrigation efficiency and increased pumping costs have resulted in some reductions in application since the mid-1970's. Table 2 shows measured application, growing-season precipitation, measured total applied water, estimated total applied water from the regression, and the difference between measured and

Table 1.--*Annual growing-season (April-September) precipitation for selected weather stations, 1973-82*

Station	Growing-season precipitation (inches)									
	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
Holyoke, Colo.	15.51	8.65	10.61	9.68	17.98	14.58	14.80	12.96	18.81	21.36
Julesburg, Colo.	[1]--	6.56	14.85	7.54	15.85	[2]--	[2]--	10.72	14.59	[2]--
Wray, Colo.	17.77	9.83	12.38	8.76	15.26	10.01	10.93	15.27	14.59	22.87
Benkelman, Neb.	18.37	11.86	12.09	9.37	16.27	9.34	12.67	15.50	18.40	15.32
Enders Lake, Neb.	20.27	13.11	14.76	13.19	17.98	10.61	12.19	15.13	16.43	20.35
Imperial, Neb.	17.61	12.83	13.73	11.10	15.29	13.94	9.60	14.10	16.61	21.41
Madrid, Neb.	[1]--	10.94	13.61	12.19	14.70	9.97	15.25	12.82	15.06	20.58
Average	17.91	10.54	13.14	10.26	16.19	11.41	12.57	13.78	16.35	20.32

[1]Station values not included for 1973 because application data used in conjunction with growing-season precipitation was collected in Chase and Dundy Counties only in 1973.

[2]Station had one or more months of missing precipitation data.

Table 2.--*Measured application, growing-season precipitation, measured total applied water, and estimated total applied water from regression analysis.*

[Difference = measured minus estimated average total inches of water applied]

Year	Measured application (inches)	Growing-season precipitation (inches)	Total applied water (inches)		Difference (inches)
			Measured	Estimated	
1973	15.0	17.9	32.9	31.5	1.4
1975	[1]--	13.1	[1]--	30.5	[1]--
1976	[1]--	10.3	[1]--	30.1	[1]--
1977	[1]--	16.2	[1]--	29.6	[1]--
1978	17.0	11.4	28.4	29.2	-0.8
1979	13.3	12.6	25.9	28.7	-2.8
1980	13.3	13.8	27.1	28.2	-1.1
1981	11.4	16.4	27.8	27.7	0.1
1982	9.3	20.3	29.6	27.2	2.4

[1]Measured data for application were not available for use in calculating total applied water.

estimated total inches of water applied for 1973-82. Average application for 1975, 1976, and 1977 was estimated by subtracting growing-season precipitation from estimated average total inches of water applied that was computed from the regression.

The single average application values were used to develop 1-minute-cell matrices of application for 1975-77. A consistent areal trend in the 1-minute-cell application values for each of the 5 years (1978-82) was noted. Based on this trend, a scaled-average matrix of application was computed for use in estimating the 1975-77 individual average application values. Each of the application matrices for 1978-82 was smoothed to enhance the areal trends that were present; a mean average application matrix for the 5-year period was then computed. This mean average application matrix was scaled by dividing by the mean of the matrix. This resulted in a matrix that contained a value of 1.0 for cells that originally contained a value equal to the mean of the matrix (12.8 inches), and a value of less than or greater than 1.0 for cells that originally contained values less than or greater than the mean, respectively, as shown in figure 5. This scaled 5-year average application matrix was multiplied by each of the average application values for 1975, 1976, and 1977 to create 1-minute-cell matrices of estimated application for the 3 years. These estimated application matrices were multiplied by the corresponding matrices of irrigated acreage (determined from Landsat data) to calculate matrices of estimated pumpage for 1975-77.

The calculation of pumpage estimates for 1975-77 completed the process of developing a pumpage history from 1975 through 1983. The 9-year pumpage matrix was calculated by summing each of the annual pumpage matrices for 1975-83. Figure 6 shows the distribution of 9-year pumpage for the study area

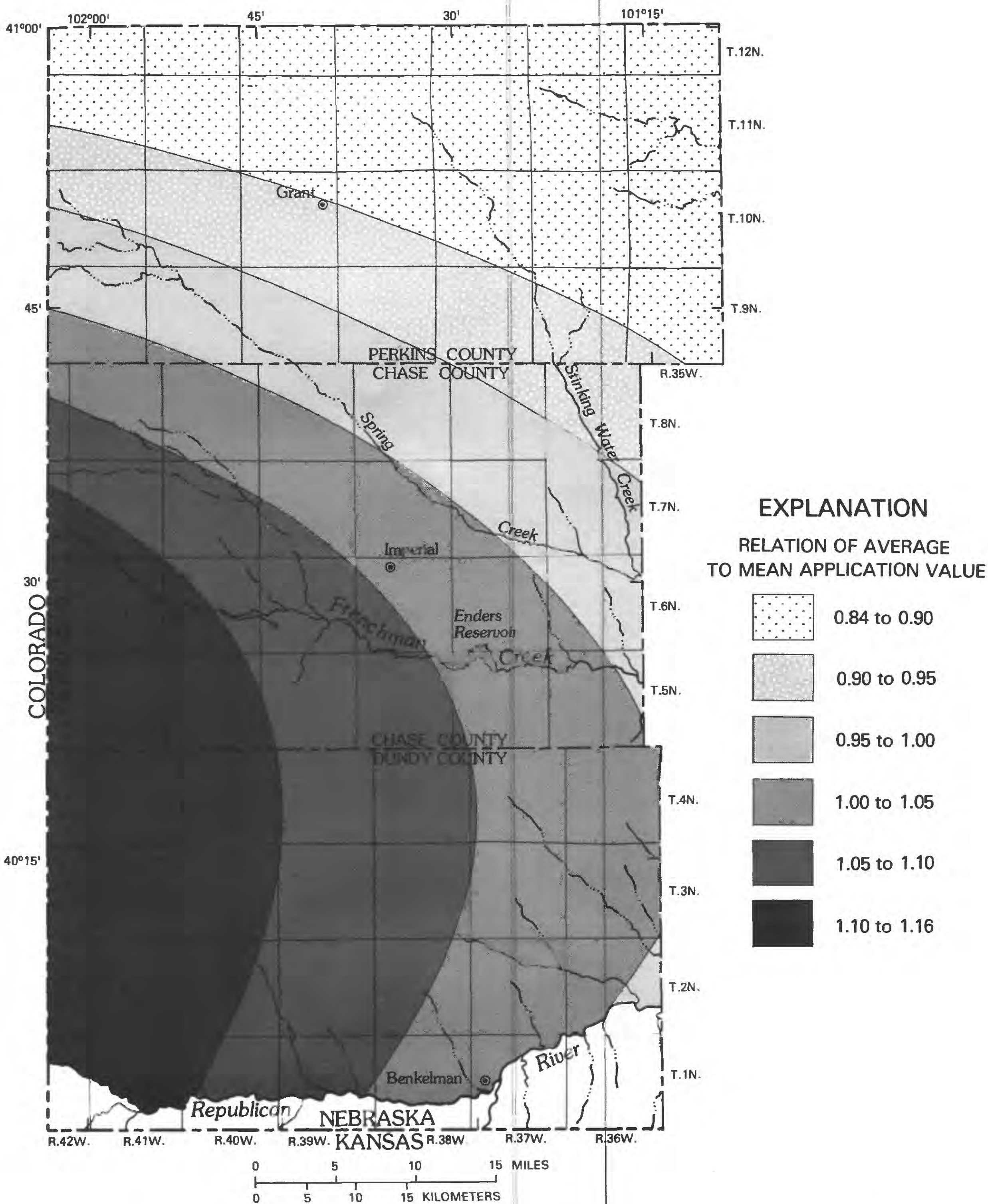

Figure 5.--Relation of average to mean application value for 1978-82.

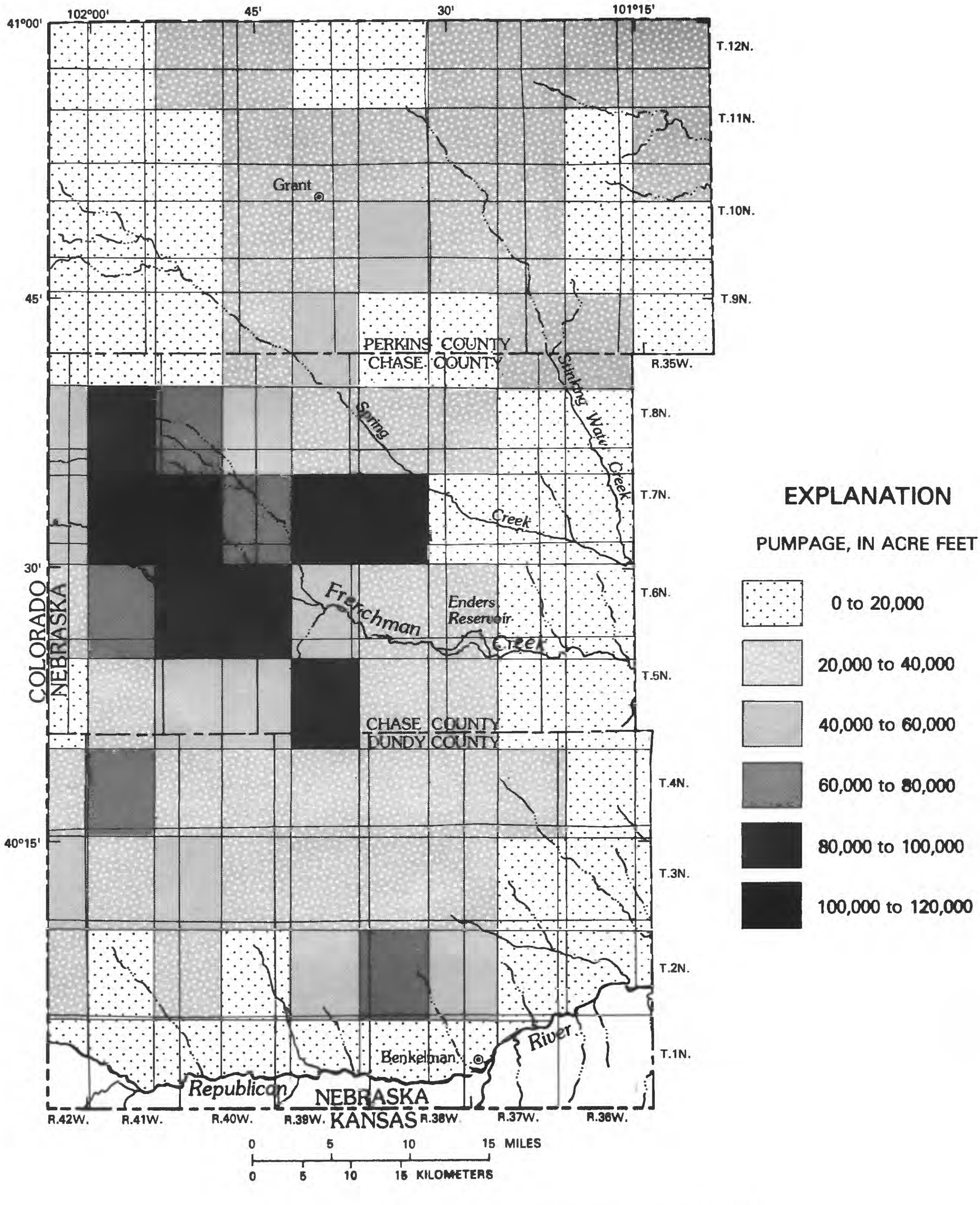

Figure 6.--Total estimated pumpage for 1975-83.

aggregated by 5-minute cells. The estimated 9-year pumpage for the study area was 3,425,000 acre-feet, including 1,680,900 acre-feet in Chase County, 907,400 acre-feet in Dundy County, and 836,700 acre-feet in Perkins County.

CHANGE IN STORAGE

Change in storage is the volume of water removed from the aquifer underlying the study area for the 9 years from 1975 through 1983. Change in storage was calculated by multiplying the matrix of water-level decline for the 9 years by the matrix of specific yield of the aquifer material. The following sections on "Water-level change," "Specific-yield estimates," and "Calculation of change in storage" present a detailed discussion of the approaches used to estimate change in storage.

Water-Level Change

A 9-year, water-level-change matrix of 1-minute cells was calculated using the procedure outlined in the steps below. A detailed discussion of each of the steps follows the listing.

1. Calculate 9-year water-level change at each of the selected observation wells.
2. Plot the values of water-level change on a map of the study area and contour the data.
3. Interpolate 9-year water-level-change values for each 1-minute cell from the contour map generated in step 2.

Water-level changes for the 9-year period from 1975-83 were determined for 281 observation wells distributed throughout the study area. Water levels in observation wells are measured during the late winter or early spring before pumping for irrigation begins and after the water levels have stabilized from the effects of pumping during the previous growing season. Calculation of the water-level change, in feet, for each of the observation wells was done by subtracting the 1975 water-level measurement (water level at the beginning of the 1975 irrigation season) from the 1984 water-level measurement (water level at the end of the 1983 irrigation season). Negative values from this calculation indicate a decline and positive values indicate a rise in water levels during the 9-year period.

The location of the observation wells and the associated water-level changes were plotted on a 1:250,000-scale base map of the study area so that the values could be contoured. Because pumpage for irrigation is the principal factor controlling water-level change in the aquifer, a map of irrigated acreage was used as a guide to contouring. The location of stream channels and topography also were used as a guide in positioning contours. The map of 9-year water-level change for the study area is shown in figure 7.

The final step in the process of creating a 9-year water-level-change matrix was to interpolate 1-minute-cell values from the contour map. A 1-minute-cell matrix was overlain on the contour map and water-level-change values were selected for 1-minute cells. The location and distribution of

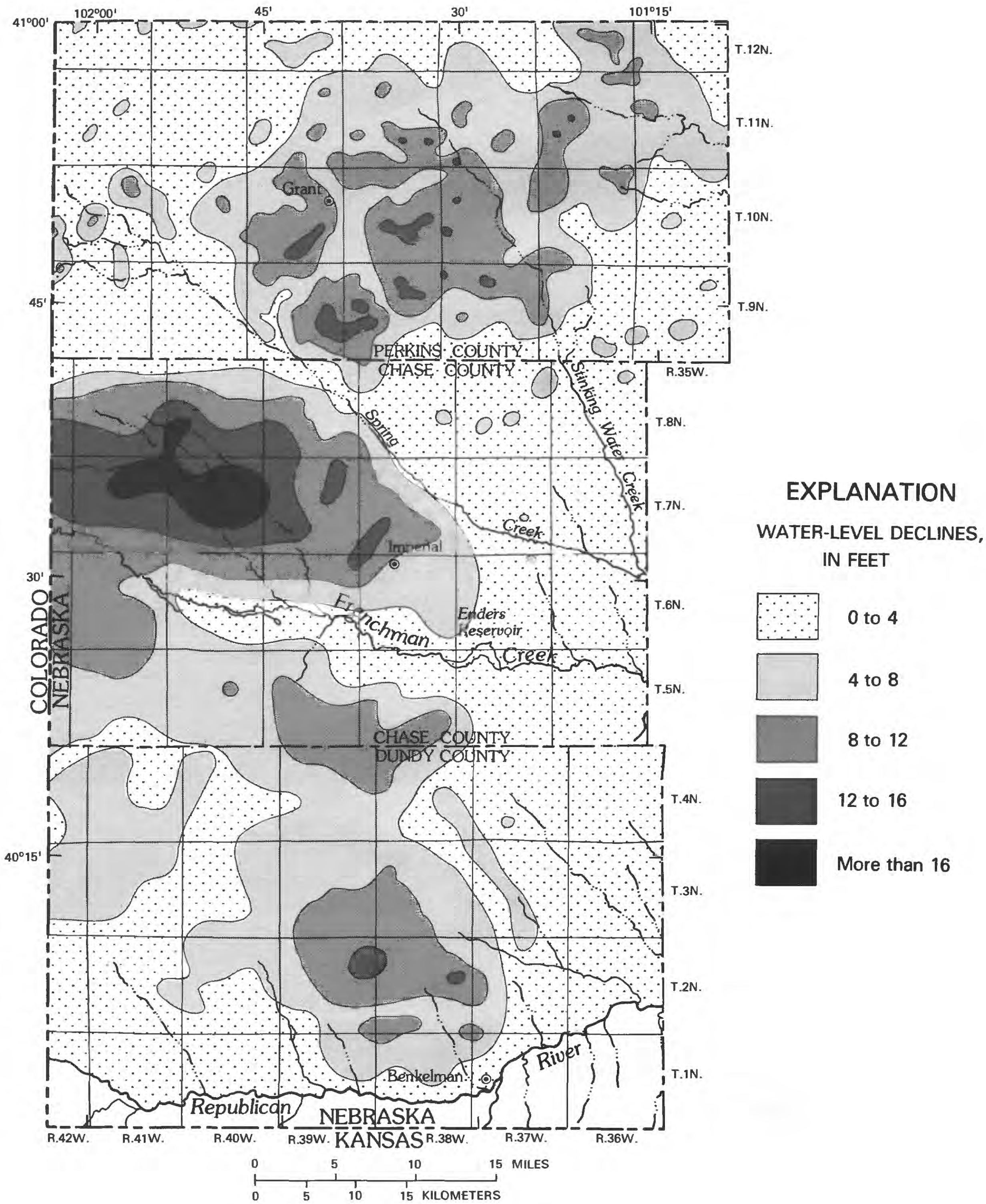

Figure 7.--Water-level changes in the study area, 1975-83.

irrigated acreage was used to aid in interpolating contours. The interpolation process produced a 1-minute-cell matrix of 9-year water-level change that could be combined with specific yield to calculate change in storage.

Specific-Yield Estimates

The calculation of a specific-yield matrix for computing change in storage was accomplished using the procedure outlined in the steps below. A detailed discussion of the procedure follows the listing.

1. Determine if vertical distribution of sediment types in the aquifer is random.
2. Calculate specific yield from drillers' logs for selected wells.
3. Assign specific-yield values determined at selected well sites to the appropriate 1-minute cells.
4. Calculate specific yield for all 1-minute cells in the study area from the data compiled in step 3 using a weighted interpolation and smoothing algorithm.

Logs from 532 wells distributed throughout the study area were analyzed to estimate specific yield. An analysis of the vertical distribution of sediment types within the aquifer underlying the study area confirmed that the distribution was random (Gutentag and others, 1984, p. 23). This random distribution indicates that all sediment types present in the aquifer are equally likely to be present at any position in the vertical section, and that estimates of specific yield do not change significantly with changes in saturated thickness.

Specific yields were assigned to lithologic descriptions from drillers' logs for the 532 wells using the values in table 3. These values were determined from a study on specific yield by Johnson (1967) and studies of the relation between lithology and specific yield in the High Plains of Nebraska made by the U.S. Geological Survey (M.J. Ellis, U.S. Geological Survey, written commun., 1978). For each driller's log, the specific-yield values assigned to lithologic units were multiplied by the corresponding thickness of the units to calculate thickness-weighted specific-yield values for each unit in the saturated section. The average specific yield for the total saturated section was calculated by summing the thickness-weighted specific-yield values for all lithologic units in the saturated section and dividing by the saturated thickness.

The average specific-yield values determined from the logs at each of the 532 well locations were assigned to the appropriate 1-minute cell in the matrix. The smoothing and interpolation algorithm (see "Estimated pumpage" section) was used to smooth the original data and interpolate specific-yield values for 1-minute cells without data. An effective radius of 40,000 feet and a smoothing factor of 40,000 feet were used to provide a complete matrix of 1-minute-cell values of specific yield. The smoothing and interpolation algorithm provided a smooth matrix of specific yield without greatly altering

Table 3.--*Specific-yield values assigned to lithologies of the High Plains aquifer*

["Mag" is a local term that identifies magnesia rock, which is a form of caliche.]

Lithology	Specific yield (percent)
Clay	3
Clay and "mag"	3
Clay and sand	10
Clayey sand and gravel	17
Clayey sand and sandstone	10
Clayey sandstone and sand and gravel	17
Coarse sand	24
Limestone	5
"Mag"	5
"Mag" and clay	5
"Mag" and sandy clay	5
Sand and gravel	25
Sand and gravel with clay	8
Sand and gravel with sandy clay	10
Sandstone	5
Sandy clay	5
Shale	3
Top soil	3
Top soil with clay and "mag"	3

the original values interpreted from the 532 drillers' logs (fig. 8). The average specific yield for the 532 logs was 12.9 percent. The average specific yield for the smoothed and interpolated 1-minute-cell matrix was 13.1 percent for the study area, 12.3 percent for Chase County, 14.7 percent for Dundy County, and 12.2 percent for Perkins County.

Calculation of Change in Storage

Change in storage was calculated by multiplying the 1975-83 water-level change by the specific yield to obtain an effective depth of water removed from the aquifer. The effective depth of water was multiplied by the average area of a 1-minute cell (634.8 acres) to compute change in storage. The distribution of change in storage in acre-feet per acre is shown in figure 9. The distribution of change in storage is similar to the distribution of the water-level change (fig. 7) for 1975-83. Change in storage for 1975-83 was 1,042,300 acre-feet in the study area, 431,600 acre-feet in Chase County, 267,700 acre-feet in Dundy County, and 343,000 acre-feet in Perkins County.

EVALUATION OF DIFFERENCES BETWEEN PUMPAGE AND CHANGE IN STORAGE

The comparison between pumpage and change in storage was evaluated to determine if pumpage significantly exceeded change in storage. Preliminary analysis of the entire High Plains had indicated that change in storage was about 37 percent of pumpage from predevelopment to 1980 (Gutentag and others, 1986). A comparison of pumpage and change in storage calculated for this study indicates similar differences. Table 4 shows the 9-year pumpage and change in storage, and the difference between pumpage and change in storage by county and for the study area. The change in storage for the study area was 1,042,300 acre-feet, which was about 30 percent of the 3,425,000 acre-feet pumped during the 9-year period. This comparison indicates that a volume equal to about 70 percent of pumpage was added to the aquifer during the 9-year period.

The change in storage in Chase and Dundy Counties was 26 and 30 percent of pumpage, respectively. These percentages are similar to the 30 percent difference found for the study area. The change in storage in Perkins County was 41 percent of pumpage. The reason for the smaller difference between pumpage and change in storage in Perkins County is not readily apparent, but it may be a function of lower average application (fig. 5) of water to crops and a larger proportion of fine-grained soils in Perkins County relative to Chase and Dundy Counties. Lower application rates and a larger area of fine-grained soils would tend to reduce the potential for recharge to the aquifer.

The large differences between pumpage and change in storage (table 4) could be caused by one or more of the following: (1) Errors in estimates of pumpage or change in storage; (2) enhanced recharge from precipitation resulting from cultivation; and (3) additional recharge caused by irrigation. The following sections, "Potential errors," "Estimates of recharge caused by cultivation," and "Estimates of recharge caused by irrigation," explore each of these factors in detail.

Potential Errors

It is not possible to measure quantitatively the accuracy of the estimates of pumpage and change in storage. However, a qualitative assessment of the accuracy can be made by examining the potential error associated with pumpage estimates, water-level changes, and specific-yield estimates. Each of these components are discussed below.

The reliability of NRD metered pumpage was evaluated in a separate report that compared independent measurements of pumpage, obtained using a portable flowmeter (Stephens and others, 1984 and 1985), with metered pumpage from selected sites in the study area during 1983 and 1984 (Heimes and others, 1986). The difference in the mean of the metered pumpage and the mean of the pumpage determined using a portable flowmeter was 1.8 percent for sites sampled in 1983 and 2.3 percent for sites sampled in 1984.

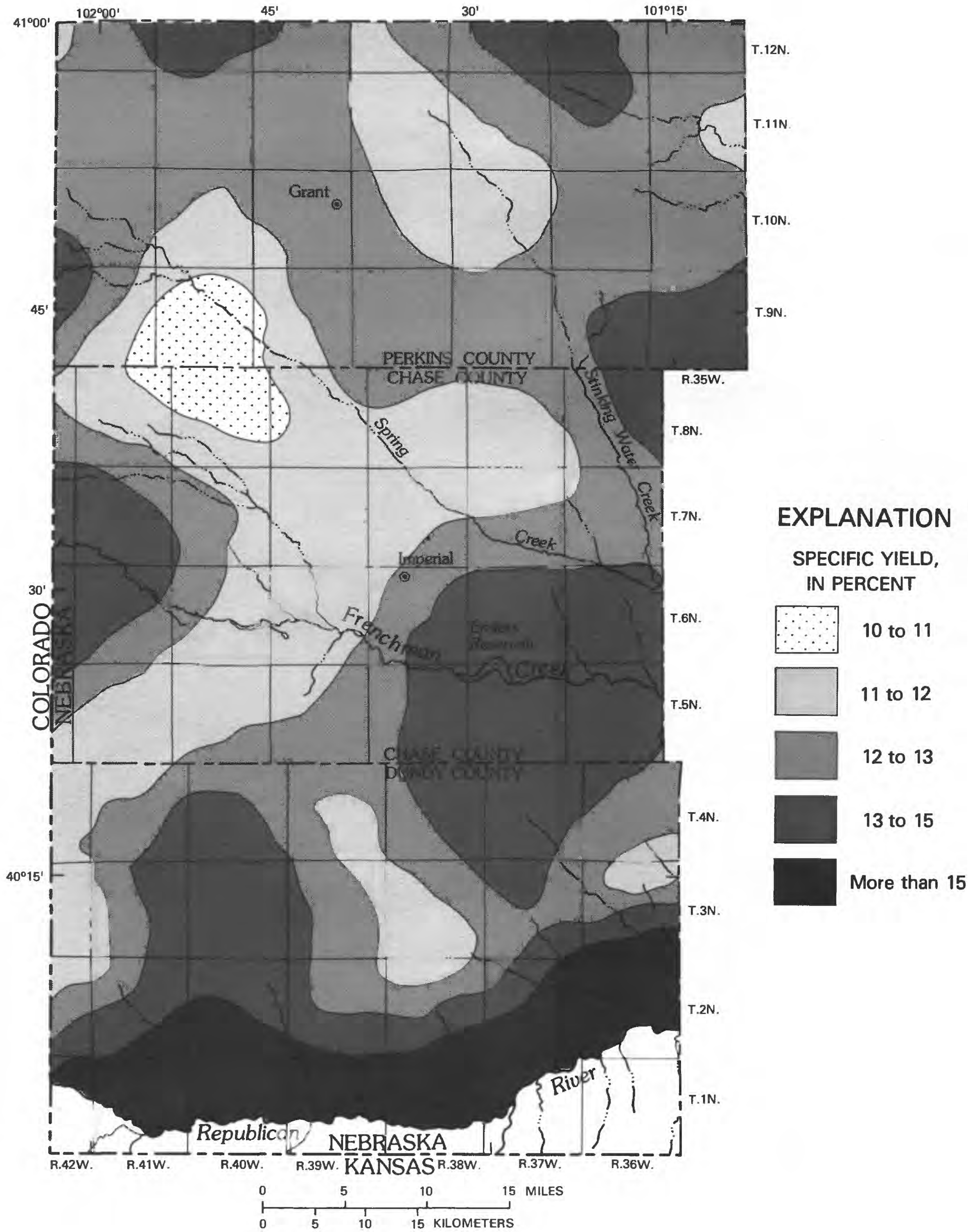

Figure 8.--Specific yield of the High Plains aquifer.

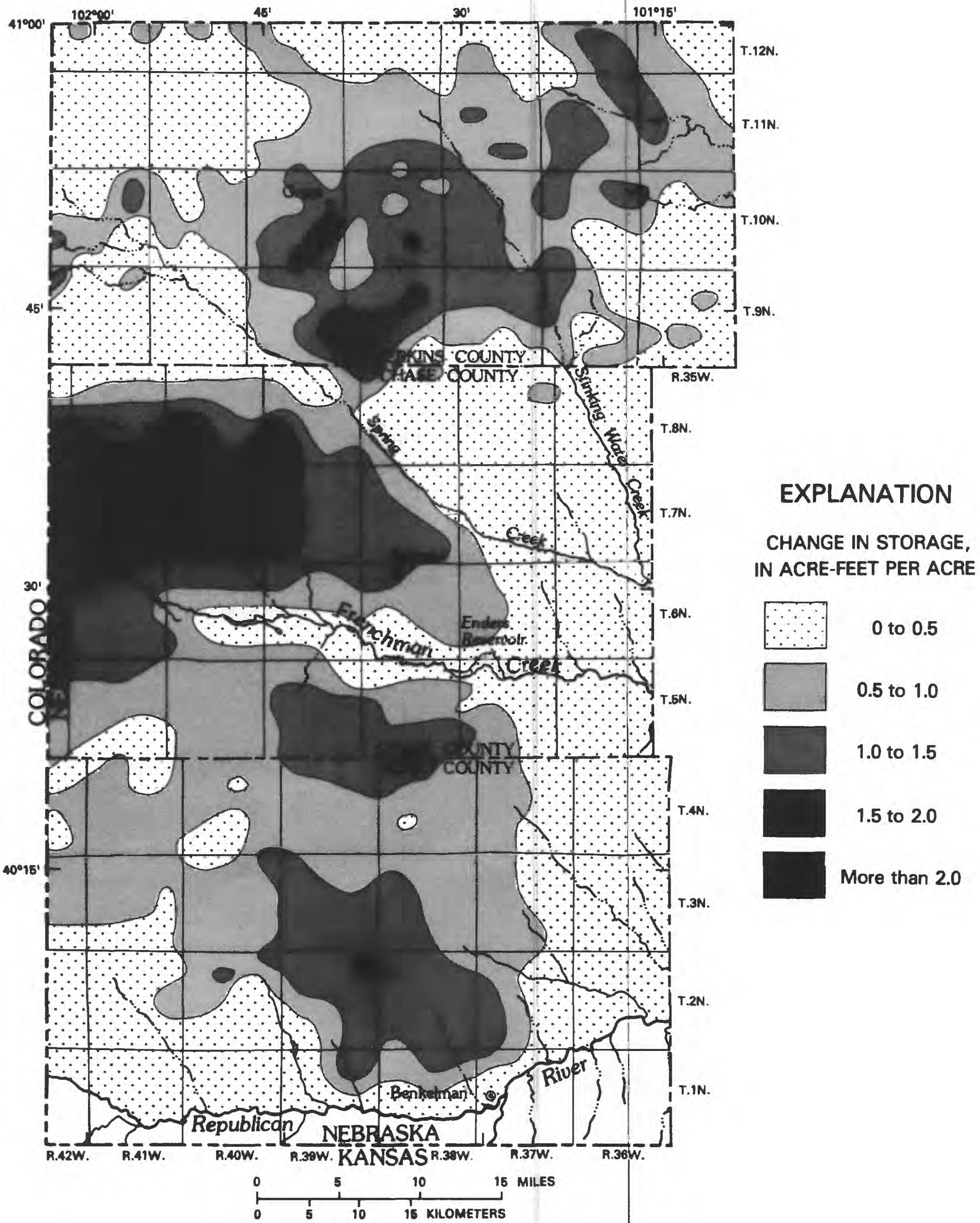

Figure 9.--Change in storage in the High Plains aquifer, 1975-83.

Table 4.--*Comparison of pumpage and change in storage, 1975-83*

Area	Pumpage (acre-feet)	Change in storage (acre-feet)	Pumpage minus change in storage (acre-feet)	(percentage of pumpage)
Chase County	1,680,900	431,600	1,249,300	74
Dundy County	907,400	267,700	639,700	70
Perkins County	836,700	343,000	493,700	59
Study area	3,425,000	1,042,300	2,382,700	70

Pumpage estimates for 1978 and 1979 were derived from a partial set of metered pumpage data combined with irrigated acreage estimated from Landsat data. A similar procedure, using pumpage determined at a small number of sample sites and irrigated acreage estimated from Landsat data, was used to estimate pumpage for the entire study area for 1983 and 1984 (Heimes and others, 1986). Comparisons of these pumpage estimates with metered pumpage showed a difference of 11 percent in 1983 and 5 percent in 1984.

The pumpage estimates for 1975-77 have a greater potential for error because measured pumpage data were not available. Pumpage estimates for 1975-77 were calculated using irrigated acreage mapped from Landsat data and measured total inches of water applied. Landsat data have been used to map irrigated acreage in the study area (Heimes and others, 1986) and in the entire High Plains (Thelin and Heimes, in press). The results indicate that computer analysis of Landsat data provided reliable estimates of irrigated acreage in these areas. Also, the estimates of total water applied to crops in the study area for 1973 and 1978-82 showed little variation between years. Given these factors, it is unlikely that the estimates of pumpage for 1975-77 deviate substantially from actual pumpage.

The potential error in the pumpage estimates is least for years with metered data and greatest for years without. However, based on the large amounts of measured data available and the predictability of trends in pumpage from year to year, there is little chance that the 9-year pumpage estimates developed for this study deviate substantially from the actual pumpage for 1975-83.

Water-level-change information for 1975-83 was compiled from a network of 281 observation wells distributed throughout the study area. A map of irrigated acreage was used as a guide in determining the position of contours. Based on the large number of observation wells used, the consistency of the water-level measurements, and the considerable care exercised in developing the map of water-level changes, the potential for error in the 9-year water-level-change data is relatively small.

Specific-yield estimates were made from logs of 532 wells distributed throughout the study area. The large number of well logs provided an excellent data set for determining the distribution of specific yield within the study area. However, as reported by Johnson (1967), the specific yield associated with a given lithology is not definitive because the quantity of water that will drain by gravity depends on variables such as duration of drainage, temperature, mineral composition of the water, and various physical characteristics of the rock or soil under consideration. In his comparison of specific-yield values used in a variety of studies, Johnson found that estimates of specific yield assigned to a given lithology varied considerably, especially for finer textured materials. The specific-yield estimates used in this study are reasonable estimates based on reported data and careful interpretation of lithologic logs. However, based on the variability in specific-yield estimates presented by Johnson (1967, p. D1), there is a relatively large potential for error in estimating specific yield compared to the pumpage estimates and the calculations of water-level change.

In order to evaluate the effects of potential errors associated with estimating specific yield, change in storage was recalculated using minimum and maximum specific-yield values for lithologies present in the study area. Table 5 shows the minimum and maximum values of specific yield from Johnson (1967, p. D1) interpreted for the principal lithologies in the study area. Table 5 also shows the values of specific yield originally estimated for this study. Four drillers' logs that were representative of the general lithology were selected for each of the three counties. These 12 logs were analyzed to compute a minimum and maximum specific yield for each log using the information presented in table 5. Table 6 summarizes the minimum and maximum specific yield estimated for each of the 12 logs and the original specific yield estimated for each log. For comparison, the mean specific yield, based on the estimates from the 532 logs used initially, is 12.3 percent for Chase County, 14.7 percent for Dundy County, 12.2 percent for Perkins County, and 13.1 percent for the study area.

Change in storage was recalculated by: (1) Computing the ratio of the mean minimum or mean maximum specific yield for each county and the study area (from table 6) and the original (from the 532 logs) mean specific yield for each county and the study area; and (2) multiplying the ratio by the original change in storage to obtain an adjusted change in storage for each county and the study area. The results of these calculations are presented in table 7 and discussed further in the section entitled "Estimates of recharge caused by irrigation."

Estimates of Recharge Caused by Cultivation

Numerous estimates of recharge in the High Plains have been made, including the study area (Gutentag and others, 1984, table 7). These estimates range from 0.024 in/yr in the southern High Plains of Texas to as much as 6.0 in/yr in south-central Kansas. Many of these recharge estimates are based on water-budget calculations or computer-model analyses assuming steady-state conditions (inflow to the aquifer equals outflow from the aquifer with no change in storage). The aquifer was assumed to be in steady state when the entire study area was rangeland. This assumes that recharge from rangeland is accounted for in outflow and storage in the aquifer would not change. However, agricultural development in the study area has resulted in

Table 5.--*Comparison of minimum and maximum specific yield with specific yield originally assigned to principal lithologies of the High Plains aquifer in the study area*

[Minimum and maximum specific-yield estimates were interpreted from the specific-yield values presented in Johnson (1967, p. D1) to fit the lithologic units of the High Plains aquifer in the study area; original specific-yield estimates are those presented in table 3]

Lithology	Specific yield, in percent		
	Minimum	Original	Maximum
Clay	0	3	5
Clayey sandstone	0	5	5
"Mag" and clay	0	5	5
Sandy clay	3	5	12
Tight clay and sand	3	8	12
Clayey sand	10	10	28
Sand and gravel with clayey sandstone streaks	10	10	32
Sand	15	25	32
Clayey sand and gravel	17	17	35
Clayey "mag" with sand and gravel	20	20	35
Sand and gravel	20	25	35

Table 6.--*Comparison of minimum, maximum, and original specific-yield estimates interpreted for selected drillers' logs*

[Specific-yield estimates for drillers' logs were made using the values for lithologies in table 5]

County and Site location	Specific yield, in percent		
	Minimum	Original	Maximum
Chase County			
6N-40W-25B	8.8	12.4	19.5
7N-40W-2C	8.7	12.4	18.0
6N-40W-18BBB	10.8	11.9	23.4
5N-40W-4CB	12.0	12.1	27.3
Chase County mean	10.1	12.2	22.1
Dundy County			
4N-40W-32AAC	12.7	14.5	28.4
2N-41W-31DD	11.9	13.6	23.6
4N-37W-36ABB	9.4	13.0	22.8
3N-41W-3BA	11.4	14.6	27.8
Dundy County mean	11.4	13.9	25.7
Perkins County			
11N-41W-14CCD	9.4	12.6	19.8
10N-41W-30C	8.7	12.5	18.9
12N-35W-33BBD	9.6	12.2	20.5
9N-38W-14BBD	8.6	11.3	19.6
Perkins County mean	9.1	12.2	19.7
Study area mean	10.2	12.8	22.5

Table 7.--*Comparison of change-in-storage values calculated using estimates of minimum, original, and maximum specific yield.*

Area	Change in storage, in acre-feet		
	Minimum specific yield	Original specific yield	Maximum specific yield
Chase County	353,900	431,600	776,900
Dundy County	206,100	267,700	468,400
Perkins County	253,800	343,000	552,200
Study area	813,800	1,042,300	1,797,500

cultivation of the land and, more recently, irrigation of cultivated land, both of which have the potential to increase recharge and affect change in storage. Recharge that occurs as a result of cultivation of the land is discussed in this section. Recharge that occurs as a result of irrigation, and is in addition to recharge that results from cultivation, is discussed in the following section, "Estimates of recharge caused by irrigation." Because of the variability in reported recharge estimates and a lack of data for calculating recharge, minimum and maximum values of recharge resulting from cultivation were estimated. A minimum recharge of zero seemed reasonable because the average annual precipitation in the area is about 19 inches and the mean annual Class-A-pan evaporation is about 75 inches. Estimating a maximum value for recharge was much more difficult and required evaluation of historical conditions in the study area.

The study area has been extensively cultivated since the turn of the century. In fact, the proportion of cropland in the study area has remained relatively constant from the 1920's to the present (1985) at about 50 to 60 percent. The principal change during this period was the introduction of irrigation in the 1950's, which resulted primarily in the conversion of dry-land cropland to irrigated cropland, and to a lesser extent, the conversion of rangeland to irrigated cropland.

If cultivation of rangeland resulted in additional recharge to the aquifer for the period between the turn of the century and the beginning of irrigation development, then streamflow hydrographs for perennial streams that receive ground water from the aquifer might show increased discharge and well hydrographs should show water-level rises. Examination of streamflow hydrographs presented in Lappala (1978) show no trend in increased discharge. Of the available water-level information for the study area, only five wells had a sufficient length of record (10 to 20 years) prior to 1955 for evaluating trends in water levels. Evaluation of the water-level data from these five wells (one in Perkins County, two in Dundy County, and two in Chase County) indicated different trends. The well in Perkins County (11N-39W-35DDD) indicated a steady rise in water level of about 0.4 ft/yr and the two wells in Chase County (7N-38W-20DD and 7N-38W-28CC) showed a very slight rise in water levels averaging less than 0.1 ft/yr. The two wells in Dundy County showed opposite trends, one with a rising water level (1N-37W-7AAB) of about

0.4 ft/yr and the other with a declining water level (2N-37W-36DB) of about 0.4 ft/yr. These very limited data indicate that there could have been rising water levels in the study area (nonsteady-state conditions) between the turn of the century and the beginning of irrigation development (in the 1950's). If so, these rises probably would be related to increased recharge from precipitation as a result of cultivation.

No large scale water-level rises have been reported by previous studies prior to irrigation development so the magnitude of any water-level rise would have to be small. After evaluating the effects of various recharge rates on water-level change in the aquifer, a recharge rate of 1 in/yr applied to the cultivated land was selected as the maximum rate that could go undetected during the period between the turn of the century and the 1950's. This rate of recharge would result in an average annual rise in the water table throughout the study area of about 0.5 ft/yr or 25 feet of rise from 1900 to 1950. It is very unlikely that a water-level rise of this magnitude across the entire study area would not have been documented.

The volume of water that could be supplied to the aquifer during 1975-83 was calculated using the maximum recharge rate of 1 in/yr applied to cultivated land. The average amount of cropland in the study area was estimated from the Census of Agriculture (U.S. Department of Commerce, 1974-82). Table 8 shows the average cropland, compiled from the 1974, 1978, and 1982 Census of Agriculture data, for each county (Dundy data modified to include only area north of Republican River) and the study area. The maximum in acre-feet was calculated by multiplying the acres of cropland (table 8) by 0.75 foot (1 inch of recharge per year for 9 years equals 9 inches or 0.75 foot). The maximum recharge that could be caused by cultivation for 1975-83 was estimated to be 674,300 acre-feet for the study area, 216,400 acre-feet for Chase County, 133,300 acre-feet for Dundy County, and 324,600 acre-feet for Perkins County.

Table 8.--*Average amount of cropland in Chase, Dundy, and Perkins Counties during 1975-83*

[Average cropland is the mean of the acreages for cropland reported by the U.S. Department of Commerce (1974-82) for 1974, 1978, and 1982 acreages for Dundy County adjusted to represent only the area north of the Republican River]

Area	Total land area (acres)	Average area of cropland (acres)	Average area of cropland (percentage of total land area)
Chase County	569,728	288,539	51
Dundy County	512,890	177,754	35
Perkins County	566,080	432,785	76
Three-county area	1,648,698	899,078	55

Estimates of Recharge Caused by Irrigation

Recharge caused by irrigation represents that part of the water, in excess of recharge caused by cultivation practices, that resupplies the aquifer beneath the irrigated land. It includes a combination of return flow of applied irrigation water and enhanced recharge from precipitation on irrigated land. Irrigation may cause additional recharge from precipitation because of the increased moisture in the soil profile that was provided by the applied water. Estimates of recharge caused by irrigation were calculated for 1975-83 as shown in table 9. The estimates of recharge caused by irrigation are presented as a range in values that depend on specific-yield estimates and the assumed recharge from precipitation on cultivated land.

The maximum amount of recharge caused by irrigation (table 9) would occur if (1) there was no recharge from precipitation on cultivated land, and (2) the minimum specific yield for the aquifer material was used to calculate change in storage. In this case, estimates of recharge caused by irrigation vary from 70 percent of pumpage in Perkins County to 79 percent of pumpage in Chase County, and average 76 percent of pumpage for the study area. The minimum amount of recharge caused by irrigation (table 9) would occur if recharge from precipitation on cultivated land was 1.0 in/yr, and the maximum specific yield for the aquifer material was used to calculate change in storage. In this case, estimates of recharge caused by irrigation vary from -5 percent of pumpage in Perkins County to 41 percent of pumpage in Chase County, and average 28 percent of pumpage for the study area. The -5 percent in Perkins County indicates a slight increase in the volume of water in storage in the aquifer.

The range in estimated recharge caused by irrigation is summarized in figure 10. The diagonal lines in the figure show the relation of estimated recharge caused by irrigation (as a percentage of pumpage) to specific yield for conditions of (1) no recharge from cultivated land, and (2) 1 in/yr of recharge from precipitation on cultivated land. The shaded area between the lines graphically represents the range of estimated recharge that could be caused by irrigation (as a percentage of pumpage) presented in table 9.

CONCLUSIONS

Pumpage and change in ground-water storage were compared in this study. Although a number of assumptions were made, the analysis of potential errors indicated that the estimates for pumpage and the range of estimates developed for change in storage are realistic for the study area for 1975-83. This study found that specific-yield estimates--a key component in computing change in storage--can differ widely. Additional research to determine specific yield is needed. The study also showed that greater understanding of the effects of cultivation on recharge is needed. Although both of these factors affect change in storage in the aquifer, errors in estimates of specific yield potentially have a much greater effect on change in storage than errors in estimates of recharge resulting from cultivation of the land.

The results of this study indicate that a substantial amount of recharge to the aquifer occurs as a result of irrigation. Estimates of recharge caused by irrigation ranged from a minimum of 953,200 acre-feet (28 percent of pumpage) to a maximum of 2,611,200 acre-feet (76 percent of pumpage) for the 9-year study period. The actual amount of recharge caused by irrigation probably is between these extremes. These results are important for predicting the effects of future pumpage on change in ground-water storage. If, in fact, a large part (28 to 76 percent) of pumpage is resupplied to the aquifer as a direct result of recharge caused by irrigation, reductions in pumpage associated with increased efficiency in irrigation practices may not result in comparable savings of water in the aquifer. A reduction in the amount of applied water would also reduce the potential for recharge from irrigation.

Table 9.--*Comparison of pumpage with estimates of recharge caused by irrigation computed using three estimates of specific yield and two estimates of recharge from precipitation on cultivated land*

Area	Pumpage (acre feet)	Recharge caused by irrigation					
		Minimum specific yield		Original specific yield		Maximum specific yield	
		(acre-feet)	(percentage of pumpage)	(acre-feet)	(percentage of pumpage)	(acre-feet)	(percentage of pumpage)
No recharge from precipitation on cultivated land							
Chase County	1,680,900	1,327,000	79	1,249,300	74	904,000	54
Dundy County	907,400	701,300	77	639,700	70	439,000	48
Perkins County	836,700	582,900	70	493,700	59	284,500	34
Study area	3,425,000	2,611,200	76	2,382,700	70	1,627,500	48
One inch of recharge from precipitation on cultivated land							
Chase County	1,680,900	1,110,600	66	1,032,900	61	687,600	41
Dundy County	907,400	568,000	63	506,400	56	305,700	34
Perkins County	836,700	258,300	31	169,100	20	-40,100	-5
Study area	3,425,000	1,936,900	57	1,708,400	50	953,200	28

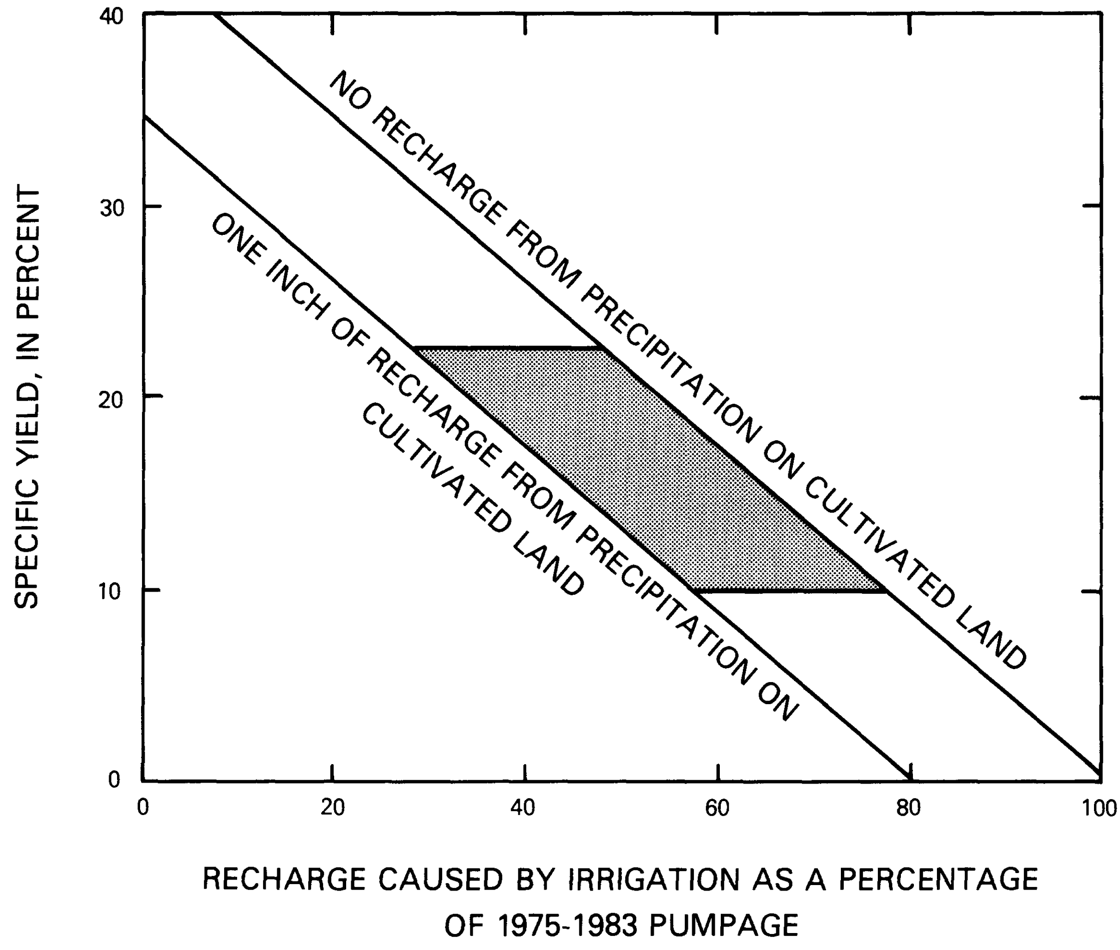

Figure 10.--Relation of estimates of recharge caused by irrigation to estimates of specific yield and recharge from precipitation on cultivated land.

REFERENCES CITED

Ferrigno, C.F., 1986a, A data-management system for detailed areal interpretive data: U.S. Geological Survey Water-Resources Investigations Report 86-4091, 103 p.

_____ 1986b, Machine-readable files from the High Plains regional aquifer-system analysis in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 86-4063, 23 p.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B, 63 p.

Heimes, F.J., and Luckey, R.R., 1982, Method for estimating historical irrigation requirements from ground water in the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 82-40, 64 p.

Heimes, F.J., Luckey, R.R., and Stephens, D.M., 1986, Evaluation of sampling methods used to estimate irrigation pumpage in Chase, Dundy, and Perkins Counties, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 86-4092, 27 p.

Johnson, A.I., 1967, Specific yield - compilation of specific yields for various materials: U.S. Geological Survey Water-Supply Paper 1662-D, 74 p.

Lappala, E.G., 1978, Quantitative hydrogeology of the Upper Republican Natural Resources District, southwest Nebraska: U.S. Geological Survey Water-Resources Investigations Report 78-38, 200 p.

Leonard, G.J., and Huntoon, P.W., 1974, Groundwater geology of southwest Nebraska Ground Water Conservation District: Nebraska Water Survey Paper No. 37, 37 p.

Luckey, R.R., and Ferrigno, C.F., 1982, A data-management system for areal interpretive data for the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 82-4072, 112 p.

Mackey, G.W., 1987, Comparison of irrigation pumpage and change in water storage of the High Plains aquifer in Castro and Parmer Counties, Texas, 1975-83: U.S. Geological Survey Water-Resources Investigations Report 87-4032, 48 p.

Stephens, D.M., Heimes, F.J., and Luckey, R.R., 1984, Irrigation data from Chase, Dundy, and Perkins Counties, southwestern Nebraska, 1983: U.S. Geological Survey Open-File Report 84-471, 31 p.

Stephens, D.M., Heimes, F.J., and Luckey, R.R., 1985, Irrigation data from Chase, Dundy, and Perkins Counties, southwestern Nebraska, 1984: U.S. Geological Survey Open-File Report 85-164, 32 p.

Thelin G.P., and Heimes, F.J., in press, Mapping irrigated agriculture from Landsat for determination of water use from the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-C.

U.S. Department of Commerce, 1974-82, Census of agriculture: Bureau of the Census, agricultural data for 1974, 1978, and 1982 for Nebraska.

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