EFFECTS OF CLIMATE, VEGETATION, AND SOILS ON CONSUMPTIVE WATER USE AND GROUND-WATER RECHARGE TO THE CENTRAL MIDWEST REGIONAL AQUIFER SYSTEM, MID-CONTINENT UNITED STATES

By Jack T. Dugan and Jon M. Peckenpaugh

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ILLUSTRATIONS

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CONVERSION OF INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI)

Multiply Inch-Pound Units	By	To Obtain SI Units
foot (ft)	0.3048	meter
inch (in.)	25.40	millimeter
square mile (mi^2)	2.509	square kilometer
degree Fahrenheit (°F)	(°F -32)/1.8	degree Celsius

GLOSSARY OF SELECTED TERMS

Actual evapotranspiration (AET). The actual, consumptive water use of a given vegetation or crop type under certain soil-moisture conditions. It is a function of the consumptive water requirement (CWR) of the vegetation or crop type and the availability of soil moisture within a certain root-zone depth. In this report AET equals CWR minus the soil-moisture deficit and is expressed in inches of water.

Available water capacity (AWC). The capacity of the soil to hold water for use by most plants. It is the difference between the amount of water in the soil at field capacity and the wilting point. It is largely dependent on soil texture, with coarse-textured materials such as sand having the least capacity and silts having the highest. It is expressed as inches of water per inch of soil.

Consumptive irrigation requirement (CIR). In this report it is the amount of supplemental water required to keep the available water capacity for a given soil and root-zone depth at 50 percent of capacity during the irrigation season of June through August. This value, expressed as inches of water, varies with crop type and is dependent on the consumptive water requirement (CWR).

Consumptive water requirement (CWR). The seasonal or monthly water demands of specific vegetation or crop types in relation to potential evapotranspiration (PET). The assumption is that water availability is not a limiting factor. CWR is expressed as a ratio, fraction, or percentage of PET.

Deep percolation (DP). The water that moves through the soil zone and is no longer available to plants and becomes potentially available for ground-water recharge. It is computed in this report as moisture that exceeds the consumptive water requirement (CWR) and water-storage capacity of the soil as expressed by the available water capacity (AWC) for a given root-zone depth.

Infiltration. The movement of water into the soil. It is a function of the soil's surface permeability, the surface cover characteristics (vegetation), and topographic conditions, and is expressed in inches per hour.

Percent of possible sunshine. The percent of potential daylight hours that are not overcast or that solar radiation reaching the earth's surface (solar radiation) is not obscured by cloud cover or dense haze. It is independent of the number of hours of daylight and the intensity of solar radiation. Furthermore, it does not imply completely cloud-free sky conditions. Percent possible sunshine is computed by dividing the number of hours or minutes of sunshine, measured by a sunshine recorder, by the potential number of hours or minutes of sunshine for a given day of the year.

Permeability. The rate at which soil, under saturated conditions, transmits water in a vertical direction under a unit head of pressure. It is a function of the soil's physical properties of texture, structure, and porosity and is expressed in inches per hour.

Potential evapotranspiration (PET). The loss of water that would occur from the soil (evaporation) and through plants (transpiration) if the availability of water is not a limiting factor. The assumption is that the surface is completely covered with healthy, continuously growing vegetation, and there are no limitations caused by soil characteristics (Mather, 1974; Jensen, 1974). It is largely a function of solar radiation, air temperature, humidity, and wind velocity. Alfalfa is frequently used as a comparative standard. PET is expressed in inches of water in this report.

Root-zone depth. The depth or thickness in which the root system of specific vegetation or crop types can actively utilize available soil moisture. It is expressed in inches.

Soil-moisture deficit (STD). The difference between the amount of water required to meet the consumptive water requirement (CWR) and the water available within the plant root zone (STD equals CWR minus available water). STD is expressed in inches of water.

Surface runoff. Precipitation that does not infiltrate the soil and is not available for consumptive water use or ground-water recharge. It is largely a function of soil permeability, soil slope, and vegetative cover. In this report it is expressed in inches and is calculated as precipitation minus infiltration equals surface runoff.

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ABSTRACT

The Central Midwest regional aquifer system, in parts of Arkansas, Colorado, Kansas, Missouri, Nebraska, New Mexico, South Dakota, and Texas, is a region of great hydrologic diversity. This study examines the relationships between climate, vegetation, and soil that affect consumptive water use and recharge to the ground-water system. Computations of potential recharge and consumptive water use were restricted to those areas where the aquifers under consideration were the immediate underlying system.

The principal method of analysis utilizes a soil-moisture computer model. This model requires four types of input: (1) Hydrologic properties of the soils, (2) vegetation types, (3) monthly precipitation, and (4) computed monthly potential evapotranspiration (PET) values. The PET simulation is based on the Jensen-Haise method, which requires monthly solar radiation and temperature data.

The climatic factors that affect consumptive water use and recharge were extensively mapped for the study area. Nearly all the pertinent climatic elements confirmed the extreme diversity of the region. PET and those factors affecting it--solar radiation, temperature, and humidity--show large regional differences; mean annual PET ranges from 36 to 70 inches in the study area.

Precipitation shows even greater regional variation, with mean annual precipitation ranging from less than 12 inches in parts of eastern Colorado to more than 50 inches in parts of Arkansas. Furthermore, the variability of annual precipitation tends to increase as average annual precipitation decreases.

The seasonal climatic patterns indicate significant regional differences in those factors affecting seasonal consumptive water use and recharge. In the southern and western parts of the study area, consumptive water use occurs nearly the entire year; whereas, in northern parts it occurs primarily during the warm season (April through September).

Results of the soil-moisture program, which add the affects of vegetation and the hydrologic characteristics of the soil to computed PET values, confirm the significant regional differences in consumptive water use or actual evapotranspiration (AET) and potential ground-water recharge. Under two different vegetative conditions--the 1978 conditions and pre-agricultural conditions consisting of only grassland and woodland--overall differences in recharge were minimal. Recharge values were significantly different from pre-agricultural conditions only in selected areas where tame hay (principally alfalfa) or fallow acreages were appreciable.

Mean annual recharge under both conditions averaged slightly more than 4.5 inches for the entire study area, but ranged from less than 0.10 inch in eastern Colorado to slightly more than 15 inches in Arkansas. Patterns of annual recharge closely paralleled yearly and cool season precipitation (October through March). It was concluded that climatic effects dominated overall regional recharge patterns in the study area, with local variations resulting from differences in vegetation and soil.

INTRODUCTION

The process is quite complex by which precipitation that falls on the earth's surface ultimately reaches an underlying aquifer as natural recharge. Precipitation, which potentially is available for ground-water recharge, is subjected to the effects of climate, vegetation, and soils. Usually, only a small amount of this precipitation becomes available for recharge, with the remainder being returned to the atmosphere through the process of evapotranspiration or to the sea as surface runoff.

The mathematical simulation of an aquifer system requires a careful assessment of recharge to that system, particularly the spatial differences. Because actual measurement of recharge over large areas is not possible, an estimation process based on those factors affecting recharge must be used.

Purpose and Scope

The purpose of this report is to analyze and discuss those climatic, vegetative, and soil characteristics that affect consumptive water use and natural recharge to aquifer systems in the Central Midwest Regional Aquifer-Systems Analysis (CMRASA) in parts of Arkansas, Colorado, Kansas, Missouri, Nebraska, New Mexico, South Dakota, and Texas. This report resulted from a study in which the principal objective was to compute potential recharge in those selected areas as input to a ground-water model. Figure 1 indicates the location of the CMRASA study area and those parts included within this study.

The CMRASA study is concerned principally with aquifers composed of materials of Cretaceous age or older. This report is restricted to those parts of the study area where these aquifers are the uppermost ground-water system, because climatic, vegetative, and soil conditions directly affect natural recharge only to the uppermost aquifer. The major aquifers composed of Tertiary age and younger materials, therefore, are excluded from this analysis. These units are contained in the High Plains Regional Aquifer-Systems Analysis Project.

This report is organized in a manner that follows the natural sequential processes of consumptive water use and ground-water recharge. The section following the Introduction examines those factors that affect consumptive water use and includes a detailed discussion of those climatic elements that affect potential evapotranspiration (PET) and the resultant PET patterns. Next, the effects of vegetation and soils are added to the PET to determine consumptive water use or actual evapotranspiration losses. An examination of precipitation patterns follows in order to provide a perspective on the relationship between water needs and the availability of water to meet those needs. The final major section discusses the potential recharge patterns of the study area calculated through computer analyses of the data.

Location and General Characteristics of the Study Area

The geographic extent and location of the study area, containing about 275,000 square miles and spanning nearly 10 degrees of latitude (fig. 1), preordains a certain degree of potential diversity in the factors affecting consumptive water use and ground-water recharge. The study area occupies a mid-latitude continental location, where an abrupt transition between polar and tropical climatic conditions occur. The abruptness of this transition is most evident during the cool season (October through March) when strong regional contrasts exist among the several climatic factors. Three distinctively different global climatic types occur within the study area -- humid subtropical in the southeast, subhumid continental in the north, and semiarid in the west.

Vegetation of the study area is quite diverse. Woodlands and grasslands used for grazing predominate, but large areas suitable for cultivation are used for a variety of row crops, winter wheat, alfalfa, and fallow.

The characteristics of the soils that are hydrologically significant span a broad continuum within the study area. These range from deep, silty soils with minimal slopes formed on loess or alluvium deposits to thin, rocky soils formed on steep uplands from bedrock. Dugan (1985) provides a more complete description of the soils of the study area.

Sources of Data

The climatic information required for this study, including temperature, sunshine, and precipitation data, are published by the National Oceanic and Atmospheric Administration (NOAA) in monthly, annual, and 10-year summaries. For this study, the climatic data base consists of data derived from 99 precipitation stations, 27 temperature stations, and 12 solar (percent of possible sunshine) stations. Observed monthly data for the period of study (1951-80) were used for these climatic factors. Only those stations with complete, continuous records for the 30-year period were used. The objective was to obtain a relatively uniform distribution of observation points for each climatic factor. Data from metropolitan areas were avoided where possible because of possible anomalous urban influences.

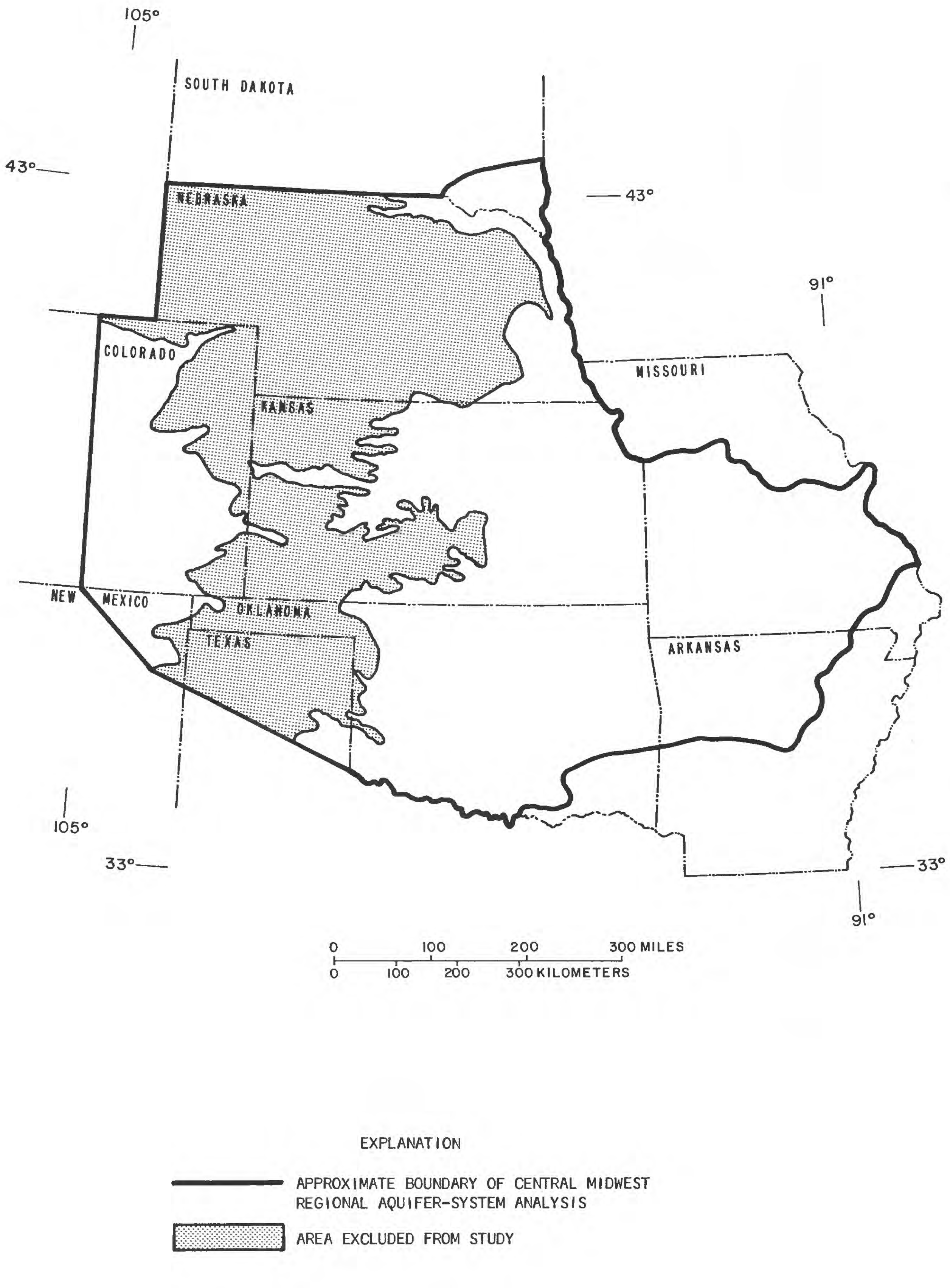


Figure 1.--Location of study area.

Land-use data, by county, which provided vegetation patterns, were derived from 1978 statistics collected for the census of agriculture (U.S. Department of Commerce, 1980). Changes in vegetation have occurred during the period of study, but those changes were gradual and generally small, and a detailed analysis of them is not warranted for this generalized study. The soils information used in this study was derived from a separate report by Dugan (1985), which consists of quantitative descriptions and areal distributions of the soils in the study area based on their hydrologic characteristics.

Methods of Analysis

The estimation of consumptive water use and natural recharge for a region as extensive and diverse as the study area requires relatively complex mathematical calculations using the large amounts of input data previously discussed. These estimates are derived from computer programs that calculate potential evapotranspiration (PET), soil-moisture, and water-use or pumpage. The PET program is based on the Jensen-Haise solar-radiation method (Jensen and Haise, 1963; Jensen and others, 1970); the soil-moisture program was developed by the U.S. Bureau of Reclamation and modified by Lappala (1978) and by Peckenpaugh and Dugan (1983); and the pumpage program was modified from Peckenpaugh and Dugan (1983).

The PET program, which is more thoroughly discussed in a subsequent section, provides values of potential evapotranspiration for the soil-moisture program from which actual evapotranspiration or consumptive use is calculated based on vegetation and soil characteristics.

Lappala (1978) discussed the conceptual operation of the soil-moisture program. The program uses a water-balance method that varies consumptive water use based on differences in the hydrologic responses of soils and the growth characteristics and rooting depths of crops or vegetation. Hydrologic responses of the soils include the infiltration-runoff characteristics and the ability of the soil to retain water (available water capacity). In addition to seasonal growth characteristics of the different types of vegetation, the infiltration-runoff characteristics of soils under different vegetative covers are considered.

The soil-moisture program accounts for moisture entering, leaving, and remaining within the soil zone. The schematic diagram shown in figure 2 indicates the basic operation of the PET and soil-moisture programs. It also is summarized in the following simple equation:

$$R = (S + P - O - E) - C$$

where

R = Recharge (deep percolation)
S = Antecedent soil moisture
P = Precipitation
O = Surface runoff
E = Actual evapotranspiration (AET)
C = Moisture storage capacity of the soil zone

This report emphasizes the precipitation (P) and actual evapotranspiration or consumptive water use (E) aspects of the study area. Moisture storage capacity of the soil zone (C) and runoff-infiltration relationships (O) are largely functions of the physical properties of the soil, principally soil slope and texture, which are discussed extensively by Dugan (1985). Soil slope and texture are extremely important to consumptive water use and potential ground-water recharge, because they affect the amount of water infiltrating to and stored within the soil zone.

The soil-moisture program calculates, on a monthly interval, moisture stored in the soil zone, moisture deficits, consumptive water use, and deep percolation or recharge. The soil zone is treated as a "bank" with available soil moisture carried over from one month to the next; therefore, antecedent soil-moisture conditions (S) affect succeeding periods of recharge or moisture deficits.

The soil-moisture program computes the results for each climatic (precipitation) station for the various possible combinations of the soils and land uses in the study area. This output is then areally distributed through a program termed "the water-use program" that weights the outputs on the basis of percentage of occurrence of the various land uses and soils within the grid elements used for the ground-water modeling of the study area. The 356 model grid elements within the study area are approximately 790 square miles each.

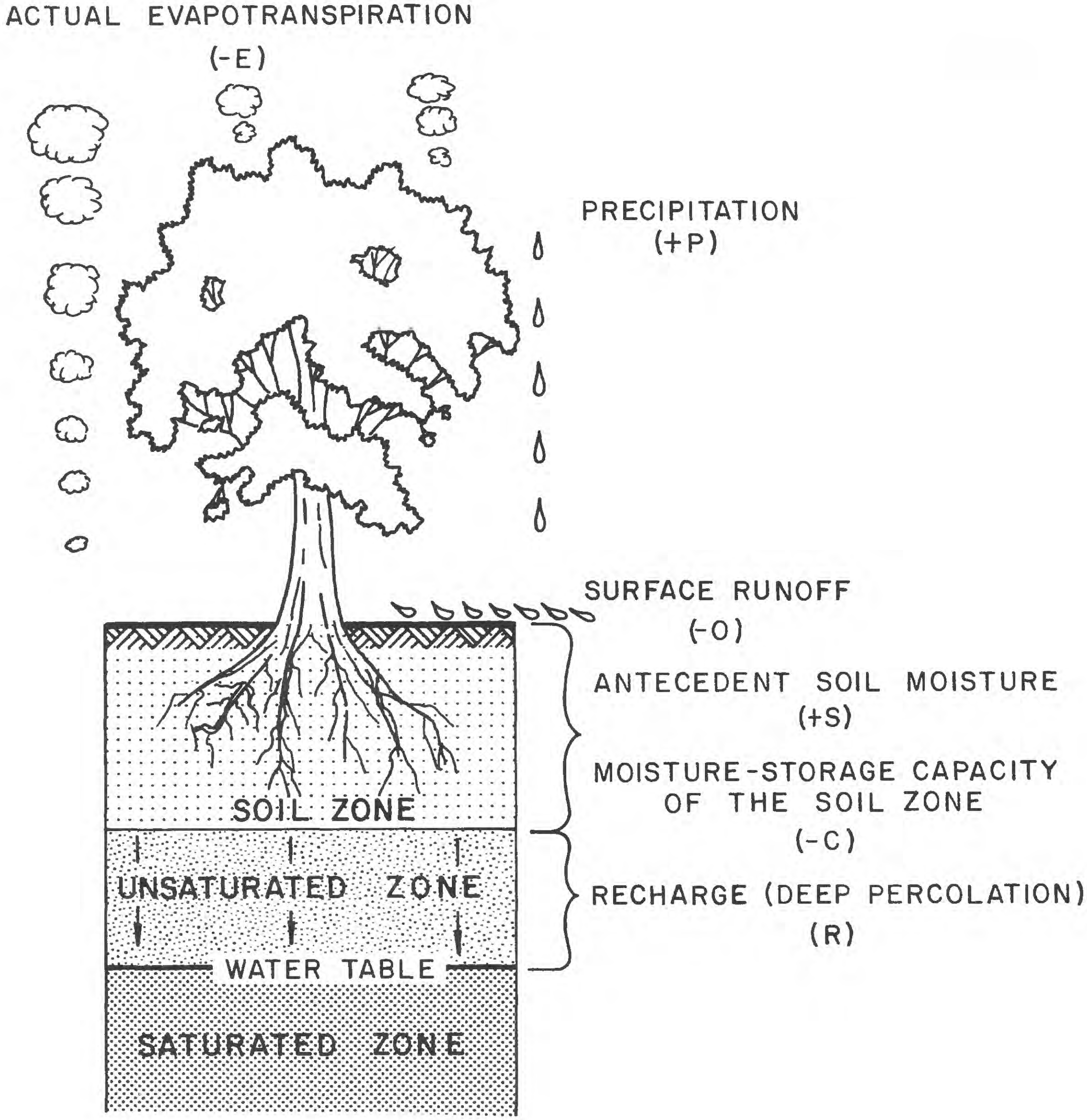


Figure 2.--Schematic diagram of the basic elements of the soil-moisture program.

An additional step in this water-use program linearly interpolates the soil-moisture program output from two or three climatic stations to the centerpoint of the grid elements that contain no climatic station. This is a weighting procedure based on the concept of a declining relationship with distance or "distance decay."

It is not the purpose of this report to discuss the detailed mechanics of the PET, soil-moisture, and water-use programs, but only to provide a conceptual framework for their operation. Documentation and program listing for the PET and soil-moisture program used in this study are presented by Cady and Peckenpaugh (1985).

ENVIRONMENTAL FACTORS AFFECTING CONSUMPTIVE WATER USE AND GROUND-WATER RECHARGE

Consumptive water use or actual evapotranspiration (AET) and the availability of water for ground-water recharge involve a complex set of interrelationships, as indicated in figure 2. Meteorological or climatic conditions are the primary controlling factors in the consumption and availability of water. The role of vegetation and soils in this process is secondary, but still significant.

To comprehend consumptive water use is to understand the process of evapotranspiration. Evapotranspiration is the combined loss of water from the soil by the processes of direct evaporation, and the loss of moisture through the physiological function of plants by the process of transpiration. On a densely vegetated surface, evapotranspiration predominantly is a function of transpiration (Mather, 1974). Both evaporation and the physiological processes of plants causing transpiration to occur are primarily a function of the availability of energy reflected in meteorological or climatic conditions.

Different types of vegetation have varying consumptive water requirements (CWR) that determine their potential rate of transpiration or water use. Both the life cycles of different plants and their responses to meteorological conditions regulate CWR over time. As will be discussed subsequently in this report, CWR varies considerably for different plant types, and this greatly affects potential ground-water recharge for variations in land use.

Soil is significant in consumptive water use in that it affects the availability of water for plants. The physical characteristics of a soil largely determine the rate of infiltration of precipitation and the ability of the soil to retain water for use by plants. Different soils with wide variations in their physical characteristics can significantly affect the amount of recharge.

The preceding phenomena are concerned with the factors affecting consumptive water use or needs. Precipitation, however, is the natural source to meet these needs and to provide water for recharge of ground-water systems. While absolute amounts of precipitation are important, the patterns of occurrence, both temporally and spatially, are equally significant.

The remainder of this section examines the environmental factors and their patterns within the study area. First, potential evapotranspiration (PET) and those climatic factors used to compute it are discussed. Next, vegetation and soils are analyzed as they affect consumptive water requirements and actual evapotranspiration (AET). Finally, precipitation, the moisture source, is examined.

Climatic Factors Affecting Potential Evapotranspiration

Potential evapotranspiration (PET) is a theoretical measurement of the amount of water loss that would occur from the soil and through the plants, assuming an adequate supply of soil moisture to meet the plants' demands existed at all times. Potential evapotranspiration is primarily a function of the combined effects of meteorological or climatological conditions. Vegetation type and soil factors, including the available water capacity, are unimportant to a theoretical measurement of potential evapotranspiration (Mather, 1974).

Several meteorological factors affect potential evapotranspiration, including net solar radiation, humidity, wind velocity, and ambient temperature. Of these, net solar radiation is by far the most significant, because it is the element that regulates the evaporation mechanism and is a principal regulator of plant growth.

Humidity, or water-vapor content of the atmosphere, affects potential evapotranspiration by affecting the rate at which the atmosphere can absorb additional water vapor. The absorptive ability of the atmosphere is expressed as the vapor-pressure gradient or saturation deficit at the evaporating surface, such as the soil or the leaf surface of a plant, and is a difficult factor to measure because it is a complex process occurring on a microscale (Mather, 1974).

Wind tends to create turbulence and eddy currents in the atmosphere that transport water vapor away from the evaporating or transpiring surface, thus maintaining the vapor-pressure gradient. Because of the extreme spatial and temporal variability in wind velocity, this factor has also been difficult to measure.

Temperature has a less direct relationship with evapotranspiration, but is a strong indicator of potential soil-moisture consumption. The ability of the atmosphere to hold water vapor increases greatly with temperature (by a factor of 10, from 30° to 100°F). Also, higher temperatures enhance moisture loss by affecting rates of plant growth, determining the length of the growing season, and increasing the effectiveness of solar radiation in the evaporation process.

Several methods, based on commonly available data, exist for estimating potential evapotranspiration. One of the most reliable and accurate approaches for a variety of climates is the Penman combination method using solar radiation, vapor pressure, and wind velocity (Barry, 1973). This method, however, requires meteorological data, vapor pressure, and wind velocity, and these data are not readily available. Simplistic methods, such as Thornthwaite (Barry, 1973) and Blaney-Criddle (Chow, 1964) that require only mean monthly temperature, have frequently been proven to be unreliable for such diverse climatic conditions as occur within this study area (Peckenpaugh, 1980).

The method selected for this study is the Jensen-Haise method, which has been shown to be quite reliable for diverse climates, particularly for semiarid conditions (Robb, 1966; Jensen and Haise, 1963, Jensen and others, 1969; Jensen, 1974; Peckenpaugh, 1980). The Jensen-Haise method is based primarily on solar radiation, similar to the Penman approach but without a requirement for the wind velocity factor and with a modified technique of estimating humidity. The general equation for the Jensen-Haise method is as follows (from Jensen and others, 1970, p. 32-33, and Lappala, 1978, p. 34-35):

$$PET = R_s C \, (T - T_p)$$

where

PET = monthly potential evapotranspiration, in inches;

R_s = total monthly solar radiation, in inches of evaporation equivalent;

= $.000673\ R_L$

where R_L = total monthly radiation, in langleys;

C = air temperature coefficient for a given location and

= $1/\ [68 - 0.0036E + 650/(e_2 - e_1)]$

where E = altitude, in feet (to adjust for the environmental lapse rate effect);

e_2 = saturation vapor pressure of water, in millibars, for the mean maximum air temperature in the warmest month of the year;

= $-5.53 + 0.5234\ MAX - 0.0085\ MAX^2 + 0.000104\ MAX^3$

MAX = mean maximum air temperature of warmest month.

e_1 = saturation vapor pressure of water, in millibars, at the mean minimum air temperature for warmest month of the year;

= $-5.53 + 0.5234\ MIN - 0.0085\ MIN^2 + 0.000104\ MIN^3$

MIN = mean minimum air temperature of warmest month.

T = mean monthly air temperature, °F

T_p = a constant for a given location and

= $27.5 - 0.25\ (e_2 - e_1) - (E/1{,}000)$.

Solar Radiation

As was discussed above, solar radiation is the most significant single factor affecting potential evapotranspiration; this is particularly evident in the Jensen-Haise method. Only a few sites exist in the study area where actual solar radiation is measured, and at most of these sites the data are not complete for the period of study (1951-80). Therefore, solar radiation was computed for sites recording percent of possible sunshine or cloud-cover data.

Jensen and Haise (1963) and Lappala (1978), among others, used a method developed by Fritz and MacDonald (1949) based on a series of maps of potential solar radiation from Fritz (1949) with the following equation:

$$R = R_p (0.61 S + 0.35)$$

where

R = mean daily radiation, in langleys (gm cal/cm^2);

R_p = radiation, in langleys, on cloudless days (from Fritz, 1949);

S = percent of possible sunshine.

This equation, however, was considered to be too general for a region as diverse as the study area. Therefore, an alternate method was adopted based on an equation derived by multiple regression using the actual physical factors affecting solar radiation and observed solar radiation data (Dugan, 1978). The equation assumes the following form:

$$R = 281.90S + 4.24A + 38.91D + 0.01E - 441.91$$

where

R = mean daily radiation, in langleys (gm cal/cm^2);

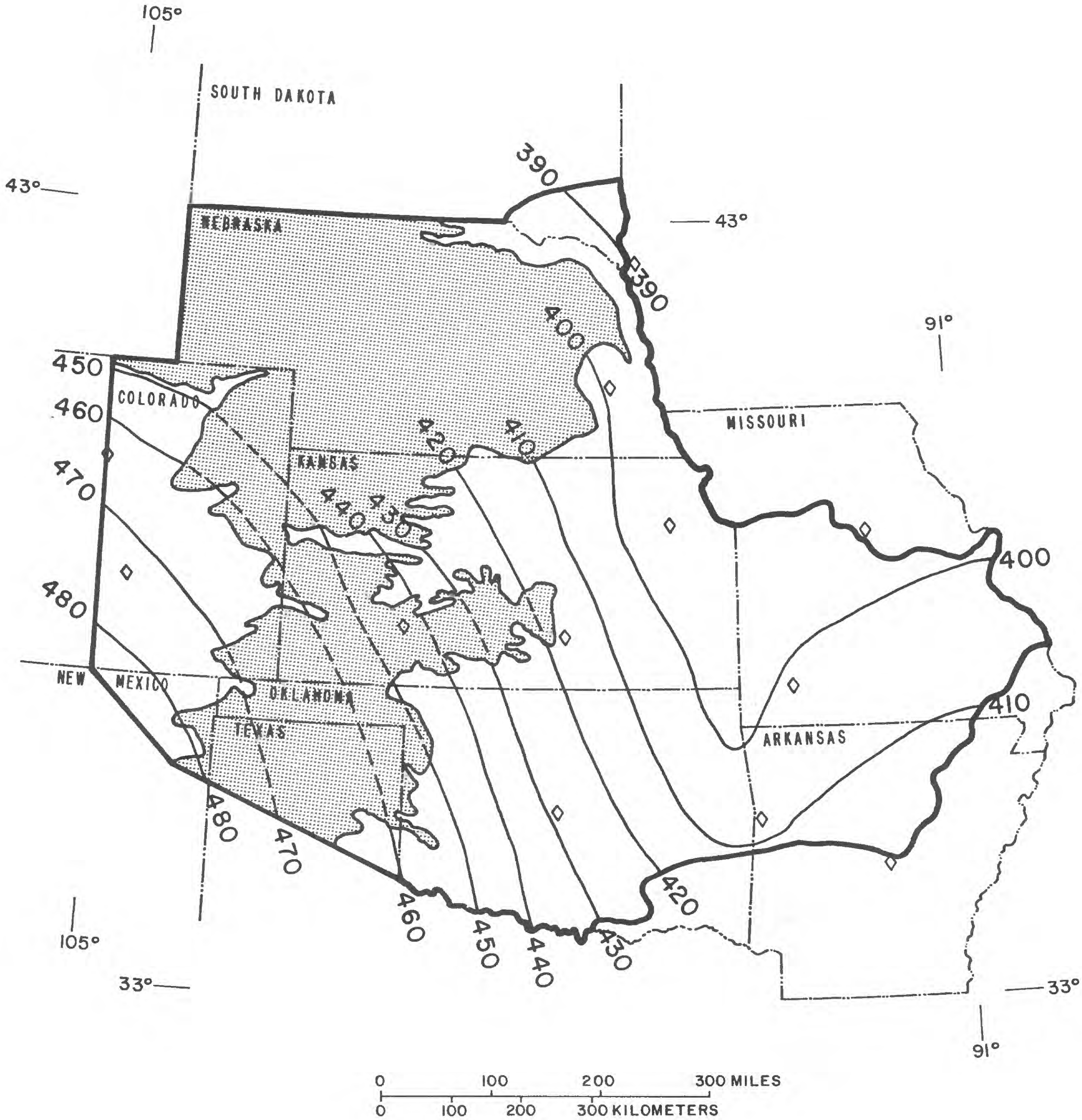
S = percent of possible sunshine (expressed as a fraction) for month;

A = angle of sun's inclination at zenith (noon) for midpoint of each month;

D = hours of possible sunshine (midpoint of month);

E = altitude of site, in feet, above sea level.

The preceding equation, based on 72 degrees of freedom (n-size of 77), has a standard error of estimate of 20.98 and an R^2 (coefficient of explanation) of 0.98 when regressed against observed data. Thus, the equation appears to reasonably estimate the solar radiation.



EXPLANATION

—460— LINE OF EQUAL SOLAR RADIATION--Dashed where inferred. Interval 10 ℓangleys (1 ℓangley = 1 gram calorie per square centimeter)

◇ STATION MEASURING PERCENT OF POSSIBLE SUNSHINE

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 3.--Computed mean annual daily solar radiation, 1951-80.

Table 1.--Monthly midpoint of solar angle and daylight at "percent of possible sunshine" stations

[Solar angle given in degrees (zero aspect) and daylight given in hours; values rounded to nearest tenth]

Station	Altitude above sea level	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Fort Smith, Ark.	458												
Solar angle		37.4	46.7	53.2	61.3	69.1	76.9	72.0	64.0	56.2	48.5	40.1	33.0
Daylight1/		10.0	10.8	12.0	13.0	13.9	14.6	14.3	13.5	12.3	11.2	10.1	9.6
Little Rock, Ark.	257												
Solar angle		38.0	47.3	53.8	61.9	69.7	77.5	72.6	64.6	56.8	49.1	40.7	33.6
Daylight		10.1	10.9	12.0	13.0	13.9	14.6	14.3	13.5	12.3	11.3	10.3	9.7
Oklahoma City, Okla.	1,280												
Solar angle		37.3	46.6	53.1	61.3	69.0	76.8	71.9	63.9	56.1	48.4	40.4	32.9
Daylight		10.0	10.8	12.0	13.0	13.9	14.6	14.3	13.5	12.3	11.2	10.1	9.6
Columbia, Mo.	778												
Solar angle		33.7	43.0	49.5	57.7	65.4	73.2	68.3	60.3	52.5	44.8	36.8	29.3
Daylight		9.7	10.7	12.0	13.1	14.3	14.9	14.7	13.7	12.4	11.1	10.1	9.4
Springfield, Mo.	1,265												
Solar angle		35.5	44.8	51.3	59.5	67.2	75.0	70.1	62.1	54.3	46.6	38.6	31.1
Daylight		9.9	10.7	12.0	13.0	14.1	14.8	14.5	13.7	12.4	11.1	10.1	9.5
Topeka, Kans.	879												
Solar angle		33.6	42.9	49.4	57.6	65.3	73.1	68.2	60.2	52.4	44.7	36.7	29.2
Daylight		9.7	10.7	12.0	13.2	14.3	14.9	14.7	13.8	12.4	11.1	10.1	9.4
Wichita, Kans.	1,372												
Solar angle		35.0	44.3	50.8	59.0	66.7	74.5	69.6	61.6	53.8	46.1	38.1	30.6
Daylight		9.8	10.7	12.0	13.1	14.2	14.8	14.6	13.7	12.4	11.1	10.1	9.4
Dodge City, Kans.	2,594												
Solar angle		34.9	44.2	50.7	58.9	66.6	74.4	69.5	61.5	56.7	46.0	38.0	30.1
Daylight		9.8	10.7	12.0	13.1	14.2	14.8	14.6	13.7	12.4	11.1	10.1	9.4
Lincoln, Nebr.	1,150												
Solar angle		31.8	41.2	47.7	55.9	63.6	71.4	66.5	58.4	50.7	43.0	35.0	27.5
Daylight		9.5	10.8	12.0	13.3	14.5	15.1	14.9	13.8	12.4	11.1	10.0	9.2
Sioux City, Iowa	1,095												
Solar angle		30.3	39.6	46.1	54.3	62.0	69.8	64.9	56.9	49.1	41.4	33.4	25.9
Daylight		9.4	10.5	12.0	13.3	14.6	15.3	15.0	13.9	12.4	11.1	9.9	9.1
Denver, Colo.	5,292												
Solar angle		32.9	42.2	48.7	56.9	64.6	72.4	67.5	59.5	51.7	44.0	36.0	28.5
Daylight		9.6	10.6	12.0	13.2	14.4	15.0	14.8	13.8	12.4	11.1	10.0	9.3
Pueblo, Colo.	4,637												
Solar angle		34.4	43.7	50.2	38.4	66.1	73.9	69.0	61.0	53.2	45.5	37.5	30.0
Daylight		9.8	10.7	12.0	13.1	14.2	14.8	14.6	13.7	12.4	11.1	10.1	9.4

1/ Daylight hours based on Chow (1964, p. 21-9).

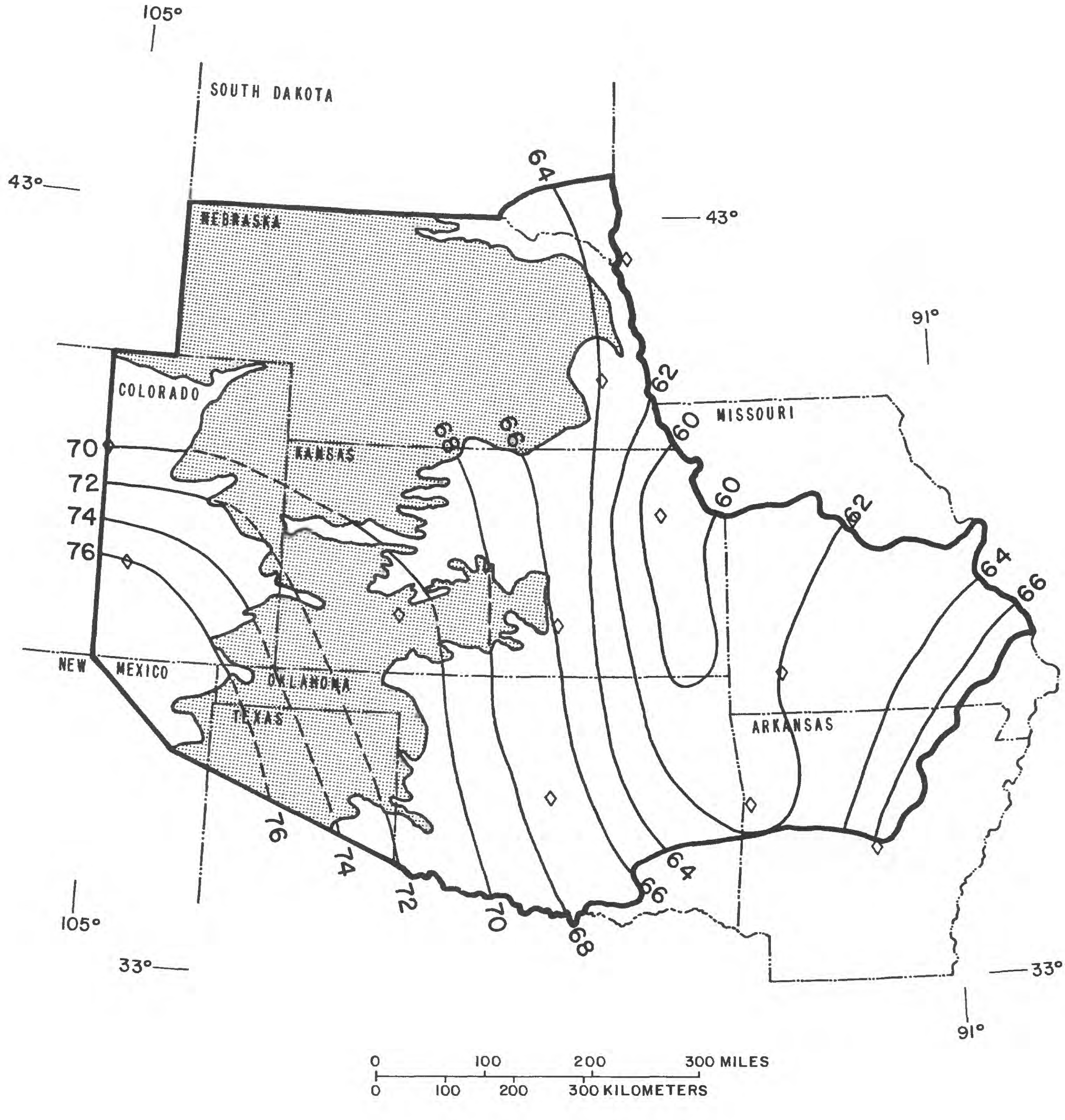
Using this linear equation derived from regression, mean daily solar radiation was calculated monthly for 12 sites shown in figure 3. These sites are those in or near the study area containing complete records of percent of possible sunshine data. In addition to sunshine data, the angle of the sun's inclination and daylight hours were calculated for the midpoint of each month at these sites (table 1). These data along with a constant factor (altitude) at each site, were then used to calculate mean daily solar radiation values, in langleys (gm cal/cm^2), for each month.

Computed mean daily solar radiation for the study area is shown in figure 3. Solar radiation increases nearly 20 percent across the study area from northeast to southwest. This difference is largely accounted for by: (1) increased percent of possible sunshine, or cloudless conditions (fig. 4), (2) increased solar angle resulting from latitudinal differences (approximately 8 degrees across the study area), and (3) increased altitude from east to west (from less than 300 ft to more than 5,000 ft).

Regional differences in solar radiation are most striking in the low-sun period, or winter. The solar radiation during December, as shown in figure 5, indicates that the northeast part of the study area receives less than 60 percent of the radiation received in the extreme southwest. This is a result of a combination of factors, including an increase in percent of possible sunshine (fig. 6) from east to west, and an increase in daylight hours from north to south.

Regional differences in solar radiation are significantly moderated in high-sun periods, or summer, during which the increase of daylight hours compensates for the lower sun angle from south to north (approximately 30 minutes longer from south to north). Also, regional differences in percent of possible sunshine (fig. 7) are less in June than in December. In June, areas with the lowest solar radiation receive approximately 10 percent less than areas with the highest solar radiation (fig. 8).

A comparison of seasonal extremes between June and December indicates a significant difference in solar energy received, which is 2 to 3.5 times greater in June than in December. This affects potential as well as actual seasonal evapotranspiration patterns.



EXPLANATION

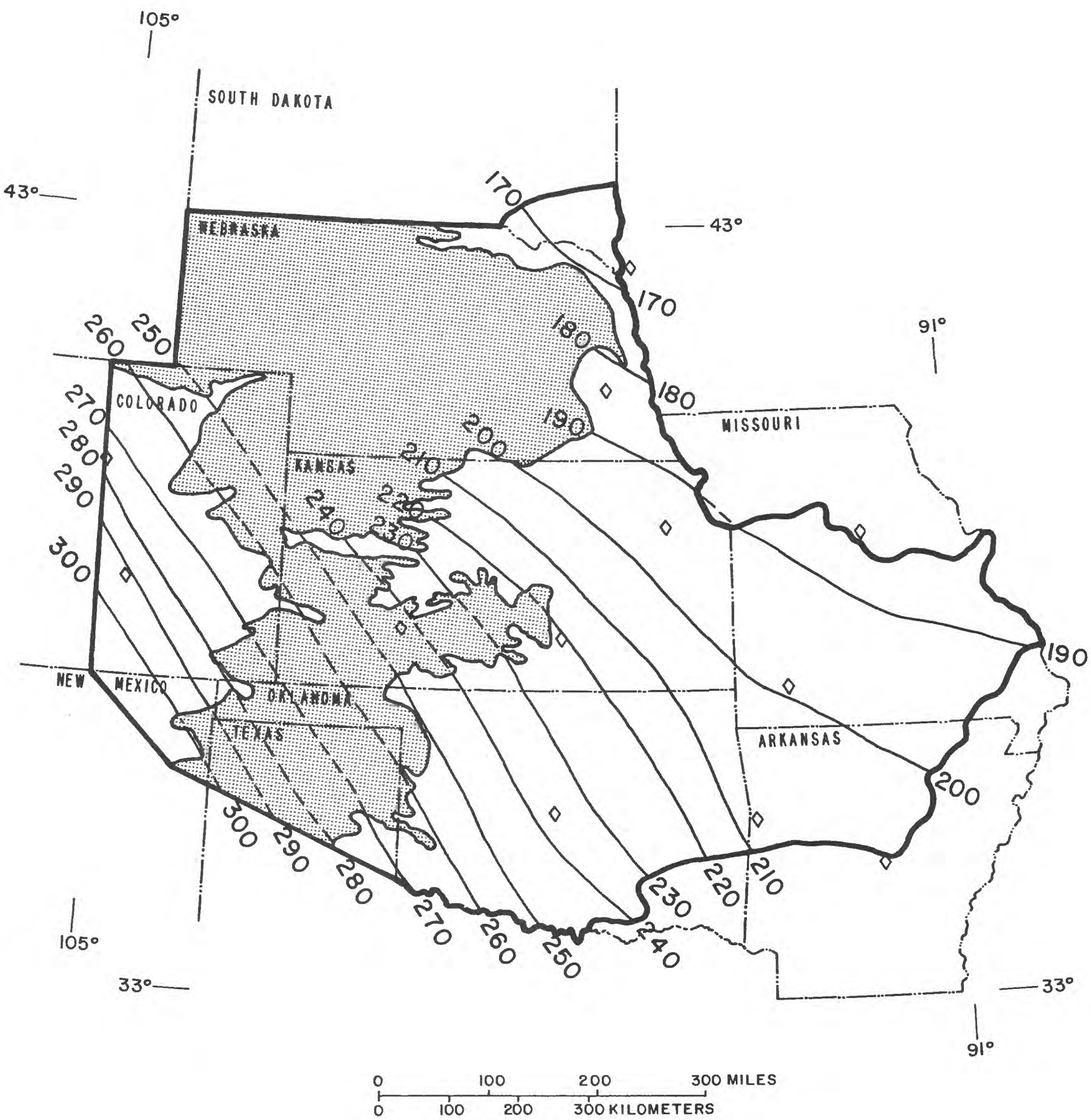
—72— — LINE OF EQUAL PERCENT OF POSSIBLE SUNSHINE-- Dashed where inferred. Interval 2 percent

◇ STATION MEASURING PERCENT OF POSSIBLE SUNSHINE

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 4.--Mean annual percent of possible sunshine, 1951-80.



EXPLANATION

— 250 — — LINE OF EQUAL PERCENT OF POSSIBLE SUNSHINE--Dashed where inferred. Interval 10 ℓangleys (1 ℓangley = 1 gram calorie per centimeter)

◇ STATION MEASURING PERCENT OF POSSIBLE SUNSHINE

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 5.--Computed mean daily solar radiation during December, 1951-80.

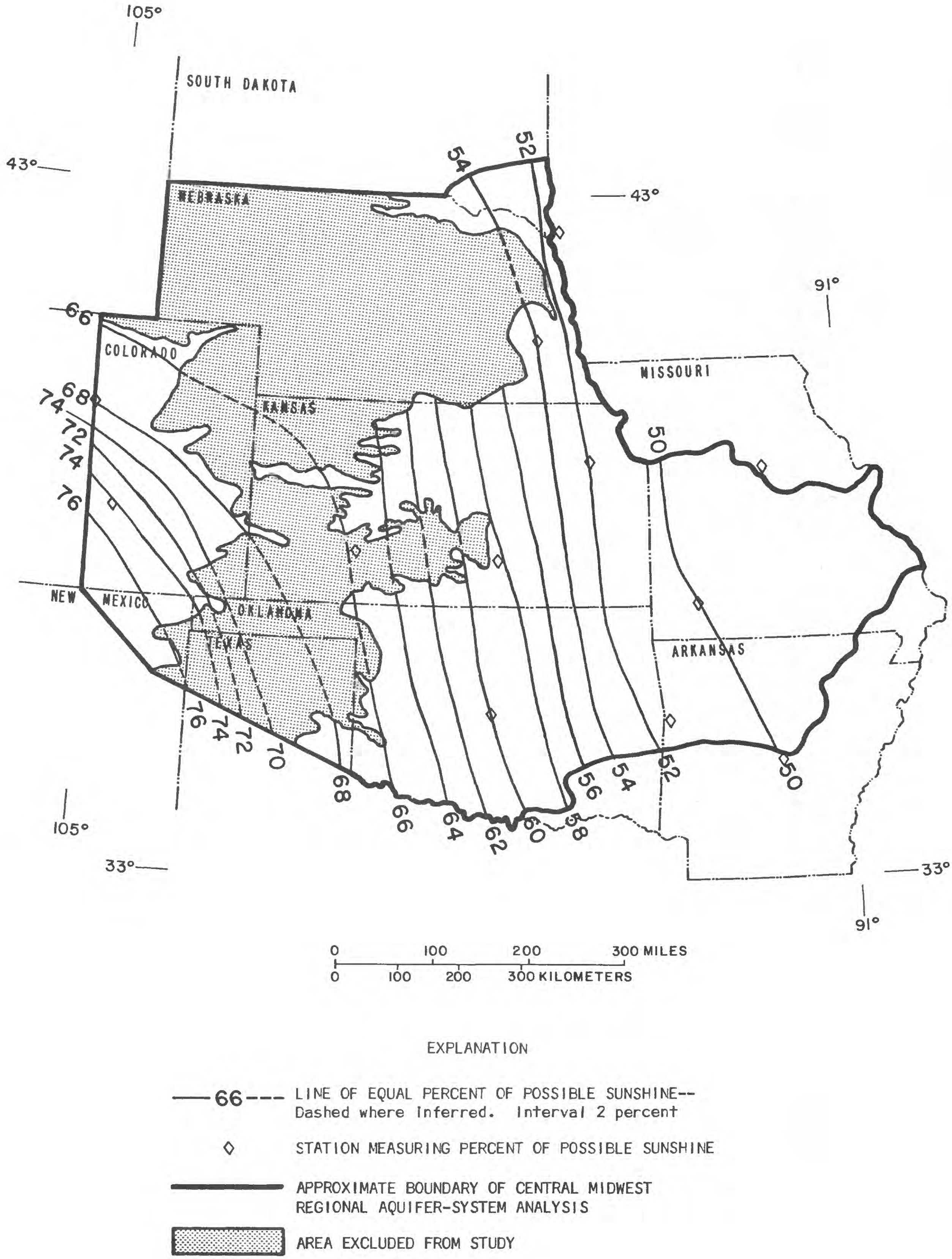
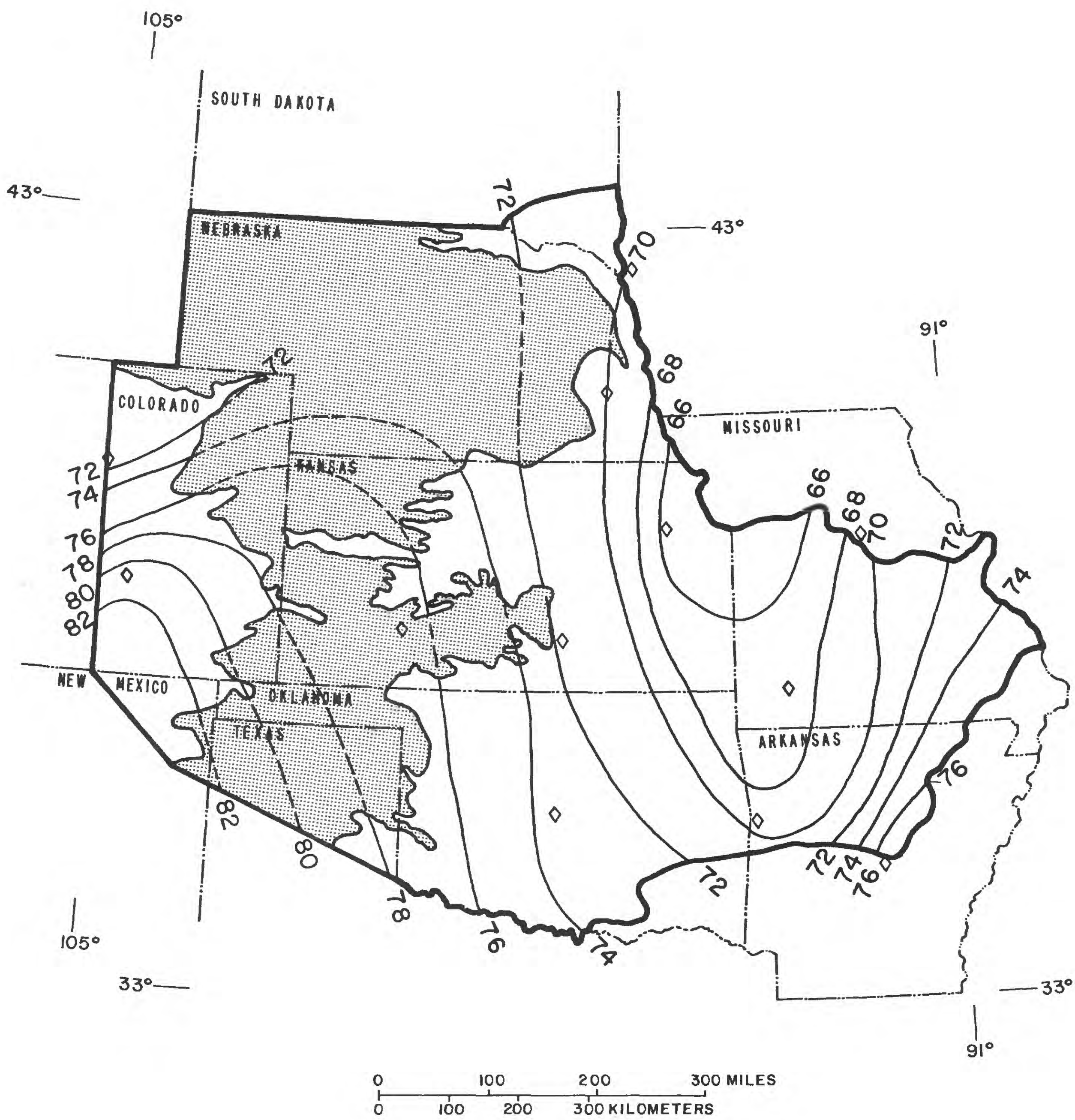


Figure 6.--Mean percent of possible sunshine during December, 1951-80.



EXPLANATION

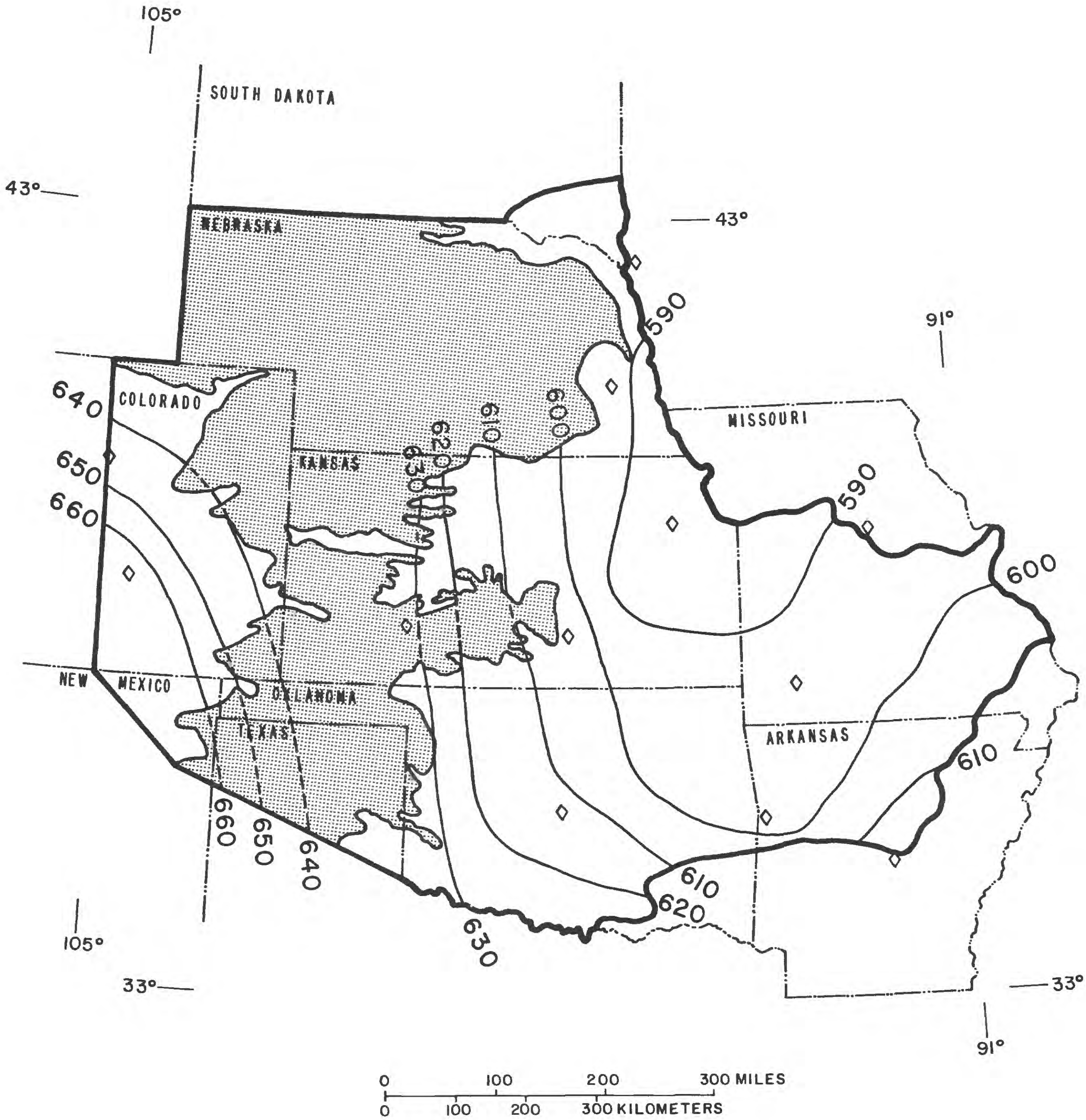
—74--- LINE OF EQUAL PERCENT OF POSSIBLE SUNSHINE--Dashed where inferred. Interval 2 percent

◇ STATION MEASURING PERCENT OF POSSIBLE SUNSHINE

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 7.--Mean percent of possible sunshine during June, 1951-80.



EXPLANATION

—610--- LINE OF EQUAL PERCENT OF POSSIBLE SUNSHINE--Dashed where inferred. Interval 10 ℓangleys (1 ℓangley = 1 gram calorie per centimeter)

◇ STATION MEASURING PERCENT OF POSSIBLE SUNSHINE

▬ APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

▩ AREA EXCLUDED FROM STUDY

Figure 8.--Computed mean daily solar radiation during June, 1951-80.

Humidity

Humidity, or water vapor in the atmosphere, affects the rate of both potential and actual evapotranspiration. Significant differences in humidity exist across the study area. This is largely related to distance from the major source of atmospheric water vapor, the Gulf of Mexico, and the prevailing atmospheric circulation patterns. Regional humidity differences in the study area are evident in figure 9. An examination of precipitation patterns in the area indicates a close relationship with atmospheric water vapor. The Jensen-Haise method measures humidity from saturation vapor-pressure estimates derived mathematically from maximum and minimum temperatures of the warmest month (normally July) adjusted for the altitude effect. Usually an inverse relationship exists between humidity and the difference between maximum and minimum temperatures because of the release of latent heat by condensation from moist air. Moist air tends to cool less at night than dry air because of the increased release of sensible heat by condensation of the water vapor into dew or frost. As is evident in figure 10, the difference in average maximum and minimum temperatures increases significantly from east to west, which corresponds to the trend for relative humidity in figure 9. Some anomalous patterns or values in New Mexico and southern Colorado are indicated in figure 10, which may be the result of local site characteristics that influence radiation cooling at night.

Temperature

Temperature patterns in the study area display significant variations. As was discussed previously, temperature affects potential evapotranspiration by determining the length of the growing season (transpiration period) and by conditioning the effectiveness of solar radiation as an evaporation agent.

The range of mean annual temperatures depicted in figure 11 indicates nearly a true north-south gradient. This gradient is approximately 2°F per 1° of latitude, typical of a mid-latitude continental location. Average annual temperature isotherms, however, may obscure other temperature patterns that may be more significant to evapotranspiration.

EXPLANATION

—— 45 - - - LINE OF EQUAL RELATIVE HUMIDITY--Dashed where inferred. Interval 5 percent

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 9.--Average relative humidity at noon during July, 1899-1938.

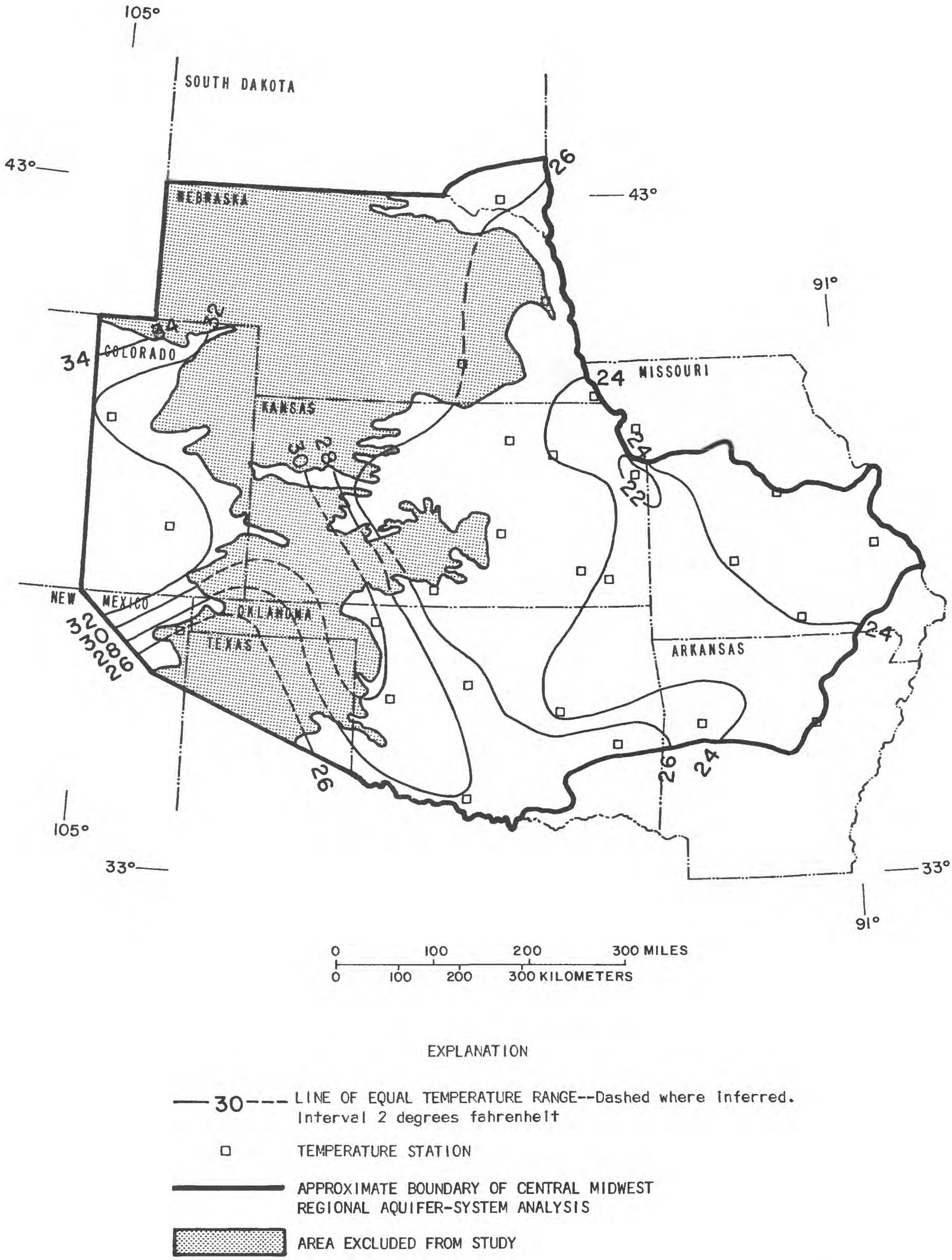


Figure 10.--Mean range between maximum and minimum temperatures during July, 1951-80.

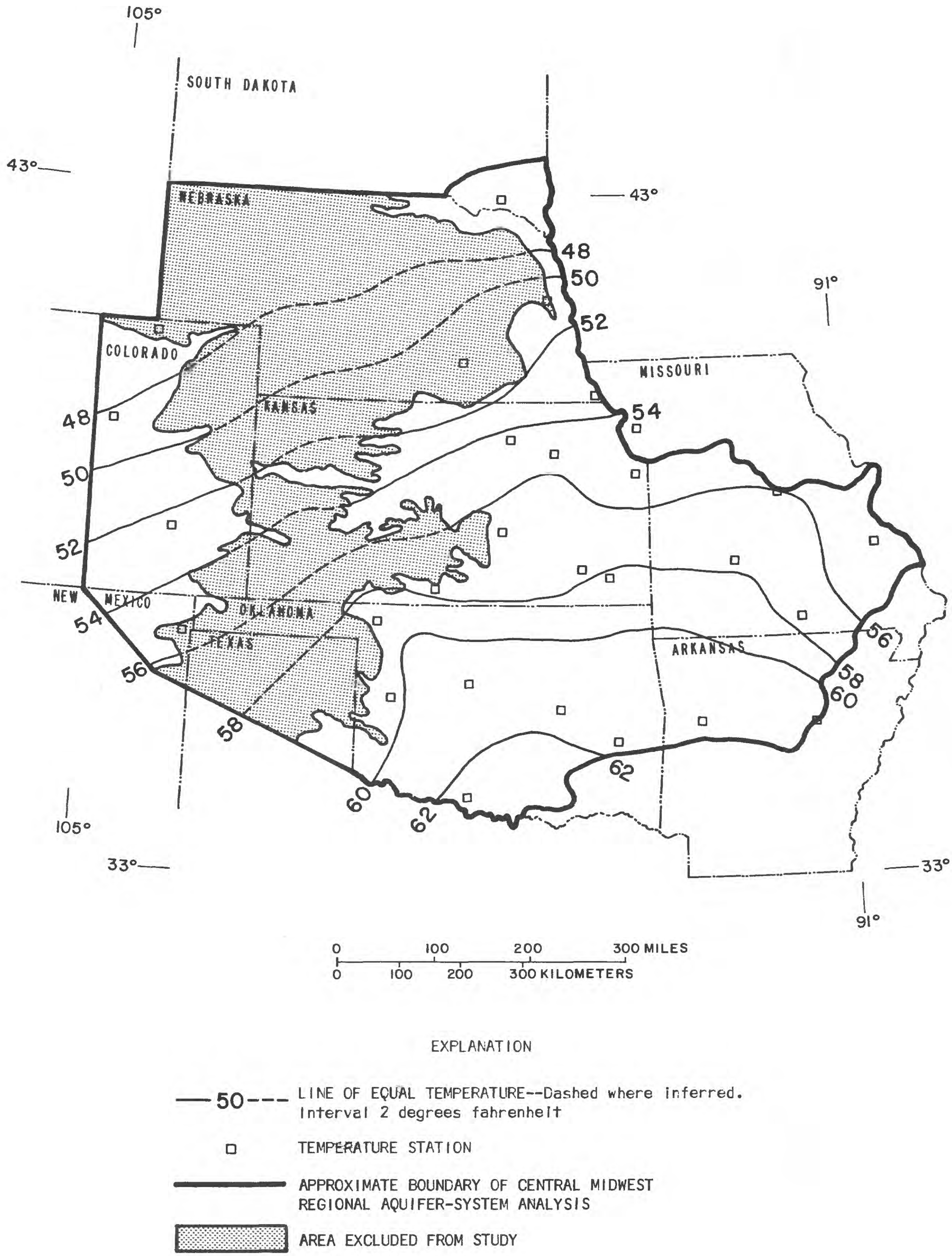


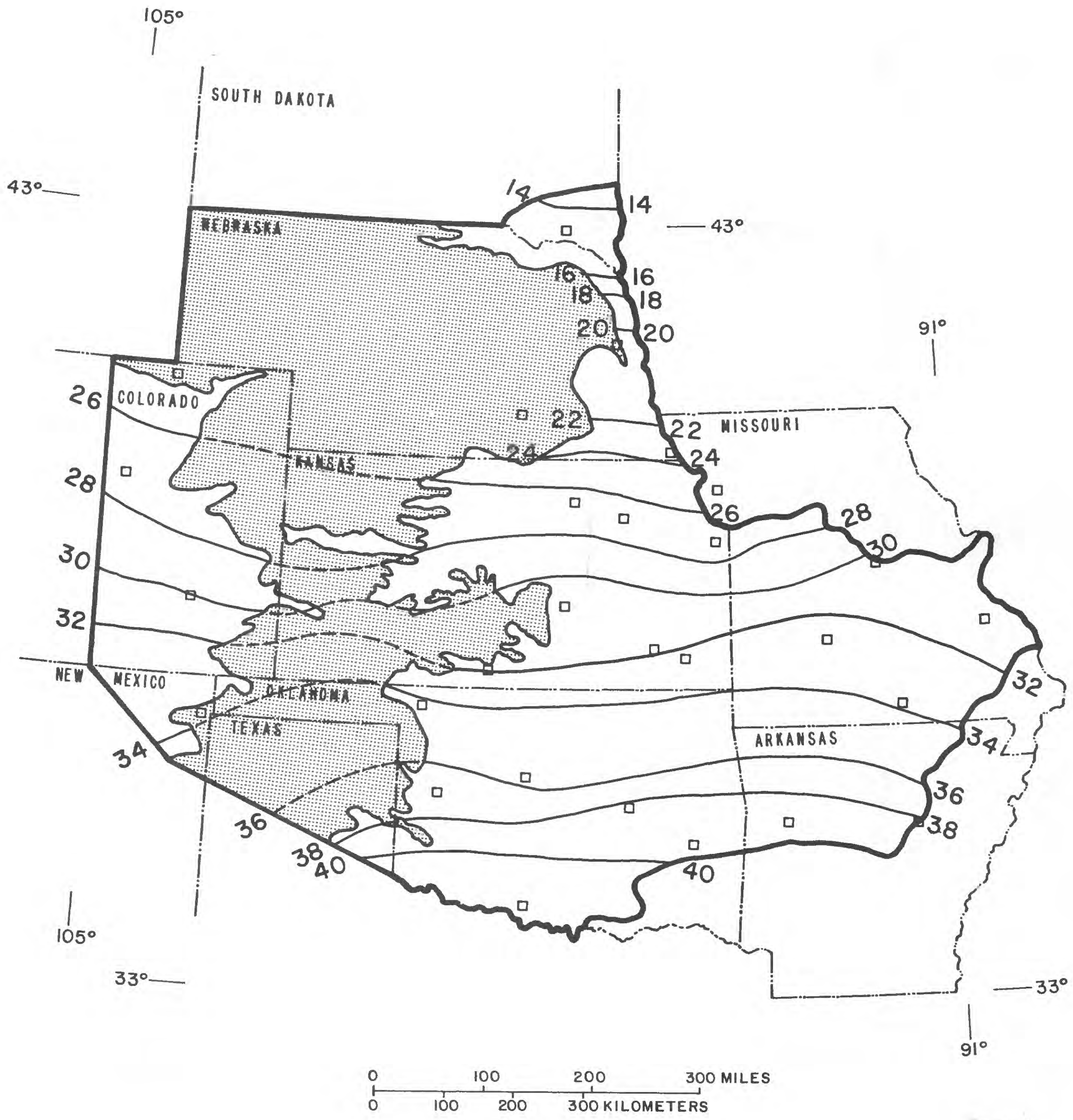
Figure 11.--Mean annual temperature, 1951-80.

Mean temperatures in the region are quite different in their seasonal patterns. Using January and July mean temperatures as indicators of seasonal extremes, large contrasts are evident. The map of mean temperatures during January (fig. 12) indicates a difference greater than 25°F in a somewhat uniform east-west trend across the study area. The map of mean temperatures during July (fig. 13), however, indicates a much different pattern; only a 10°F differential exists across the same latitudinal range. A comparison of the relationship between January and July isotherms indicates that annual temperatures increase northward from about 44°F in the south to about 60°F in the north. These seasonal mean temperatures are closely related to seasonal solar radiation with much greater regional contrasts in winter than in summer. Furthermore, the polar front and jet stream, which separates the polar and tropical air masses, normally passes through the study area in winter, causing increased regional temperature contrasts.

The compensating factors of increased daylight hours and increased percent of possible sunshine (less cloud cover) in the north minimize both regional radiation and temperature contrasts in summer. Also, the polar front and jet stream move poleward in summer, allowing tropical air masses to persist over the entire region.

The mean temperatures during July (fig. 13) show the effect of altitude and humidity on temperature. Eastern Colorado, with altitudes ranging from 4,000 to 6,000 feet above sea level, is 5 to 6 degrees cooler than at equivalent latitudes in the eastern section of the study area where altitudes are generally less than 1,500 feet. This implies an environmental lapse-rate cooling effect, resulting from the increased altitude from east to west. The lower humidity in eastern Colorado (fig. 9) also increases nighttime cooling, which would lower the mean temperature during July. Figure 13 also shows a distinct ridge of higher temperatures through the central part of the study area, particularly in Kansas. This may result from a relatively persistent pattern of atmospheric circulation during the summer that moves warmer air northeastward.

Length or duration of certain mean temperatures is significant to consumptive water use and subsequent potential recharge in the study area. A mean temperature of 40°F is the approximate threshold temperature for the commencement of growth by many cool-season plants such as certain grasses and winter grains (wheat). A significant difference exists for areas in which the number of months are above or below this threshold value (fig. 14). In the extreme southeast, only the month of January has a monthly mean temperature of less than 40°F; whereas, in northern



EXPLANATION

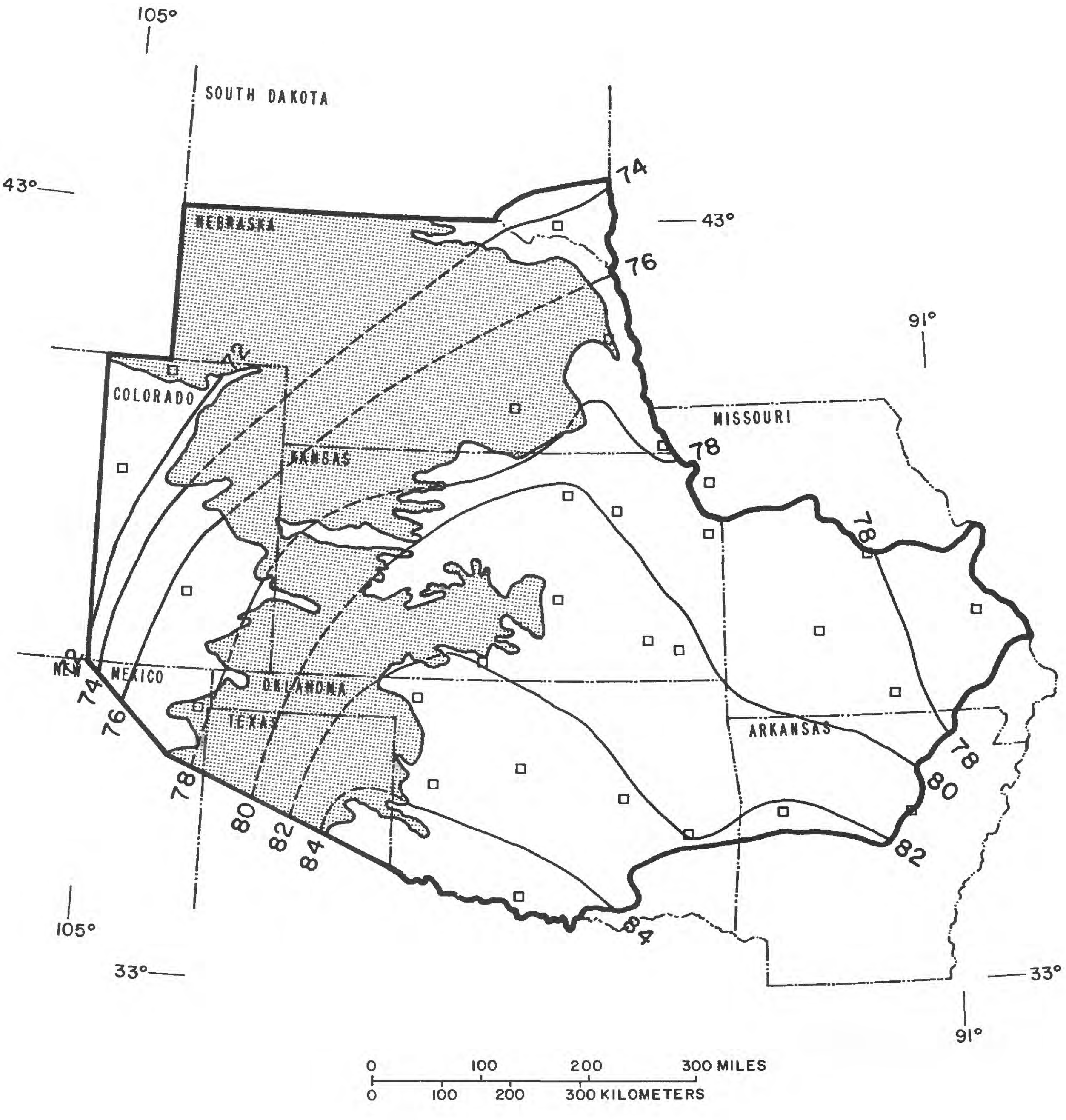
—34--- LINE OF EQUAL TEMPERATURE--Dashed where inferred. Interval 2 degrees fahrenheit

□ TEMPERATURE STATION

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 12.--Mean temperature during January, 1951-80.



EXPLANATION

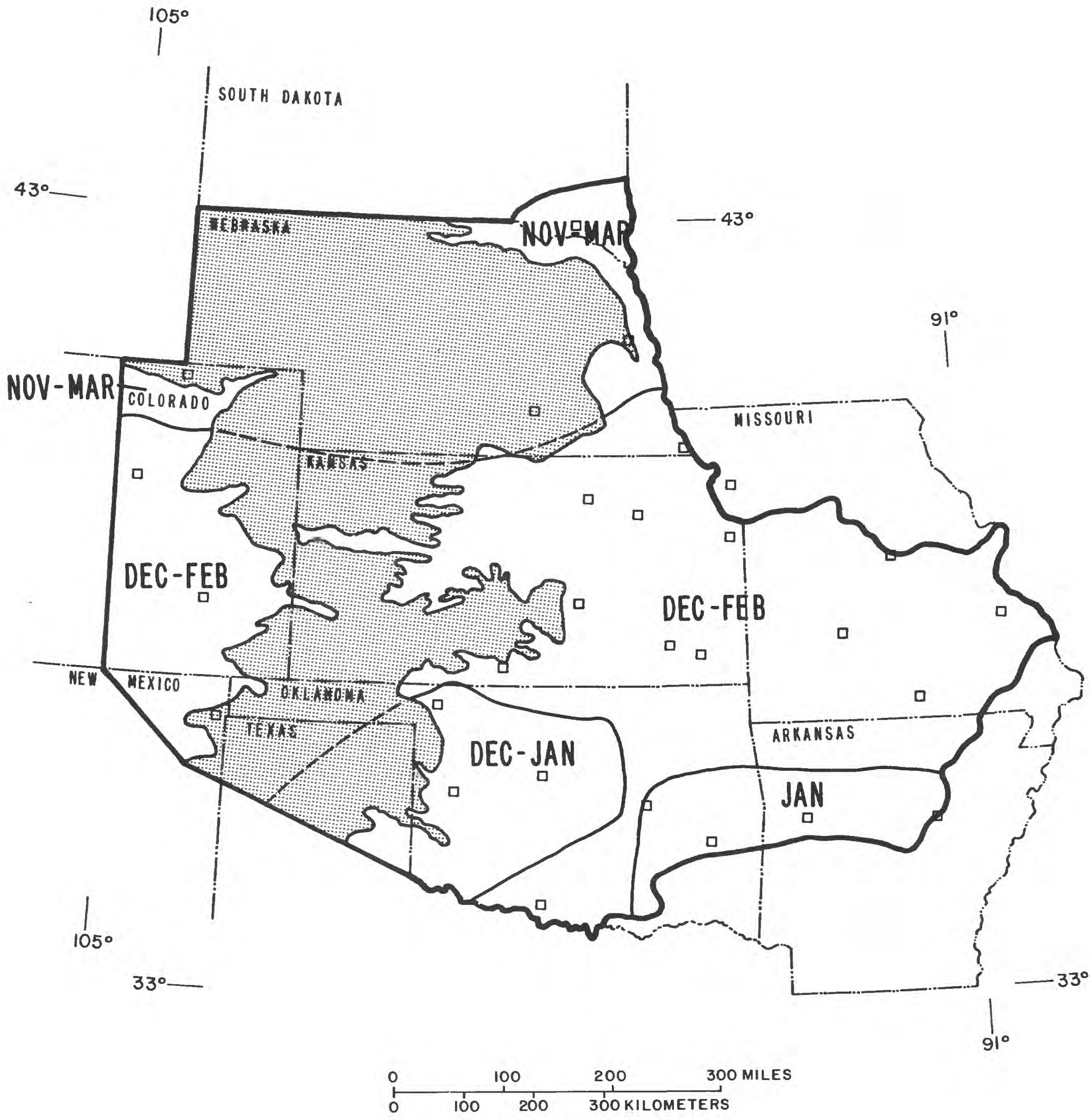
—— 80 - - - LINE OF EQUAL TEMPERATURE--Dashed where inferred. Interval 2 degrees fahrenheit

□ TEMPERATURE STATION

▬▬ APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

▒ AREA EXCLUDED FROM STUDY

Figure 13.--Mean temperature during July, 1951-80.



EXPLANATION

BOUNDARY OF MONTHLY TEMPERATURE AREAS

TEMPERATURE STATION

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 14.--Months in which mean temperature is less than 40 degrees Fahrenheit, 1951-80.

parts of the study area, monthly mean temperature is less than 40°F for as long as 5 months (November through March), with the majority of the region having 3 consecutive months with a mean temperature less than 40°F. While not necessarily having a direct relationship with potential evapotranspiration, figure 14 does indicate the length of the effective plant growth season and the period of significant and continuous actual evapotranspiration or consumptive water use.

The assumption can be made that potential evapotranspiration (PET) will achieve greater rates with higher temperatures. For most temperate and mid-latitude plants, the optimum temperature for growth ranges from 75° to 85°F (Wilsie, 1962, p. 197). At the optimum temperature for a plant, assuming adequate soil moisture, maximum physiological activity will occur, resulting in maximum transpiration rates. Figure 15 shows areas and months in which the mean temperature exceeds 75°F. Number of months vary from four in the extreme south to none in the northern and western parts of the study area. Although irrigation is not considered directly in this report, mean monthly temperatures exceeding 75°F result in increased water requirements that frequently cause soil-moisture deficits and, therefore, the need for supplemental irrigation.

Potential Evapotranspiration Patterns

The preceding discussion of climatic factors provides the basis for the computation of potential evapotranspiration (PET) by the Jensen-Haise method. Caution should be used in attempting to draw too strong an inference between individual climatic factors and PET, because these factors operate together with varying degrees of contribution in the computational procedures.

Variations in annual PET are quite significant, as shown in figure 16. PET nearly doubles from northeast to southwest across the study area. This spatial difference is quite closely associated with differences in annual solar radiation shown in figure 3; however, altitude (not shown), humidity (indicated in figs. 9 and 10), and temperatures (figs. 11-15) show some contributing effects. Higher solar radiation in the west and southwest parts of the study area is largely a result of greater percent of possible sunshine (fig. 4) and increased altitude, which in conjunction with significantly lower humidity, greatly increases PET in this area.

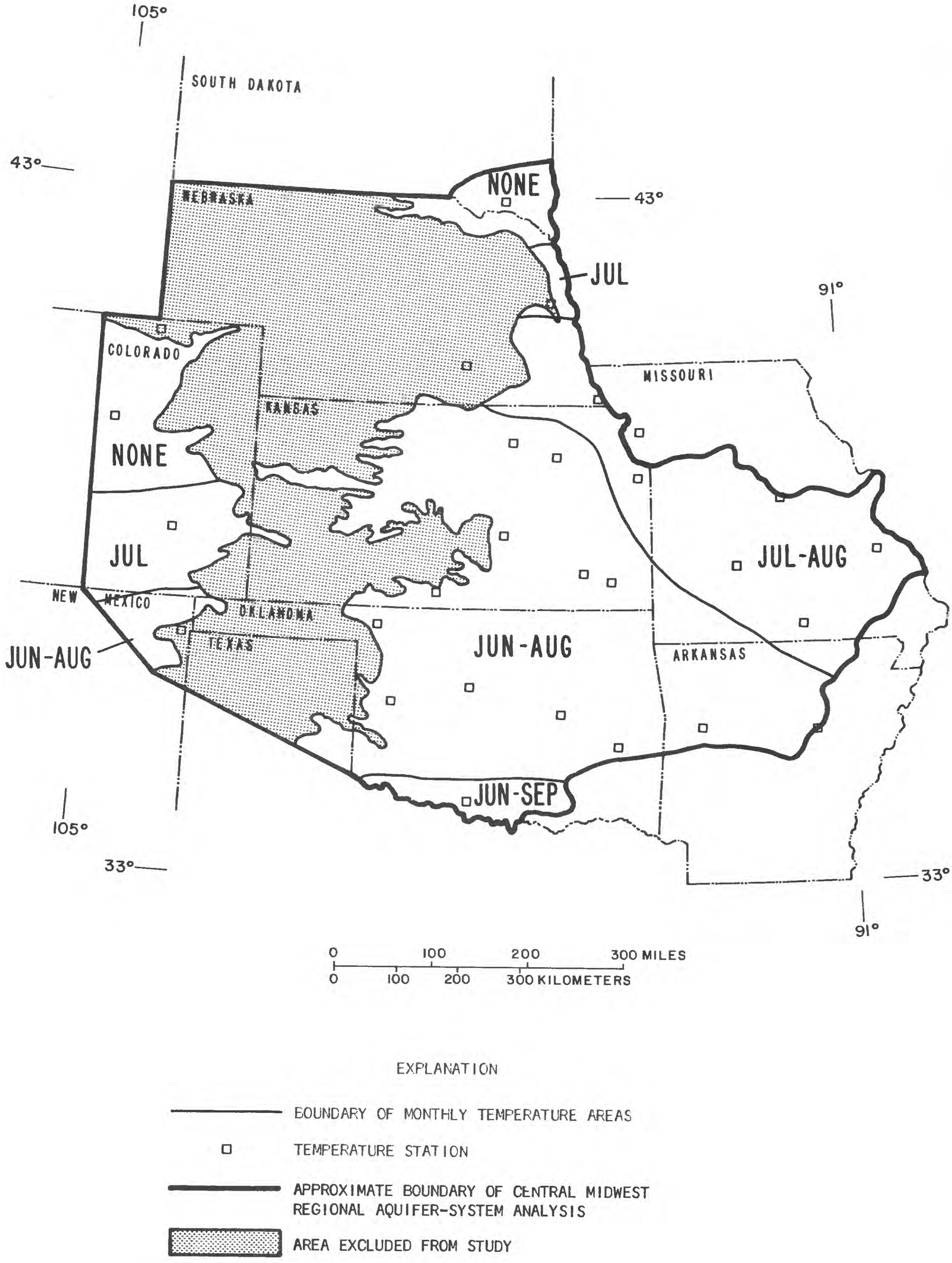
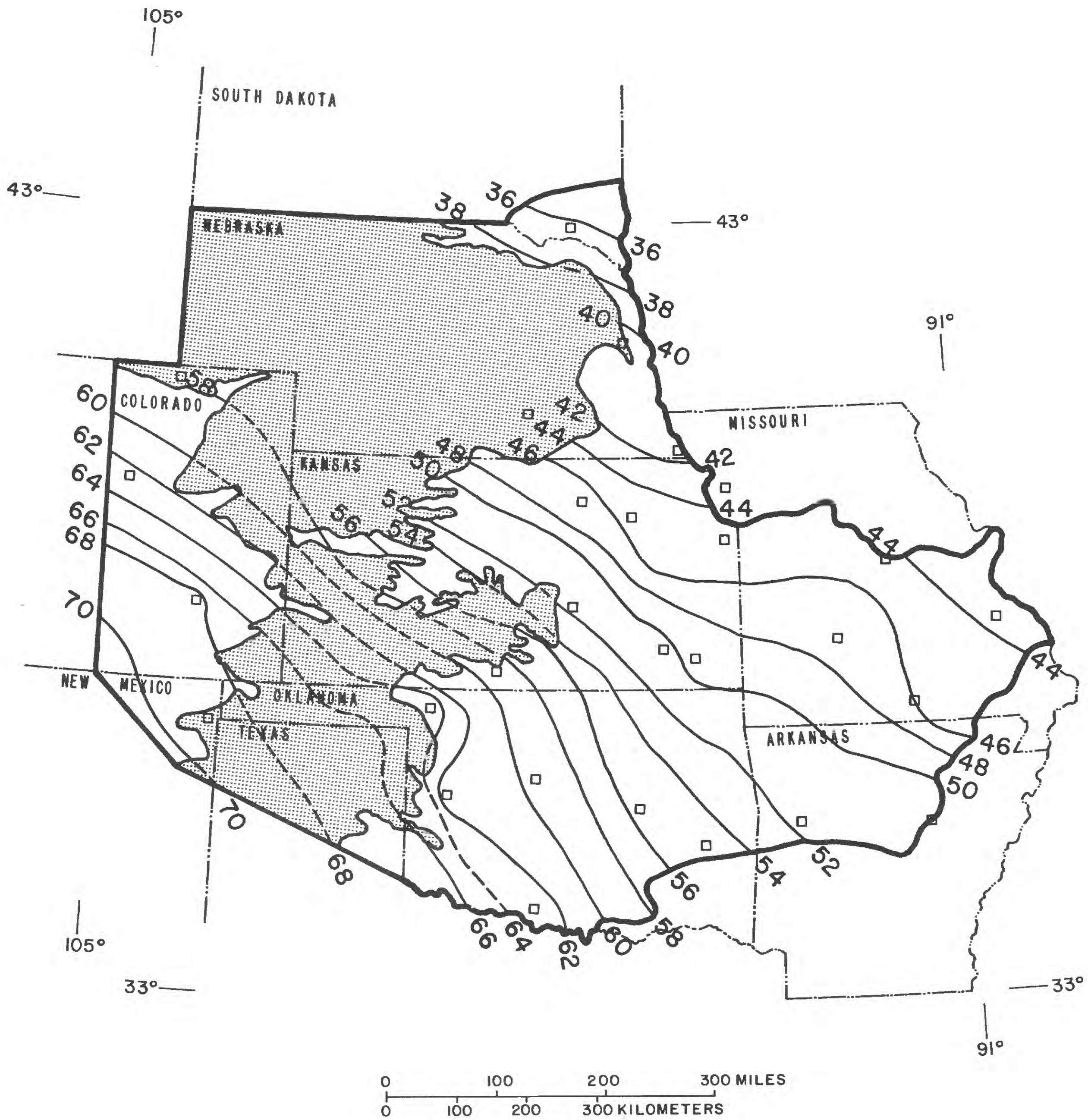


Figure 15.--Months in which mean temperature exceeds 75 degrees Fahrenheit, 1951-80.



EXPLANATION

—60--- LINE OF EQUAL POTENTIAL EVAPOTRANSPIRATION--dashed where inferred. Interval 2 inches

□ TEMPERATURE STATION

▬ APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

▒ AREA EXCLUDED FROM STUDY

Figure 16.--Computed mean annual potential evapotranspiration, 1951-80.

The effect of air temperature on PET within the study area is less significant. Cooler average temperatures from east to west are more than compensated for by the increase in solar radiation. This increase in the range between daily maximum and minimum temperatures during July from east to west (fig. 10), which coincides with a lower dewpoint and less humidity, compares well to PET.

Seasonal PET patterns indicate some significant characteristics. More than 75 percent of the PET in the study area occurs during the warm season (April through September), with the highest percentage (approximately 90 percent) occurring in the north and east. Average warm- and cool-season PET are shown in figures 17 and 18. Significant PET occurs in the southwestern part of the study area during the cool season, which could limit potential moisture surpluses and resultant recharge. In contrast, the cool season PET in the north and east is quite low, contributing to possible soil-moisture surpluses and recharge. A strong relationship appears to exist between cool-season PET and solar radiation patterns, in figures 5 and 18.

Potential evapotranspiration provides a theoretical measure of the combined influence of meteorological or climatological elements upon soil moisture. A further analysis, including variations in vegetation (land use), soils, and precipitation, however, is necessary to provide the interrelationship among available soil moisture, consumptive water use, and ground-water recharge.

Effects of Vegetation on Consumptive Water Use

Six general vegetation types occur in the study area. Each type has distinctive seasonal consumptive water requirements, rooting depths, and infiltration-runoff relationships that create significantly different demands on available moisture. Vegetation (land use) types include: (1) row crops, principally corn, soybeans, and grain sorghum; (2) tame hay, principally alfalfa; (3) small grain, principally winter wheat; (4) native grasslands or pasture; (5) fallow or idle land; and (6) woodlands (urban land included). While many other crops and land uses are present within the study area, they can be included under one of the six general types without significantly affecting consumptive water use or water-requirement calculations. For example, the small amount of cotton grown in the study area fits reasonably well into the row-crop category.

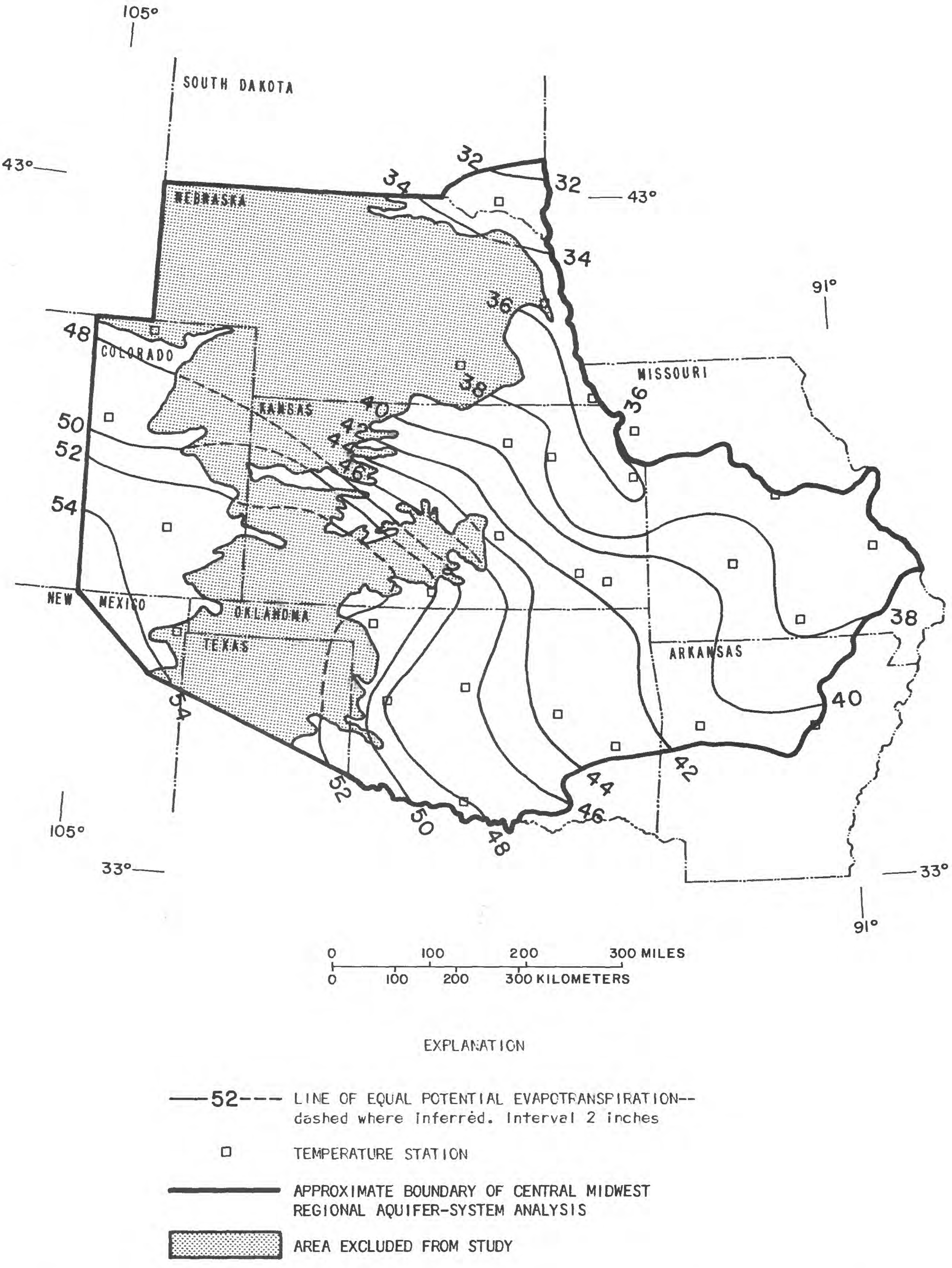


Figure 17.--Computed mean potential evapotranspiration during the warm season (April through September), 1951-80.

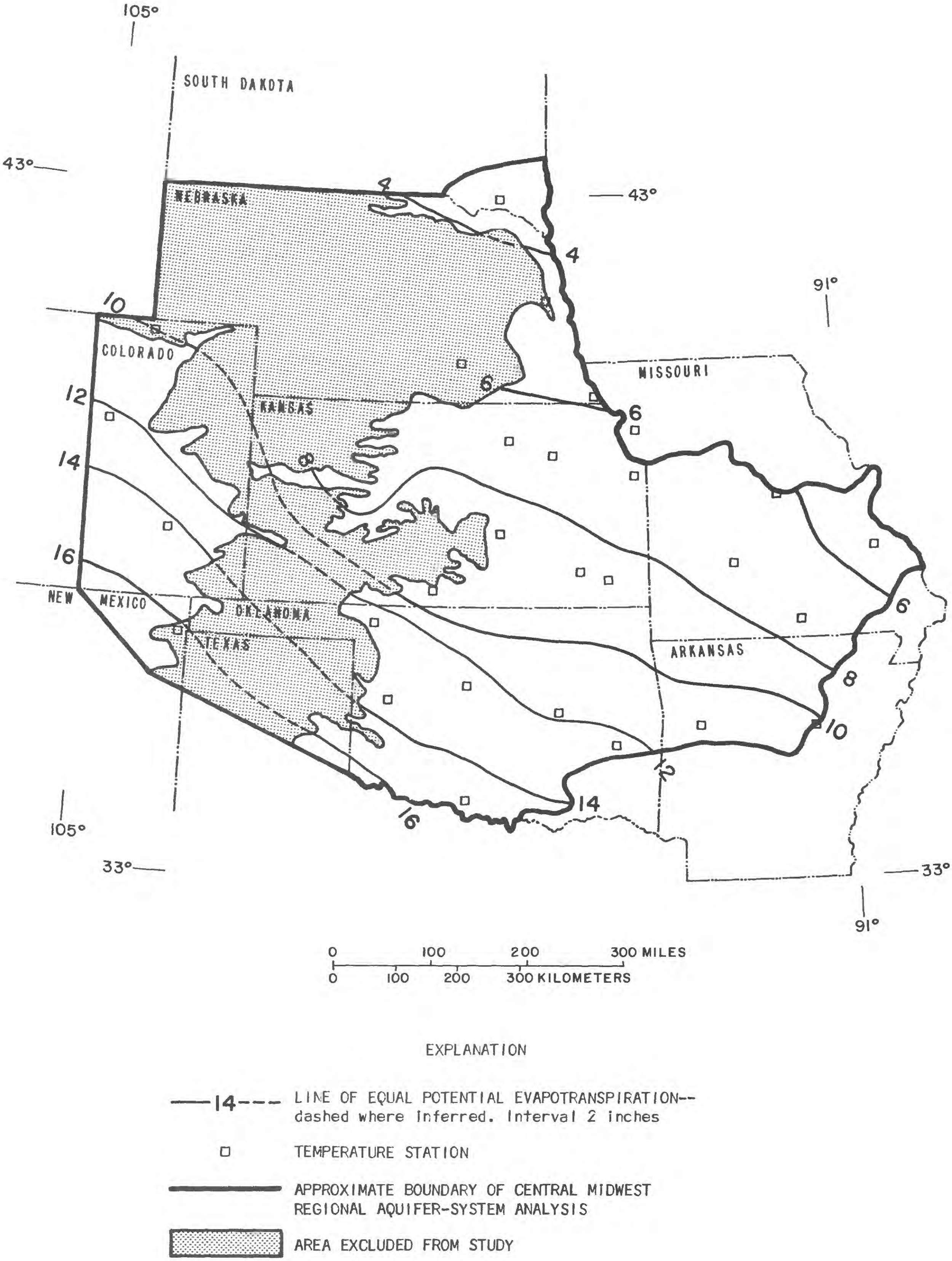


Figure 18.--Computed mean potential evapotranspiration during the cool season, 1951-80.

Vegetation Patterns

Vegetation or land-use patterns are derived from the census of agriculture conducted in 1978 (U.S. Department of Commerce, 1980). While this census provides vegetation patterns for a single year only, major changes have not occurred in the last 30 years (1951-80), particularly between cultivated and uncultivated land uses. Vegetation patterns shown in figure 19 were generalized from county data. To qualify as a predominant vegetation in a multiple pattern (three or more), approximately 20 percent or more of the land area in a county must occur under that category. Where only one vegetation type is mapped in figure 19, usually more than 60 percent of the land area is in that category.

The study area encompasses much of the traditional corn, grain sorghum, and winter wheat belts, but in reality only a small part of this area is in cultivated crops. Table 2 indicates that uncultivated land (range and woodland) accounts for approximately 64 percent of the total land area in 1978. This large percentage is due mainly to soil or topographic limitations.

Percent of land in the various vegetation types was converted from the county data to the grid elements of the CMRASA ground-water model for computation in the water-use program. These data consist of simple proportions of the grid elements occupied by the six vegetation types.

Table 2.--Percent of study area in the vegetation-type categories in 1978

Vegetation type	Percent
Row crops	11.2
Small grains	9.0
Tame hay	8.9
Fallow or idle	7.1
Rangeland and pasture	38.1
Woodland	25.7
Total	100.0

Source: U.S. Department of Commerce, Bureau of the Census, 1980.

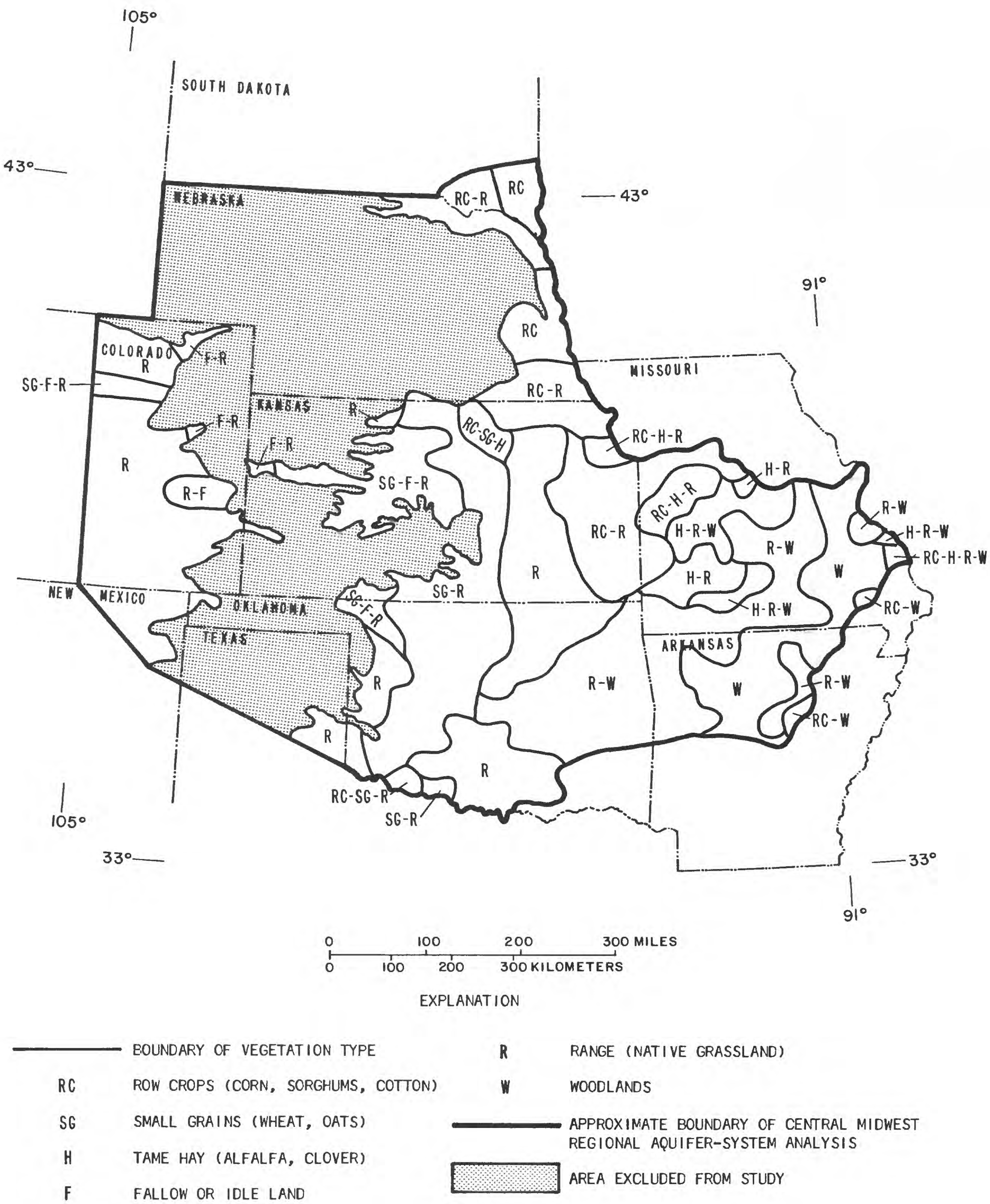


Figure 19.--Generalized vegetation patterns in the study area, 1978.

Consumptive Water Requirements of Various Vegetation Types

Within the soil-moisture program, computed potential evapotranspiration (PET) is modified to derive consumptive water requirements (CWR) of the various vegetation types on the basis of their growth or physiological characteristics. While PET assumes that a theoretical vegetation system functions constantly at a maximum physiological rate for a given set of meteorological conditions, CWR considers actual changes in the physiological rates inherent to particular types of plants. These changes are determined by the life or maturation cycles of plants primarily through their responses to heat and solar radiation.

CWR is similar to PET in that both assume no soil-moisture deficits or resultant plant stress. CWR differs fundamentally from actual evapotranspiration (AET), which accounts for periods of soil-moisture deficits and plant stress. AET is net consumptive water use and cannot exceed available moisture (residual soil moisture and precipitation). This term will be more fully discussed later.

CWR is expressed as a simple ratio or part of the potential PET rate. Figure 20 indicates the average monthly CWR/PET ratios for various vegetation types that are used in the soil-moisture program.

Differences in the CWR/PET ratio among the various vegetation types, as well as seasonal changes within each type, are shown in figure 20. Although most plants have a low CWR/PET ratio during the nongrowing season or winter months when they are dormant, winter small grains (wheat) are the major exception. Crops or plants that essentially complete their life cycles in a single growing season (annuals such as row crops) essentially simulate fallow conditions during the nongrowing season.

Variations in CWR within the growing season are largely related to a plant's warm- or cool-season physiological tendencies. Grasses, tame hay (alfalfa), and small grains are considered cool-season plants, while row crops (corn, sorghum, soybeans, cotton) and most tree species in the study area (hardwood deciduous) are classified as warm-season plants. The CWR for grasslands and woodlands, however, are generalized to a considerable extent because of the wide range of species that may possess either warm- or cool-season growth characteristics.

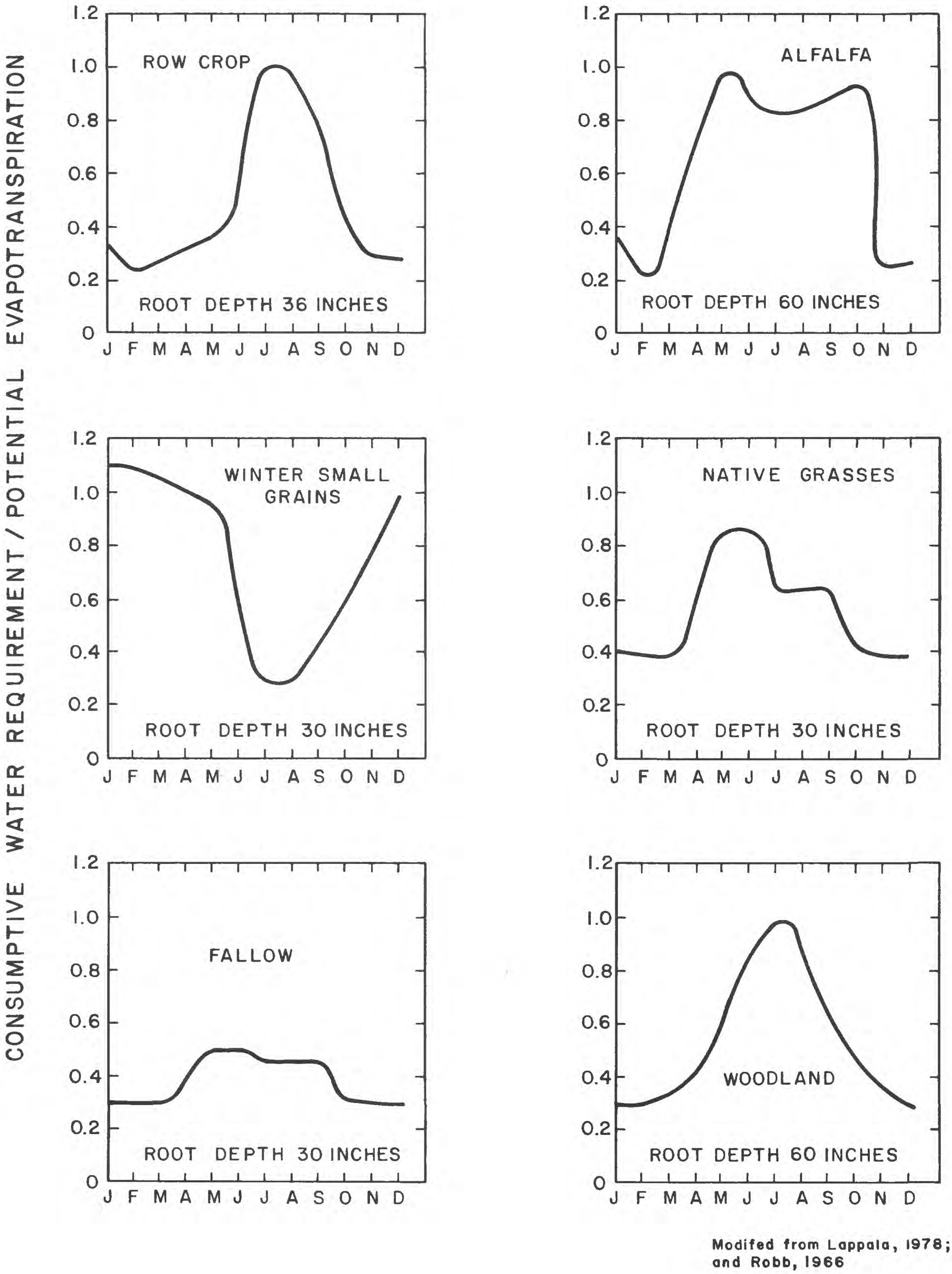


Figure 20.--Ratio of consumptive water requirement to potential evapotranspiration and effective rooting depths for selected vegetation types.

A preliminary assessment of selected output from the soil-moisture program in table 3 provides the simulated effects of the various vegetation types on certain hydrologic characteristics under controlled climatic and soil conditions. The site used (Newton, Kansas) is representative of the overall average climatic conditions of the study area. Infiltration and consumptive water requirement (CWR) are the key variables, because they control the amount of water entering the soil and the amount of water a type of vegetation would use, if available. Deep percolation in this table equals infiltration minus actual evapotranspiration (AET). The variables in table 3 are more fully defined in the Glossary of Selected Terms.

Table 3.--Mean annual infiltration, consumptive water requirements (CWR), actual evapotranspiration (AET), consumptive irrigation requirements (CIR), and deep percolation under dryland conditions, in inches, computed by the soil-moisture program under Soil Group 1 conditions for selected vegetation types at Newton, Kansas (1951-80)

[Based on mean annual precipitation of 30.77 inches and mean annual potential evapotranspiration of 51.59 inches]

Vegetation type	Infiltration	CWR	AET	CIR	Deep percolation under dryland conditions
Row crop	25.84	33.10	22.53	11.41	3.31
Alfalfa	27.65	41.43	27.29	13.68	.44
Small grains	27.65	31.28	24.58	4.73	3.07
Native grasses	27.65	33.89	24.51	9.79	3.14
Woodland	27.65	35.71	26.33	11.18	1.32
Fallow	25.84	22.57	19.82	3.63	6.02

Effects of the Soils' Physical Characteristics upon Availability of Water and Consumptive Water Use

Soil patterns within the study area are discussed in an earlier report (Dugan, 1985). In this report, the 56 soil groups identified in that published study are reduced to the 10 groups shown in table 4 for computational purposes within the soil-moisture program.

As table 4 indicates, over 65 percent of the study area is covered by finer-textured soils (clay to silty-clay loam). A nearly equal distribution of the soils occur within the three general slope or topographic groups (flat, rolling, or steep).

The three physical characteristics of the soil (permeability, available water capacity, and slope) affect the availability of water for consumptive use by regulating both infiltration and the ability of the soil profile to store water. Infiltration is largely a function of permeability and slope, while the water-storage capacity is determined by the product of the available water capacity (AWC) and the root-zone depth.

Table 4.--Physical characteristics of the soil groups used in the soil-moisture program for the Central Midwest Regional Aquifer-System Analysis

Soil group number	Texture	Permeability (inch/hour)	Average available water capacity (inch/inch)	Topography	Percent of slope	Percent of study area
1	Clay to silty clay loam	0 - 1.0	0.17	Flat	0-7	24
2	---do--------	0 - 1.5	.16	Rolling	7-15	24
3	---do--------	0 - 1.5	.15	Steep	> 15	21
4	Silt loam to sandy loam	1.5 - 5.0	.16	Flat	0-7	8
5	---do--------	1.5 - 5.0	.15	Rolling	7-15	3
6	---do--------	1.5 - 5.0	.14	Steep	> 15	14
7	Loamy sand to sand	5.0 - 10.0	.12	Flat	0-7	1
8	---do--------	5.0 - 10.0	.10	Rolling	7-15	2
9	Sand to dune-sand	> 10.0	.08	Flat to rolling	0-15	1
10	---do--------	> 10.0	.07	Steep	> 15	2

To demonstrate the effect of the soils' physical characteristics, table 5 shows simulated runoff, infiltration, actual evapotranspiration, and resultant deep percolation calculated by the soil-moisture program for the 10 possible soil groups at the Newton, Kansas, site. For this demonstration, climatic conditions and vegetation type (grassland) were held constant for all 10 soil types. Only the physical characteristics of the soil were allowed to vary.

Based on a joint interpretation of tables 4 and 5, those finer-textured soils on steeper slopes generally have less deep percolation than those with coarser textures and lesser slopes. Table 4 indicates that the finer-textured soils have lower permeabilities and higher available water capacity, which slows infiltration but increases the overall soil-moisture storage capacity. Steeper slopes, with the same vegetative cover and soil permeability, generally have more runoff and less infiltration. Sandy soils limit runoff, thus increasing infiltration which results in greater deep percolation or potential recharge. The higher AET associated with finer-textured soils (1 through 7) indicates greater available water capacity; therefore, more water is available for consumptive water use.

Table 5.--Mean annual runoff, infiltration, actual evapotranspiration, and deep percolation computed by the soil-moisture program for soil groups under native grassland conditions at Newton, Kansas

[Mean annual potential evapotranspiration = 51.59 inches; mean annual consumptive water requirement = 33.89 inches; mean annual precipitation = 30.77 inches; root-zone depth = 30 inches]

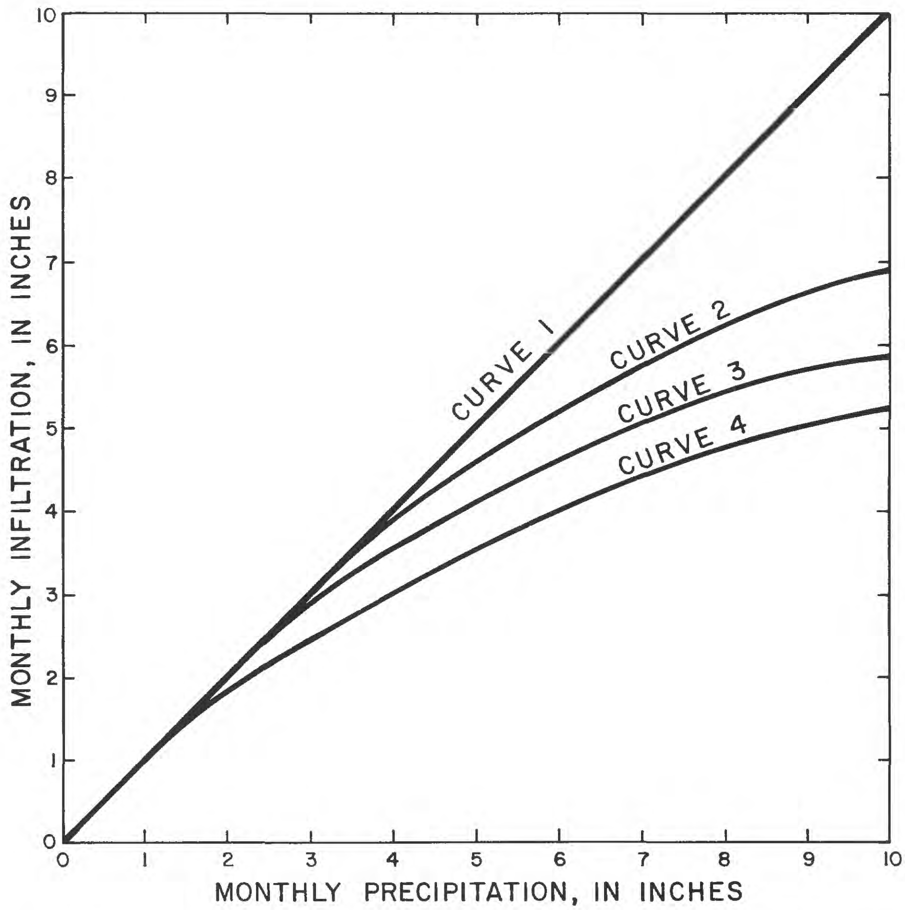
Soil group number	Runoff (inches)	Infiltration (inches)	Actual evapotranspiration (inches)	Deep percolation (inches)
1	3.12	27.65	24.51	3.14
2	4.93	25.84	23.46	2.38
3	4.93	25.84	23.26	2.58
4	3.12	27.65	24.30	3.35
5	3.12	27.65	24.09	3.56
6	4.93	25.84	23.05	2.79
7	0.00	30.77	28.04	6.73
8	3.12	27.65	22.85	4.80
9	0.00	30.77	22.85	7.92
10	0.00	30.77	22.50	8.27

The relationship between precipitation and infiltration is depicted in figure 21. These precipitation-infiltration curves were developed by Otradovsky (1981) from empirical rainfall-runoff relationships for varying soils, topography, and land-use conditions reported by the U.S. Department of Agriculture, Agricultural Research Service, Soil and Water Conservation Research Branch (1957). Because these precipitation-infiltration relationships were developed from data on small watersheds, the soil-moisture program contains modification provisions to adjust the relationships for larger watersheds to account for additional infiltration that may occur during the initial period of storm runoff (Fred J. Otradovsky, personal commun., 1979). These adjustments were made in this study because of the large areas of the model grid elements used in the CMRASA ground-water modeling.

The precipitation-infiltration relationships used in this study were based on average rainfall intensities in south-central Nebraska. According to regional rainfall-intensity studies by Beasley (1972, p. 83-84), average intensities vary across the study area, with slightly higher intensities in the southeast and lower intensities in the west. Generally, higher rainfall intensities are indicative of less infiltration and more runoff; the converse occurs with lower rainfall intensities. Beasley's data show that the average rainfall intensities in south-central Nebraska approximate the overall average of the study area, with nearly all of the study area within ± 10 percent of this intensity (Beasley, 1972, p. 83).

Relationships of the Spatial and Temporal Patterns of Precipitation to Consumptive Water Use and Ground-Water Recharge

The preceding discussion focused on those elements that affect the loss or consumptive use of water; however, just as significant is the availability of water. This section centers on the precipitation of the study area, which provides the water for both plant growth and recharge to ground-water supplies. Of all climatic or meteorological elements, precipitation probably is the most complex spatially and temporally. The other principal climatic elements discussed in this report, solar radiation and temperature, while showing seasonal extremes, are more predictable and less changeable from year to year. Differences in these factors, particularly spatially, are expressed as fractional variability. However, because of the complexity and unreliable nature of the precipitation-forming processes, particularly in the mid-latitudes, precipitation in the study area can vary spatially and temporally by several orders of magnitude.



Soil	Vegetation type	Curve number and topography Hilly (>15 percent slope)	Rolling (7-15 percent slope)	Flat (0-7 percent slope)
Silty clay loam-Silt loam	Row crop	4	4	3
	Pasture	3	2	2
	Alfalfa	4	3	2
	Small grain	4	3	2
	Woodland	3	2	2
	Fallow	4	4	3
Loam-Sandy loam	Row crop	3	3	2
	Pasture	3	2	2
	Alfalfa	2	1	1
	Small grain	3	2	2
	Woodland	3	2	2
	Fallow	3	3	2
Loamy sand-Sand	Row crop	2	2	1
	Pasture	2	2	1
	Alfalfa	1	1	1
	Small grain	2	2	1
	Woodland	2	2	1
	Fallow	2	2	1
Sand-Dune sand	Row crop	2	1	1
	Pasture	1	1	1
	Alfalfa	1	1	1
	Small grain	1	1	1
	Woodland	1	1	1
	Fallow	2	1	1

(Modified from Lappala, 1978)

Figure 21.--Infiltration-precipitation relationships based on soil, vegetation types, and topography.

Precipitation in the study area was analyzed in several ways that affect actual consumptive water use (AET) and recharge. This required careful examination of seasonal patterns and the vagaries of occurrence. Data are based on 99 stations with continuous records for the 30-year (1951-80) period. An attempt was made to achieve approximately 50-mile spacing between stations, although this was not possible in more sparsely populated areas.

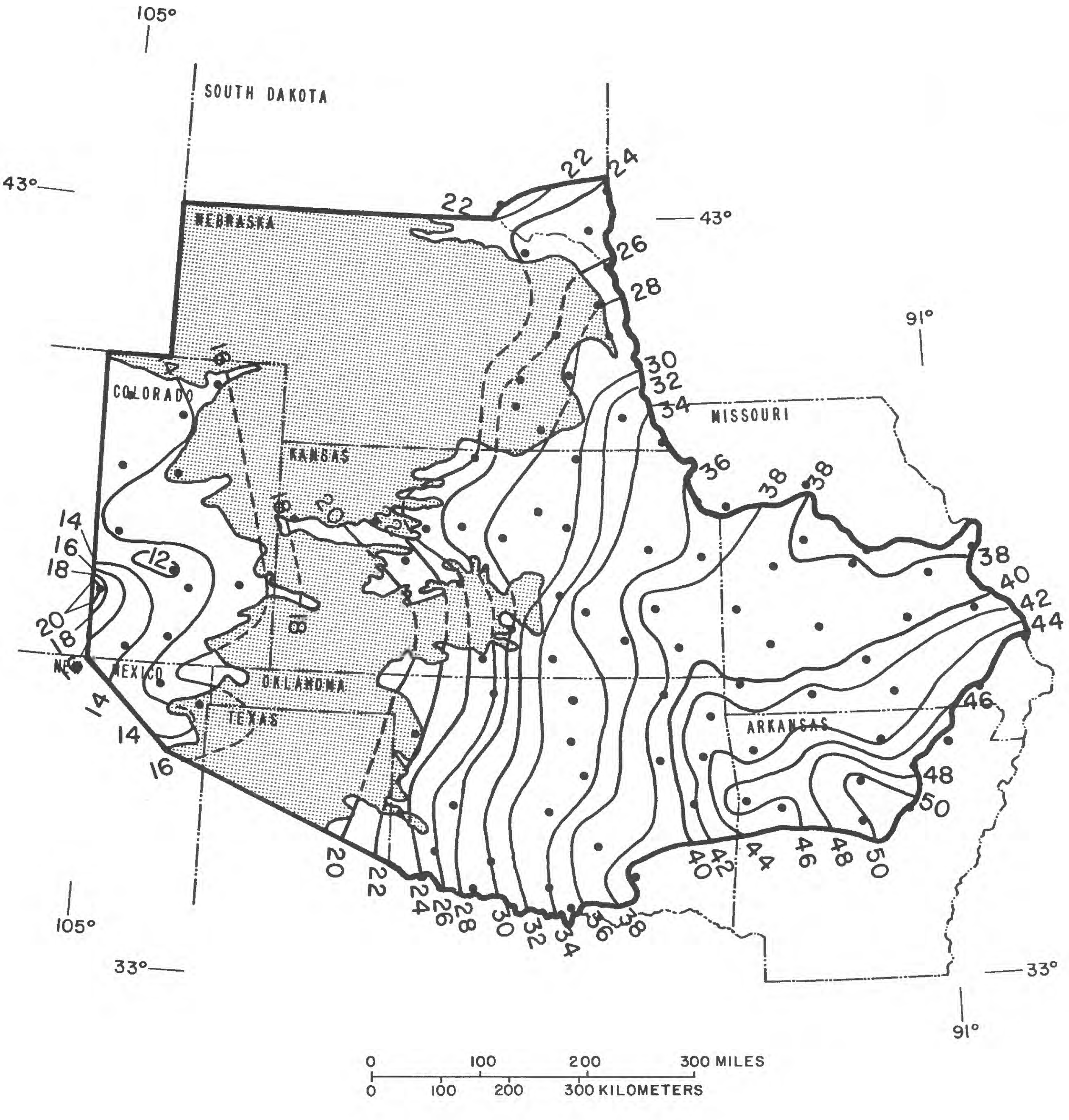
Annual Precipitation Patterns

Mean annual precipitation (fig. 22) varies from more than 50 inches in parts of Arkansas to less than 12 inches in a small area of Colorado. An examination of 30-year median precipitation shows nearly an identical pattern to the mean, which indicates approximately a normal distribution occurred at nearly all precipitation points during the 1951-80 study period.

Reliability of precipitation is significant both to the meeting of the normal water demands of a region and to the temporal patterns of recharge. An indicator of reliability of precipitation is the coefficient of variation (standard deviation/mean, expressed as a percent), which is depicted for the study area in figure 23; this value ranges from slightly less than 20 percent in parts of the more humid southeast to more than 30 percent in much of the central area and small areas of the extreme west. The average coefficient of variation for the entire study area is slightly less than 25 percent. The results tend to dispel the widely held belief that precipitation is significantly less reliable in semiarid regions than in humid and subhumid regions.

In semiarid regions, substantial ground-water recharge often occurs only during periods of extremely high precipitation. Figure 24, showing maximum annual precipitation for the 30-year period, indicates a range from approximately 18 to 85 inches across the study area. Substantial recharge can be anticipated during these extreme periods in the southeast, but the rather moderate precipitation in the western parts indicates that substantial recharge is unlikely.

Minimum 30-year annual precipitation (figure 25) indicates the potential severity of long-term drought conditions and soil-moisture deficits. The central and western parts of the study area experience extreme droughts, but the southeast does not appear to experience long periods of soil-moisture deficits.



EXPLANATION

—16--- LINE OF EQUAL PRECIPITATION--Dashed where inferred. Interval 2 inches

• PRECIPITATION STATION

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 22.--Mean annual precipitation, 1951-80.

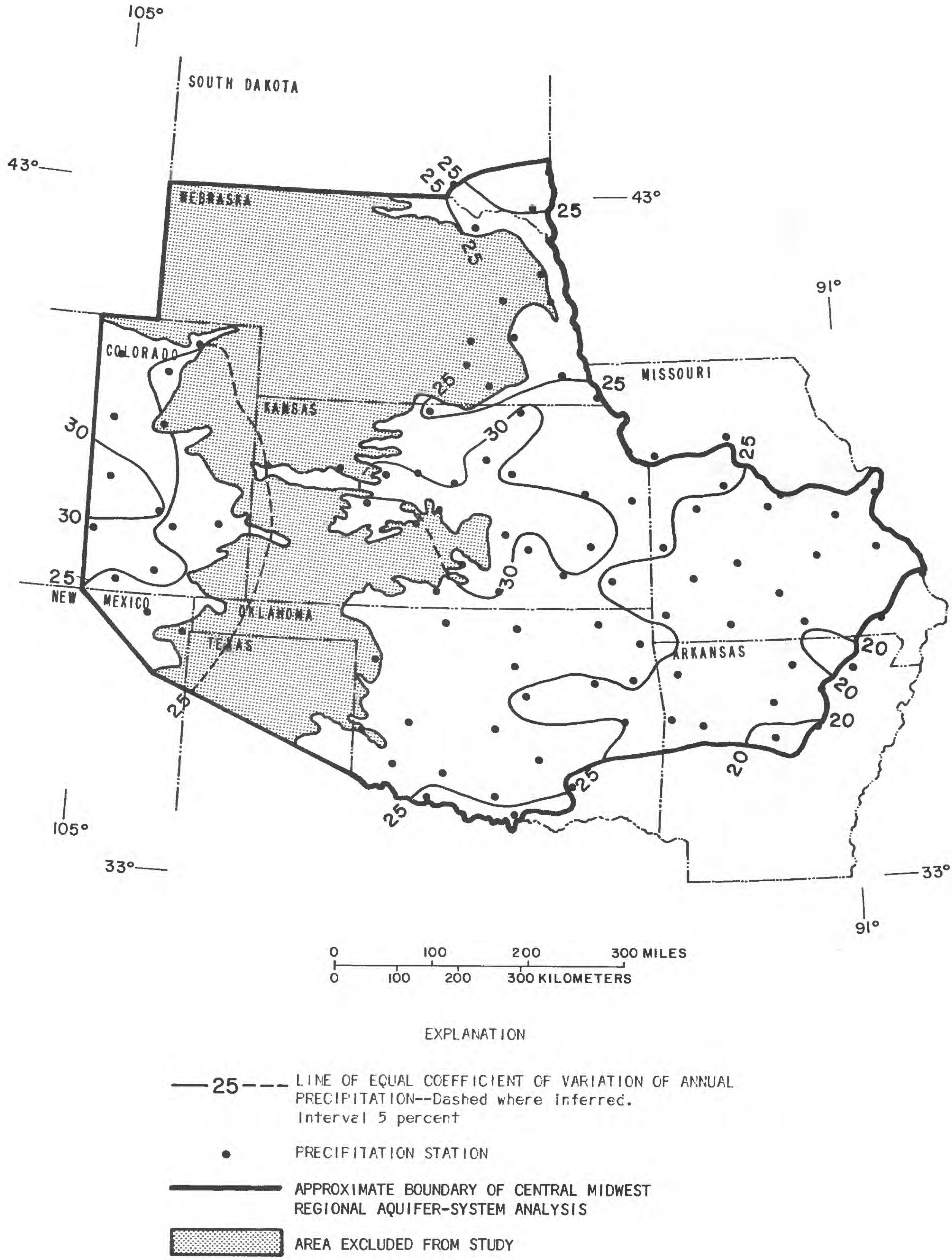


Figure 23.--Coefficient of variation of annual precipitation, 1951-80.

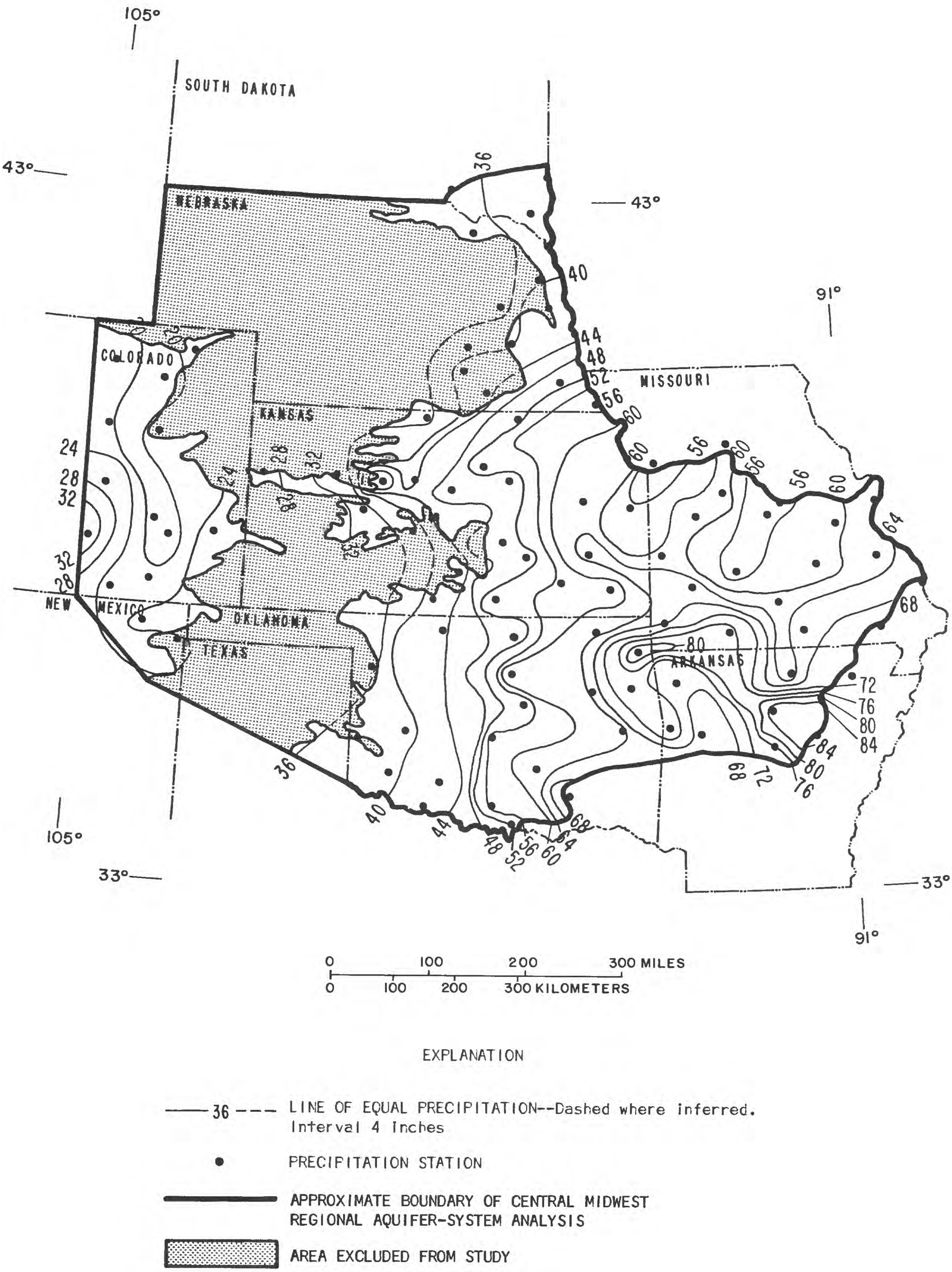


Figure 24.--Maximum annual precipitation, 1951-80.

EXPLANATION

——8——— LINE OF EQUAL PRECIPITATION--Dashed where inferred. Interval 2 inches

• PRECIPITATION STATION

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 25.--Minimum annual precipitation, 1951-80.

Seasonal Precipitation Patterns

Abundant soil moisture, which is necessary for deep percolation and ground-water recharge, is seasonal in nature. Excess soil moisture is most likely to occur during the cool season when consumptive-water demands or ET are at a minimum.

Figures 26, 27, and 28, depicting cool-season mean precipitation, percent of annual precipitation, and coefficient of variation, respectively, all indicate the potential for more favorable soil moisture and subsequent recharge in the southeastern part of the study area. The larger quantities and greater reliability of precipitation in the cool season in this area are related to a somewhat increased incidence of cyclonic activity and more frequent presence of maritime tropical air masses originating in the Gulf of Mexico.

Mean warm-season precipitation patterns (fig. 29) are significantly different from the cool-season patterns (fig. 26). Warm-season precipitation across the study area varies from 10 to 26 inches as compared to 4 to 24 inches in the cool season, or a difference in the seasonal magnitude range of 2.6 (warm) to 6 (cool). Furthermore, as implied from figure 27, the percentage of mean annual precipitation during the warm season, increases from 55 percent in the southeast to more than 75 percent in the northern and western parts of the study area.

Precipitation appears to be more reliable throughout the study area during the warm season than during the cool season (fig. 30). Warm-season precipitation generally is less significant to potential recharge, but is quite important in fulfilling water needs during the growing season.

The irrigation season throughout the study area is generally in July and August, which normally are the warmest months. At this time, most crops, particularly row crops, have their greatest consumptive water requirements (fig. 19), due to the crops' rapid vegetative and developmental growth. Rarely does precipitation during this period match consumptive water requirements in any part of the study area, and water deficits typically occur. Irrigation-season mean precipitation shown in figure 31, shows minimal differences across the study area. This is the only season in which the wettest area does not coincide with the southeastern part of the study area.

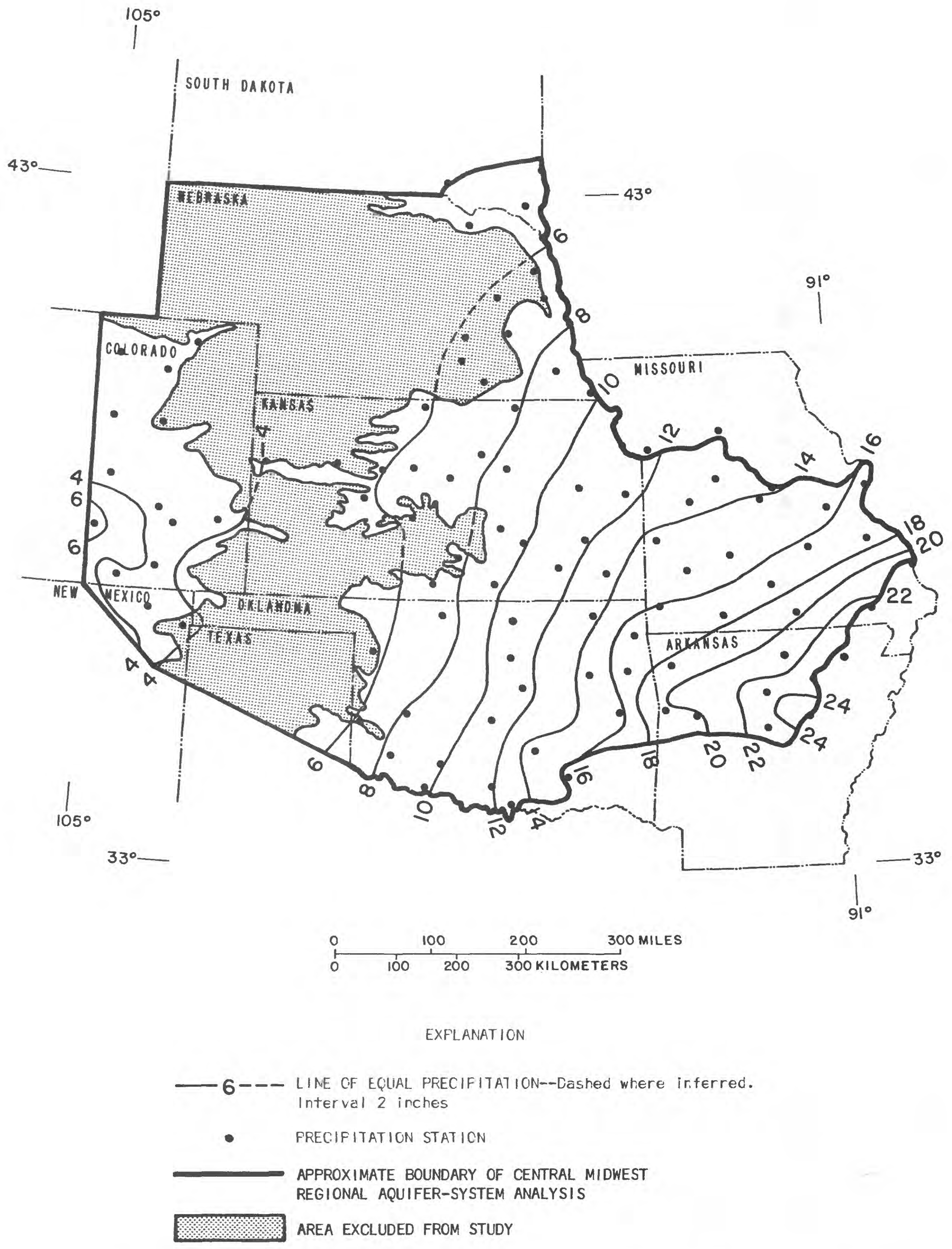
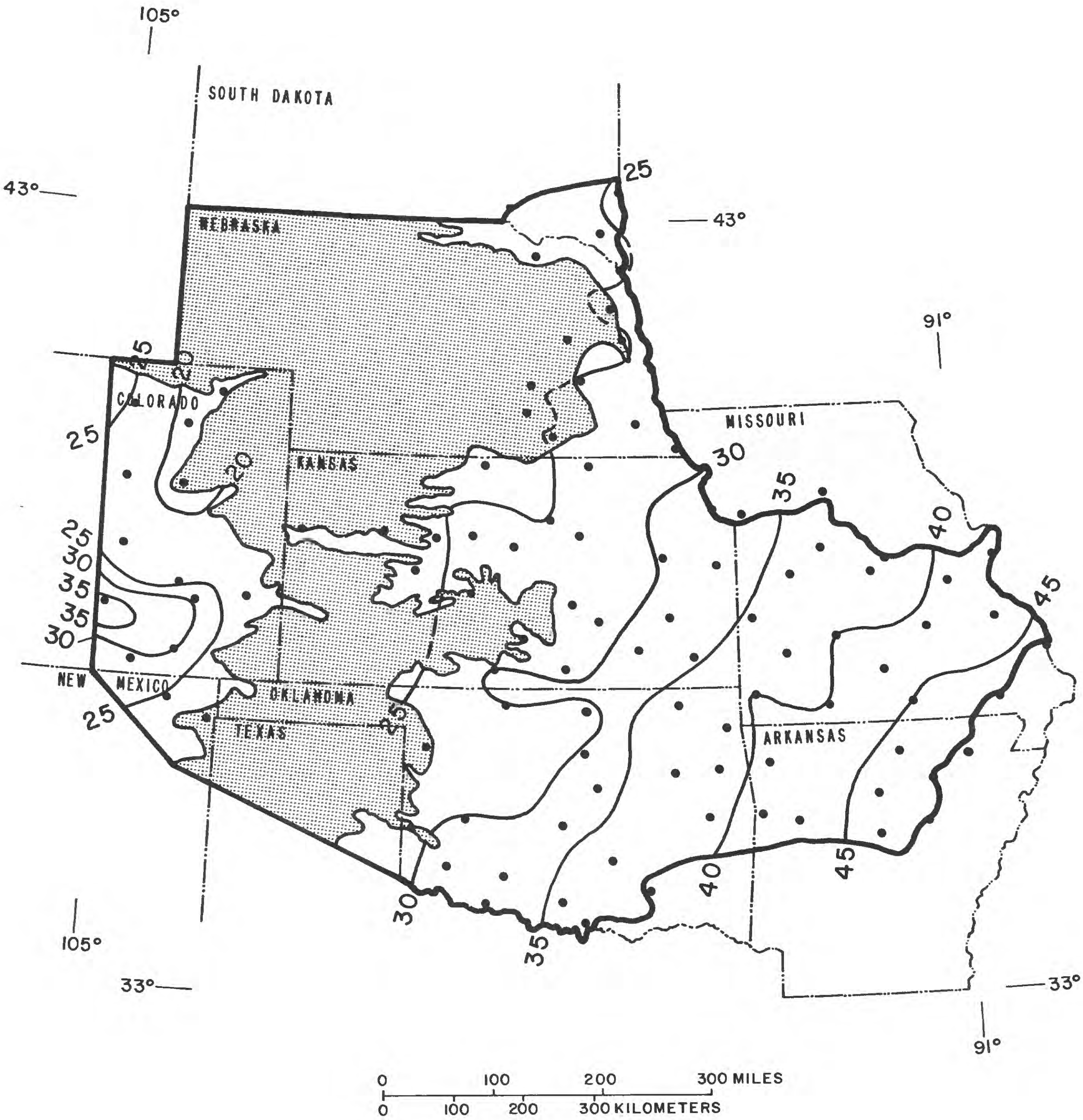


Figure 26.--Mean precipitation during the cool season (October through March), 1951-80.



EXPLANATION

—25--- LINE OF EQUAL PRECIPITATION--Dashed where inferred. Interval 5 percent

• PRECIPITATION STATION

▬ APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 27.--Percent of mean annual precipitation during the cool season (October through March), 1951-80.

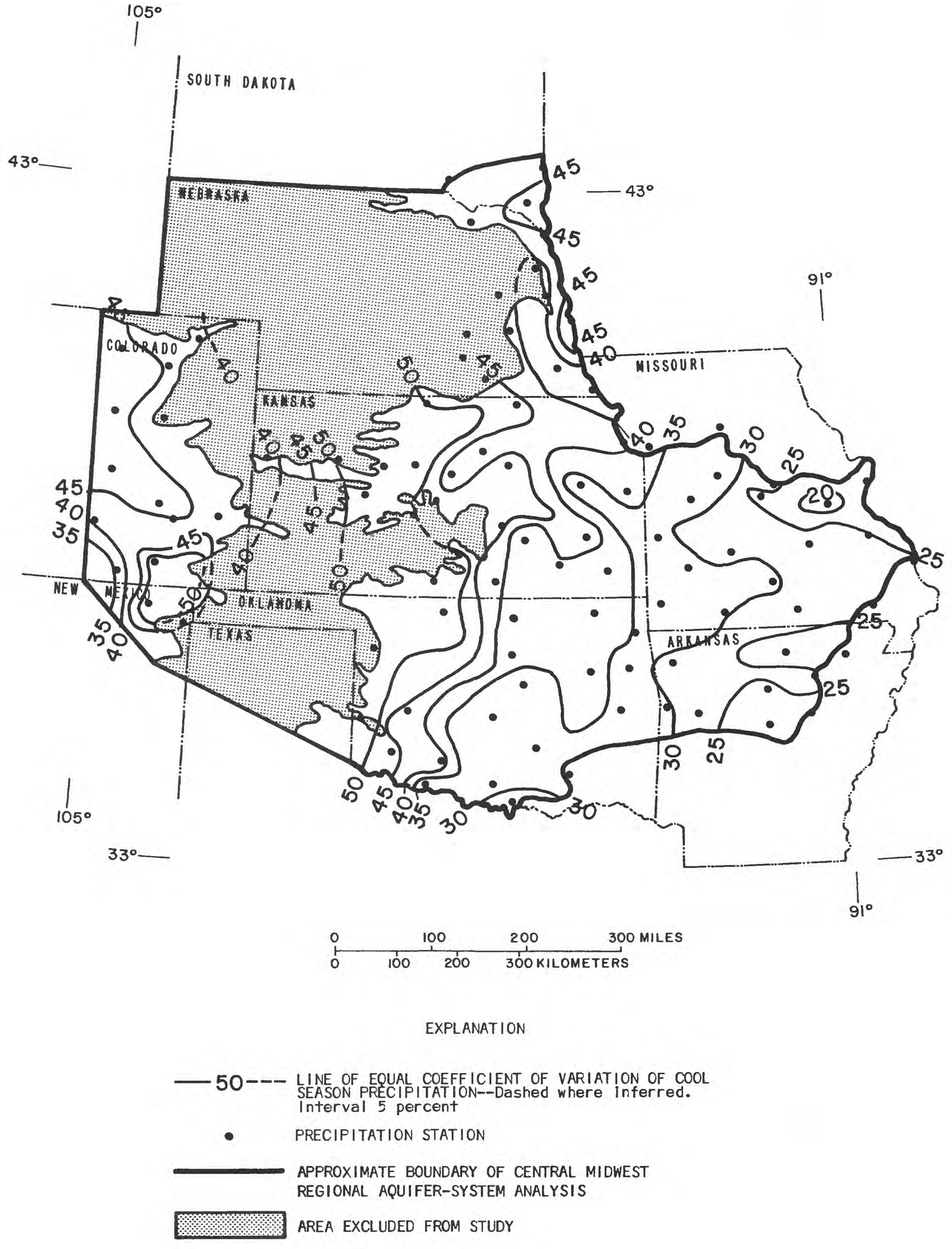


Figure 28.--Coefficient of variation of precipitation during the cool season (October through March), 1951-80.

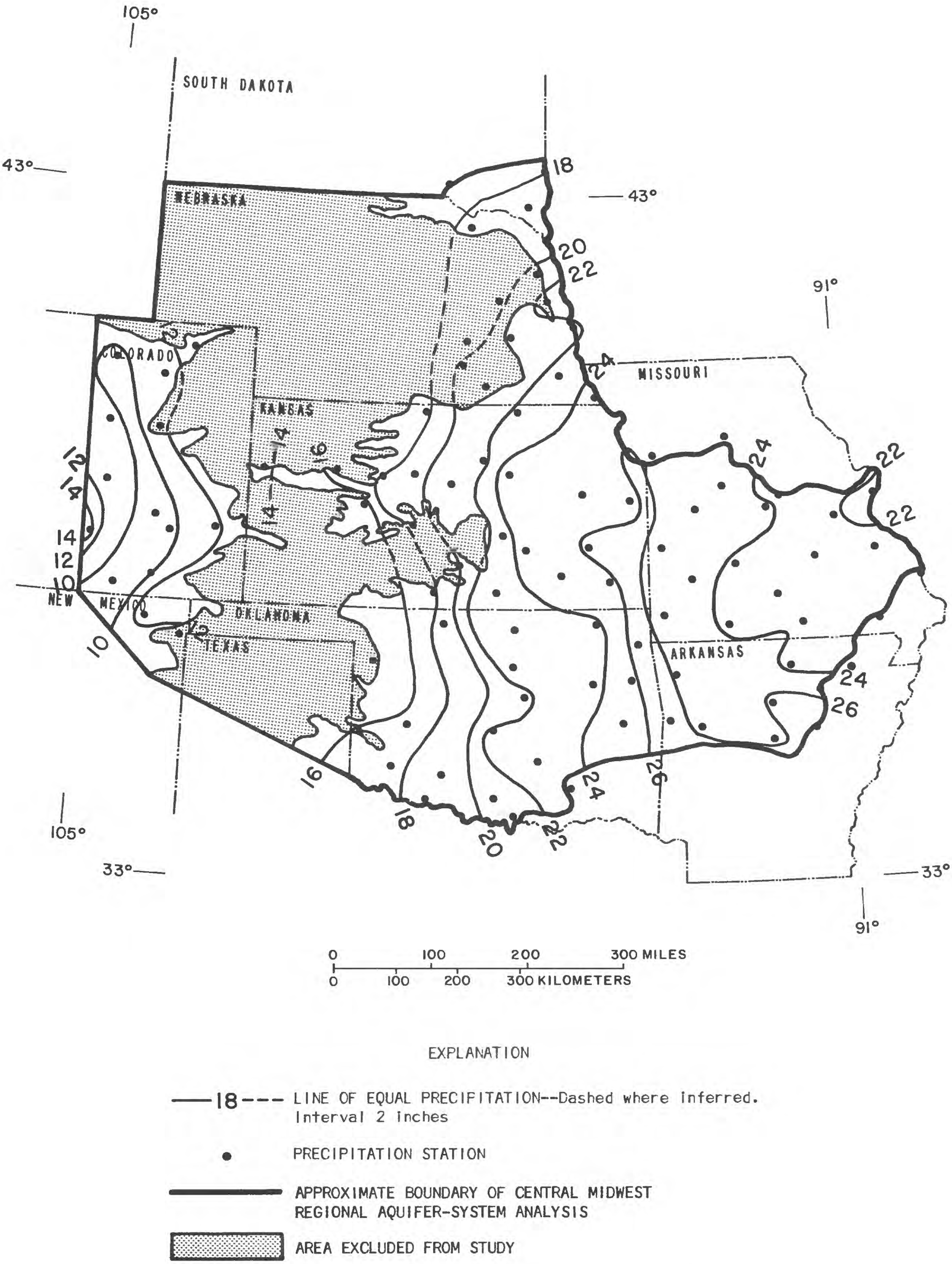


Figure 29.--Mean precipitation during the warm season (April through September), 1951-80.

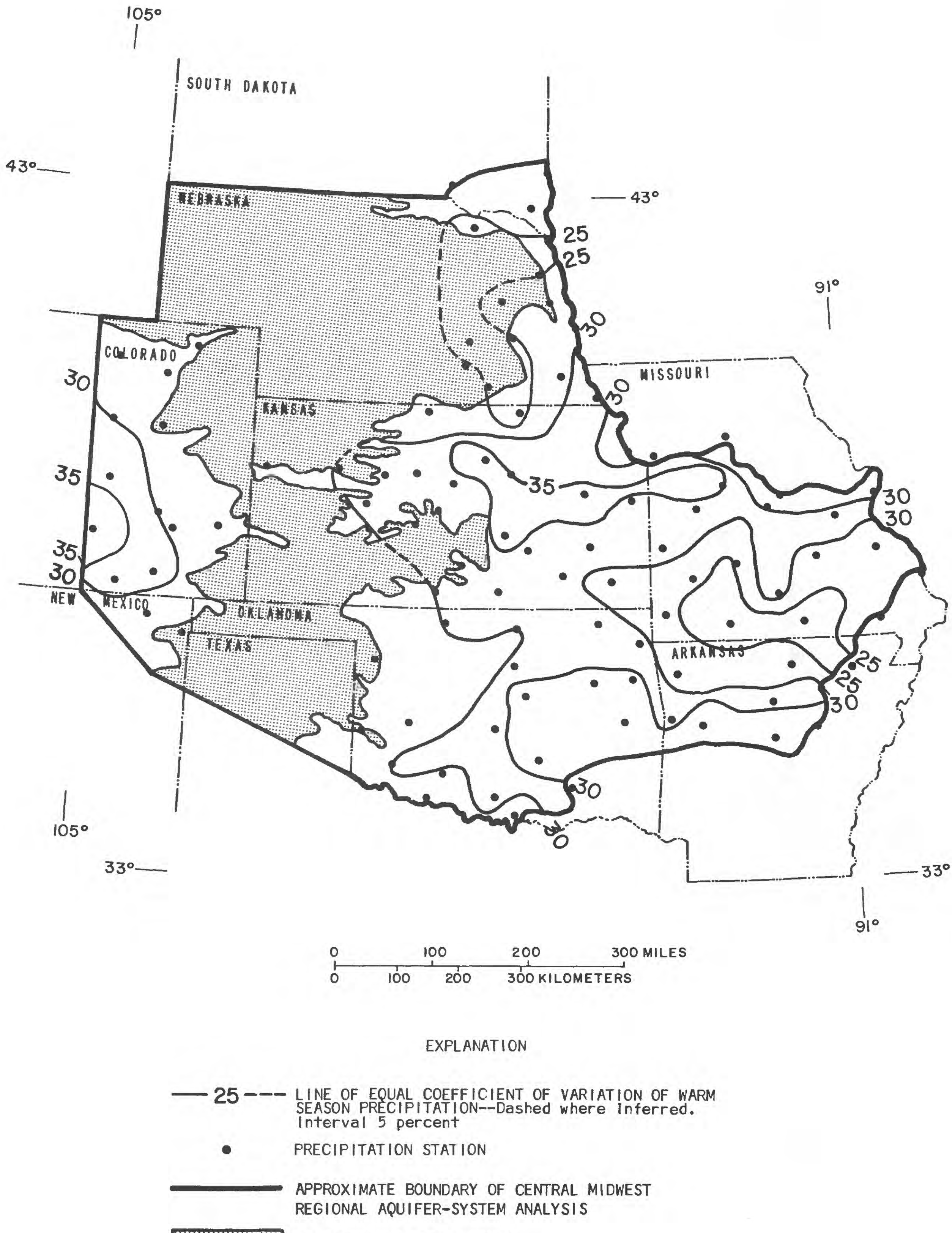
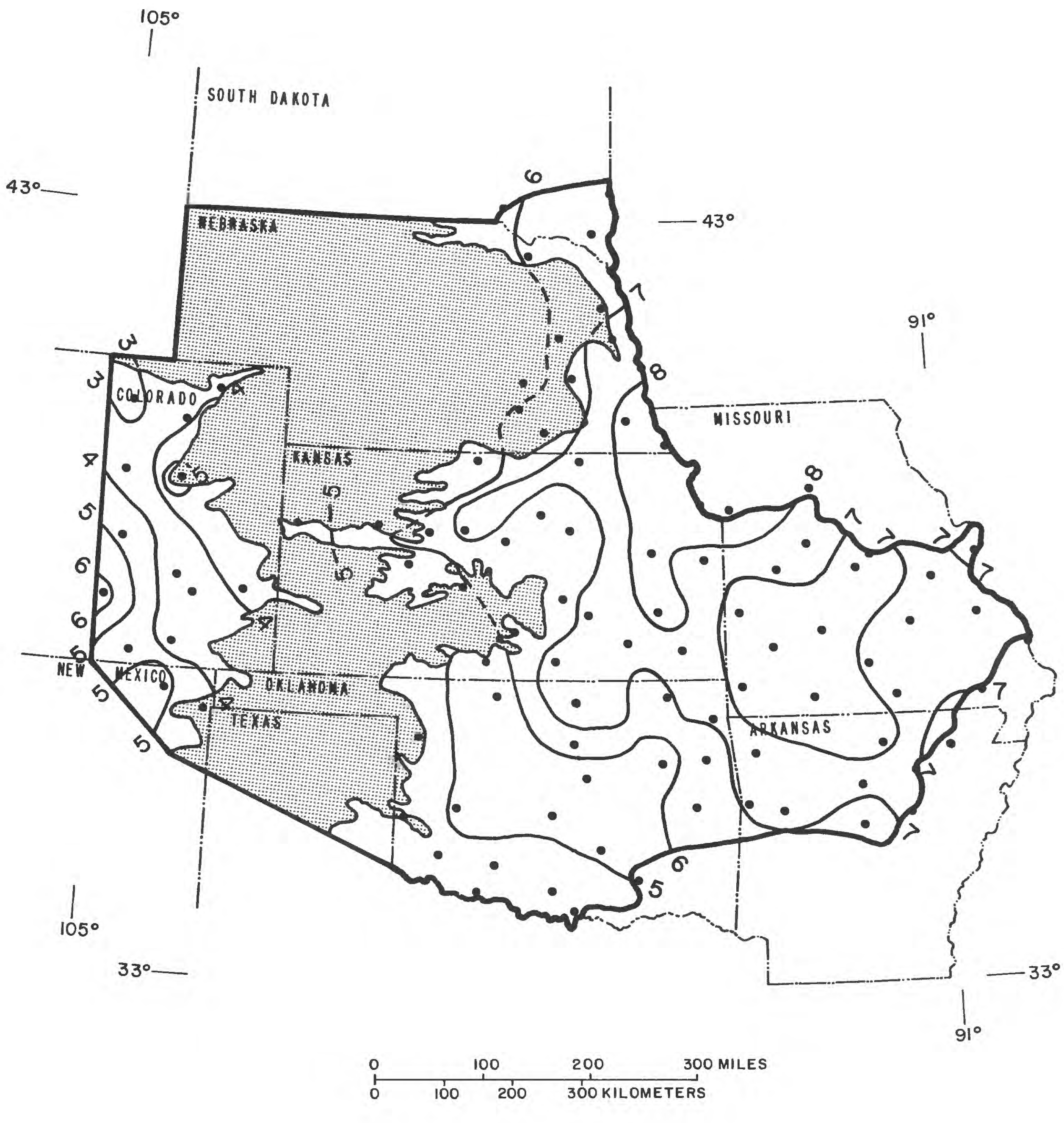


Figure 30.--Coefficient of variation of precipitation during the warm season (April through September), 1951-80.



EXPLANATION

—6--- LINE OF EQUAL PRECIPITATION--Dashed where inferred. Interval 1 inch

• PRECIPITATION STATION

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 31.--Mean precipitation during the irrigation season, 1951-80.

The reliability of precipitation decreases throughout the study area during the irrigation season, as indicated by a coefficient of variation generally exceeding 40 percent. This is, in part, a result of the short time period, which causes greater statistical unreliability, and also because nearly all precipitation during July and August in the study area is of convective origin. Convective-induced precipitation (thunderstorms) is usually more localized and erratically distributed, resulting in wide variations even within small areas. Also, the relatively low quantities of precipitation in the southern extremes of the study area during the irrigation period are often related to the dominance of the Bermuda high pressure system (anticyclonic circulation and atmospheric subsidence). This high pressure system weakens northward and westward, resulting in a relatively higher incidence of thunderstorms and more precipitation in southeast Nebraska, northeast Kansas, and northwest Missouri (fig. 31).

Many spatial and temporal precipitation patterns could be analyzed within the study area because of the region's vast extent and climatic diversities. Those previously discussed are only a few, but they represent some of the more significant spatial and seasonal patterns causing distinct regional contrasts. These patterns have a significant effect on both available soil moisture and potential ground-water recharge, as will be seen in the concluding section of this report.

RESULTS OF THE COMPUTER-GENERATED MODELS OF CONSUMPTIVE WATER USE AND GROUND-WATER RECHARGE

The principal objective of this study is to compute potential ground-water recharge in parts of the CMRASA study area as input to a ground-water model. The preceding sections of this report were intended to develop an understanding of the individual factors that affect consumptive water use and recharge. Initially, climatic factors (solar radiation, temperature, and computed PET), vegetation patterns, and hydrologic properties of the soils that determine actual evapotranspiration (consumptive water use) were analyzed; then the spatial and temporal patterns of precipitation as a natural source of soil moisture and potential recharge were examined. This part of the report combines water requirements and availability to produce the resultant estimation of ground-water recharge.

Results of the Soil-Moisture Program

The soil-moisture program, as described earlier, incorporates PET, vegetation, hydrologic properties of the soils, and precipitation factors to provide a running balance of soil-moisture conditions. A variety of outputs from the program by vegetation type, soil type, and climatic site are computed on a monthly basis; the outputs include: (1) infiltration, (2) surface runoff, (3) CWR, (4) soil moisture under dryland conditions (STD), (5) AET, (6) deep percolation from drylands, (7) soil moisture in storage under drylands, (8) soil moisture in storage under irrigated lands, (9) consumptive irrigation requirements (CIR), and (10) deep percolation from irrigated lands.

The soil-moisture program computed a total of 5,940 different sets of the above data based on the combination of 99 climatic (precipitation) sites, 10 soils, and 6 vegetation types. Considering the monthly output for 30 years of data for the 10 different parameters, several million soil-moisture values were generated through time and space.

The results of the soil-moisture program reflect the effects that diverse climatic conditions within the study area have on soil-moisture conditions. The six sites in figure 32 were selected for their location and apparent climatic differences to demonstrate these variations in soil-moisture conditions that occur with each type of vegetation and soil present in the site area.

Figure 32.--Representative sites for soil-moisture program results (shown in table 6).

Selected factors from the program output that are relevant to this study are shown for these sites in table 6. Those soil-moisture conditions under an irrigation regime are deleted, with the exception of consumptive irrigation requirement (CIR). Also, soil moisture in storage under dryland conditions was deleted because the output value from the program represents the value at a point in time rather than an annual average and would have little meaning in relation to the other factors. The soil-moisture terms in table 6 are defined in the section, Glossary of Selected Terms.

Consumptive irrigation requirement (CIR) cannot be defined directly by the other variables in table 6, since it represents the water required to maintain the soil root zone at 50 percent of its available water capacity. The following equations aid in understanding some of the computations in the table:

Infiltration = Mean annual precipitation minus surface runoff

AET = CWR minus STD

DP = Infiltration minus AET

Mean annual precipitation and PET at each site in table 6 indicate the relative water needs and potential recharge for the given area. However, for a more precise comparison among sites, soil-moisture conditions must be compared under identical vegetation types and soil conditions. For example, considering row crops in soil group 1: The calculated CIR at the La Junta, Colo., site is nearly four times greater than at the Vermillion, S. Dak., site (25.41 versus 6.77 in). This disparity can be attributed to differences in PET, which is primarily controlled by solar radiation (figs. 3 and 8) and warm-season precipitation (fig. 30). The comparison of calculated deep percolation at the La Junta and Paris, Ark., sites under the same vegetation and soil conditions, indicates an even greater contrast (0.0 versus 11.67 in). This difference mainly results from differences in cool-season precipitation shown in figure 26 (4 versus 20 in).

Certain values obviously are hypothetical, such as consumptive irrigation requirement (CIR) for fallow, since fallow is not likely to be irrigated. Instead, this represents only the amount of supplemental water required to keep fallowed land at the required 50 percent capacity to match soil-moisture loss due to evaporation.

Table 6.--Mean annual values, in inches, of selected output from the soil-moisture program at selected sites in the CMRASA study area

[CWR = consumptive water requirements; STD = soil-moisture deficit under dryland conditions; AET = actual evapotranspiration (consumptive water use under dryland conditions); DP = deep percolation (recharge); CIR = consumptive irrigation requirements]

Soil group	Vegetation type	Infiltration	Surface runoff	CWR	STD	AET	DP	CIR
PARIS, ARK. - Mean annual precipitation = 44.70 inches Mean annual potential evapotranspiration = 51.53 inches								
1	Row crop	36.45	8.25	32.14	7.36	24.78	11.67	8.98
	Alfalfa	39.51	5.19	40.59	6.82	33.77	5.74	9.13
	Small grain	39.51	5.19	32.35	2.55	29.80	9.71	3.26
	Grassland	39.51	5.19	33.29	6.02	27.27	12.24	7.61
	Woodland	39.51	5.19	34.76	4.41	30.35	9.16	7.92
	Fallow	36.45	8.25	22.26	1.19	21.07	15.38	2.10
2	Row crop	32.11	12.59	32.14	8.90	23.24	8.87	10.17
	Alfalfa	39.51	5.19	40.59	7.29	33.30	6.21	9.40
	Small grain	36.45	8.25	32.35	3.27	29.08	7.37	3.80
	Grassland	36.45	8.25	33.39	7.18	26.21	10.24	8.49
	Woodland	36.45	8.25	34.76	5.44	29.32	7.13	8.96
	Fallow	32.11	12.59	22.26	1.70	20.56	11.55	2.84
3	Row crop	32.11	12.59	32.14	9.25	22.89	9.22	10.35
	Alfalfa	36.45	8.25	40.59	8.97	31.62	4.83	10.73
	Small grain	36.45	8.25	32.35	3.45	28.90	7.55	3.78
	Grassland	36.45	8.25	33.39	7.46	25.92	10.53	8.62
	Woodland	36.45	8.25	34.76	5.95	28.81	7.64	4.25
	Fallow	32.11	12.59	22.26	1.86	20.40	11.71	2.98
4	Row crop	39.51	5.19	32.14	7.13	25.01	14.50	8.62
	Alfalfa	44.70	.00	40.59	6.31	34.28	10.42	11.57
	Small grain	39.51	5.19	32.35	2.71	29.64	9.87	3.27
	Grassland	39.51	5.19	33.39	6.40	26.99	12.52	7.76
	Woodland	39.51	5.19	34.76	4.85	29.91	9.60	8.20
	Fallow	39.51	5.19	22.26	1.20	21.06	18.45	2.04
6	Row crop	36.45	8.25	32.14	8.41	23.73	12.72	9.52
	Alfalfa	39.51	5.19	40.59	8.31	32.28	7.23	9.99
	Small grain	36.45	8.25	32.35	3.63	28.72	7.73	3.76
	Grassland	36.45	8.25	33.39	7.76	25.63	10.82	8.74
	Woodland	36.45	8.25	34.76	6.51	28.25	8.20	9.55
	Fallow	36.45	8.25	22.26	1.58	20.68	15.77	2.48

Table 6.--Mean annual values, in inches, of selected output from the soil-moisture program at selected sites in the CMRASA study area--Continued

Soil group	Vegetation type	Infil-tra-tion	Surface runoff	CWR	STD	AET	DP	CIR
NORMAN, OKLA. - Mean annual precipitation = 32.83 inches Mean annual potential evapotranspiration = 55.05 inches								
1	Row crop	28.65	5.17	34.36	11.14	23.22	4.43	11.92
	Alfalfa	29.57	3.25	43.15	14.17	28.98	.59	14.31
	Small grain	29.57	3.25	34.53	7.57	26.96	2.61	5.22
	Grassland	29.57	3.25	35.48	9.71	25.77	3.80	10.55
	Woodland	32.83	.00	37.01	8.03	28.98	3.85	10.61
	Fallow	27.65	5.17	23.72	2.78	20.94	6.71	3.98
2	Row crop	24.66	8.16	34.36	12.58	21.78	2.88	12.97
	Alfalfa	29.57	3.25	43.15	14.29	28.86	.71	14.38
	Small grain	27.65	5.17	34.53	8.53	26.00	1.65	5.47
	Grassland	27.65	5.17	35.48	10.73	24.75	2.90	11.28
	Woodland	32.83	.00	37.01	8.36	28.65	4.18	10.86
	Fallow	24.66	8.16	23.72	3.56	20.16	4.50	4.71
4	Row crop	29.57	3.25	34.36	10.91	23.45	6.12	11.64
	Alfalfa	32.83	.00	43.15	12.36	30.79	2.04	12.97
	Small grain	29.57	3.25	34.53	7.71	26.82	2.75	5.12
	Grassland	29.57	3.25	35.48	9.96	25.52	4.05	10.68
	Woodland	32.83	.00	37.01	8.36	28.65	4.18	10.86
	Fallow	29.57	3.25	23.72	2.80	20.92	8.65	3.89
5	Row crop	27.65	5.17	34.36	11.78	22.58	5.07	12.26
	Alfalfa	32.83	.00	43.15	12.58	30.57	2.26	13.10
	Small grain	29.57	3.25	34.53	7.86	26.67	2.90	5.04
	Grassland	29.57	3.25	35.48	10.23	25.25	4.32	10.81
	Woodland	32.83	.00	37.01	8.71	28.30	4.53	11.11
	Fallow	27.65	5.17	23.72	3.22	20.50	7.15	4.25
6	Row crop	27.65	5.17	34.36	12.10	22.26	5.39	12.42
	Alfalfa	29.57	3.25	43.15	14.57	28.58	.99	14.52
	Small grain	27.65	5.17	34.53	8.83	25.70	1.95	5.28
	Grassland	27.65	5.17	35.48	11.25	24.23	3.42	11.50
	Woodland	32.83	.00	37.01	9.11	27.90	4.93	11.37
	Fallow	27.65	5.17	23.72	3.46	20.26	7.39	4.40
10	Row crop	29.57	3.25	34.36	14.02	20.34	9.23	13.22
	Alfalfa	32.83	.00	43.15	15.74	27.41	5.42	14.26
	Small grain	32.83	.00	34.53	9.21	25.32	7.51	4.34
	Grassland	32.83	.00	35.48	12.10	23.38	9.45	10.90
	Woodland	32.83	.00	37.01	12.81	24.20	8.63	13.37
	Fallow	29.57	3.25	23.72	5.15	18.57	11.00	5.25

Table 6.--Mean annual values, in inches, of selected output from the soil-moisture program at selected sites in the CMRASA study area--Continued

Soil group	Vegetation type	Infil-tra-tion	Surface runoff	CWR	STD	AET	DP	CIR
BUFFALO, MO. - Mean annual precipitation = 38.88 inches Mean annual potential evapotranspiration - 47.09 inches								
1	Row crop	32.95	5.94	30.02	6.42	23.60	9.35	8.34
	Alfalfa	35.35	3.53	37.72	6.17	31.55	3.80	8.29
	Small grain	35.35	3.53	28.80	1.59	27.21	8.14	2.61
	Grassland	35.35	3.53	30.85	5.11	25.74	9.61	6.65
	Woodland	38.88	.00	32.38	3.38	29.00	9.88	6.50
	Fallow	32.95	5.94	20.55	.67	19.88	13.07	1.89
2	Row crop	29.12	9.77	30.02	7.82	22.20	6.92	9.44
	Alfalfa	35.35	3.53	37.72	6.50	31.22	4.13	8.54
	Small grain	32.95	5.94	28.80	2.14	26.66	6.29	3.03
	Grassland	32.95	5.94	30.85	5.90	24.95	8.00	5.86
	Woodland	38.88	.00	32.38	3.76	28.62	10.26	6.74
	Fallow	29.12	9.77	20.55	1.16	19.39	9.73	2.49
3	Row crop	29.12	9.77	30.02	8.16	21.86	7.26	9.61
	Alfalfa	32.95	5.94	37.72	7.78	29.94	3.01	9.72
	Small grain	32.95	5.94	28.80	2.29	26.51	6.44	3.08
	Grassland	32.95	5.94	30.85	6.15	24.70	8.25	7.62
	Woodland	38.88	.00	32.38	4.17	28.21	10.67	7.01
	Fallow	29.12	9.77	20.55	1.33	19.22	9.90	2.60
5	Row crop	32.95	5.94	30.02	7.09	22.93	10.02	8.70
	Alfalfa	38.88	.00	37.72	6.10	31.62	7.26	7.97
	Small grain	35.35	3.53	28.80	1.89	26.91	8.44	2.73
	Grassland	35.35	3.53	30.85	5.54	25.31	10.04	6.95
	Woodland	38.88	.00	32.38	4.17	28.21	10.67	7.01
	Fallow	32.95	5.94	20.55	.94	19.61	13.34	2.11
6	Row crop	32.95	5.94	30.02	7.43	22.59	10.36	8.87
	Alfalfa	35.35	3.53	37.72	7.21	30.51	4.84	9.03
	Small grain	32.95	5.94	28.80	2.46	26.34	6.61	3.10
	Grassland	32.95	5.94	30.85	6.42	24.43	8.52	7.75
	Woodland	38.88	.00	32.38	4.59	27.79	11.09	7.28
	Fallow	32.95	5.94	20.55	1.11	19.44	13.51	1.08

Table 6.--Mean annual values, in inches, of selected output from the soil-moisture program at selected sites in the CMRASA study area--Continued

Soil group	Vegetation type	Infiltration	Surface runoff	CWR	STD	AET	DP	CIR
ABILENE, KANS. - Mean annual precipitation = 29.24 inches Mean annual potential evapotranspiration = 46.42 inches								
1	Row crop	24.73	4.51	30.23	8.71	21.52	3.21	9.72
	Alfalfa	26.40	2.84	37.81	11.84	25.97	.43	11.99
	Small grain	26.40	2.84	27.65	4.41	23.23	3.17	3.76
	Grassland	26.40	2.84	30.83	7.40	23.43	2.97	8.30
	Woodland	26.40	2.84	32.64	7.39	25.25	1.15	9.20
	Fallow	24.73	4.51	20.49	1.66	18.83	5.90	2.62
2	Row crop	22.10	7.15	30.23	10.21	20.02	2.08	10.88
	Alfalfa	26.40	2.84	37.81	11.93	25.88	.52	12.01
	Small grain	24.73	4.51	27.65	5.14	22.51	2.22	4.19
	Grassland	24.73	4.51	30.83	8.44	22.39	2.34	9.08
	Woodland	24.73	4.51	32.64	8.73	23.91	.82	11.76
	Fallow	22.10	7.15	20.49	2.30	18.19	3.91	3.30
3	Row crop	22.10	7.15	30.23	10.44	19.79	2.31	10.99
	Alfalfa	24.73	4.51	37.81	13.41	24.40	.33	13.15
	Small grain	24.73	4.51	27.65	5.28	22.37	2.36	4.13
	Grassland	24.73	4.51	30.83	8.63	22.20	2.53	9.14
	Woodland	24.73	4.51	32.64	8.88	23.76	.97	10.41
	Fallow	22.10	7.15	20.49	2.45	18.04	4.06	3.41
4	Row crop	26.40	2.84	30.23	8.40	21.83	4.57	9.31
	Alfalfa	29.24	.00	37.81	10.16	27.65	1.59	10.63
	Small grain	26.40	2.84	27.65	4.56	23.09	3.31	3.75
	Grassland	26.40	2.84	30.83	7.60	23.23	3.17	8.39
	Woodland	26.40	2.84	32.64	7.58	25.06	1.34	9.41
	Fallow	26.40	2.84	20.49	1.60	18.89	7.51	2.54
5	Row crop	24.73	4.51	30.23	9.24	20.99	3.74	9.99
	Alfalfa	29.24	.00	37.81	10.32	27.49	1.75	10.70
	Small grain	26.40	2.84	27.65	4.63	23.02	3.48	3.72
	Grassland	26.40	2.84	30.83	7.81	23.02	3.38	8.47
	Woodland	26.40	2.84	32.64	7.79	24.85	1.55	9.61
	Fallow	24.73	4.51	20.49	1.90	18.59	6.14	2.84

Table 6.--Mean annual values, in inches, of selected output from the soil-moisture program at selected sites in the CMRASA study area--Continued

Soil group	Vegetation type	Infil-tra-tion	Surface runoff	CWR	STD	AET	DP	CIR
VERMILLION, S. DAK. - Mean annual precipitation = 24.24 inches Mean annual potential evapotranspiration - 55.05 inches								
1	Row crop	21.47	2.78	24.62	5.61	19.01	2.46	6.77
	Alfalfa	22.74	1.51	30.56	7.99	22.57	.17	8.50
	Small grain	22.74	1.51	20.31	1.44	18.87	3.87	2.30
	Grassland	22.74	1.51	24.76	4.60	20.07	2.67	5.59
	Woodland	22.74	1.51	26.64	4.75	21.89	.85	6.33
	Fallow	21.47	2.78	16.37	.57	15.80	5.67	1.21
2	Row crop	19.18	5.07	24.62	7.03	17.59	1.59	7.94
	Alfalfa	22.74	1.51	30.56	8.06	22.50	.24	8.52
	Small grain	21.47	2.78	20.31	1.82	18.49	2.98	2.53
	Grassland	21.47	2.78	24.76	5.36	19.40	2.07	6.12
	Woodland	21.47	2.78	26.64	5.66	20.98	.49	7.11
	Fallow	19.18	5.07	16.37	.89	15.48	3.70	1.69
3	Row crop	19.18	5.07	24.62	7.23	17.39	1.79	8.05
	Alfalfa	21.47	2.78	30.56	9.19	21.37	.10	9.38
	Small grain	21.47	2.78	20.31	1.92	18.39	3.08	2.56
	Grassland	21.47	2.78	24.76	5.53	19.23	2.24	6.20
	Woodland	21.47	2.78	26.64	5.80	20.84	.63	7.28
	Fallow	19.18	5.07	16.37	.96	15.41	3.77	1.80
4	Row crop	22.74	1.51	24.62	5.35	19.27	3.47	6.43
	Alfalfa	24.24	.00	30.56	7.08	23.48	.76	7.81
	Small grain	22.74	1.51	20.31	1.55	18.76	3.98	2.34
	Grassland	22.74	1.51	24.76	4.84	19.92	2.82	5.67
	Woodland	22.74	1.51	26.64	4.91	21.73	1.01	6.49
	Fallow	22.74	1.51	16.37	.58	15.79	6.95	1.23
5	Row crop	21.47	2.78	24.62	6.09	18.53	2.94	7.04
	Alfalfa	24.24	.00	30.56	7.23	23.33	.91	7.85
	Small grain	22.74	1.51	20.31	1.69	18.62	4.12	2.37
	Grassland	22.74	1.51	24.76	5.00	19.76	2.98	5.76
	Woodland	22.74	1.51	26.64	5.07	21.57	1.17	6.66
	Fallow	21.47	2.78	16.37	.69	15.68	5.79	1.39

Table 6.--Mean annual values, in inches, of selected output from the soil-moisture program at selected sites in the CMRASA study area--Continued

Soil group	Vegetation type	Infiltration	Surface runoff	CWR	STD	AET	DP	CIR
6	Row crop	21.47	2.78	24.62	6.35	18.27	3.20	7.18
	Alfalfa	22.74	1.51	30.56	8.20	22.36	.38	8.55
	Small grain	21.47	2.78	20.31	2.04	18.27	3.20	2.58
	Grassland	21.47	2.78	24.76	5.70	19.06	2.41	6.29
	Woodland	21.47	2.78	26.64	5.96	20.68	.79	7.44
	Fallow	21.47	2.78	16.37	.76	15.61	5.86	1.49
7	Row crop	24.24	0.00	24.62	6.02	18.60	5.64	6.63
	Alfalfa	24.24	.00	30.56	7.82	22.74	1.50	8.05
	Small grain	24.24	.00	20.31	2.02	18.29	5.95	2.30
	Grassland	24.24	.00	24.76	5.22	19.54	4.70	5.76
	Woodland	24.24	.00	26.64	5.25	21.39	2.85	6.78
	Fallow	24.24	.00	16.37	.85	15.52	8.72	1.57
10	Row crop	22.74	1.51	24.62	8.01	16.61	6.13	7.85
	Alfalfa	24.24	.00	30.56	9.26	21.30	2.94	8.57
	Small grain	24.24	.00	20.31	3.18	17.13	7.11	2.29
	Grassland	24.24	.00	24.76	6.57	18.19	6.05	6.38
	Woodland	24.24	.00	26.64	7.05	19.59	4.65	7.90
	Fallow	22.74	1.51	16.37	1.77	14.60	8.14	2.31
LA JUNTA, COLO. - Mean annual precipitation = 12.39 inches; Mean annual potential evapotranspiration = 68.93 inches								
1	Row crop	12.00	0.39	43.32	31.32	12.00	.00	25.41
	Alfalfa	12.22	.17	54.27	42.05	12.22	.00	28.43
	Small grain	12.22	.17	42.89	30.67	12.22	.00	10.86
	Grassland	12.22	.17	44.61	32.39	12.22	.00	21.17
	Woodland	12.22	.17	46.65	34.43	12.22	.00	29.20
	Fallow	12.00	.39	29.80	17.80	12.00	.00	13.38
2	Row crop	11.36	1.14	43.32	31.96	11.36	.00	25.79
	Alfalfa	12.22	.17	54.27	42.05	12.22	.00	28.13
	Small grain	12.00	.39	42.89	30.89	12.00	.00	10.78
	Grassland	12.00	.39	44.61	32.61	12.00	.00	21.14
	Woodland	12.00	.39	46.65	34.65	12.00	.00	29.06
	Fallow	11.26	1.14	29.80	18.54	11.26	.00	13.69

Table 6.--Mean annual values, in inches, of selected output from the soil-moisture program at selected sites in the CMRASA study area--Continued

Soil group	Vegetation type	Infiltration	Surface runoff	CWR	STD	AET	DP	CIR
3	Row crop	11.26	1.14	43.32	32.06	11.26	0.00	25.61
	Alfalfa	12.00	.39	54.27	42.27	12.00	.00	27.96
	Small grain	12.00	.39	42.89	30.89	12.00	.00	10.63
	Grassland	12.00	.39	44.61	32.61	12.00	.00	20.99
	Woodland	12.00	.39	46.65	34.65	12.00	.00	28.78
	Fallow	11.26	1.14	29.80	18.54	11.26	.00	13.54
4	Row crop	12.22	.17	43.32	31.10	12.22	.00	25.04
	Alfalfa	12.39	.00	54.27	41.88	12.39	.00	28.02
	Small grain	12.22	.17	42.89	30.67	12.22	.00	10.71
	Grassland	12.22	.17	44.61	32.39	12.22	.00	21.02
	Woodland	12.22	.17	46.65	34.43	12.22	.00	28.93
	Fallow	12.22	.17	29.80	17.59	12.21	.01	13.09
7	Row crop	12.39	.00	43.32	31.00	12.32	.07	24.23
	Alfalfa	12.39	.00	54.27	41.88	12.39	.00	26.82
	Small grain	12.39	.00	42.89	30.59	12.30	.09	10.10
	Grassland	12.39	.00	44.61	32.24	12.37	.02	20.31
	Woodland	12.39	.00	46.65	34.26	12.39	.00	27.65
	Fallow	12.39	.00	29.80	17.55	12.25	.14	12.51
8	Row crop	12.22	.17	43.32	31.19	12.13	.09	24.06
	Alfalfa	12.39	.00	54.27	41.88	12.39	.00	26.22
	Small grain	12.22	.17	42.89	30.74	12.15	.07	9.85
	Grassland	12.22	.17	44.61	32.44	12.17	.05	20.12
	Woodland	12.22	.17	46.65	34.43	12.22	.00	27.19
	Fallow	12.22	.17	29.80	17.74	12.06	.16	12.32
10	Row crop	12.22	.17	43.32	31.37	11.95	.27	23.66
	Alfalfa	12.39	.00	54.27	41.89	12.38	.01	25.32
	Small grain	12.39	.00	42.89	30.74	12.15	.24	9.47
	Grassland	12.39	.00	44.41	32.17	12.24	.15	19.59
	Woodland	12.39	.00	46.65	34.13	12.37	.02	26.17
	Fallow	12.22	.17	29.80	17.97	11.83	.39	11.96

While many significant differences exist among the sites in table 6, differences also are apparent within the same sites for various vegetation types and soil combinations. At the Abilene, Kans., site, computed annual deep percolation ranges from 0.33 inches for alfalfa on steep, clayey soils to over 7.5 inches for fallow on flat, sandy loam soils. For a more accurate assessment of water needs and potential ground-water recharge of a region, the computed results of the soil-moisture program must be interpreted in relation to the vegetation and soil characteristics of that region. The water-use program based on vegetation and soil distributions, places the results of the soil-moisture program in a spatial context.

Results of the Water-Use Program

The output from the soil-moisture program, which includes all possible combinations of soils and vegetation for the 99 climatic sites, is input to the water-use program that weights or proportions these data on the basis of vegetation and soil type within the grid elements of the CMRASA ground-water model. The interpolation procedure is based on the distance of the two or three nearest climatic (precipitation) sites to weight or adjust the soil-moisture programs's output to the centerpoint of each element. If a climatic site occurred within a model grid element, only the soil-moisture program's results at that site were used for that element.

Two vegetation scenarios were computed for the study area. The first reflects vegetation statistics derived from the 1978 agricultural census (U.S. Department of Commerce, 1980), which was assumed to represent vegetation conditions during the period 1951-80. The second scenario reflects pre-agricultural vegetation that considers only woodland and range or grassland conditions. In this pre-agricultural scenario, woodland area was the same as that in 1978, while the 1978 cultivated land or cropland was treated as pre-agricultural grassland. The pre-agricultural scenario was based on the premise that most cultivated land occurred at the expense of grasslands, and probably very little woodland was actually cleared even in the heavily forested areas of the Ozarks. These rugged areas are still more than 90 percent forested.

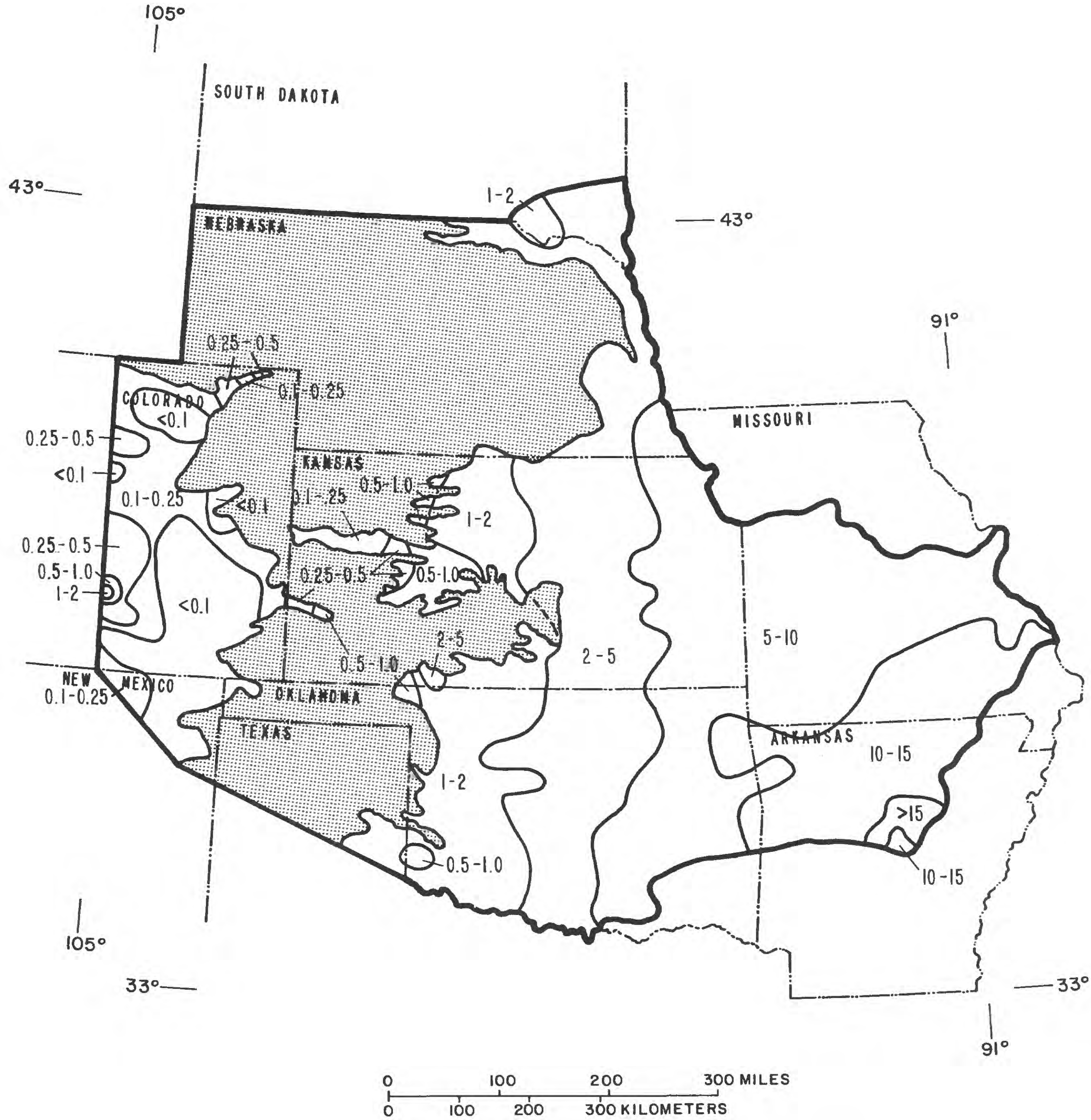
Both vegetation scenarios are based on the 1951-80 climatic sequence. There appears to be little consistent evidence to indicate that long-term climatic trends immediately prior to cultivated agriculture were much different than the present. The 30-year sequence used in this study contains a wide range of short-term climatic extremes that are characteristic of this region.

The 1978 and pre-agricultural scenarios produced mean annual recharge values of 4.5 and 4.7 inches, respectively. The lower recharge value for the 1978 scenario can be attributed principally to alfalfa or tame hay production, which has much higher consumptive water requirements than range or grassland. An examination of the simulated data indicates that higher pre-agricultural recharge occurs in the eastern part of the study area where large areas are devoted to tame hay. In the western part, the 1978 scenario has slightly higher potential recharge because significant areas of fallow occur in conjunction with winter wheat. The recharge differences between the two scenarios, however, do not appear to be significant except in localized areas.

The two recharge patterns are shown in figures 33 and 34. Spatial differences are slight except in the east where the 10-inch contour extends slightly westward under pre-agricultural conditions. In the region of northeastern Oklahoma, southwestern Missouri, northeastern Arkansas, and southeastern Kansas, potential recharge is 0.50 to 1.0 inch greater for the pre-agricultural scenario, because of the significant production of tame hay or alfalfa during 1978 with their high consumptive water requirements. Percentage differences of potential recharge range from 5 to 15 percent greater per element under pre-agricultural conditions in this area.

Less potential recharge is evident in western parts of the study area under pre-agricultural conditions, particularly in eastern Colorado, because of the absence of fallow conditions. The increases in potential recharge under cultivated conditions amount to as much as 50 percent in some grid elements in eastern Colorado and western Kansas. However, the use of percentage differences is somewhat deceptive because of the low absolute amounts of recharge under consideration (less than 0.5 inch in most cases).

The overall patterns of resultant recharge within a region possessing the climatic diversity of the study area indicate that the controlling elements are the climatic factors themselves, particularly precipitation. A cursory examination of mean annual precipitation in figure 22 and mean annual ground-water recharge in figures 33 and 34 indicates very similar patterns. However, the proportion of precipitation contributed to recharge decreases as precipitation declines. A comparison of precipitation and recharge values from figures 22, 33, and 34 indicates the proportional changes that are shown in table 7.



EXPLANATION

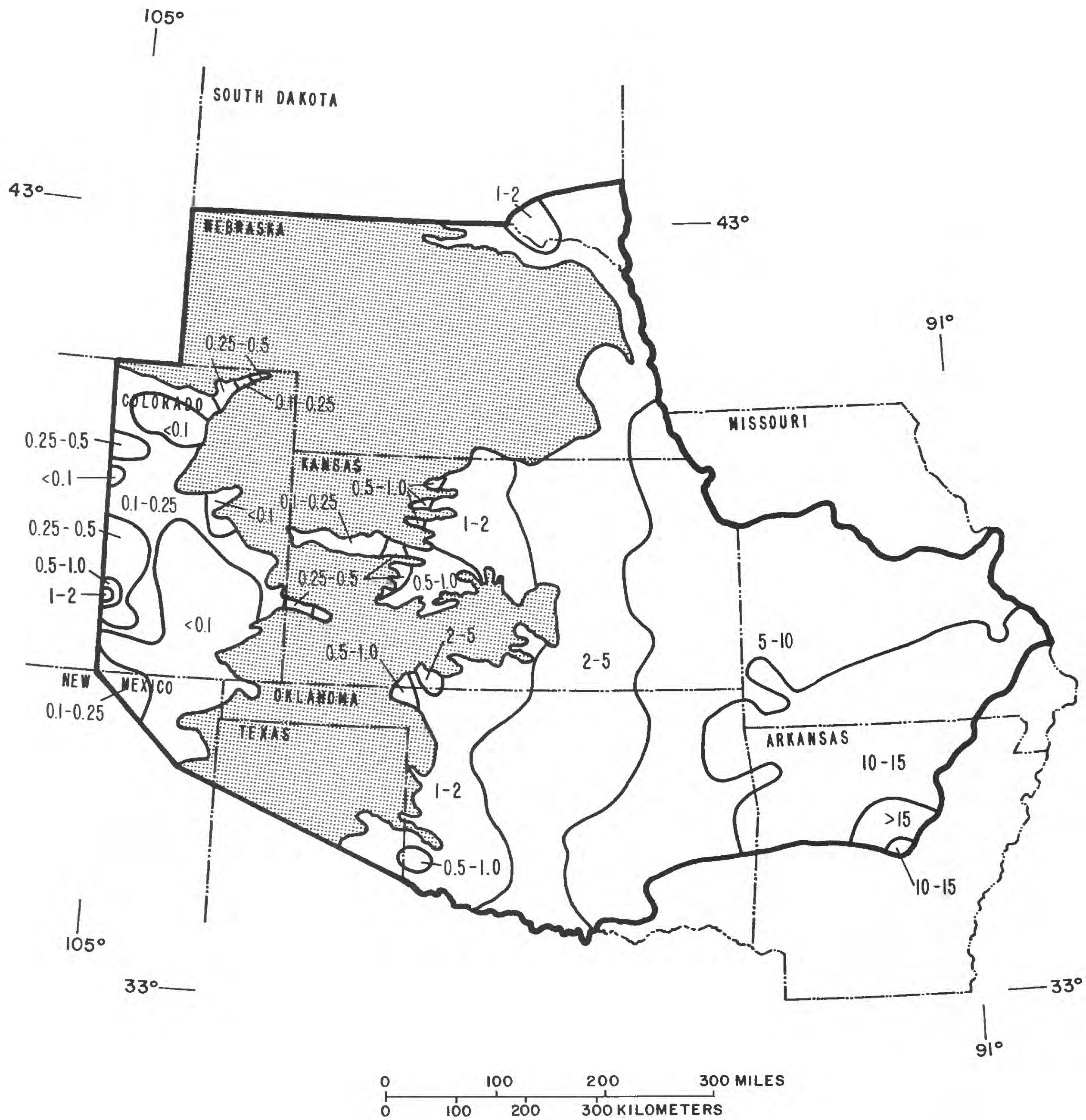
1-2 RANGE OF ANNUAL RECHARGE, IN INCHES

BOUNDARY OF RECHARGE AREAS

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 33.--Computed mean annual ground-water recharge under 1978 vegetation conditions, 1951-80.



EXPLANATION

2-5 RANGE OF MEAN ANNUAL RECHARGE, IN INCHES

BOUNDARY OF RECHARGE AREAS

APPROXIMATE BOUNDARY OF CENTRAL MIDWEST REGIONAL AQUIFER-SYSTEM ANALYSIS

AREA EXCLUDED FROM STUDY

Figure 34.--Computed mean annual ground-water recharge, 1951-80, assuming pre-agricultural vegetation conditions.

Table 7.--Generalized relationship between precipitation and potential recharge

Mean annual precipitation (inches)	Mean annual recharge (inches)	Approximate proportion (percent)
50	15.00	30
40	10.00	25
30	3.50	12
20	1.00	5
15	.25	2

The relationship shown in table 7 obviously is oversimplified. Many other factors, including other climatic conditions, vegetation, and soils also affect potential recharge. However, the generalization can be made that as precipitation declines, both the magnitude and proportion of precipitation contributed to recharge declines. Figure 35 is a scatter diagram of computed mean annual recharge (using the 1978 scenario) versus mean annual precipitation for the 356 model grid elements derived from the water-use program. The limited scatter among the points in this figure indicates a close relationship between precipitation and recharge. Furthermore, the relationship becomes approximately linear where mean annual precipitation exceeds 30 inches and recharge exceeds 3 inches. The extremely low recharge in the western part of the study area, particularly Colorado and New Mexico, appears to be closely related to the high PET (fig. 16), solar radiation (fig. 3), percent of possible sunshine (fig. 4), and lower relative humidities (fig. 9).

Seasonal distribution of precipitation also shows a strong relationship to recharge. Areas of high cool-season precipitation (figs. 26 and 27) tend to receive higher amounts of recharge. Comparisons of recharge (figs. 33 and 34) and cool-season precipitation (fig. 26) are summarized in table 8. Where PET (fig. 16) is low and long winters prevail, particularly in the Nebraska and South Dakota parts of the study area, the relationship in table 8 deteriorates somewhat because of the increased effectiveness of cool-season precipitation as a source of recharge. Overall, when cool-season precipitation is less than 5 inches, recharge is minimal.

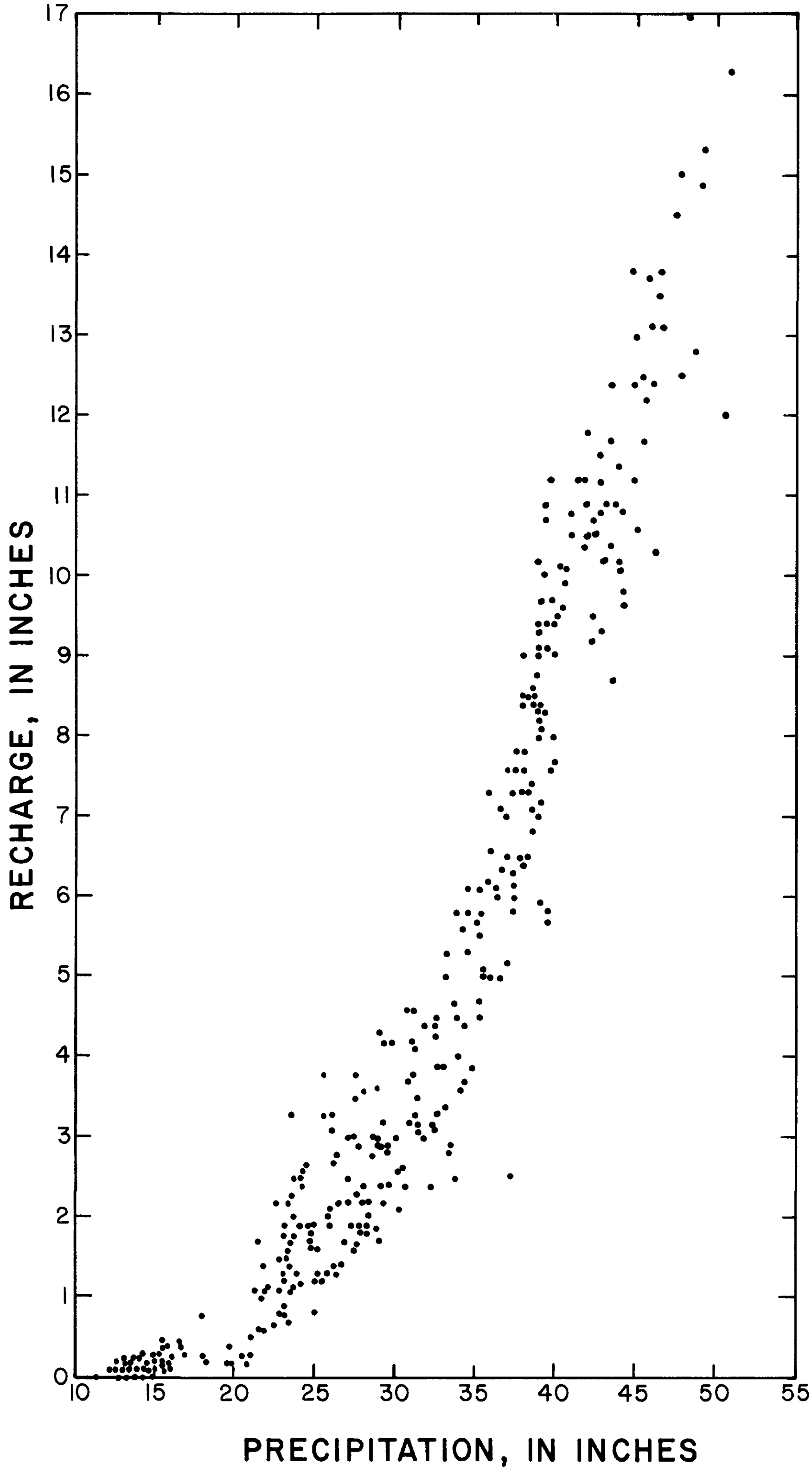


Figure 35.--Computed mean annual recharge versus mean annual precipitation, by model grid element.

Table 8.--Generalized relationship between cool-season precipitation and potential recharge

Mean cool-season precipitation (inches)	Mean annual recharge (inches)	Approximate proportion (percent)
24	15	63
18	10	56
12	5	42
6	1.5	25
4	.25	6

From the preceding comparisons, it appears that generalized patterns of potential recharge are determined mainly by climatic conditions. Smaller variations within local areas, however, are related to differences in vegetation and soil types. The scale of this study emphasizes the significant role that climate plays in a regional appraisal of consumptive water use and recharge to the ground-water system.

Vigorous statistical testing to measure the relationship between recharge (dependent variable) and the climatic elements (particularly precipitation), vegetation, and hydrologic soil properties (independent variables) would be useful under different circumstances. However, it is not valid in this case where potential recharge is computed from these variables. The simple comparisons do indicate, however, which variables are most significant to recharge.

CONCLUSIONS

The regional diversity of the factors affecting consumptive water use and potential recharge to the ground-water system has been demonstrated. The extreme differences in mean annual recharge within the study area are attributable primarily to variations in the several climatic factors analyzed.

High rates of potential and actual (consumptive water use) evapotranspiration (PET and AET) are closely related to high incidences of solar radiation, which in turn are dependent chiefly on high percentages of possible sunshine. Areas of lower PET and AET in Nebraska and South Dakota result from less solar radiation and sunshine and longer, more intense cool seasons that cause longer periods of dormancy in plant growth.

Perhaps the most significant climatic variable is precipitation. Mean annual precipitation ranges from more than 50 inches in parts of Arkansas to less than 12 inches in parts of Colorado. Furthermore, the areas of higher annual precipitation received a much larger proportion during the cool season when PET and AET are at a minimum. Both annual and seasonal precipitation closely reflect recharge conditions.

Land use and soil conditions less obviously affect overall patterns of recharge. Local recharge differences, however, can be attributed to one or both of these factors. Variations in water use by different land uses and variations in hydrologic properties of the soils tend to "average out" recharge conditions over large areas such as the grid elements used in this study (790 square miles). Also, the predominant land uses--woodlands, which dominate in the southeast, and grasslands, which dominate in the west and central--have similar overall consumptive water requirements (CWR). Soil effects were somewhat limited because the more permeable soils that have lower available water capacity and greater recharge potential, occur mainly in semiarid areas with high PET rates where recharge potential is already limited.

Application of the soil-moisture and PET programs to climatic regimes, other than subhumid and semiarid environments for which they were originally developed, appears to have provided reasonable results. The various water-use characteristics (CWR, AET, CIR) and deep percolation values appear to reflect the different climatic conditions quite well throughout the study area, including the humid subtropical environment of the southeast.

Caution, however, should be exercised in attempting to apply various program estimations to specific areas because of the general nature of this study. The CWR/PET relationships, land use, and soil characteristics, in particular, are very generalized and require refinements for more detailed examination of specific areas. Furthermore, it was beyond the scope of this study to calibrate or statistically evaluate the results with empirically derived hydrologic data or ground-water-flow model simulations. Such tests are necessary for more detailed applications.

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