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Simulation and Analysis of Soil-Water Conditions in the Great Plains and Adjacent Areas, Central United States, 1951–80

By
Jack T. Dugan and Ronald B. Zelt

Water-Supply Paper 2427

U.S. DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

2000 Reston, Virginia

Library of Congress Cataloging in Publications Data

Dugan, Jack T.
Simulation and analysis of soil-water conditions in the Great Plains and adjacent areas, Central United States, 1951–80 / by Jack T. Dugan and Ronald B. Zelt.
p. cm. — (U.S. Geological Survey water-supply paper; 2427)
Includes bibliographical references.
Supt. of Docs. no.: I19.13:2427
1. Groundwater—Great Plains. 2. Soil moisture—Great Plains. 3. Evapotranspiration—Great Plains. 4. Irrigation water—Great Plains. I. Zelt, Ronald B. II. Title. III. Series: U.S. Geological Survey water-supply paper; 2427
GB1019.D84 1998
551.49'0978—dc20

94-31133
CIP
ISBN 0-607-89354-0

For sale by U.S. Geological Survey, Branch of Information Services
Box 25286, Federal Center
Denver, CO 80225

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
acre	0.4047	hectare
bar	100	kilopascal
foot (ft)	0.3048	meter
inch (in)	25.40	millimeter
inch per hour (in/hour)	25.40	millimeter per hour
inch per inch	1.0	millimeter per millimeter
langley	41,840	joule per square meter
mile (mi)	1.609	kilometer
mile per hour	1.609	kilometer per hour
square mile (mi^2)	2.590	square kilometer

To convert degrees Fahrenheit (F°) to degrees Celsius (C°), use the following equation:

$$°C = (F° - 32)/1.8$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

GLOSSARY

[The following terms and acronyms define selected output variables of the soil-water simulation results in this report. Although these terms may have broader meaning in hydrology and other disciplines, their definitions are restricted in this report to reflect their specific meaning in interpreting the results]

Actual evapotranspiration (AET). The actual water consumed by a particular vegetation or crop type within a given period, commonly referred to as consumptive water use. It is a function of both the consumptive water requirement (CWR) of the vegetation and the soil water available within the root zone. In this report, AET, expressed in inches, equals the consumptive water requirement (CWR) minus the soil-water deficit (SWD).

Available water capacity (AWC). The quantity of water that soil can hold for consumption by a typical plant. It is the quantity of water held between the field capacity and wilting point of the soil or between a moisture retention (matric suction) of 0.333 and 15 bars (Hillel, 1980, p. 218). It is largely dependent on soil texture, types of clay present, and organic-matter content. Sand normally has the lowest water capacity, and silty soil has the highest.

Consumptive irrigation requirement (CIR). The minimum or net quantity of supplemental water required to maintain adequate soil water for the requirements of a crop during the growing season. Satisfying CIR prevents long-term soil-water deficits detrimental to plant development. As applied in this soil-water simulation, CIR is a function of CWR, effective precipitation (EP) or infiltration, and the total available water capacity of the root zone. The term is not synonymous with irrigation pumpage requirements.

Consumptive water requirement (CWR). The quantity of water a given plant or vegetation type would consume if there were no limitations on water availability or if no soil-water deficits existed at any point during the growing season. It is a function of potential evapotranspiration (PET) and the seasonal growth characteristics of the vegetation type. CWR is computed as a fraction or percentage of the monthly PET rate.

Deep percolation (DPD, DPI, or DPW). The excess soil water that moves beyond the soil root zone and is no longer available to plants or the evapotranspiration (ET) process. It is water potentially available for ground-water recharge. Deep percolation may be computed for nonirrigated (dryland) conditions (DPD) only, irrigated conditions (DPI) only, or combined nonirrigated and irrigated conditions (DPW).

DPD. Deep percolation for dryland nonirrigated conditions.

DPI. Deep percolation for irrigated conditions.

DPW. Deep percolation weighted for combined nonirrigated and irrigated conditions.

Effective precipitation (EP). See **infiltration.**

Evapotranspiration (ET). See **actual evapotranspiration** and **potential evapotranspiration.**

Infiltration (designated as EP, effective precipitation, in SWASP). That part of natural precipitation that infiltrates the soil and is either consumed by evapotranspiration (ET) or becomes deep percolation (DPD, DPI, or DPW). Infiltration is computed from infiltration-precipitation equations based on soil texture, slope, and cover conditions. Any precipitation that is not infiltration is considered overland runoff (RO).

Geographic information system (GIS)

High-water-demand row crops (HRC). Corn, cotton, and sugar beets.

Low-water-demand row crops (LRC). Grain sorghum and soybeans.

Net flux from water table under irrigated conditions (NFI). The net quantity of water withdrawn from ground-water storage to meet the CIR of selected crops. It is computed by subtracting DPI or DPW from CIR. The resultant value provides an approximation of the net demand on ground water in an irrigated region. NFI may be a positive flux to ground-water storage if DPI or DPW exceeds the CIR. Under nonirrigated conditions, DPD provides a positive net flux to ground-water storage.

Overland runoff (RO). Any precipitation that is not infiltration is considered overland runoff.

Potential evapotranspiration (PET). The theoretical water consumption or loss that would occur from the soil root zone if water availability were not a limiting factor. It is the combined potential water loss directly from the soil and its surface as evaporation and from plants through transpiration. In addition to an unlimited supply of soil water, the other assumptions are that the soil surface is completely covered with healthy, continuously growing vegetation and that there are no limitations to water consumption imposed by soil characteristics (Jensen, 1974; Mather, 1974). PET can be interpreted as an expression of the energy available for water consumption and is largely a function of such meteorological factors as solar radiation, temperature, humidity, and wind speed.

Regional Aquifer-System Analysis (RASA). A U.S. Geological Survey program started in 1978 following a Congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States.

Soil root zone. The depth or thickness of the soil zone in which the root system of a given vegetation or crop type can actively extract or utilize available soil water to meet the CWR. This root zone is dynamic in that it varies seasonally, reflecting the seasonal growth characteristics of the vegetation. The root zone specified in this report is not necessarily the maximum extent of vertical root development but represents a weighted value for a zone in which the root system theoretically can extract all available soil water.

Soil-water simulation program (SWASP). A computer program used in this study to calculate soil-water characteristics based on computed PET, precipitation, hydrologic soil properties, and vegetation water use.

Soil-water deficit (SWD). The quantity of water that is not available in the soil root zone to fulfill the CWR of a given vegetation type. It is a function of CWR and water available as infiltration.

Simulation and Analysis of Soil-Water Conditions in the Great Plains and Adjacent Areas, Central United States, 1951–80

By Jack T. Dugan[1] *and* Ronald B. Zelt

Abstract

Ground-water recharge and consumptive irrigation requirements (CIR) in the Great Plains and adjacent areas largely depend on an environment extrinsic to the ground-water system. This extrinsic environment, which includes climate, soils, and vegetation, determines the water demands of evapotranspiration, the availability of soil water to meet these demands, and the quantity of soil water remaining after these demands are met for potential ground-water recharge.

The geographic extent of the Great Plains contributes to large regional differences among all elements composing the extrinsic environment, particularly the climatic factors. Mean annual potential evapotranspiration ranges from about 26 inches in northeastern North Dakota to about 68 inches in eastern New Mexico. Mean annual precipitation ranges from about 10 inches in north-central Montana to about 48 inches in central Arkansas. Cool-season precipitation, the seasonal precipitation most critical to recharge, is even more regionally variable and ranges from about 2 inches in northeastern Montana to about 23 inches in Arkansas. Variability of soils and vegetation tends to modify local soil-water balances.

A soil-water simulation program, SWASP, which synthesizes selected climatic, soil, and vegetation factors, was used to simulate regional soil-water conditions during 1951–80. The output from SWASP consists of several soil-water characteristics, including surface runoff, infiltration (effective precipitation), consumptive water requirements, actual evapotranspiration, potential recharge or deep percolation under various conditions, consumptive irrigation requirements, and net fluxes from the ground-water system under irrigated conditions (NFI).

Simulation results indicate that regional patterns of potential recharge, CIR, and NFI are largely determined by evapotranspiration and precipitation. The local effects of soils and vegetation on potential recharge, however, cause potential recharge to vary by more than 50 percent in some areas having similar climatic conditions.

The following are some of the more significant simulation results: (1) infiltration in the study area is typically 90 to 95 percent of the mean annual precipitation, (2) potential recharge under nonirrigated conditions (DPD) ranges from about 0.25 inch in the western parts of the Great Plains to about 10 inches in parts of northeastern Texas and Arkansas, and (3) DPD as a percentage of mean annual precipitation ranges from about 1 percent in the drier western parts to about 25 percent in parts of eastern North Dakota, northeastern Texas, and Arkansas.

CIR for high-water-demand row crops (including corn) in intensively irrigated areas ranges from about 10 inches in northeastern Nebraska to 19 inches in parts of southwestern

[1]Deceased.

Kansas. Net losses from the ground-water system (NFI) in irrigated areas range from about 2 inches in northeastern Nebraska to more than 21 inches in northeastern New Mexico and southeastern Colorado.

INTRODUCTION

The ground-water hydrology of a region typically is defined almost exclusively by its hydrogeology or the properties intrinsic to the system. However, an extrinsic environment affects this system that is equally significant but commonly is neglected because of the difficulties in assessment. The extrinsic environment comprises a group of interrelated factors external to the ground-water system, as defined by the saturated and unsaturated zones, that determine the quantity of water available to recharge the underlying aquifers and to sustain plant growth.

These extrinsic factors can be classified into three primary groups: (1) the climate or atmospheric conditions, (2) the hydrologic properties of the soils, and (3) vegetation. Although these factors typically are described and measured independently of one another in relation to hydrology, they are best considered within an integrated system. By interrelating each extrinsic component through a conceptually simple model, a quantitative assessment of water availability and demand can be simulated over a large region.

The Great Plains and adjacent areas are well suited for soil-water simulation. Large, contiguous parts of the area are underlain by productive unconfined aquifers. Several large areas of intensive ground-water irrigation exist within the region. A close relation exists between climate and the availability of soil water for crops and ground-water recharge. The geographic extent and location of the Great Plains ensure sufficient regional contrast among each of the extrinsic factors so that meaningful spatial analyses of soil-water conditions can result.

The variable rate of depletion of the aquifers in intensively irrigated parts of the Great Plains, including the High Plains aquifer (Dugan and Schild, 1992), indicates a need to understand the effect of the extrinsic environment upon available soil- and ground-water resources. Simulation of soil-water conditions through time can provide a useful method for analyzing this effect and the relation to changes in ground-water storage.

Purpose and Scope

This report describes the results of an analysis of potential ground-water recharge and consumptive irrigation requirements using long-term soil-water simulations in the Great Plains and adjacent areas. In addition, factors affecting soil-water conditions and resultant potential recharge and consumptive irrigation requirements in the region are described. These factors include climate, soils, vegetation, and agricultural crop patterns. Particular emphasis was placed on the effect of climate, especially precipitation and evaporation, on soil-water conditions.

The methods used in this study differ from more traditional approaches generally used in areal ground-water studies in that ground-water-recharge values derived from soil-water simulation are not dependent on geohydrology of the underlying aquifers. Thus, the assumption that long-term ground-water-recharge rates should maintain steady-state conditions in these underlying aquifers is not required in the soil-water simulation approach. Natural recharge and related soil-water phenomena in this study are considered processes occurring at the earth-atmosphere interface and in the soil root zone immediately below.

This conceptual approach removes much of the potential bias inherent in computing recharge in most ground-water simulations because soil water available from precipitation for recharge and vegetative growth is determined from factors independent of the properties of the aquifer. Spatial patterns of initial recharge and consumptive water-use values for input into ground-water models are objectively and systematically derived from measurable climatic, soil, and vegetative conditions.

The method used in this study does not determine actual values of ground-water recharge or irrigation pumpage but provides a systematically derived estimate of the potential quantity of water available or required for these processes. Application of the method is most appropriate for unconfined aquifer conditions in which the unsaturated zone is relatively permeable.

Study Area

The study area encompasses approximately 560,000 square miles extending from Canada to Mexico and from central Arkansas to northwestern Montana (fig. 1). This area contains three areas included

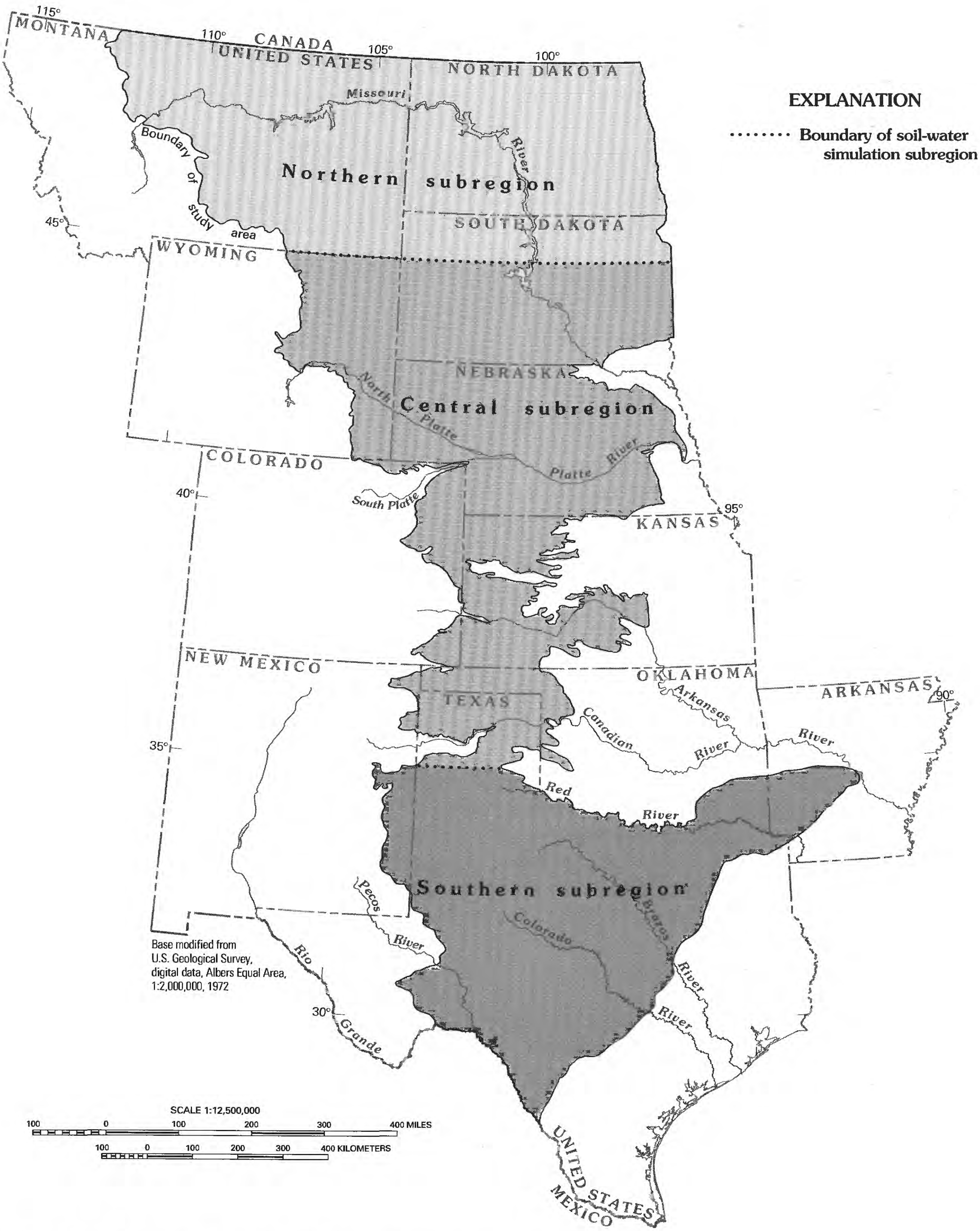


Figure 1. Study area and soil-water simulation subregions.

within the Regional Aquifer-System Analysis (RASA) Program of the U.S. Geological Survey: the northern Great Plains (herein referred to as the northern subregion), High Plains (central subregion), and Edwards-Trinity (southern subregion) regional aquifer systems (Sun and Weeks, 1991). The original boundaries of these RASA studies have been expanded or modified in certain areas to conform to more common physical and political boundaries. Certain areas not included in these three RASA studies or the adjoining central Midwest (Dugan and Peckenpaugh, 1985) or Gulf Coastal Plains RASA's (Grubb, 1986) were incorporated into this study area. Thus, the boundaries in the southeastern part of the study area do not conform exactly to the central Midwest RASA or Gulf Coastal Plains RASA boundaries (Sun and Weeks, 1991).

The geographical extent of the study area encompasses substantial variations in climate, soils, vegetation, and agriculture, which substantially affect spatial patterns of soil-water availability and demand. These large regional differences in the factors affecting soil-water availability and demand required that soil-water conditions be simulated by subregion (fig. 1).

Physical and Cultural Setting

Comprehensive descriptions of the geology and hydrogeology of the study area are provided by Gutentag and others (1984), Downey (1986), Luckey and others (1986), Sun (1986), Weeks and others (1988), Dugan, Hobbs, and Ihm (1990), and Sun and Weeks (1991). Description of the underlying geology in this report is confined to the effects on the topography and soil development in the area.

The study area commonly is perceived as a uniform depositional plain; however, the topography is quite variable. A few structural uplifts are in the study area, principally the Black Hills in South Dakota and several mountain ranges in Montana and Wyoming, but these compose only a small part of the total area (fig. 2). The northern and northeastern part of the study area was glaciated during the Pleistocene (fig. 2), which produced a depositional landscape that affects present-day soil characteristics. Much of the Great Plains and adjacent areas is eroded, producing a dissected landscape, particularly along the primary drainage system, the Missouri River, and resulting in large areas of steeply sloping topography where the soils are thin or absent (fig. 3). Severe erosion has created several badland areas, particularly in North and South Dakota, where both vegetation and developed soils are absent.

The Great Plains is defined not only by its topographic and hydrogeologic characteristics but also by its climate, soil, vegetation, economy, and agriculture, which collectively affect the ground-water resources of the region as much as the geology does. Each of these factors contributes to a unique regional characterization of the Great Plains.

Average precipitation for much of the region is not sufficient or dependable enough for most types of cultivated agriculture. Crop failures resulting from drought and associated insect infestations have been characteristic of the Great Plains throughout its agricultural development. Ground- and surface-water supplies have been developed for irrigation, where possible, in order to stabilize the agricultural economy. However, in many areas of intense ground-water irrigation development, available supplies have been depleted more rapidly than they can be replenished by natural recharge. If recent rates of water-level declines continue in parts of the High Plains, irrigation may not be economically feasible in several large agricultural areas in the near future (Sun, 1986).

The predominantly semiarid to subhumid climates of the study area result in a grassland climax vegetation, ranging from tallgrass prairie in the east to shortgrass steppe in the west. Less than 10 percent of the remaining area, including the more humid area extending into eastern Texas and Arkansas, supports a woodland climax. About one-third of the study area presently is cultivated, and more than 60 percent is classified as grassland (rangeland). The original grassland regime, however, has been degraded by overgrazing and subsequent invasion by scrub vegetation such as sage and mesquite.

Previous Studies

Comprehensive regional water-resources evaluations have been completed for the northern Great Plains and the High Plains RASA's by Gutentag and others (1984), Downey (1986), Luckey and others (1986, 1988), and Sun (1986). These reports principally describe the hydrogeology, simulation of ground-water flow, and predicted effects of irrigation. Subsequent reports by Kastner and others (1989), Dugan, Schild, and Kastner (1990), and Dugan and

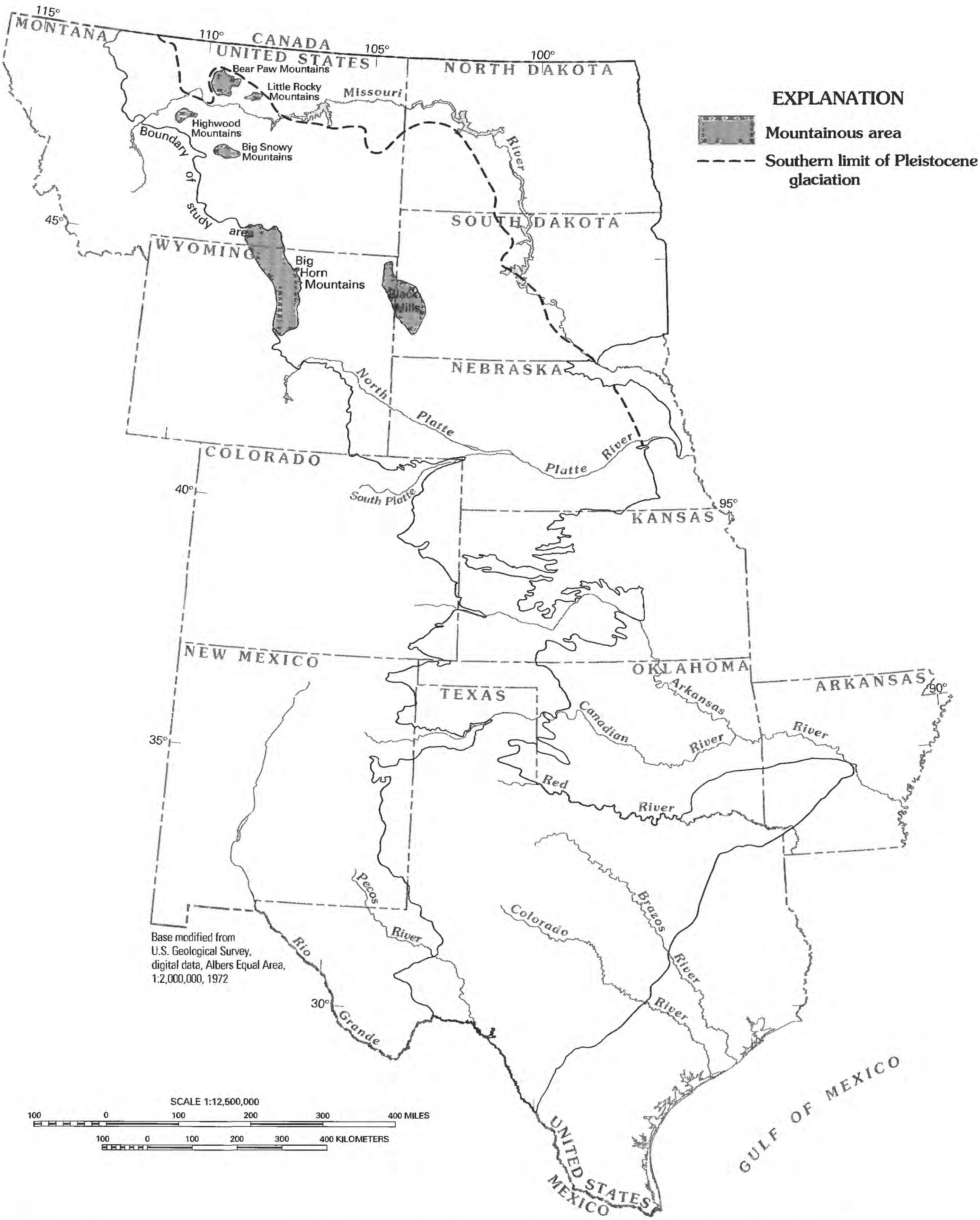


Figure 2. Major mountainous areas and southern limit of Pleistocene glaciation (modified from Flint, 1947).

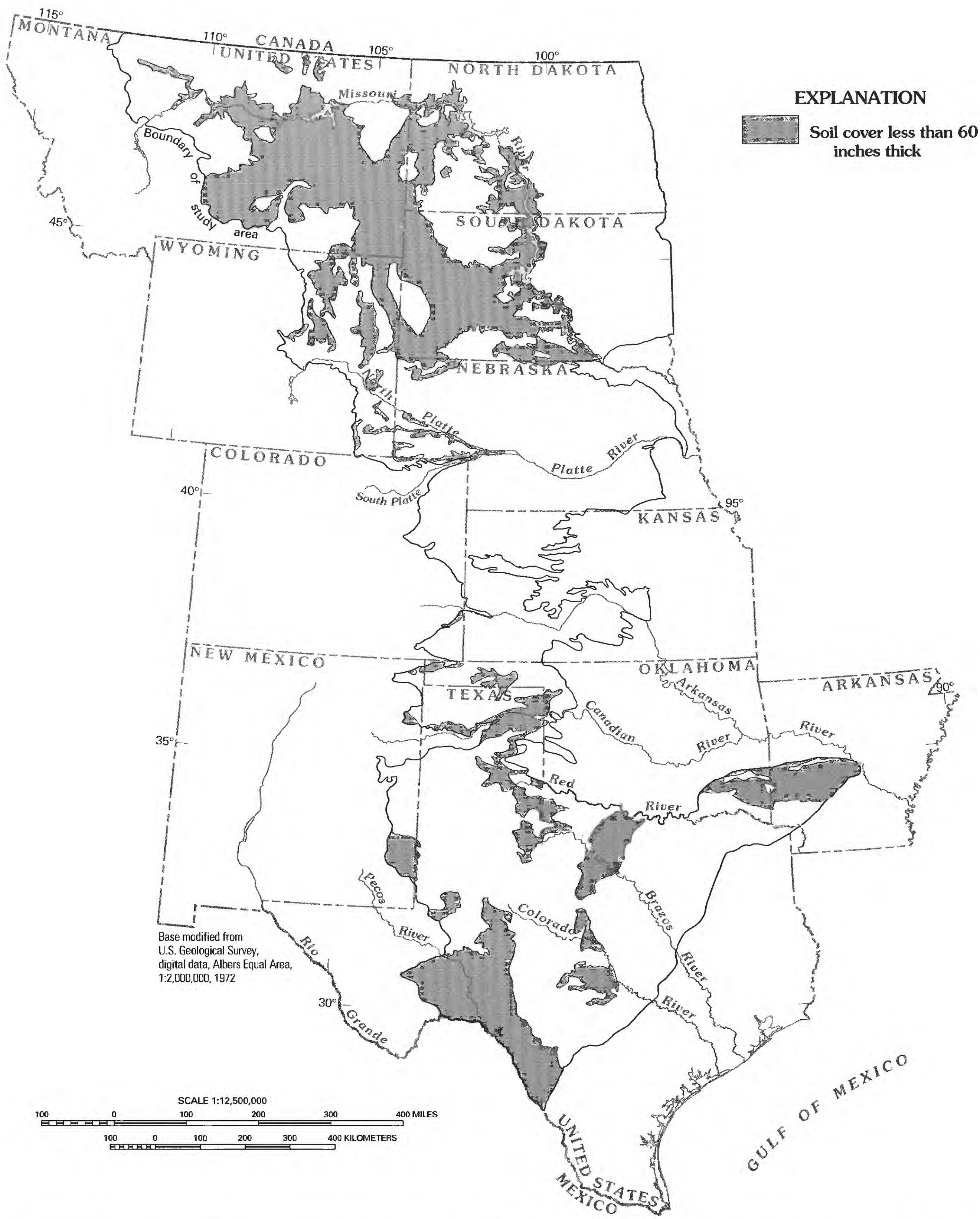


Figure 3. Areas where soils overlying bedrock are less than 60 inches thick (modified from Dugan, Hobbs, and Ihm, 1990).

Schild (1992) examined recent water-level changes in the High Plains.

The methods used in this study have been used in several smaller areas within the Great Plains (Lappala, 1978; Peckenpaugh and Dugan, 1983; Peckenpaugh and others, 1987). A study similar in scope and regional scale was completed for the central Midwest RASA (Dugan and Peckenpaugh, 1985). The hydrologic characteristics of the soil for the study area are presented in a report by Dugan, Hobbs, and Ihm (1990).

Methods

Complex methodologies are required to integrate the several climatic, soil, and vegetation factors in the simulation of the regional soil-water balance. The appendixes of this report provide a more comprehensive description of the procedures used in simulating the regional soil-water balance. Estimation of soil-water characteristics, particularly ground-water recharge and consumptive water use for ground-water simulation, can be accomplished by various methods. Previous regional ground-water studies of the High Plains and northern Great Plains RASA's derived estimates of recharge principally through ground-water-model calibration techniques.

The High Plains RASA recharge estimates for individual grid nodes from steady-state ground-water-model simulations were based on the assumption that long-term natural recharge rates balanced discharge along the eastern boundary of the study area. Initial recharge values were derived from estimates made in previous studies with some consideration given to soil and climatic differences (Gutentag and others, 1984, p. B31–B33). The consumptive irrigation requirement (CIR) in the High Plains RASA was computed by grid cell using the Blaney-Criddle evapotranspiration method (Heimes and Luckey, 1982, p. 8–11).

Recharge of the confined aquifers in the northern Great Plains RASA was assumed to occur as stream losses through isolated outcrops, such as the Black Hills in South Dakota and the Bighorn Mountains in Wyoming. Some recharge was attributed to upward leakage from underlying confined aquifers (Downey, 1986; Sun, 1986). Recharge of unconfined aquifers and water use in the northern Great Plains RASA were not considered.

The soil-water balance approach emphasizes the physical factors (climate, soils, and vegetation) that determine the availability of water for recharge and consumptive water use. Whereas in the previous studies, recharge is a residual value computed from the water needed to balance the ground-water system (recharge equals discharge), the soil-water balance approach externally computes the quantity of water potentially available for recharge and consumptive water use. This approach produces results that are derived independently of the ground-water modeling procedures and geohydrology.

In ground-water modeling applications, the soil-water balance approach uses fluxes to the system that are both spatially and temporally differentiated. Fluxes can be computed for a variety of time frames (monthly through long-term annual averages), which provide flexibility of input options in subsequent ground-water modeling. Because soil and vegetation input to the soil-water balance normally is derived from a range of values representing their hydrologic characteristics, computed initial fluxes can be adjusted logically in calibrating a ground-water model without modifying geohydrologic input.

The soil-water balance approach has certain limitations and restrictions. (1) The climate, soil, and vegetation data requirements are large and need considerable prior synthesizing. (2) The approach is not suitable for mountainous areas because of such factors as steep slopes, shallow soils, rock outcrops, and persistent snow cover. (3) The approach is not appropriate for confined aquifer conditions or areas where bedrock is near the surface.

The soil-water simulation procedures in this study consist of three components or sets of computer programs. In the first program, potential evapotranspiration (PET) is computed from solar radiation and temperature data. The second and principal component is a soil-water simulation program (SWASP), which calculates several possible soil-water characteristics based on computed PET, precipitation, hydrologic soil properties, and vegetation water use. A set of post-processing procedures, consisting of several programs, makes up the third component and converts the discrete data output from SWASP into a spatially continuous format. A simple flowchart of the input and output of each component is shown in figure 4.

The principal investigative tool used in this study is a modified version of an undocumented soil-water balance computer program developed by the U.S. Bureau of Reclamation (F.J. Otradovsky, U.S. Bureau of Reclamation, written commun., 1985). A

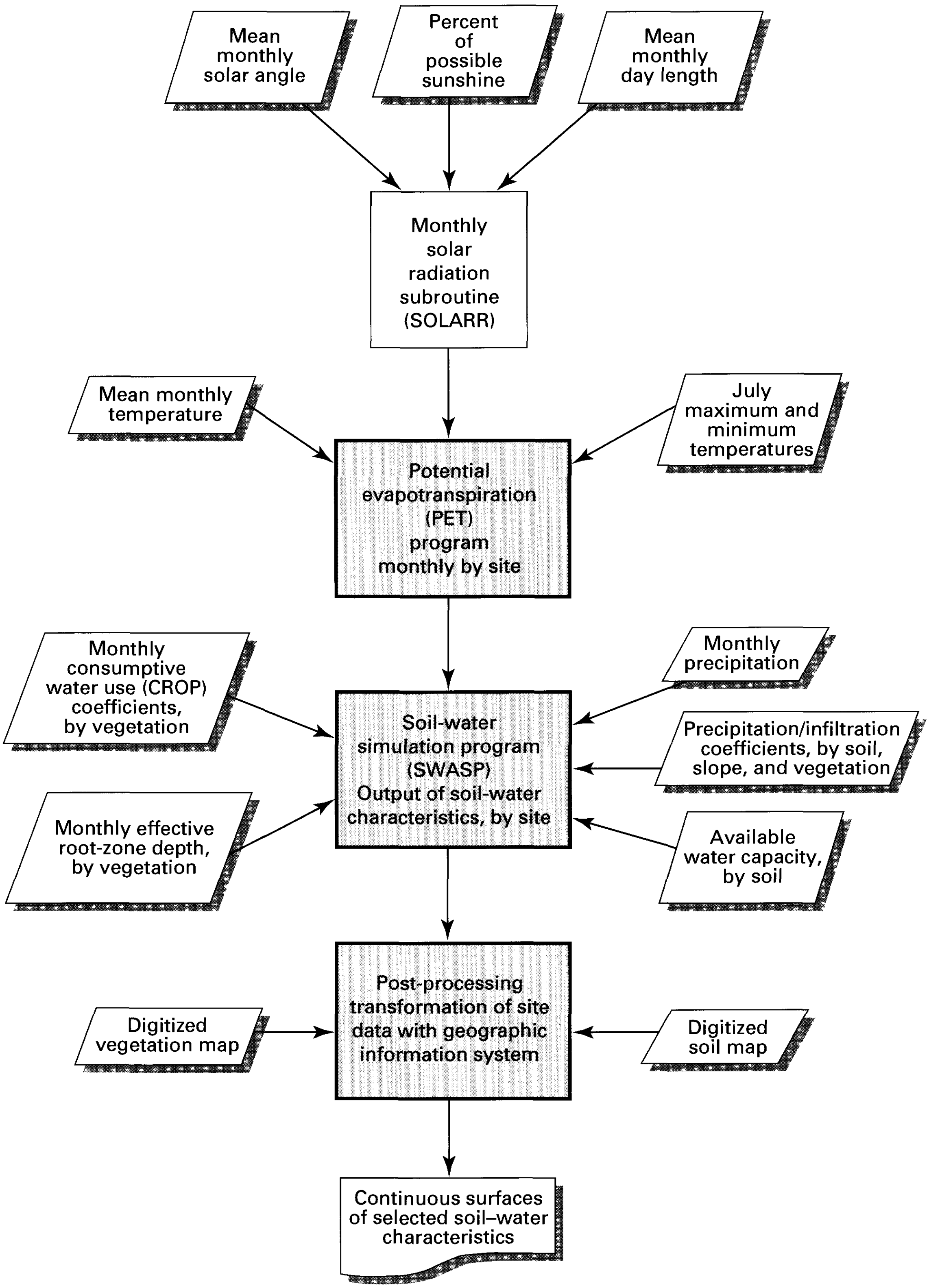


Figure 4. Flowchart of soil-water simulation.

later generation of the program, called BASIN, was developed and partially documented by Otradovsky (1981). The version implemented in this study (SWASP) contains several fundamental changes from the previous programs.

The conceptual basis of SWASP is a simplified soil-water balance approach in which the soil operates as a temporary reservoir within an open system. A given soil is assigned a certain available water capacity (AWC) and root-zone thickness, which determines the total available storage capacity or reservoir size. Precipitation infiltrates the soil, and water exits the soil as evapotranspiration and as deep percolation into the underlying unsaturated zone. The following conceptual equation and the flowchart in figure 4 summarize the soil-water model:

$$R = S+P-O-E-C, \qquad (1)$$

where

R = recharge (deep percolation), in inches per year;
S = antecedent soil water, in inches;
P = precipitation, in inches;
O = overland runoff, in inches;
E = actual evapotranspiration (AET), in inches, and;
C = moisture storage capacity of the soil zone, in inches.

The program permits deep percolation to occur only under saturated conditions, although downward soil-water movement is an ongoing process even in unsaturated soils. However, certain program options, including varying the root-zone depth, are employed in the program to account for unsaturated flow. A model with true unsaturated flow capabilities requires extremely detailed soil data and would be too cumbersome, mathematically, for macro-scale applications such as this study. By treating the soil zone as a simplistic system, available soil data, climatic data, and plant-growth characteristics can be used to estimate the soil-water balance on a regional scale.

A required input to SWASP is monthly PET output from a program entitled PET. PET uses a modified Jensen-Haise method, which is an energy-balance approximation approach (Jensen and others, 1970). It differs from the Penman combination method (Wright, 1982, p. 60) in that wind speed is not considered and humidity is estimated with a modified technique that uses maximum and minimum temperatures. Various comparative studies have shown the modified Jensen-Haise method to be reliable for diverse climates and particularly adaptable for semiarid conditions (Robb, 1966; Jensen and others, 1970, 1971; Jensen, 1974).

Monthly mean daily solar radiation is the principal input to the Jensen-Haise energy balance equation. Solar-radiation data are available from only nine sites within or near the study area for 1951–80. Therefore, an equation derived from multiple regression was used to compute estimated solar radiation at 68 temperature sites in the study area. The original equation for estimating solar radiation, which proved to be reliable in previous studies (Dugan, 1978; Dugan and Peckenpaugh, 1985), was recalculated for this study with a larger and more refined data base (see app. A).

The substantial regional differences from north to south, both in crop types and seasonal growth patterns of natural vegetation and domestic crops (phenological characteristics), required that the study area be divided into three soil-water simulation subregions (fig. 1). The northern subregion corresponds closely to the traditional spring wheat belt (north of lat 45° N.), the central subregion includes the western corn and winter wheat belts, and the southern subregion represents the western cotton belt (south of lat 35° N.). A set of vegetation and crop types, represented by their regional phenological characteristics, was selected for each subregion. These subregions then were assigned different sets of consumptive water-use values and monthly root-zone depths. The SWASP program input is presented for the three subregions in appendix A.

The output from SWASP contains discrete data for 63 combinations of soils (9 types) and vegetation (7 types) and at 152 uniformly spaced climatic sites. The final stage of the process converts the discrete data to simulated continuous data through a series of post-processing procedures, which include application of a geographic information system (GIS) to selected output from SWASP.

A grid network with a uniform spacing of 25 miles was superimposed on the study area that created 873 grid elements for input of output from SWASP to the GIS. Output from SWASP, computed at the climatic sites for the possible soil-water combinations, then was interpolated to the center of each grid element. The output of the selected soil-water factors then was weighted by the soil and vegetation types within each element. From the weighted data for each grid element, continuous patterns of the various soil-water factors were generated. Because of the extent of the study area (about 560,000 square miles) and use of generalized soil and vegetation data, the grid density or element size is adequate to simulate continuous surfaces of the various factors. Subsequent sections of the report and appendix B describe those surfaces generated using the GIS; among them are potential recharge, deep percolation for both nonirrigated (DPD) and irrigated (DPI) conditions, CIR, and AET.

FACTORS AFFECTING SOIL-WATER AVAILABILITY

Climate, soils, and vegetation determine the consumptive water requirement (CWR) and the availability of soil water to satisfy crop water needs and to provide water for potential recharge of underlying ground-water systems. The relations of these three sets of variables to soil-water conditions and their general patterns in the study area provide a basis for the more detailed, subsequent computer simulations of the regional soil-water balance.

Climate

Climate has a dual effect on the soil-water balance. One variable, energy (heat) present in the atmosphere and at the Earth's surface, determines the rate at which plants withdraw or use the available soil water in transpiration and the rate of direct evaporation of water from the soil. The other variable, precipitation, determines the volume of water available to meet CWR and subsequently available for deep percolation to the underlying ground-water system.

Energy and Potential Evapotranspiration

Energy required for transpiration and evaporation of soil water, evapotranspiration, is affected by several factors. These include solar radiation, air temperature, atmospheric water vapor (humidity), and wind. These factors are considered partially or wholly in the various computational methods of PET.

Solar radiation is essential for all plant-growth processes. In addition to its role in the process of photosynthesis, solar radiation is the energy source for transpiration. It also is the controlling factor in the thermal regimes of both the atmosphere and the Earth's surface. The large seasonal and regional variations in solar radiation are reflected directly in the temperature and phenological patterns of the study area.

Three principal factors determine the amount of radiation reaching the Earth's surface: (1) the angle at which the Earth intercepts solar radiation, (2) duration of the solar radiation (day length), and (3) percent of possible sunshine (cloud cover). A secondary factor included in the computational procedures used in the estimation of solar radiation (app. A), is altitude, which affects the intensity of solar radiation reaching the Earth's surface. The higher the altitude, the less dense the atmosphere, and the less scattering and reflection of solar radiation.

Mean daily solar radiation (fig. 5) in the study area increases about 25 percent from northeast to southwest, which is similar to the pattern and magnitude of difference in mean annual percent of possible sunshine (fig. 6). The overall decrease in cloud cover from the more humid east to the drier west is evident in the east to west increase in solar radiation (figs. 5 and 6).

Much of the variability in daily radiation (fig. 5) results from regional differences during the cool season when solar radiation decreases about 45 percent from southwest to northeast (fig. 7). This is partly attributable to a cool-season decrease in percent of possible sunshine in that direction (fig. 8). Most of the decrease in cool-season radiation results from the progressively shorter day length and more oblique solar angle from south to north.

Warm-season solar radiation (fig. 9), however, decreases only about 10 percent from southwest to northeast. Potential solar radiation does not decrease poleward significantly during the warm season because the poleward increase in day length compensates for the decreased solar angle. The slight decrease in radiation from southwest to northeast primarily results from a seasonal decrease in percent of possible sunshine (fig. 10).

Air temperature, unlike solar radiation, is more an indicator of available energy than an active factor in the evapotranspiration process. However, because air-temperature data are commonly available and can indirectly represent certain aspects of the evapotranspiration process, it is incorporated into most PET methods of computation. Temperature is a good indicator of available kinetic energy, which regulates both plant growth and length of growing season. Both of these biological factors have a substantial effect on total transpiration and resultant CWR.

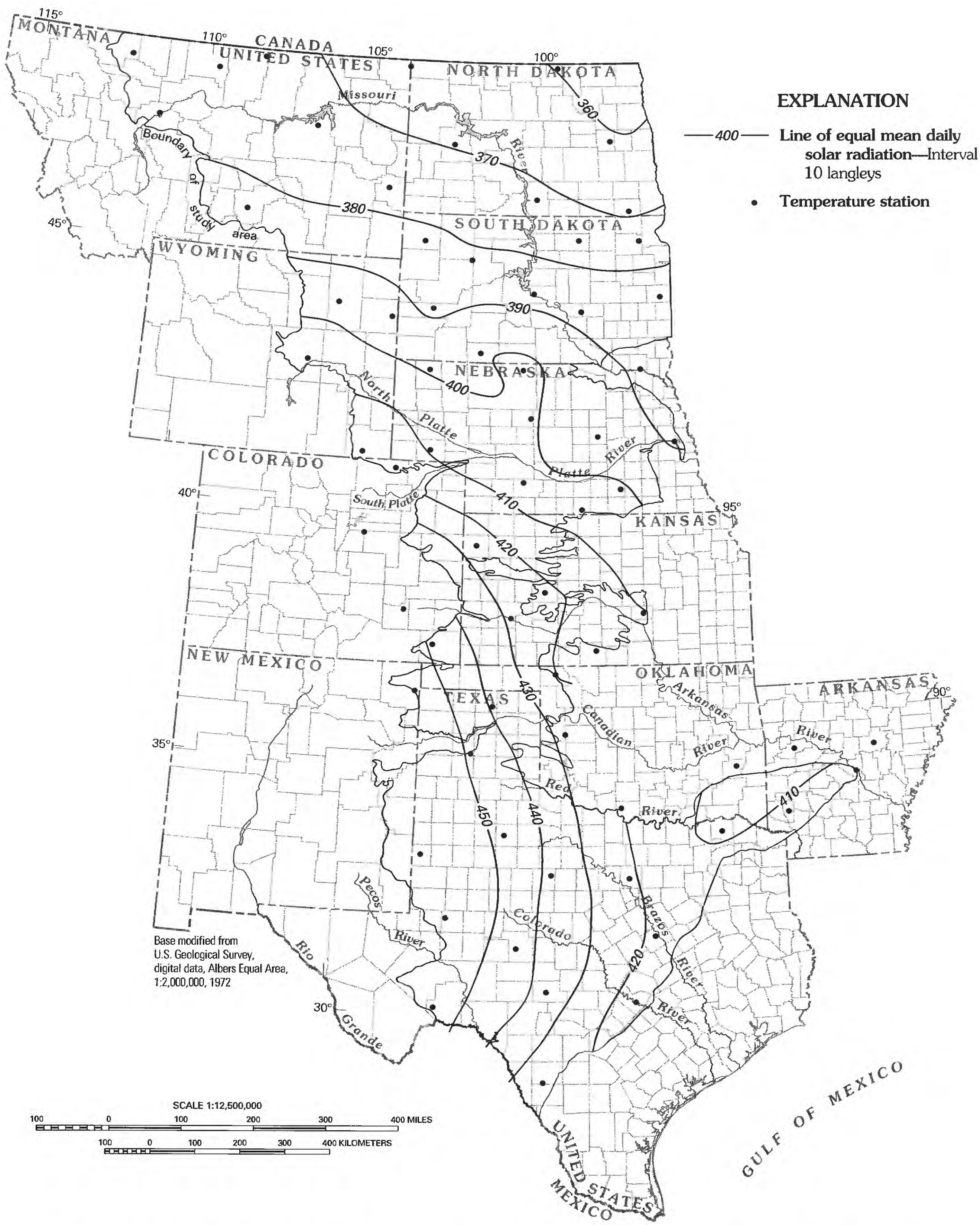


Figure 5. Mean daily solar radiation, 1951–80 (computed from data provided by the National Climatic Data Center, Asheville, N.C.).

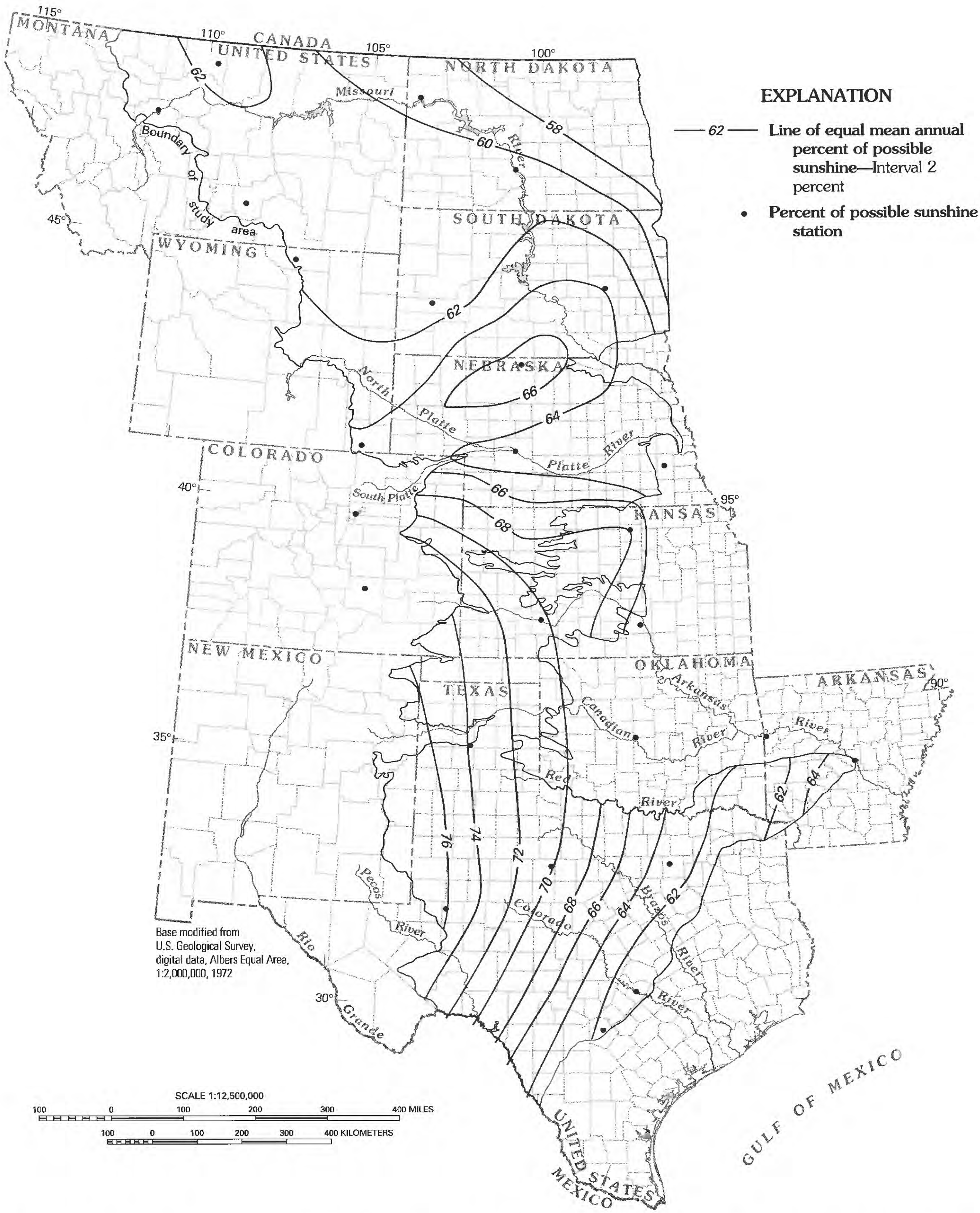


Figure 6. Mean annual percent of possible sunshine, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

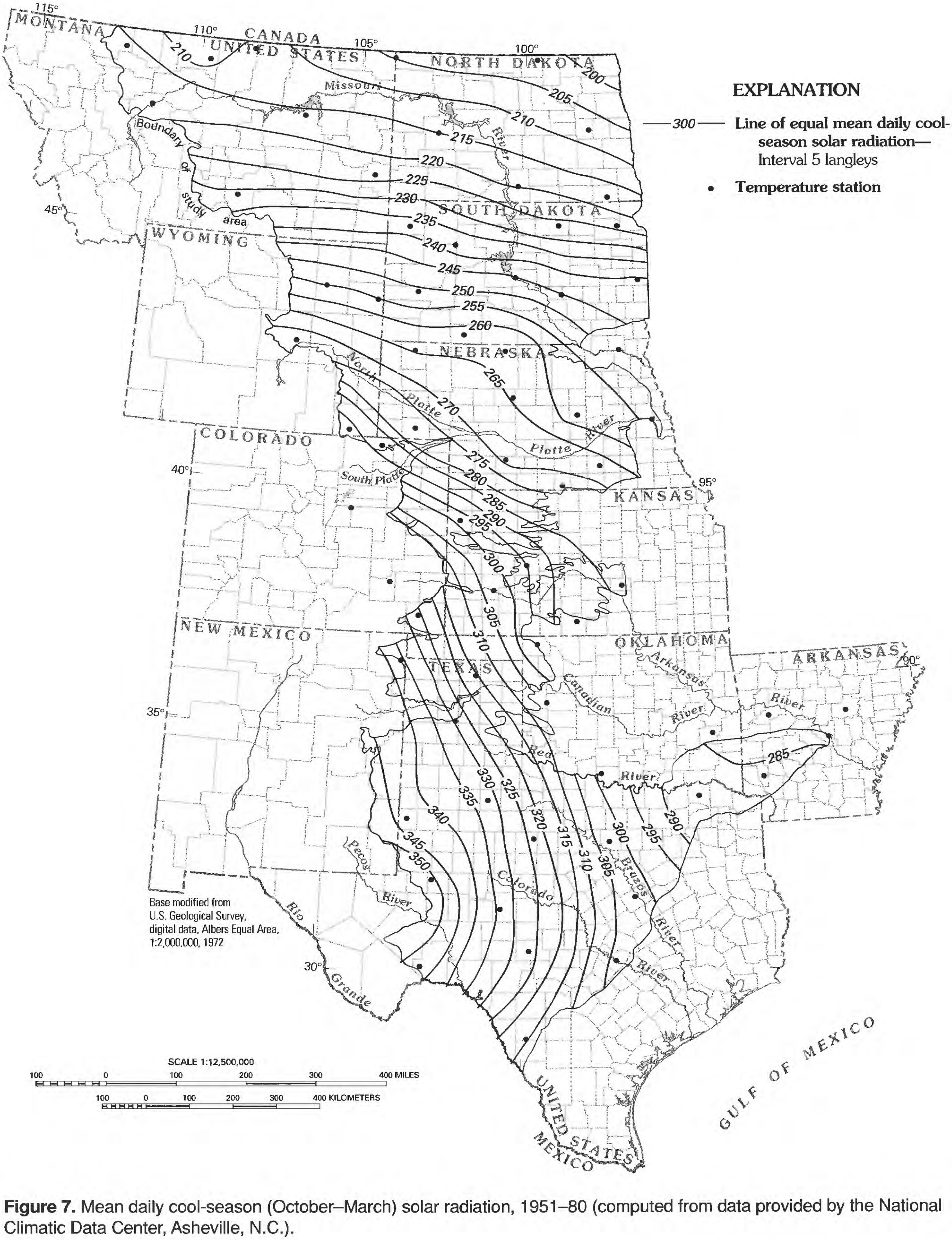


Figure 7. Mean daily cool-season (October–March) solar radiation, 1951–80 (computed from data provided by the National Climatic Data Center, Asheville, N.C.).

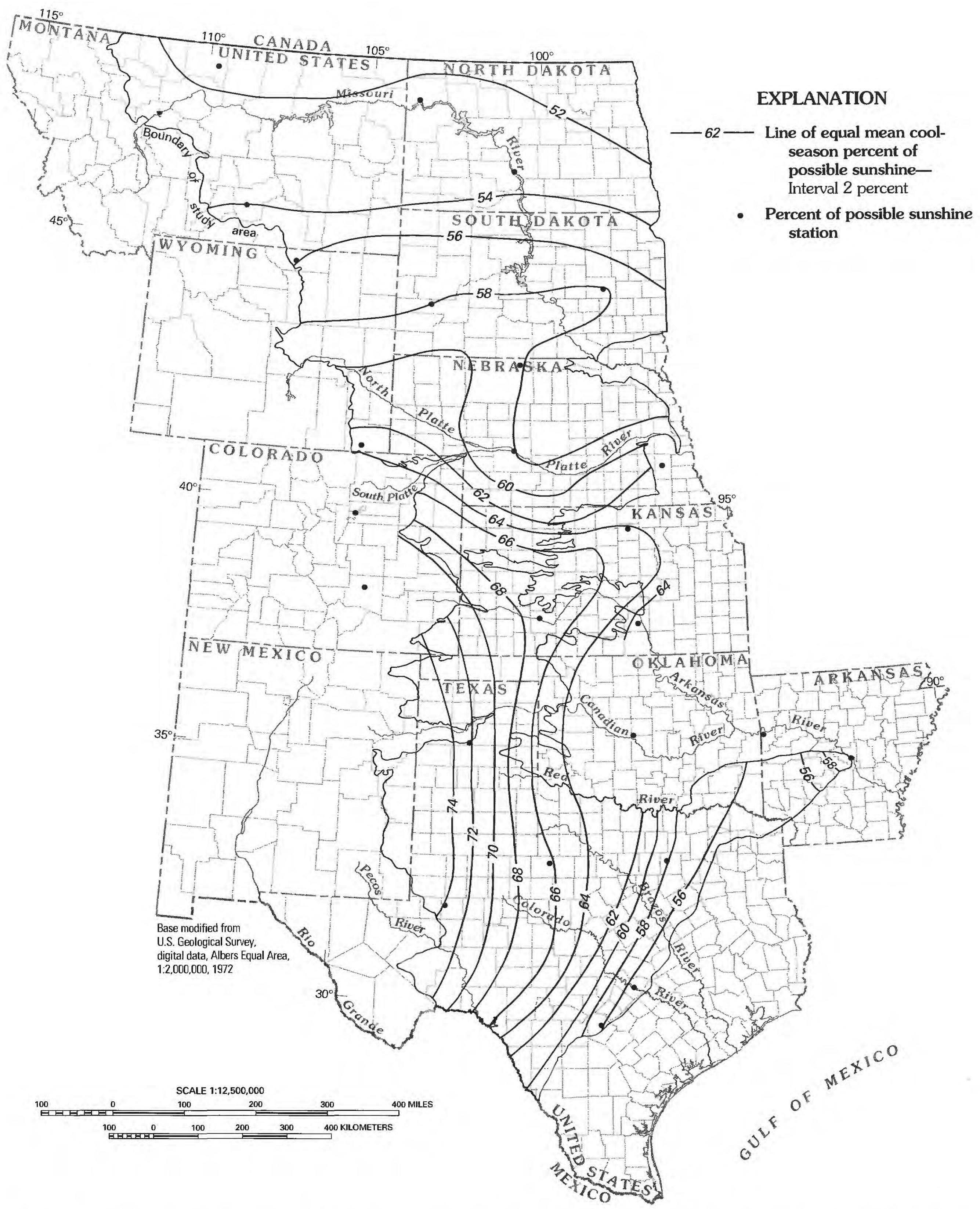


Figure 8. Mean cool-season (October–March) percent of possible sunshine, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

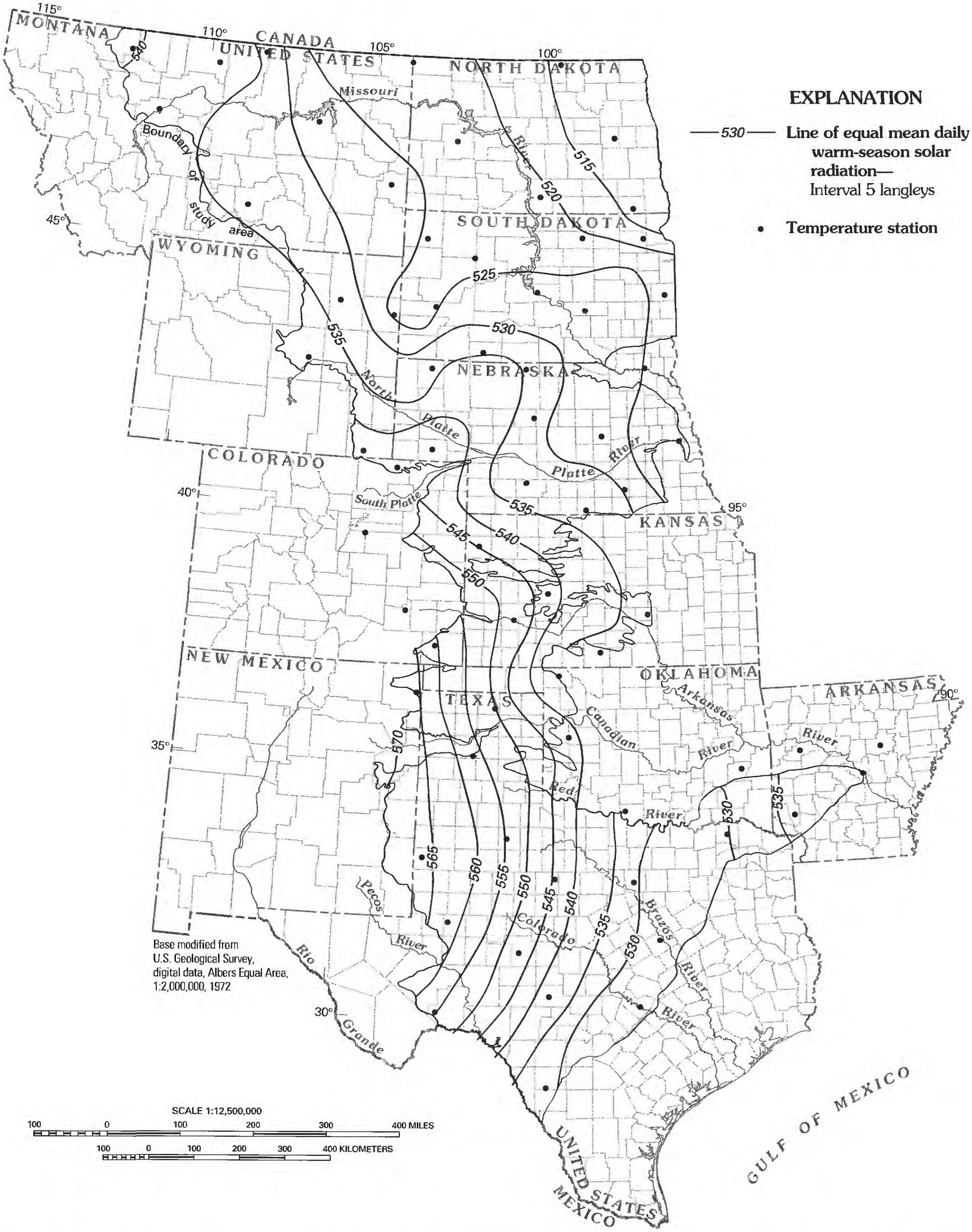


Figure 9. Mean daily warm-season (April–September) solar radiation, 1951–80 (computed from data provided by the National Climatic Data Center, Asheville, N.C.).

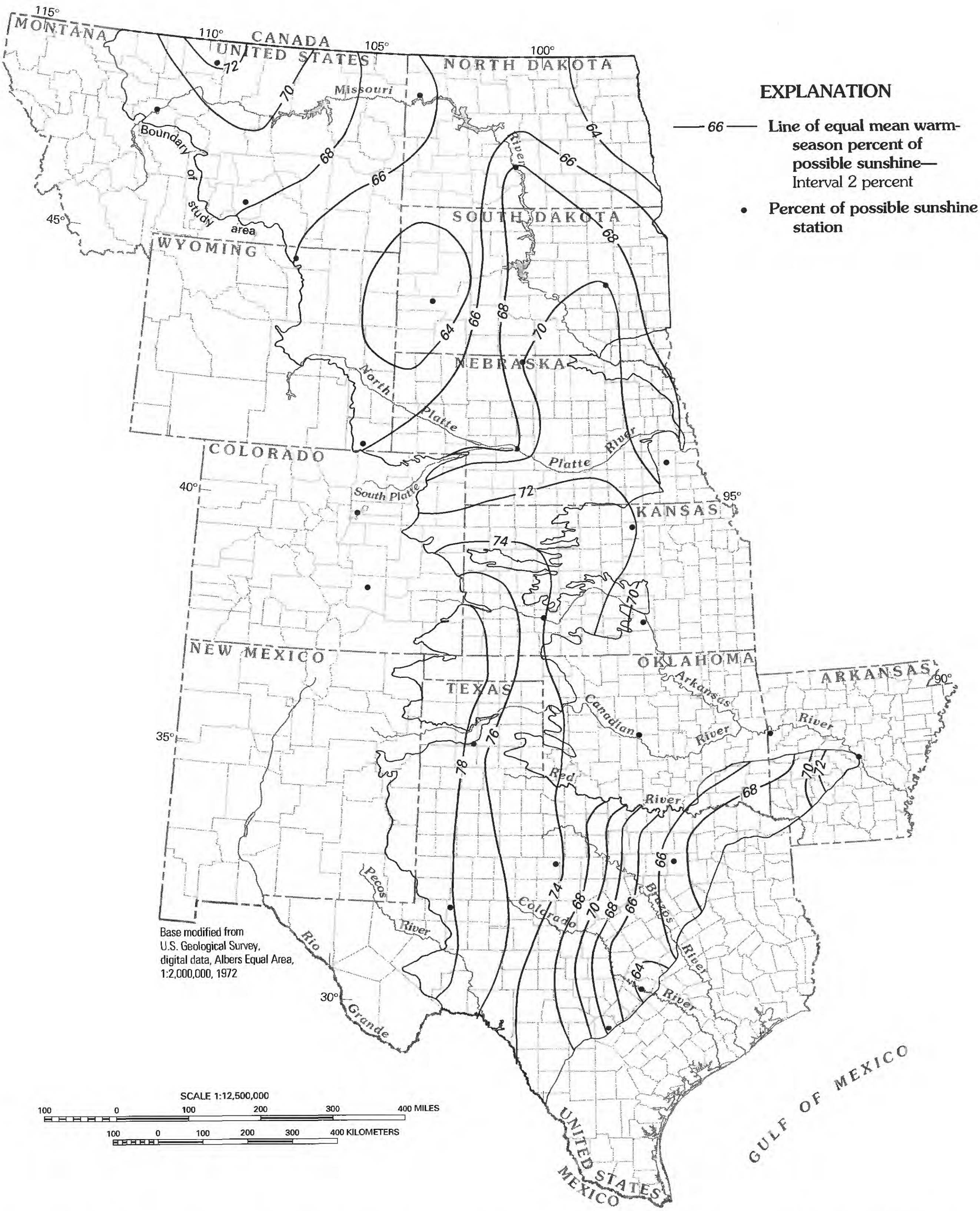


Figure 10. Mean warm-season (April–September) percent of possible sunshine, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

Spatial temperature contrasts within the study area are substantial seasonally as well as annually, which is typical of midlatitude, continental locations. These differences tend to conform closely to latitude, with a distinct north-south temperature gradient in all seasons. Mean annual temperatures (fig. 11) increase about 32°F from north to south, an approximate increase of 1.5°F per 1° of latitude.

Seasonal temperature patterns are similar to solar-radiation patterns. Marked contrasts are evident in the cool season (fig. 12) when the mean temperature range in the study area is 42°F (2.0°F per 1° of latitude). In the warm season (fig. 13), the mean temperature range decreases to about 25°F (about 1.2°F per 1° of latitude). The difference in the two seasonal patterns is even more pronounced between the coldest (January, fig. 14) and warmest (July, fig. 15) months. In January, the mean temperature range in the study area is 50°F (about 2.4°F per 1° of latitude) with a strong, uniform north-south gradient, which indicates a solar-radiation effect. In July, the range is only 18°F (about 0.9°F per 1° of latitude) because of less latitudinal control (solar radiation) and greater altitude and maritime, tropical airmass effects.

Temperature, as a causal or an inferential factor of CWR in the study area, indicates the potential for significant spatial and temporal differences. Warm-season (April–September) spatial variations in CWR are minimal, but marked spatial differences in water needs occur in the cool season (October–March), which would contribute to substantial annual variability.

The quantity of water vapor (humidity) contained in the atmosphere at a given time, as compared to what the atmosphere can hold (largely temperature dependent), serves as an effective regulator of evapotranspiration. High humidity tends to suppress rates of evapotranspiration because the atmosphere has less capacity for additional water-vapor storage. Dry or unsaturated air, however, does not limit evapotranspiration rates because of its greater water-vapor storage capacity. The general decrease in relative humidity from east to west (fig. 16) can be expected to cause potential evapotranspiration to increase from east to west.

Humidity, measured as a vapor-pressure deficit in the Jensen-Haise PET method, is computed from the mean range between July maximum and minimum daily temperatures, which provides an approximation of the wet- and dry-bulb temperature range. Conceptually, the greater the temperature range, the greater the vapor-pressure deficit or ability of the atmosphere to absorb additional water vapor. The observed mean range between July maximum and minimum daily temperature in the study area (fig. 16) indicates that the smallest (22°F) occurs in the southeast and the largest (32°F) occurs in the less humid western part.

Another climatic factor that is significant to evapotranspiration rates is wind speed. Air movement maintains an existing vapor-pressure deficit by continually advecting desiccated air over an evapotranspiration surface. The study area is one of the windiest areas in North America because of frequent cyclonic storms and few natural windbreaks. The average annual sustained peak daily wind speed for most of the study area exceeds 12 miles per hour, with parts of the north-central Great Plains and the Texas-Oklahoma Panhandles averaging 16 to 18 miles per hour (Thornthwaite, 1936). These high average wind speeds could contribute to increased evapotranspiration rates throughout the Great Plains, particularly in the peak wind-speed areas. However, because wind-speed data are not available at a sufficient number of observation sites, PET methods, such as modified Penman, requiring wind-speed data (Chow, 1964) could not be used in this study.

The previously described energy-related climatic factors, except wind speed, are required to compute PET by the Jensen-Haise method. PET is the possible evapotranspiration for a given set of energy-related climatic conditions. PET only expresses the potential energy available for consumptive water use without regard to the availability of water or soil-water storage properties of the soil (AWC). Although this potential energy essentially is a function of solar radiation, temperature and humidity (vapor-pressure deficit) serve as modifying elements in the Jensen-Haise equation.

PET was computed at the 68 sites using the method discussed in appendix A. An examination of computed mean annual PET patterns (fig. 17) indicated the collective effects of the individual variables, particularly solar radiation and one of its contributing variables, percent of possible sunshine. The effects of the other variables used in the computations, temperature and humidity, are less apparent but serve to refine the generalized patterns attributable to solar radiation.

The southwestern part of the study area has the largest PET values, exceeding 68 inches in some areas. In contrast, PET in the northeast is less than 26 inches, which results in a range of more than 42 inches across the study area. The effects of cloud cover

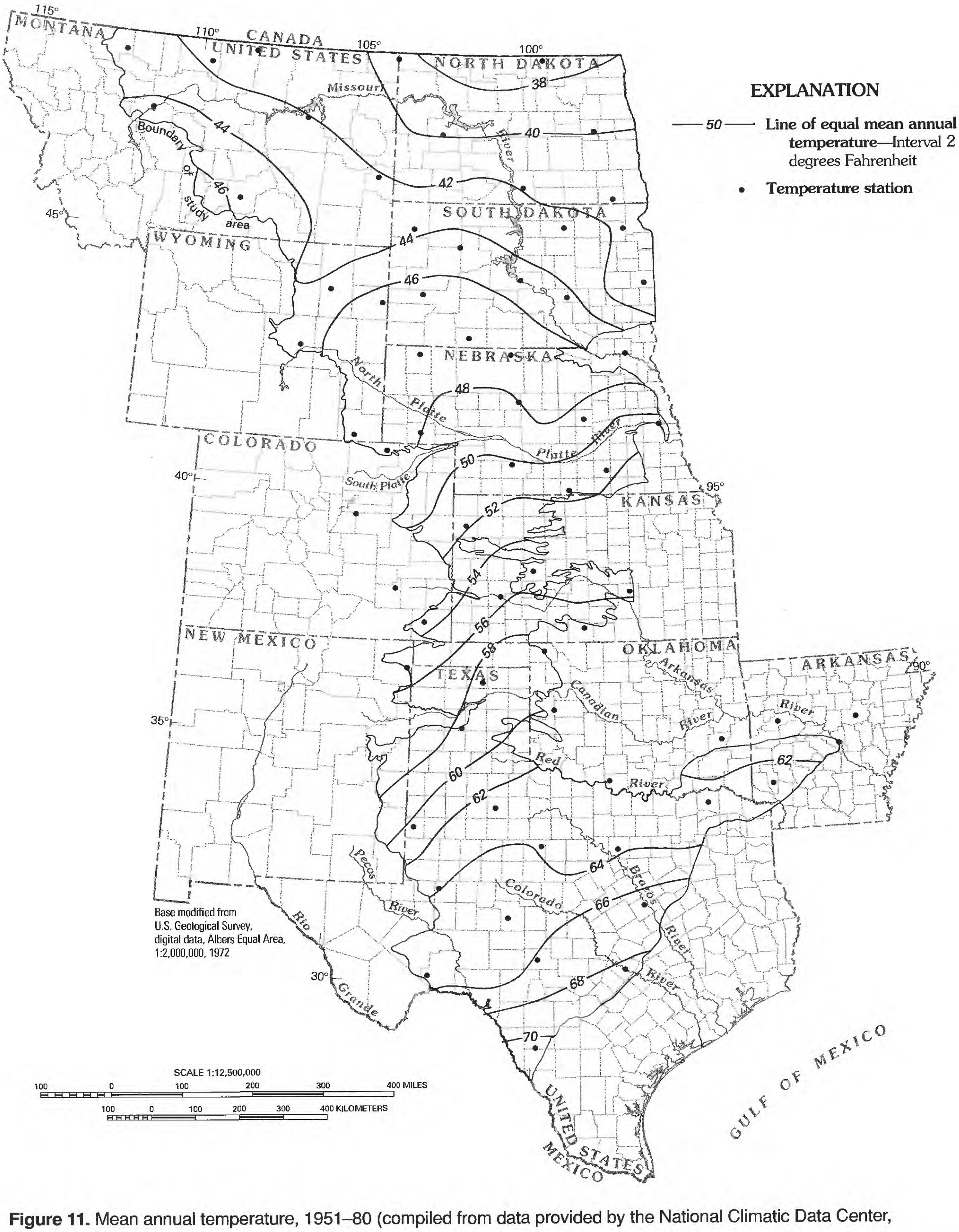


Figure 11. Mean annual temperature, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

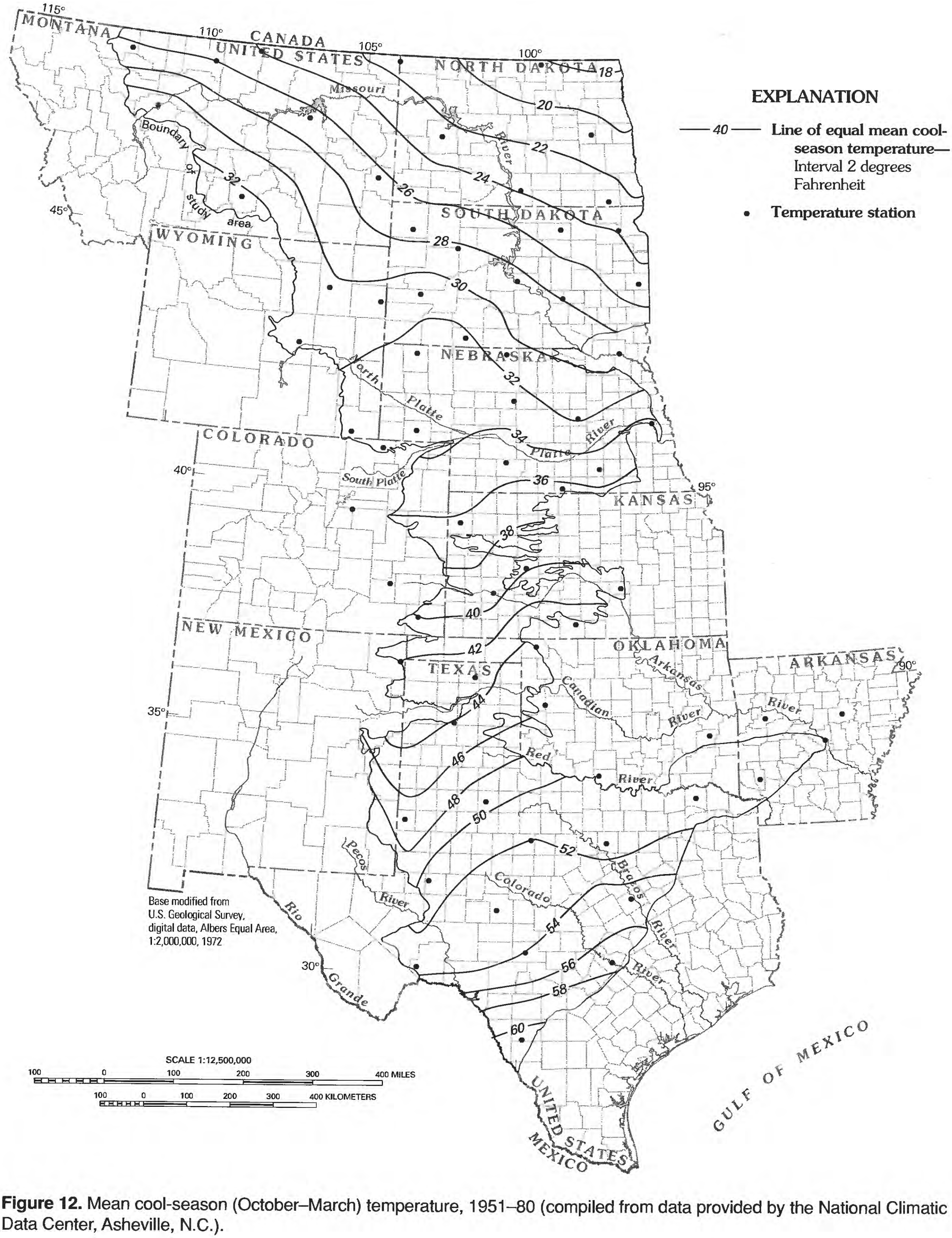


Figure 12. Mean cool-season (October–March) temperature, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

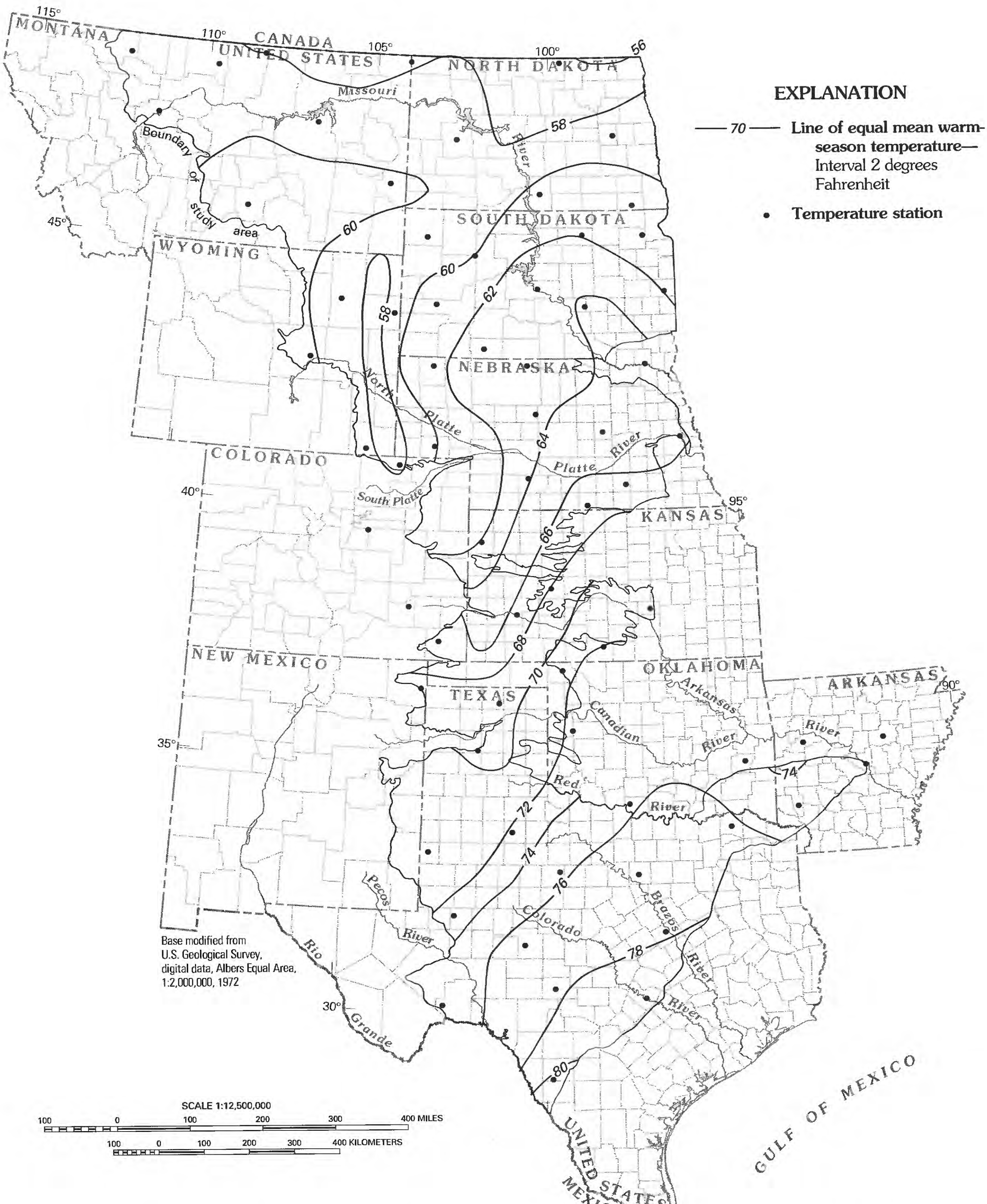


Figure 13. Mean warm-season (April–September) temperature, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

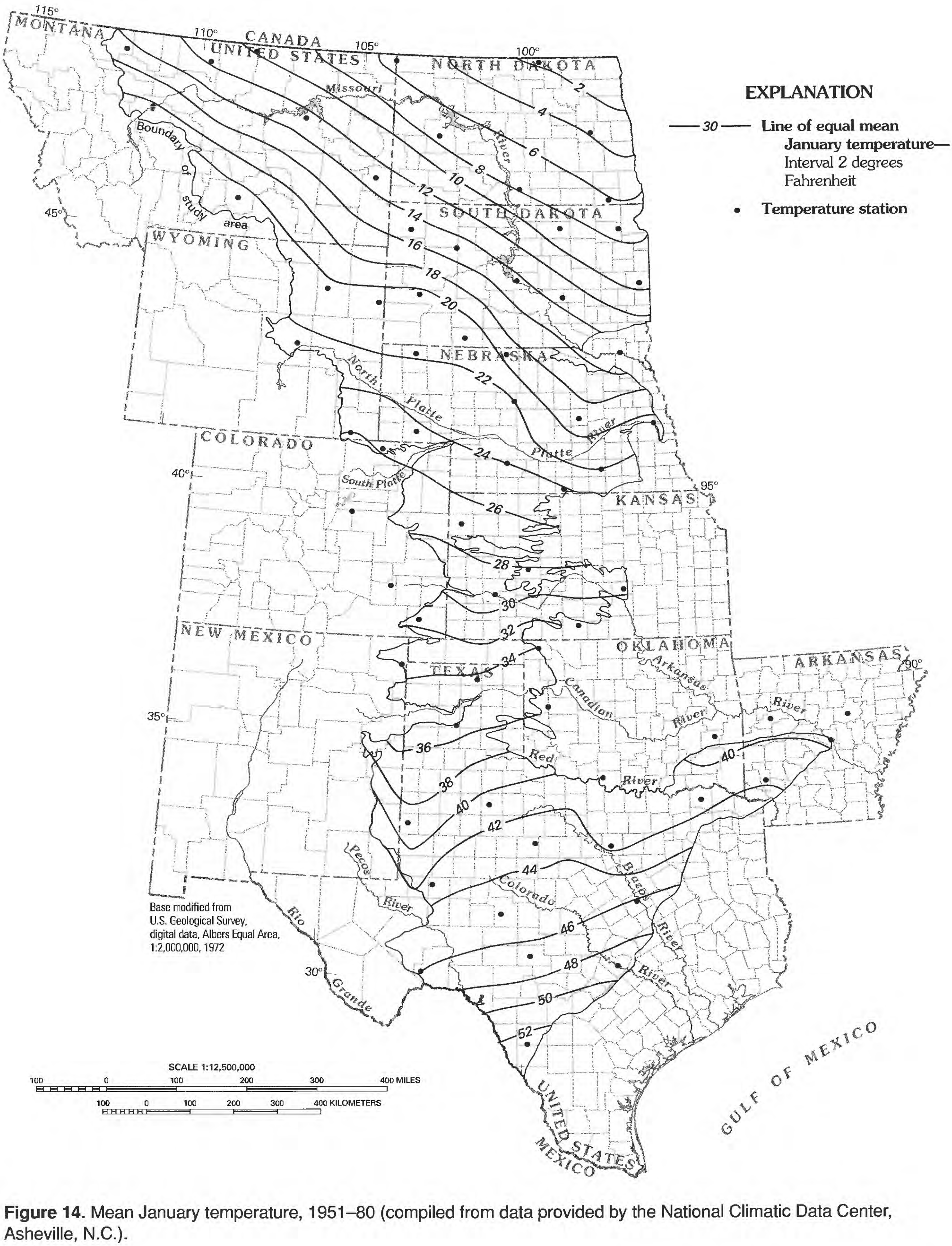


Figure 14. Mean January temperature, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

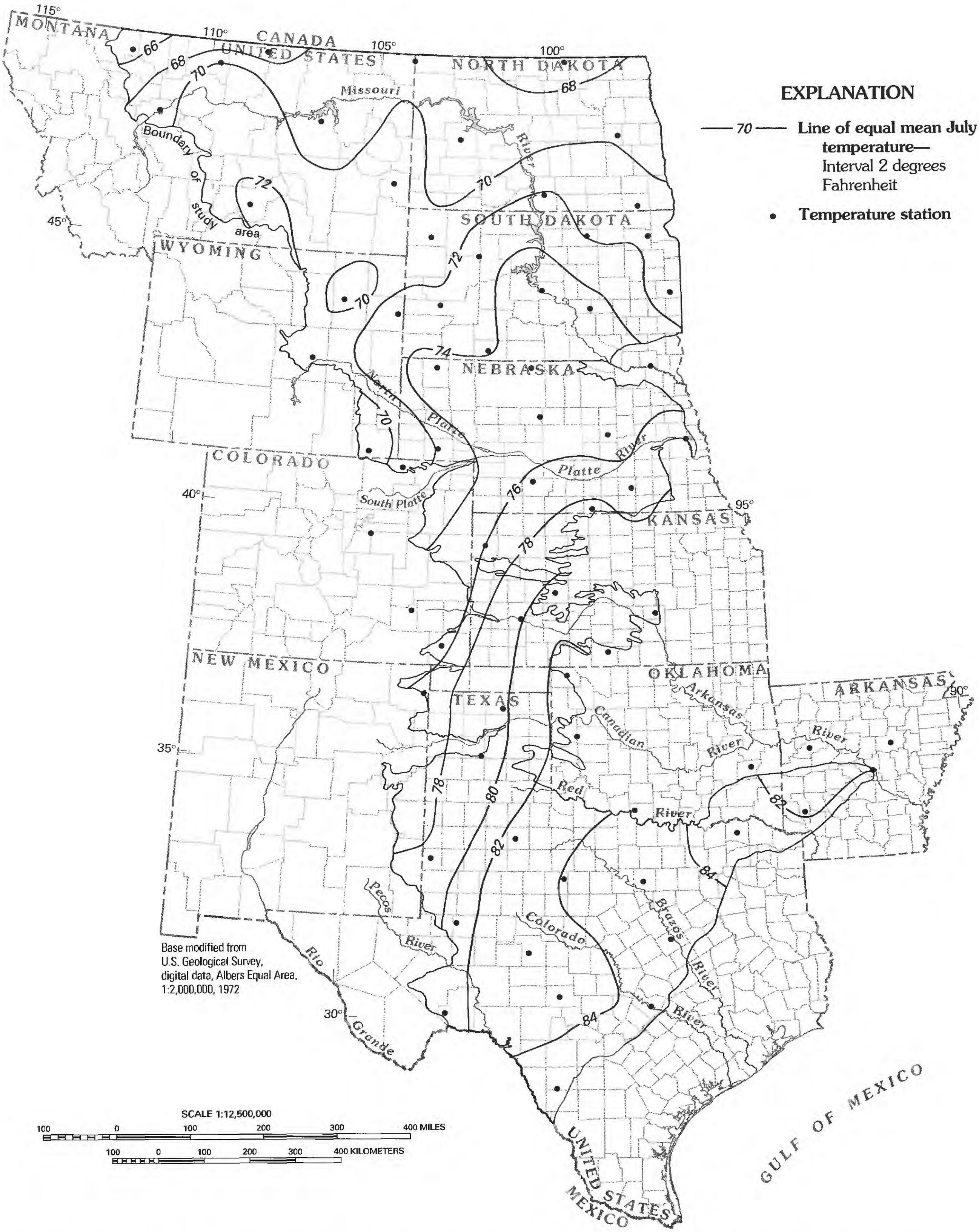


Figure 15. Mean July temperature, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

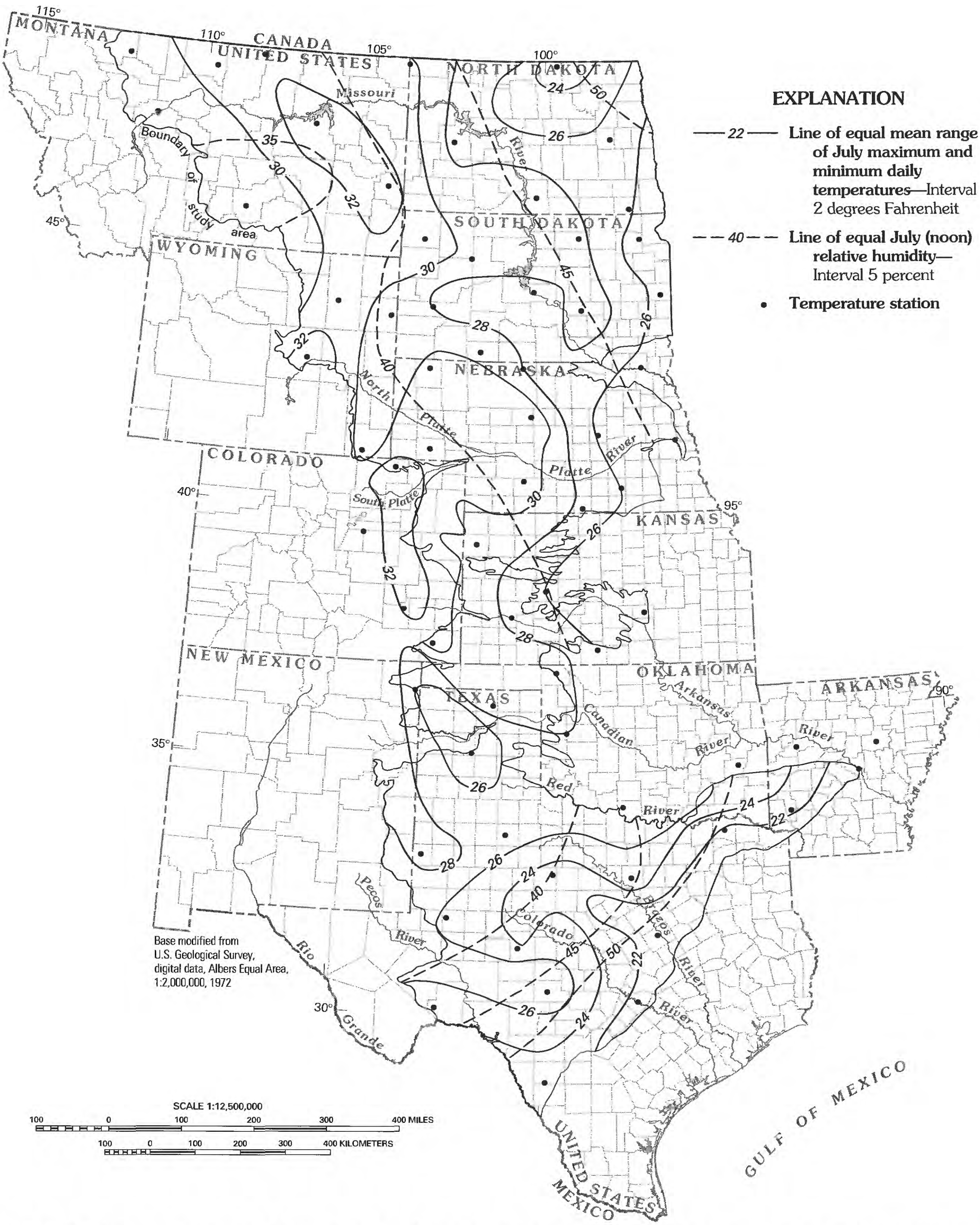


Figure 16. Mean range between July maximum and minimum daily temperature, 1951–80, and mean July (noon) relative humidity (compiled from data provided by the National Climatic Data Center, Asheville, N.C., and relative humidity data from the U.S. Department of Agriculture, 1941).

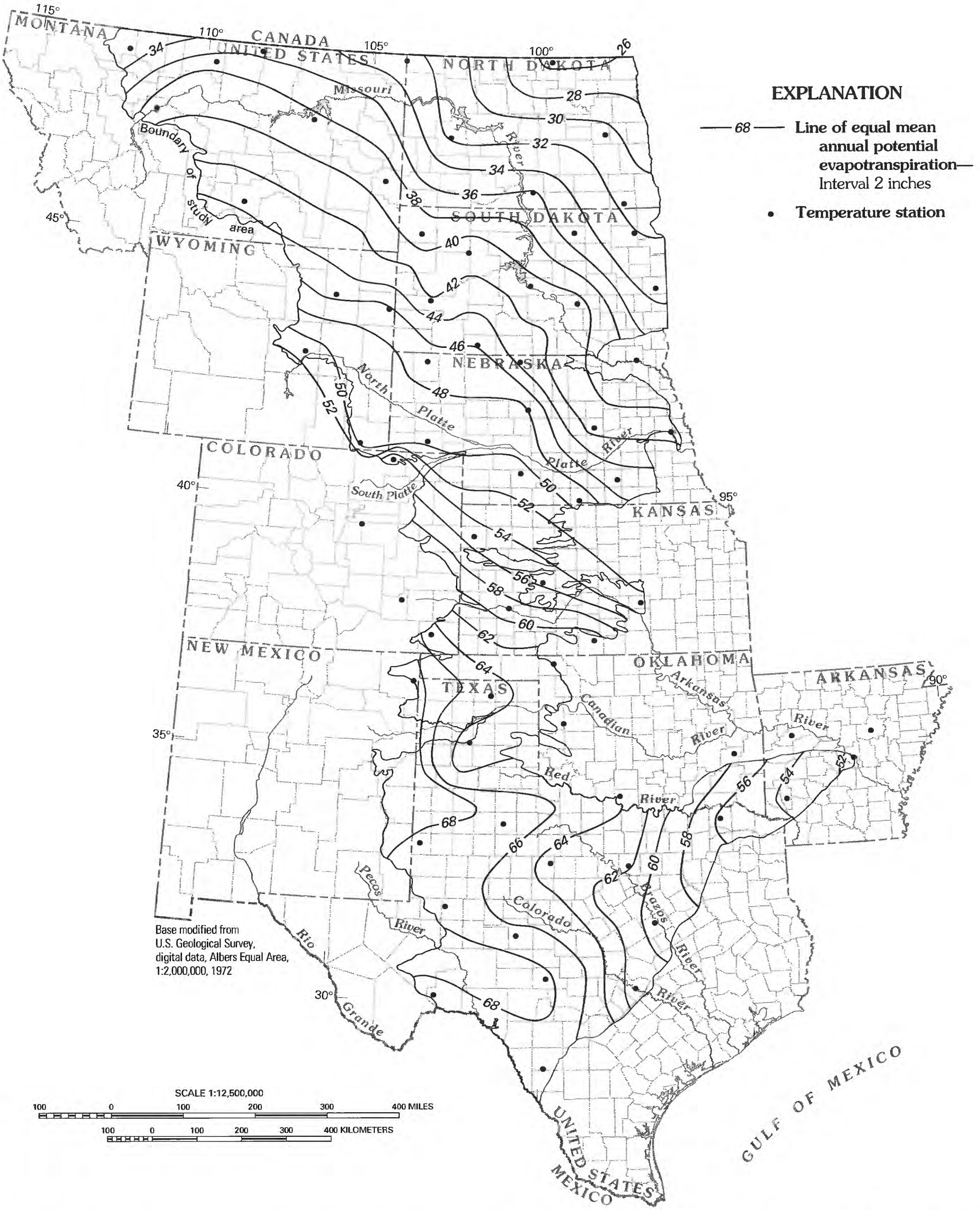


Figure 17. Mean annual potential evapotranspiration, 1951–80 (computed from data provided by the National Climatic Data Center, Asheville, N.C.).

(fig. 6) and humidity (fig. 16) become apparent when compared to PET (fig. 17). A latitudinal cross section from west Texas to Arkansas indicates a maximum PET difference of about 16 inches.

Seasonal PET patterns probably are of greater significance to ground-water recharge than annual PET. A well-defined inverse relation should exist between seasonal water demands, as expressed by PET, and the quantity of water available for deep percolation. Thus, a greater potential for recharge should exist in the cool season (October–March) than in the warm season (April–September). The significance of seasonal PET patterns to recharge needs to be interpreted in relation to seasonal precipitation.

An examination of computed cool-season PET (fig. 18) indicates substantial spatial contrasts within the study area that could have an effect on subsequent patterns of potential recharge. Cool-season PET values range from about 20 inches in the extreme south to about 2 inches in the extreme northeast. About 30 percent of the mean annual PET (fig. 17) occurs in the extreme south during the cool season contrasted with less than 8 percent in the northeast.

Small regional differences in solar radiation and associated temperatures in the warm season result in relatively small spatial variations in computed warm-season PET (fig. 19). Because PET and subsequent water demands are large during the warm season throughout the study area, average conditions are not conducive for substantial warm-season recharge.

Precipitation

PET is the climatic expression of energy available for potential consumptive water use, and precipitation is the climatic expression of the water available to fulfill this potential. AET, however, generally is limited by precipitation in that soil water consumed cannot exceed the soil water available. Other than capillary action from a high water table (subirrigation), precipitation is the only natural source for soil water. In the study area, particularly in the western Great Plains where soil water is nearly always limited, the spatial and temporal variability of precipitation is critical.

Mean annual precipitation in the study area (fig. 20) ranges from about 48 inches in the Arkansas part of the study area to about 12 inches in north-central Montana. About one-half of the study area averages less than 20 inches, which is considered the limit between semiarid and subhumid conditions. The decrease in precipitation from south to north and east to west closely corresponds to the increasing distance from the principal source area of moist, unstable airmasses (maritime tropical)—the Gulf of Mexico-Caribbean region. The precipitation anomalies occurring in the Black Hills area and central Montana are largely orographic effects. Other orographic uplift areas may exist in the study area but are not indicated by the coarse network of 128 precipitation measurement sites.

One of the most important characteristics of precipitation in the study area is yearly variability. The coefficient of variation of annual precipitation indicates that a variability of about 26 percent of the mean could be expected in any given year for most of the study area. This variability ranges from 19 percent in Arkansas to 30 percent in southwestern Texas and northern Montana. For most of the study area, the range in annual precipitation during 1951–80 equaled or exceeded the mean annual precipitation. In some locations in southwestern Texas, this range was nearly double the mean.

Data on minimum annual precipitation during 1951–80 (fig. 21) indicate that about 90 percent of the area had at least 1 year with less than 20 inches of precipitation. Only the area in eastern Texas, Oklahoma, and Arkansas had no years with less than 20 inches during this period; this is the only large area where precipitation in the driest year was not less than 50 percent of normal. Nearly one-half of the study area received less than 10 inches of precipitation in at least 1 year during 1951–80, which indicates that arid conditions are possible over much of the area in any given year.

The driest area for 1 year during 1951–80 was southwestern Texas in 1956, when precipitation was less than 2 inches, which is only 15 percent of normal for that area (U.S. Department of Commerce, National Climatic Data Center, 1951–80). Such extremely dry years did not occur in the northern and central Great Plains during the same period.

The spatial patterns of the driest years (not shown) indicate that drought conditions can be quite pervasive throughout the study area. The most areally extensive year of drought, particularly in the central and southern Great Plains, occurred in 1956. The driest multiyear period throughout most of the Plains during 1951–80 was 1954 through 1956, which also coincides with major expansion of ground-water irrigation in the Great Plains. The drought during these

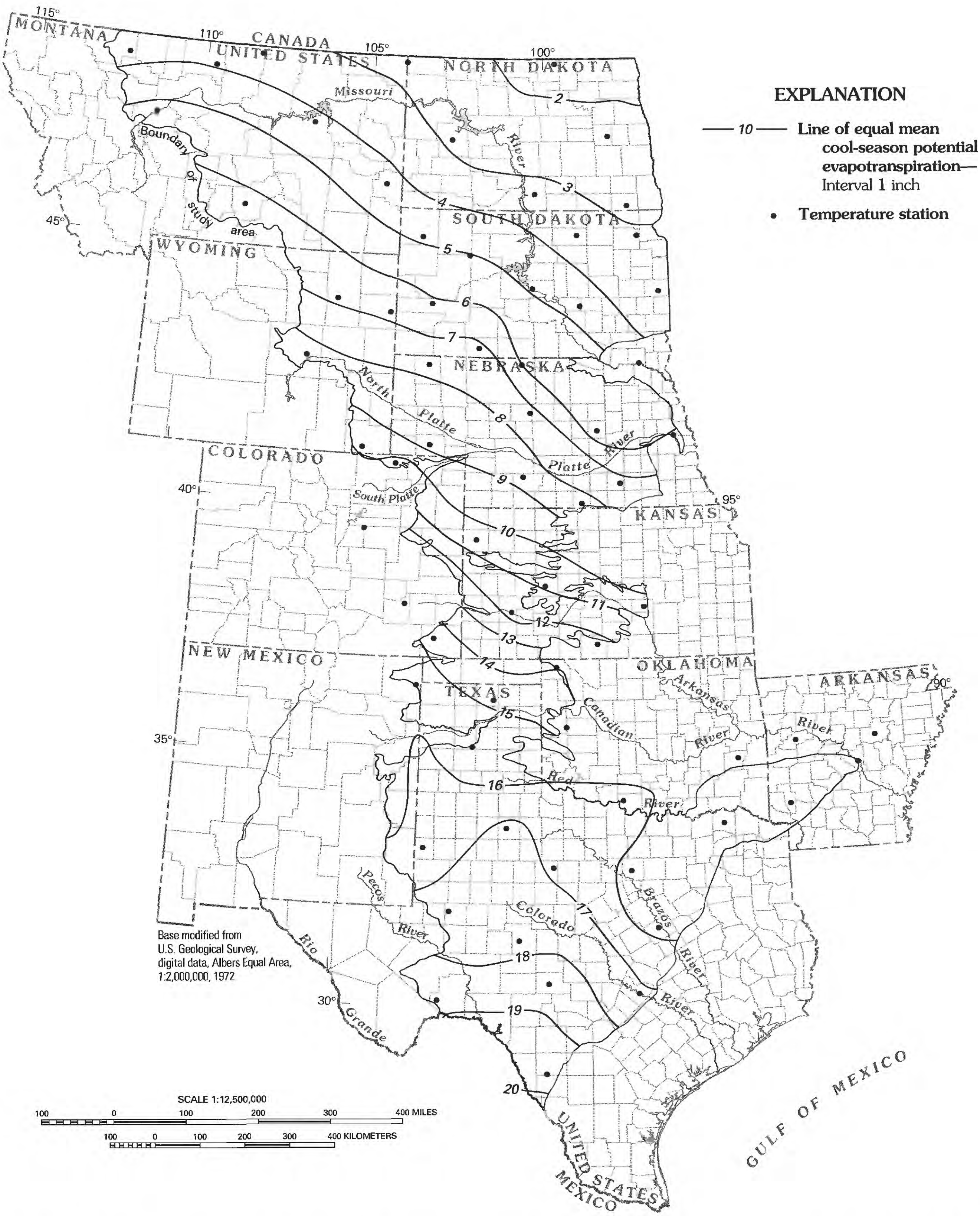


Figure 18. Mean cool-season (October–March) potential evapotranspiration, 1951–80 (computed from data provided by the National Climatic Data Center, Asheville, N.C.).

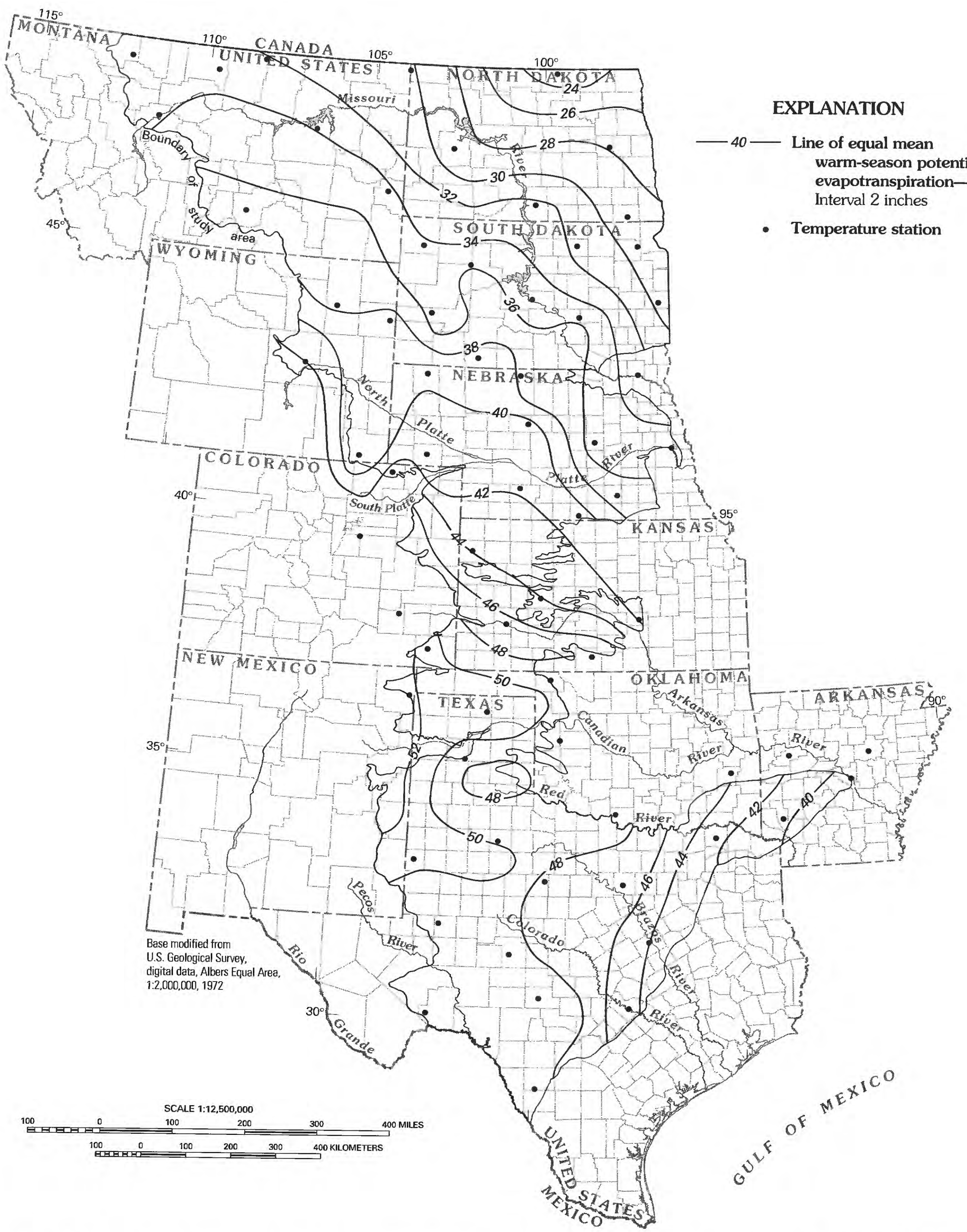


Figure 19. Mean warm-season (April–September) potential evapotranspiration, 1951–80 (computed from data provided by the National Climatic Data Center, Asheville, N.C.).

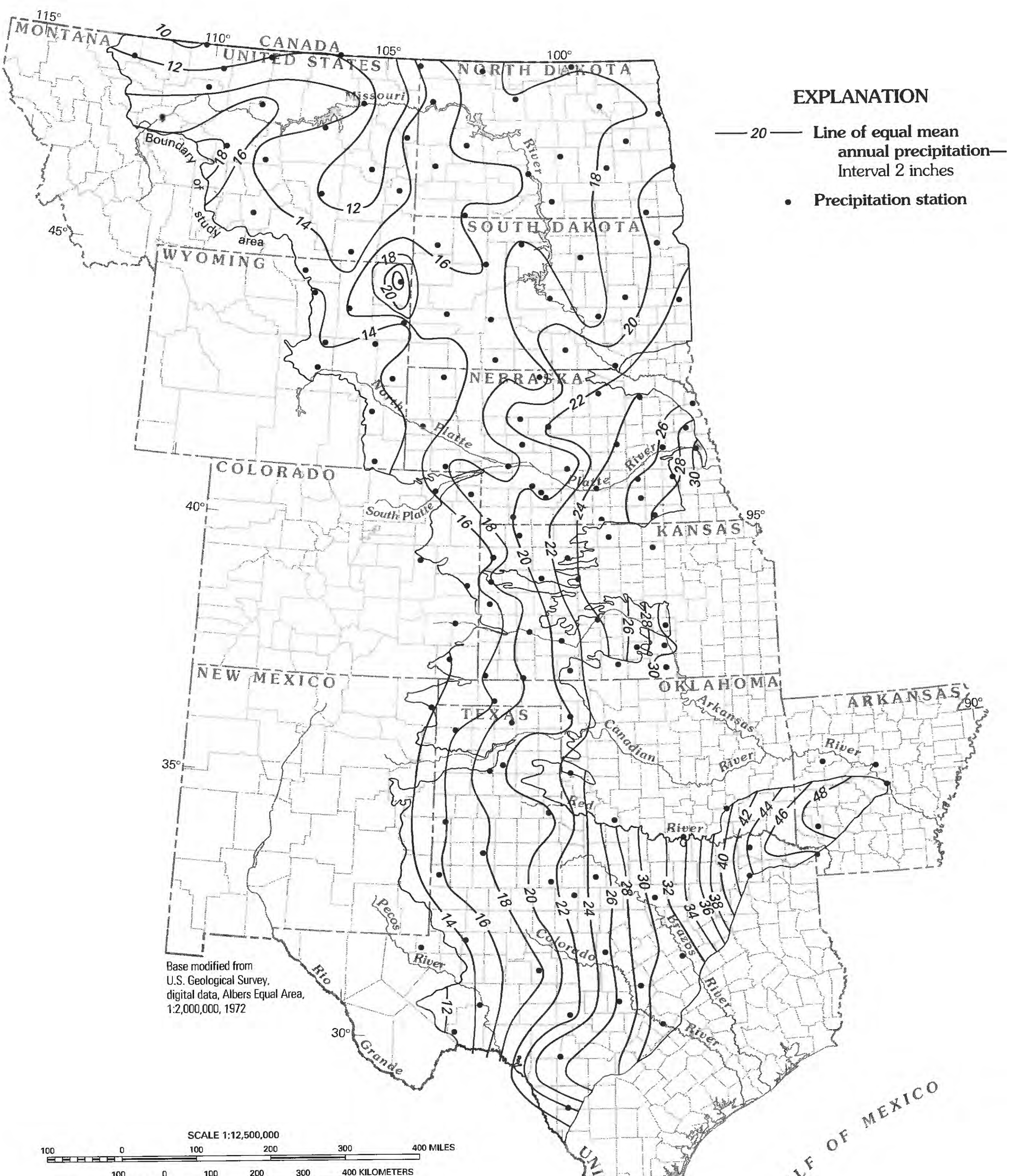


Figure 20. Mean annual precipitation, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

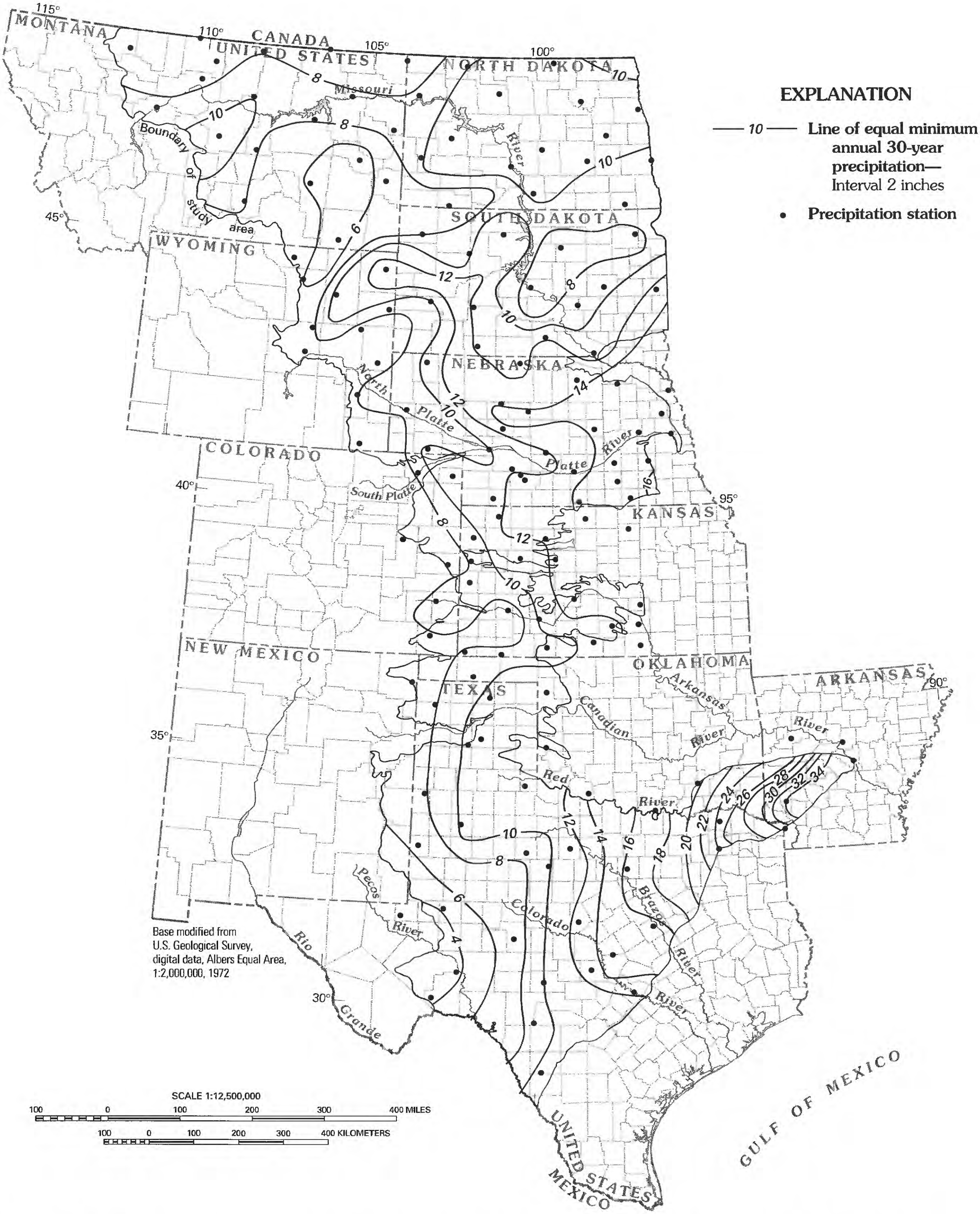


Figure 21. Minimum annual precipitation, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

years, however, does not appear to be of the same intensity or spatial extent as the drought of the 1930's in the study area.

Dry years generally are associated with warmer than average temperatures and an increase in percent of possible sunshine (greater solar radiation), causing higher rates of PET and higher CWR. Thus, the greater demands for water through increased ET associated with deficits in precipitation intensify drought conditions. These long-term, widespread drought conditions in the study area are closely associated with persistent large-scale anticyclonic circulation systems, which inhibit precipitation-forming processes and create radiation and temperature conditions conducive to higher evapotranspiration (ET).

Maximum annual precipitation at most sites exceeded 20 inches in the wettest year during 1951 through 1980 (fig. 22). During the wettest year, annual precipitation usually exceeded the normal by 50 to 75 percent. Extremely wet years seem to be much more common in southwestern Texas, where in some years precipitation exceeded the normal (fig. 20) by more than 100 percent. The precipitation commonly was associated with the residual effects of tropical disturbances, including hurricanes. Such extremely wet years were not as common in the northern and central Great Plains.

An analysis of the wettest years at individual sites indicates that regionwide wet conditions are much less common than regionwide dry conditions; atmospheric conditions conducive to intense precipitation typically are localized, small-scale systems, such as thunderstorms. Although patterns of wet years are spatially less discernible, certain years were wet in large parts of the region. In the northern plains, 1962, 1975, 1977, and 1978 were wet years; in the central plains, 1951, 1965, and 1977; in the southern plains, 1957, 1960, and 1969.

The relatively short period of record used in the analysis is marginal for reliable tests of normality; however, a brief examination of the various measures of central tendency at the individual sites, including comparisons of the mean and median, skewness, and kurtosis, does indicate some significant tendencies. Annual means and medians at individual sites seldom vary by more than 0.5 inch, with the median generally less than the mean; a slight positive or right skewness was confirmed by an examination of the coefficients of skewness. An analysis of the coefficients of kurtosis indicates the values are not clustered around the mean but are widely distributed, producing rather flat curves that are indicative of large annual ranges in precipitation. This observation also is confirmed by the relatively large standard deviations and coefficients of variation.

Generally, annual precipitation at the individual sites indicates relatively normal or uniform distributions of annual precipitation around the 30-year mean. The slight skewness and flat distribution curves, however, do indicate slight deviations from a normal distribution. Means larger than medians (right skewed) indicate that a few extremely wet years in the 30-year period increase the annual mean. The wide scattering of annual precipitation around the mean (flat distribution and large standard deviation) indicates that mean annual precipitation represents a statistical average rather than a typical condition.

The effectiveness of precipitation for meeting the overall CWR of vegetation and supplying water for potential ground-water recharge (DPD) is more dependent on seasonal patterns than on the annual precipitation amounts. A narrow balance exists between the timing or efficiency of precipitation and seasonal patterns of water needs. Generally, even relatively small quantities of precipitation occurring during periods of plant dormancy or low ET are more effective for providing soil water for recharge than larger quantities during periods of high ET rates. Conversely, the timeliness of precipitation during periods of high CWR can decrease CIR considerably.

Mean cool-season (October–March) and warm-season (April–September) precipitation data in figures 23 and 24 indicate substantial seasonal differences both temporally and spatially. During the cool season, mean precipitation ranges from about 23 inches in Arkansas to about 2 inches in some areas of Wyoming. Less than 25 percent of the mean annual precipitation occurs in the cool season for most of the northern and western Great Plains. The percentage of annual precipitation occurring during the cool season increases southeastward to nearly 50 percent in Arkansas.

Precipitation patterns during the warm season, which coincides with the growing season for most of the study area, vary substantially from the cool-season patterns. Regional differences in both relative and absolute precipitation quantities are much smaller and range from 26 inches in Arkansas to about 8 inches in eastern Wyoming. For much of the northern and western Great Plains, warm-season precipitation exceeds 75 percent of the annual total, which is important in

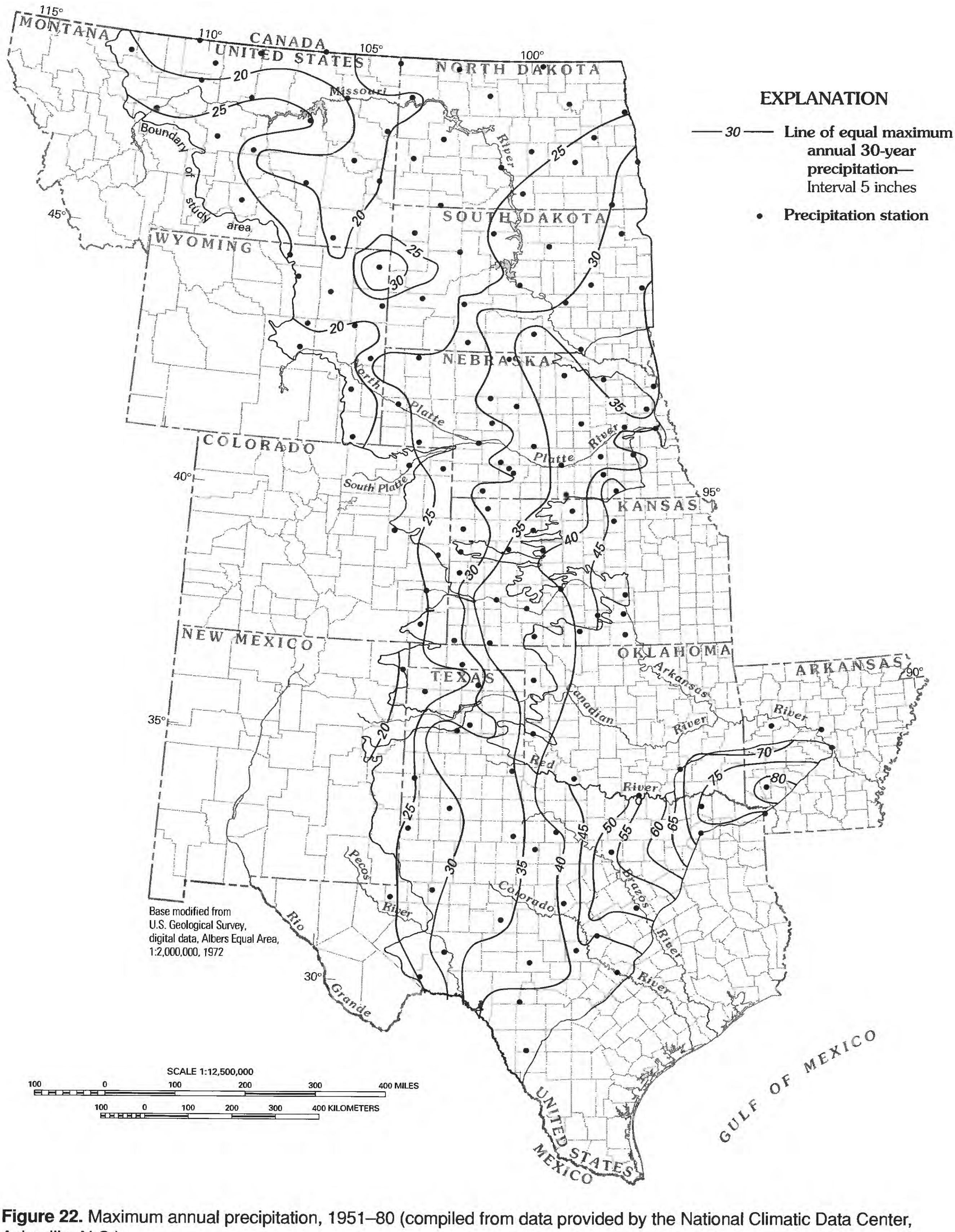


Figure 22. Maximum annual precipitation, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

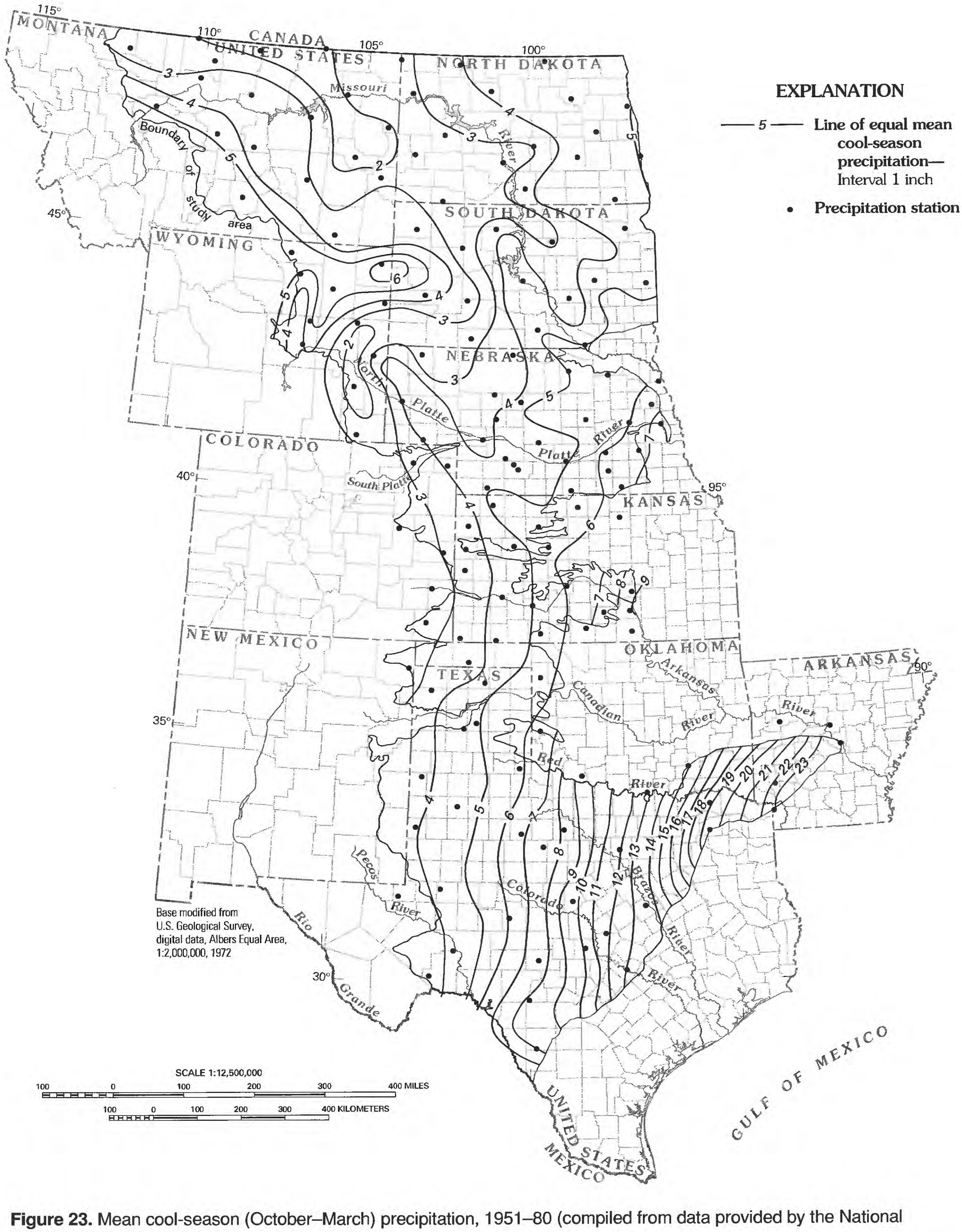


Figure 23. Mean cool-season (October–March) precipitation, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

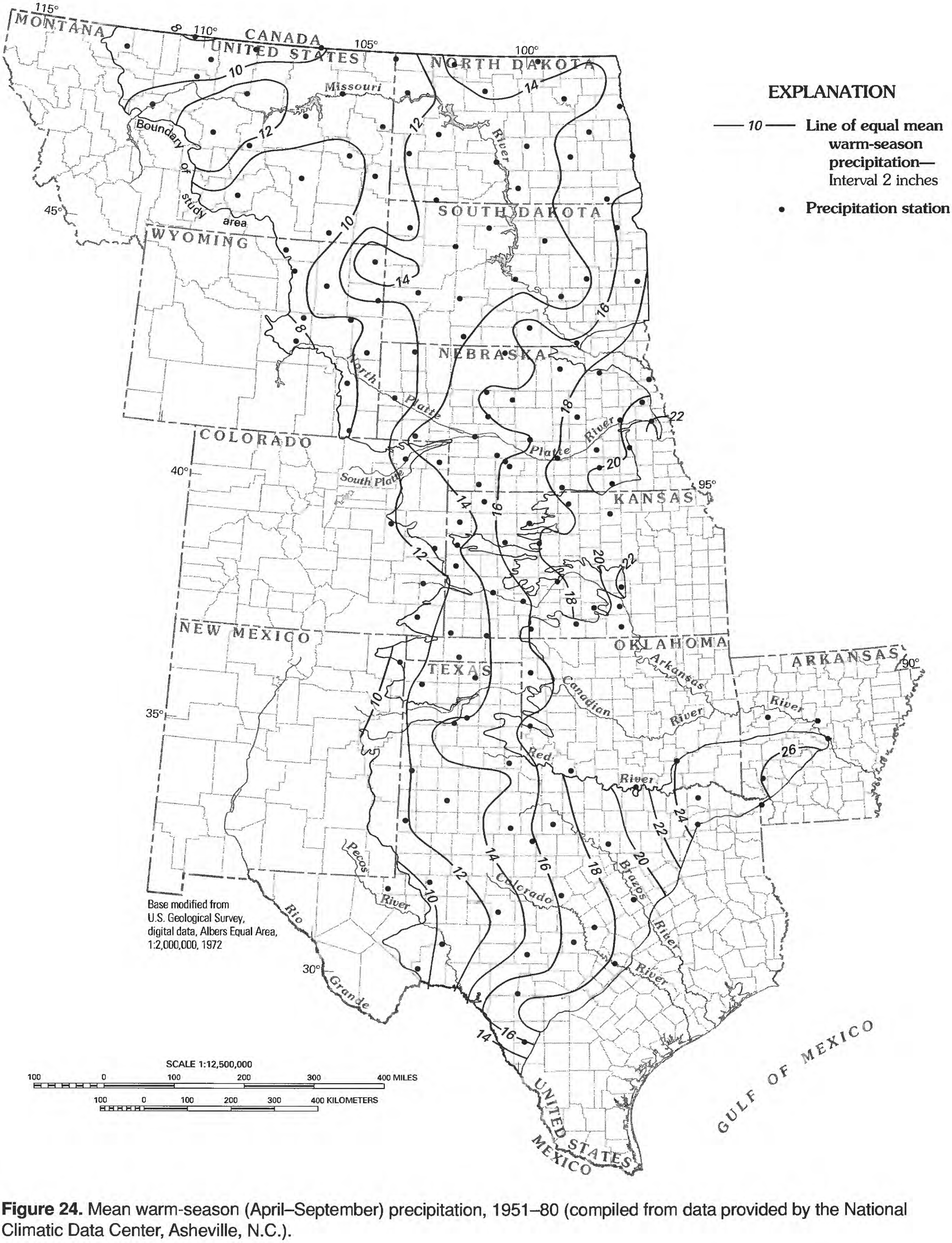


Figure 24. Mean warm-season (April–September) precipitation, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

meeting CWR but provides little surplus soil water for deep percolation.

During the cool season, precipitation tends to be much less predictable than during the warm season, particularly where the seasonal mean is smaller. From 1951 through 1980, the average coefficient of variability during the cool season for most of the study area was greater than 40 percent and exceeded 50 percent in many parts of the west-central Great Plains. During the cool season, precipitation in the wetter areas (Arkansas) is most predictable, with a coefficient of variability less than 30 percent. In the warm season, predictability substantially increases for much of the study area, with a coefficient of variability less than 30 percent. Precipitation in the warm season is least predictable in southwestern Texas.

A statistical comparison for both cool- and warm-season precipitation at the individual sites tends to show a slight positive skewness for both seasons. Positive skewness indicates the mean exceeds the median; therefore, both seasons tend to be slightly drier in most years than the seasonal means indicate.

Soils

In the complex interaction of climate, soils, and vegetation on regional hydrologic responses, soil can be classified as a passive factor because its properties are considered to be static. However, the continued gain and loss of water within the soil (root zone) implies a dynamic process. Present methods of simulating dynamic soil-water processes are not suitable for large areas. Simulation of the soil-water process in this study requires that the soil be treated as a temporary storage medium for water with fixed hydrologic properties. The hydrologic characteristics of the soils in the study area are presented in Dugan, Hobbs, and Ihm (1990). Several of these characteristics that affect the soil's hydrologic responses are integral variables in SWASP.

An important soil characteristic in soil-water availability is the ability of the soil to intake precipitation. Infiltration is dependent on several factors, including slope, soil texture, vegetative cover density, water conservation or land-management practices, and volume and intensity of precipitation. Because infiltration cannot be readily measured over large areas, in SWASP it must be estimated indirectly from empirical equations based on slope, soil texture, cover type, and volume of precipitation. Data were insufficient to include water conservation or land-management practices and precipitation intensity in the equations.

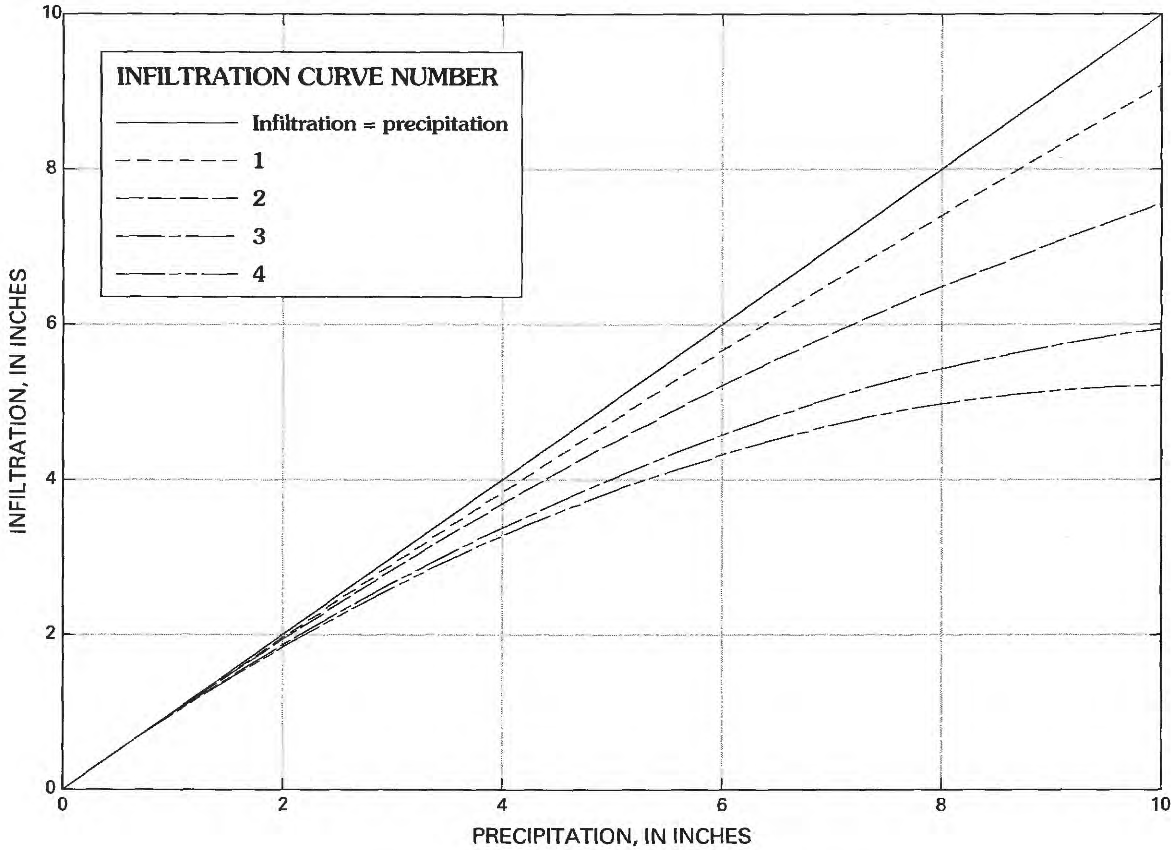
Four curves expressing the relation between infiltration and precipitation are shown in figure 25. Assignment criteria for variations in soil texture, vegetative type, and slope also are shown in figure 25. The equations for the four curves and their actual assignments in the three subregional inputs are listed in appendix A.

The hydrologic characteristic of the soil most critical for ground-water recharge is the available water capacity (AWC). This characteristic, which is analogous to specific yield in ground-water hydrology, determines the maximum storage capacity of retrievable water in the soil. Various assigned available water capacities (see app. A) would result in total available water in storage for a 60-inch-thick soil as given in table 1. These differences in resultant storage can affect substantially potential recharge and CIR. A thorough discussion of the concept of available water capacity is in Dugan, Hobbs, and Ihm (1990).

The hydrologic soil-classification scheme in Dugan, Hobbs, and Ihm (1990) produced 39 hydrologic soil groups that were generalized to 9 groups for soil-water simulation purposes (see table A2 in app. A). These 39 soil groups were reclassified into generalized groups on the basis of permeability and slope, without consideration of the depth to the seasonally high water table or soil-profile thickness. The spatial patterns of the 9 generalized soil groups are shown in figure 26. Simplification of the soil groups for soil-water simulation purposes did not cause a substantial loss of information or mapping detail.

Soils on steep slopes in the study area (fig. 26) are principally clay to silty clay loam soils of low permeability (soil 3), which would contribute to greater potential runoff and a smaller percentage of infiltration (infiltration equation curves 3 and 4, fig. 25). These areas can be expected to have proportionally less available soil water to satisfy CWR and for potential ground-water recharge. In contrast, slope becomes considerably less important to the soil-water balance on the coarser textured, rapidly permeable soils (soils 7, 8, and 9) because of less runoff and greater infiltration. These latter three soils are assigned to infiltration equations 1 or 2 (fig. 25).

Various depth-related soil characteristics have important effects on the soil-water balance. These depth characteristics include (1) thickness of the soil profile or the depth to consolidated bedrock,



ASSIGNMENT CRITERIA FOR INFILTRATION CURVES

Soil texture	Vegetation type	Slope, in percent: Greater than 15		7 to 15		0 to 7	
Clay to silty clay loam	Row crop	4		4		3	
	Small grain	4		3		2	
	Alfalfa	3	SOIL 3	2	SOIL 2	1	SOIL 1
	Range	3		2		1	
	Woodland	3		2		1	
	Fallow	4		4		3	
Silt loam to sandy loam	Row crop	3		3		2	
	Small grain	3		3		2	
	Alfalfa	2	SOIL 6	1	SOIL 5	1	SOIL 4
	Range	2		1		1	
	Woodland	2		1		1	
	Fallow	3		3		2	
Loamy sand to sand	Row crop	2		2		1	
	Small grain	2		2		1	
	Alfalfa	1	SOIL 8	1	SOIL 8	1	SOIL 7
	Range	1		1		1	
	Woodland	1		1		1	
	Fallow	2		2		1	
Sand to dune sand	Row crop	2		1		1	
	Small grain	1		1		1	
	Alfalfa	1	SOIL 9	1	SOIL 9	1	SOIL 9
	Range	1		1		1	
	Woodland	1		1		1	
	Fallow	2		1		1	

Figure 25. Infiltration curves and assignment criteria for soil texture, vegetation type, and slope.

Table 1. Assigned available water capacity and total available water storage by soil texture

Soil texture	Available water capacity (inch per inch)	Total available water storage of 60-inch-thick soil (inches)
Clay to silty clay loam	0.180	10.8
Silt loam to sandy loam	.150	9.0
Loamy sand to sand	.115	6.9
Sand to dune sand	.060	3.6

(2) seasonal depth of the root zone, and (3) depth to the water table. Although the specific effect of each of these characteristics on the soil-water balance differs, the potential for recharge is very sensitive to variations in any one of them.

Large areas of the Great Plains are covered by soils less than 60 inches thick (fig. 3). These soils, which range from a few inches thick over bedrock to completely absent with the bedrock exposed, are too complex in most areas to determine an average thickness; therefore, they are classified only as having a profile of less than 60 inches. In areas where soils are less than the assigned root zone for a given vegetation type (see app. A), soil-water simulation results from SWASP may not be valid because of possible restriction of root development.

The effective root depth is the soil zone from which vegetation can actively extract soil water or carry out actual ET functions. It is not a function of soil but of vegetation type. The effective root depth varies seasonally for each vegetation type on the basis of growth and phenological characteristics of each vegetation type. Monthly values for designated root zones in the SWASP subregional setups (app. A) range from a minimum of 15 to a maximum of 48 inches. Fifteen inches represents the maximum assigned depth at which evaporation can occur during periods of plant dormancy when transpiration is absent.

Another soil characteristic included in the soil classification by Dugan, Hobbs, and Ihm (1990) that is relevant to the soil-water balance but cannot be factored into the simulation procedures of SWASP is depth to the seasonally high water table. Capillary action from a high water table may subirrigate deep-rooted vegetation and thereby modify the soil-water balance. This condition is common in the major stream valleys or flood plains of the study area. The topographic complexity of high-water-table soils and the seasonality of these conditions make it difficult to assess their effect on the regional soil-water balance.

Vegetation

Although vegetation is a distinct element within the extrinsic component of ground-water hydrology, it also is a reflection of the climatic environment. Long- and short-term (seasonal) atmospheric conditions are apparent in vegetation. Conceptually, this relation is most applicable to natural vegetation, but it also applies to agricultural crops. The energy element of climate (solar radiation, temperature, and resultant rates of evapotranspiration) and atmospheric-moisture elements (precipitation and humidity) regulate biotic activities and spatial patterns of vegetation types.

The role of vegetation in the soil-water balance is assessed separately from the climatic role because CWR varies among vegetation types. Nearly all the water consumed by most vegetation is extracted by their root systems from available soil water and then transpired from their leaves as water vapor into the immediate surrounding atmosphere to regulate their temperature. This transpiration process by plants on a well-vegetated surface far exceeds direct evaporation losses from the soil. However, transpiration cannot be measured as a process distinct from evaporation for large areas with any degree of precision; therefore, they must be considered simultaneously as a single process, evapotranspiration. Thus, when water losses from a given area are assessed, the types of vegetation present must be considered.

The seasonal CWR:PET ratio is unique for each vegetation type (fig. 27*A–C*; app. A). In this study, the term "crop coefficient" is synonymous with CWR:PET ratio, which represents the potential monthly water demand of each general vegetation type in relation to PET. Separate sets of coefficients were developed for the three subregions to reflect the phenological progression and the differing regional representative crop types. Actual crops, such as corn and winter wheat, represent the general crop groups. Fallow indicates approximate soil-evaporation losses from nonvegetated soil surfaces.

CWR is distinct from the actual soil water consumed, or AET. CWR is potential water use if soil-water availability is not a limiting factor in contrast to AET, which is CWR minus SWD (soil-water deficits). AET cannot exceed available soil water, whereas CWR, like PET, can. By going dormant and

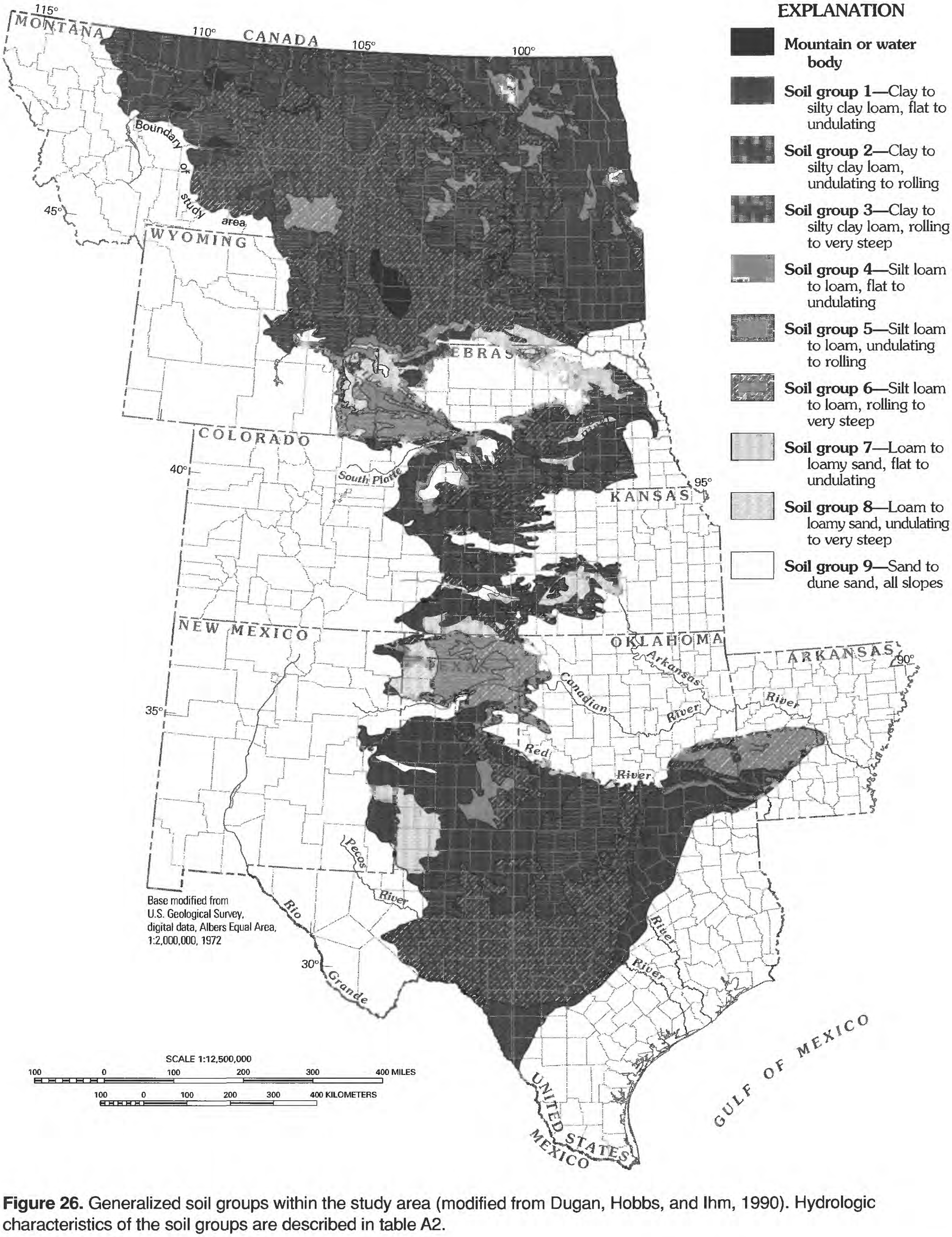


Figure 26. Generalized soil groups within the study area (modified from Dugan, Hobbs, and Ihm, 1990). Hydrologic characteristics of the soil groups are described in table A2.

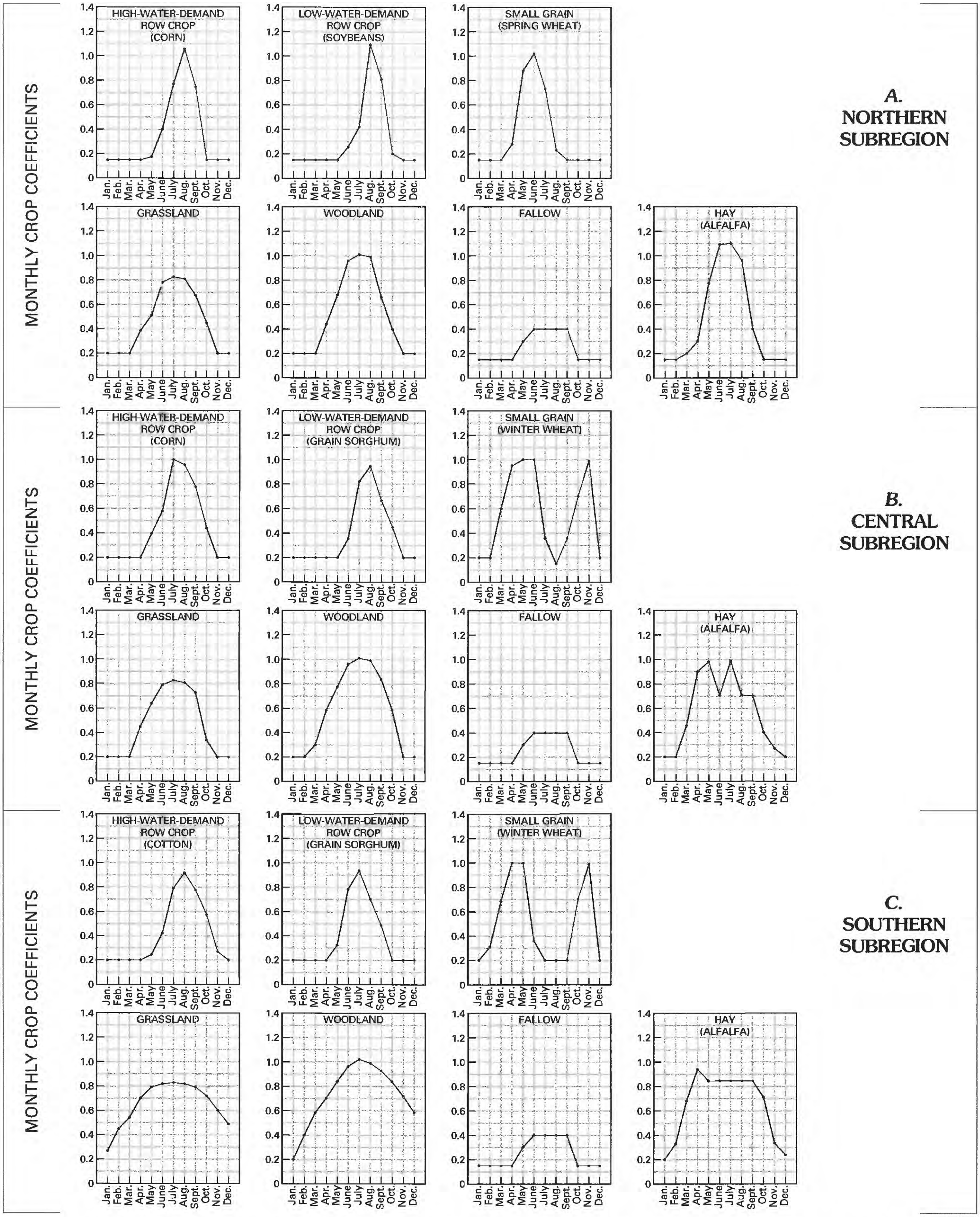


Figure 27. Monthly crop coefficients (ratio of consumptive water requirement, CWR, to potential evapotranspiration, PET) by vegetation type in *A*, northern, *B*, central, and *C*, southern subregions of the Great Plains (compiled from U.S. Soil Conservation Service, 1967; Stegman and others, 1977; Wright, 1982).

Table 2. Percentage of land area by vegetation or cover type

[Compiled from Kuchler, 1964; U.S. Bureau of the Census, 1984]

Vegetation or cover type		Percent of land area
Grassland (native)		55.7
Woodland (including scrub and orchard crops)		6.3
Cultivated land:		36.9
Hay (including harvested native grassland)	4.0	
Small grain (including wheat, oats, barley, and rye)	11.4	
High-water-demand row crops (principally corn and cotton)	6.6	
Low-water-demand row crops (principally grain sorghum and soybeans)	5.7	
Fallow (including all unplanted and unharvested cropland)	9.2	
Streams and lakes		1.1
Total		100.0

decreasing water demand, much of the natural vegetation and certain domestic crops, including native grasses, woody shrubs (mesquite and sage), and grain sorghum, can survive extended periods of water deficits when CWR greatly exceeds available soil water.

Domesticated hay, principally represented by alfalfa, but also including clover, lespedeza, and certain domesticated and native grasses harvested as hay, has the largest CWR. Alfalfa, in particular, has an almost unrestricted CWR, limited only by available energy during the growing season if no soil-water deficits occur, which makes it a good indicator crop in calibrating PET procedures (Wright, 1982). Alfalfa possesses both cool- and warm-season plant-growth characteristics and has a significant growth rate throughout the entire growing season. Alfalfa typically can fulfill this nearly unrestricted CWR with very extensive root-system development and capillary action from shallow water tables.

Grassland, the principal natural vegetation of semiarid and subhumid climates of the study area, has a cumulative annual CWR:PET ratio nearly as large as that for alfalfa (fig. 27; app. A). This is because the grasslands typically contain both cool- and warm-season species and contrasting growth and water-requirement cycles that create an almost continuously large demand throughout the growing season. Furthermore, grasses tend to have rather extensive root systems, which make them rather efficient at extracting water from the upper soil profile (Weaver and Albertson, 1956).

Woodland, the other form of natural vegetation in the study area, includes a broad range of tree species, including many forms of scrub vegetation. An average CWR represents the very generalized woodland classification, which is characterized by high-water-demand, warm-season plants that are similar to high-water-demand row crops (corn and cotton) (Holt, 1968). The warm-season classification of woodland limits the period of high water demand and results in a smaller accumulative annual CWR than grassland.

The other three general vegetation types are annual domesticated crops that have strictly seasonal water demands. Small grains (wheat, oats, barley, and rye), high-water-demand row crops (corn, cotton, and sugar beets), and low-water-demand row crops (grain sorghum and soybeans) have relatively short, high-water-demand periods and long fallow periods before and after their growing seasons. Their total annual CWR is less than the CWR's of alfalfa and grassland because of their short maturation season. The principal irrigated crops in the study area, corn and cotton, have large, short-term CWR's during their maximum growth period (June–August), but overall demand is less than that for alfalfa or grassland. Corn and cotton are not drought resistant, and they do not have particularly efficient root systems; therefore, survival and maximum yields make irrigation a necessity in the study area.

Among crops in the study area, grain sorghum is the most drought-resistant crop grown on a large scale. It is capable of withstanding severe midseason soil-water deficits by going dormant and responding quickly when soil water is available.

The six general types of vegetation or land cover plus fallow are well represented in the study area (table 2). About 5 to 10 percent of the land areas of each individual county are devoted to nonagricultural land uses, including urban, industrial, and transportation activities. These nonagricultural land areas were proportionally grouped with grassland or woodland for consumptive water-use purposes.

Uncultivated land is predominant in the study area with 62 percent of the area in grassland or woodland (table 2). The ratio of cultivated to uncultivated area has been rather stable through the study period (U.S. Bureau of the Census, 1984) because of environmental limitations that include soils, topography, climate, and water. Primarily changes in vegetative cover conditions have occurred and probably will continue on cultivated land. Small-grain and fallow acreage has decreased in recent decades, and acreage devoted to row crops (principally corn, soybeans, and grain sorghum) has increased because of irrigation development.

The general spatial patterns of vegetation and crop types (U.S. Bureau of the Census, 1984) are shown in figure 28. The general land-use patterns show considerable continuity in which cultivated conditions are concentrated in three major areas and grasslands dominate over large continuous areas, particularly in the northwestern and southern Great Plains. The patterns of grassland distribution closely reflect environmental limitations, particularly precipitation, which is not sufficient for sustained cultivation without irrigation. Woodland exceeding 50 percent of the cover is limited to two areas of sufficient precipitation in (1) eastern Texas and Arkansas and (2) the Black Hills of southwestern South Dakota and northeastern Wyoming.

Vegetation patterns tend to be most complex in cultivated areas where four or more crop or vegetation types may occupy more than 10 percent of the area. More uniform vegetation is common in uncultivated areas, particularly grassland, where 90 percent or more of an area is a single vegetation type.

Nearly 15.5 million acres of cropland in the study area were irrigated during 1982 (U.S. Bureau of the Census, 1984); approximately 90 percent of the irrigation water was supplied by ground water. Approximately 13.5 million irrigated acres were in the High Plains part of the study area (fig. 1); Nebraska (5.1 million acres), Texas (3.9 million acres), and Kansas (2.8 million acres) accounted for most of this total.

The percentage of privately owned agricultural land, including range and woodland, that was irrigated in 1982 is shown in figure 29. The intensity and concentration of irrigated agriculture in selected areas of the High Plains are even more significant because farmland accounts for more than 95 percent of the land in those areas, compared with an average of 87 percent for the entire study area. Availability of ground and surface water and suitability of topography and soils have largely determined the intensity of irrigation development (Gutentag and others, 1984).

High-water-demand row crops, principally corn and cotton, account for nearly two-thirds of the irrigated acreage in the study area. Low-water-demand row crops (grain sorghum and soybeans), hay (alfalfa), and small grains (winter wheat) account for nearly all of the remainder. These latter crop types frequently are grown as dryland crops and receive only occasional supplemental irrigation during periods of large soil-water deficits. In some parts of the study area, winter wheat fields are irrigated prior to planting and in early spring only as soil-water conditions require. Only high-water-demand row crops tend to be irrigated by schedule during peak water-demand periods (June–August). Thus, the spatial analyses of soil-water simulation results related to irrigation are based only on irrigation practices and CWR of high-water-demand row crops.

SOIL-WATER SIMULATIONS

The soil-water simulation provides a synthesis of climatic, soil, and vegetation characteristics of the region as they relate to the availability and disposition of water in the soil. Nine interrelated soil-water variables in SWASP and the post-processing procedures are defined on the basis of spatially weighted climatic (energy and precipitation), soil, and vegetative cover characteristics. The results are continuously distributed patterns of these variables in the study area. Comprehensive discussions of the conceptual and procedural aspects of SWASP and the post-processing with a GIS are contained in appendixes A and B.

Runoff and Infiltration

Precipitation, in the soil-water simulations of SWASP, becomes either runoff or infiltration. Runoff, more precisely surface runoff, is that part of precipitation that does not enter the soil and is not accounted for in the soil-water balance. All infiltration is accounted for as either ET or recharge. Simulations of runoff and infiltration in SWASP are computed from the infiltration curves shown in figure 25. These curves are assigned on the basis of soil texture, vegetation type, topography (slope), and total precipitation. Factors that affect runoff and infiltration are land-use practices (conservation tillage) and rainfall intensity, but these data commonly are not available.

The semiarid sections of the study area tend to have annual runoff values less than 1 inch. Even on steeply sloping soils having low permeability, generally lower intensity precipitation and dry antecedent soil conditions limit surface runoff. Runoff, however, exceeds 10 inches in parts of southeastern Oklahoma and Arkansas where mean annual precipitation exceeds 46 inches and the soils are steeply sloping and have low permeability.

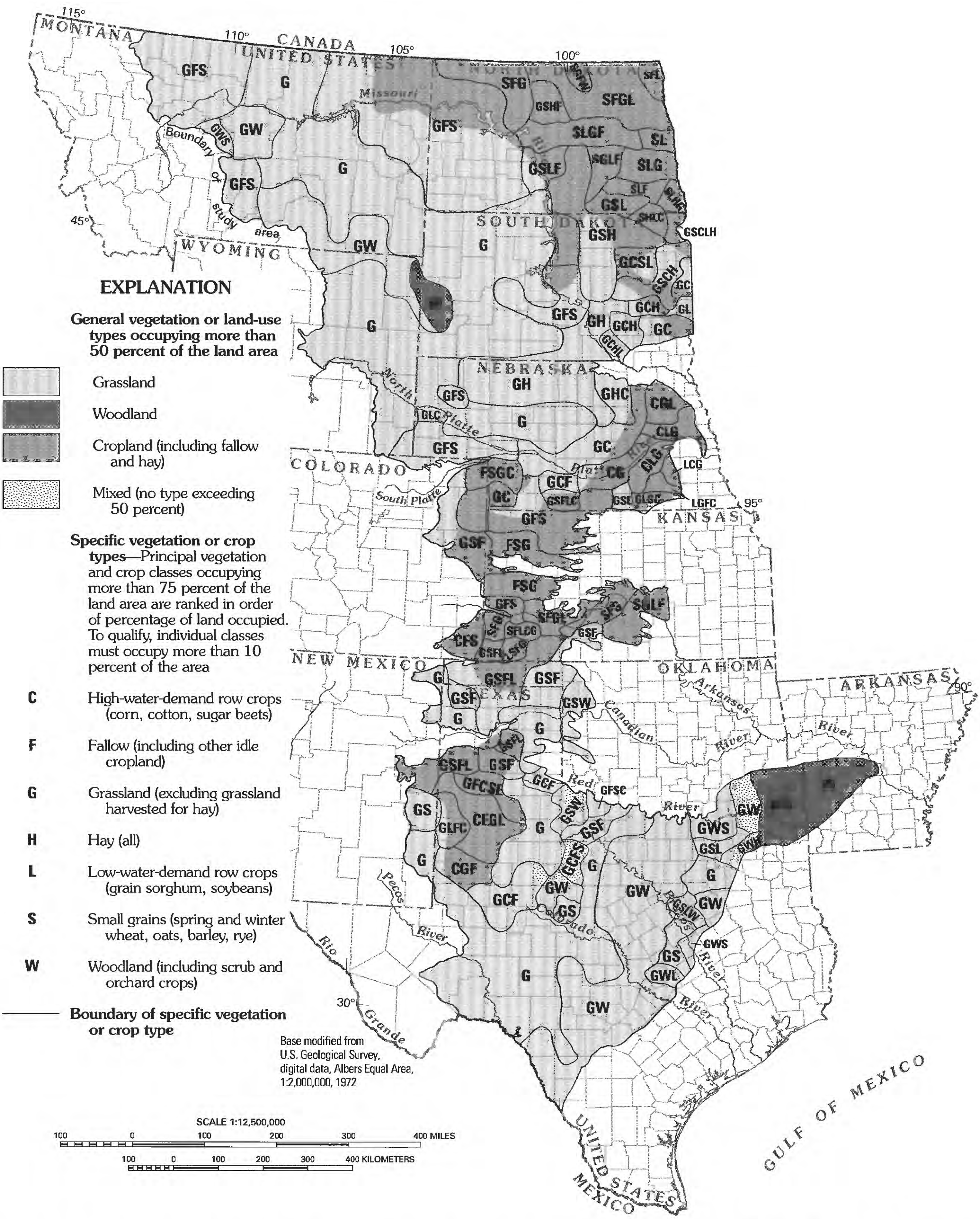


Figure 28. Generalized vegetation and crop types within the study area, 1982 (compiled from Küchler, 1964; U.S. Bureau of the Census, 1984).

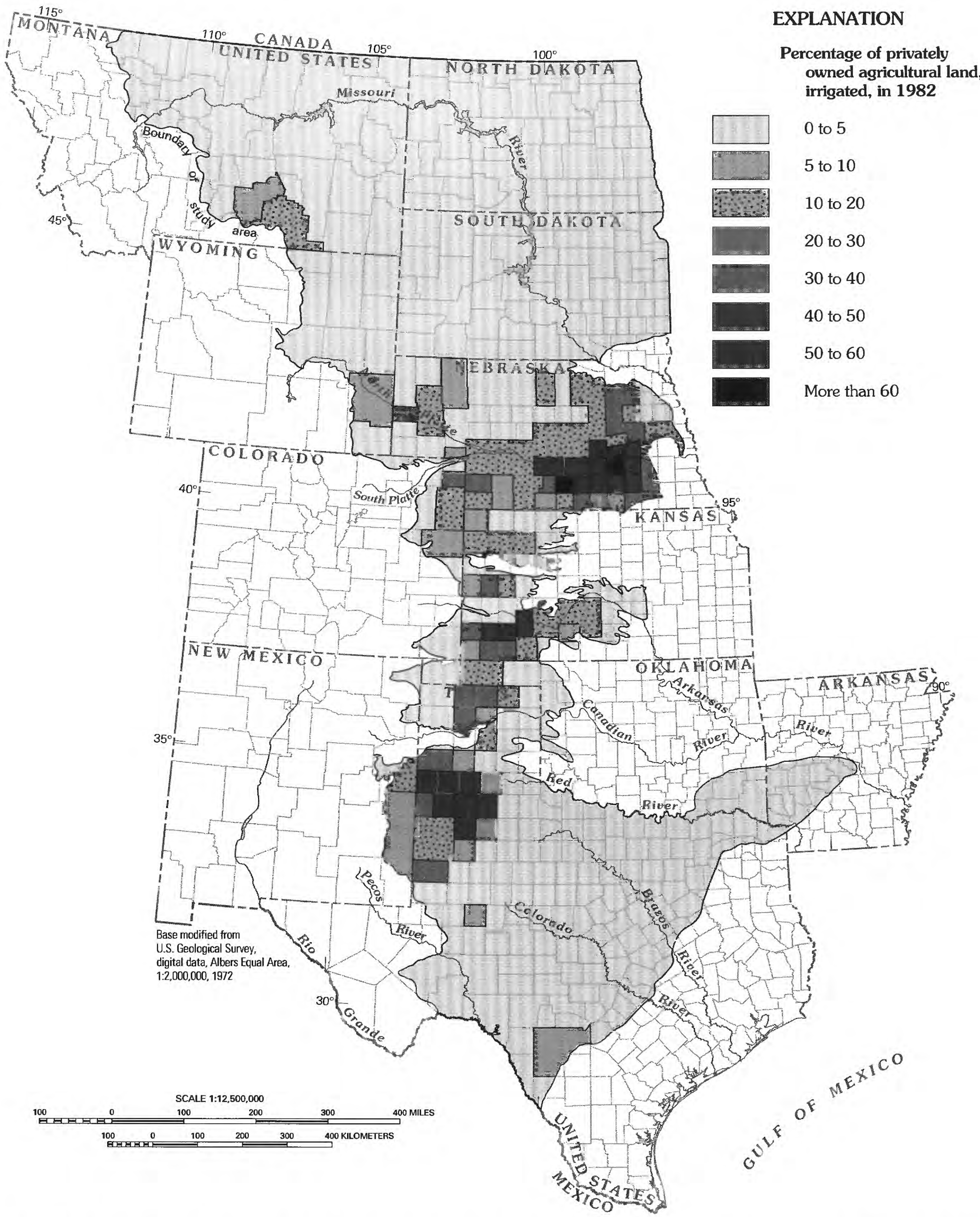


Figure 29. Percentage of privately owned agricultural land that was irrigated in 1982 (compiled from the U.S. Bureau of the Census, 1984).

In the sandy soil areas, normally assigned to infiltration curve 1, runoff is minimal regardless of precipitation quantity. In north-central Nebraska, where the largest continuous areas of sandy soils are found (fig. 26) and mean annual precipitation (fig. 20) ranges from approximately 18 to 24 inches from west to east, simulated runoff is generally less than 0.50 inch annually (fig. 30). Thus, infiltration nearly equals precipitation, which results in high potential ground-water recharge for the given climatic conditions. Almost all streamflow in north-central Nebraska is from ground-water discharge. Streams in this area have relatively uniform discharge throughout the year.

The general patterns of annual infiltration (fig. 31) are defined largely by annual precipitation (fig. 20). Infiltration ranges from less than 12 inches in east-central and northern Montana, east-central Wyoming, western Texas, and eastern New Mexico, where precipitation only slightly exceeds infiltration, to about 46 inches in Arkansas, where precipitation is about 48 inches. Annual infiltration averages from 90 to 95 percent of the average annual precipitation in most of the study area. The effects of soils on patterns of infiltration are not as apparent as they are on runoff (fig. 30). Runoff patterns tend to be defined by local soil conditions. Precipitation patterns, however, obscure most soil effects on infiltration patterns.

Consumptive Water Requirement

CWR is the quantity of water a specific vegetation type will consume if the availability of soil water is not a limiting factor. CWR is a modified form of PET because it is also a measure of energy available for water consumption by plants. However, CWR differs from PET because the seasonal growth patterns of life cycle characteristics of a specific vegetation type (fig. 27) are superimposed on seasonal and spatial patterns of PET.

The CWR in SWASP is calculated by multiplying the monthly PET values at each climatic site by the monthly crop coefficients for each vegetation type (app. A). Different sets of crop coefficients were designated for each subregion to reflect different vegetation types and phenological progression. CWR calculated at each site for each vegetation type in SWASP then was post-processed through a GIS (app. B) to derive continuous patterns of CWR weighted on the basis of vegetation types. CWR shown in figure 32 is for high-water-demand row crops only. CWR weighted by spatial patterns of vegetation types was not suitable for generalized contour mapping.

Comparison of mean annual PET and CWR for high-water-demand row crops (figs. 17 and 32) indicates very similar patterns, although values differ considerably. CWR ranges from about 16 inches in northeastern North Dakota to about 40 inches in an area that includes parts of the Oklahoma and Texas Panhandles and northeastern New Mexico (fig. 32), which are the areas of the lowest and highest PET (26 and 68 inches, respectively). These differences between CWR and PET values in comparable areas result from the seasonal water consumption characteristics specific to the given vegetation type (high-water-demand row crops). CWR for high-water-demand row crops averages about 70 to 75 percent of PET during the growing season but only 15 to 20 percent of PET during the nongrowing season. Water loss to the atmosphere does occur during the nongrowing season even when vegetation is completely dormant but only as basal evapotranspiration (largely direct evaporation losses from the soil).

The abrupt change in CWR at the northern and central subregional boundary (figs. 1 and 32) is caused partly by differences in the crop coefficients assigned to the two subregions (fig. 27 and app. A). Although this abrupt transition is partly a boundary condition, this also is a zone of rapid latitudinal climatic change that includes PET (fig. 17). The much lower PET and subsequent decrease in CWR is partially related to the south-to-north decrease in solar radiation in the northern Great Plains (fig. 5).

CWR demonstrates that PET alone is not a total indicator of regional water consumption. In addition to water consumption and developmental characteristics of specific vegetation, climatic factors that regulate the seasonal growth patterns or phenological characteristics of vegetation also affect regional water consumption. Although the CWR of only one vegetation type, high-water-demand row crops, was shown here, subsequent simulated soil-water characteristics, including AET and potential recharge, account for the effects of vegetation distribution on regional patterns of CWR.

Actual Evapotranspiration

The balance between available soil water and CWR determines the net quantity of soil water consumed, AET. AET reflects the quantity of soil water available to meet the short-term gross water demand

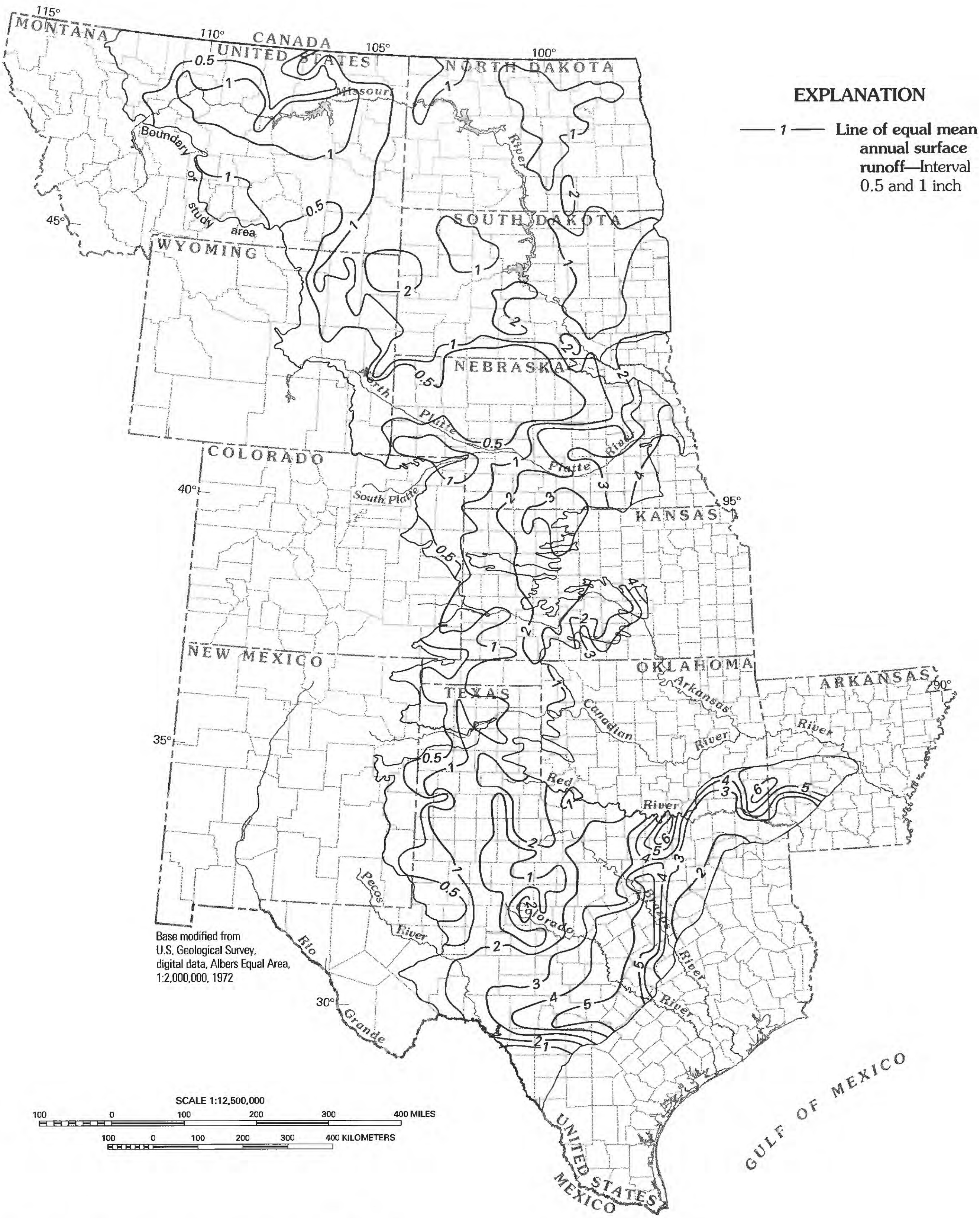


Figure 30. Mean annual overland runoff, 1951–80.

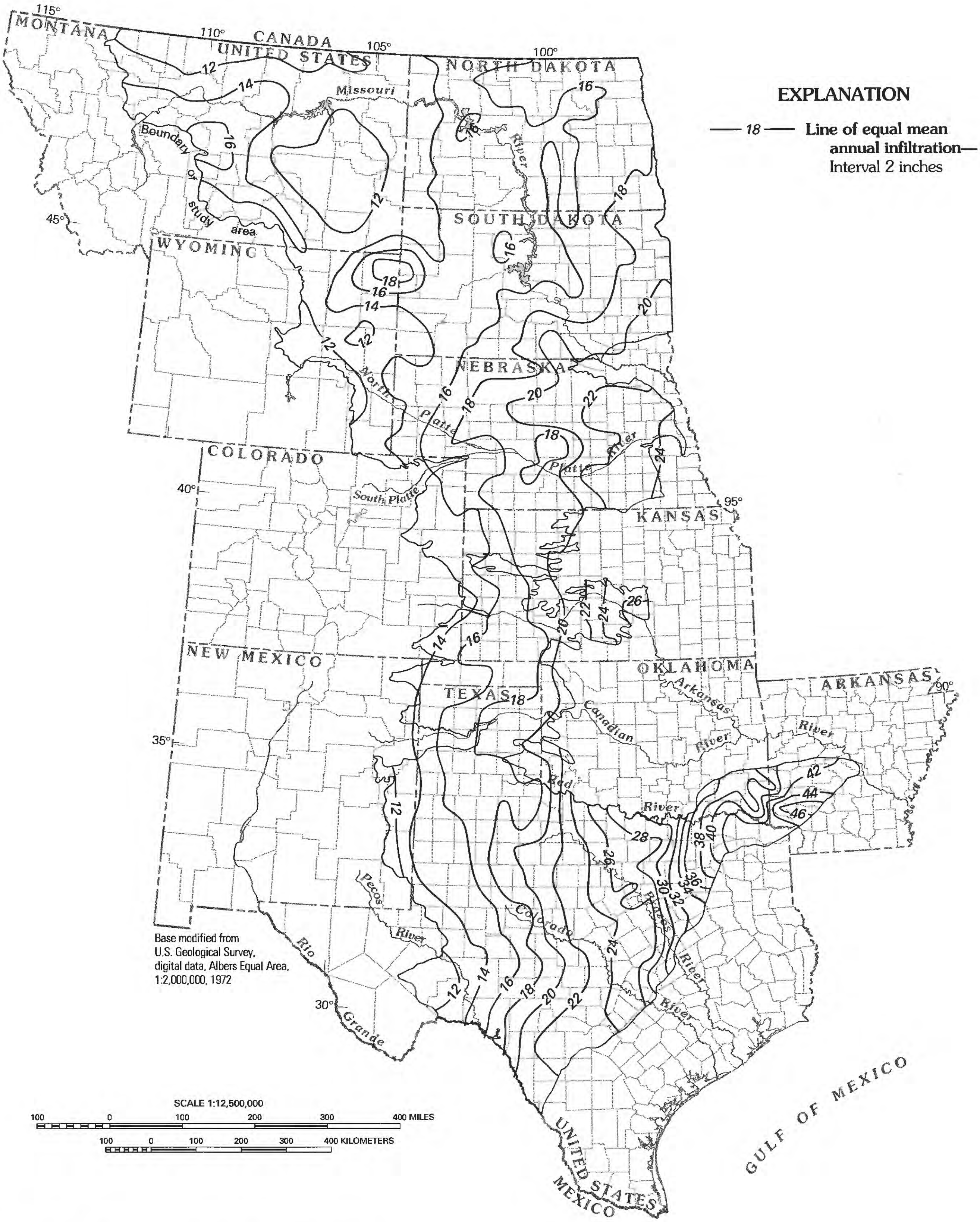


Figure 31. Mean annual infiltration, 1951–80.

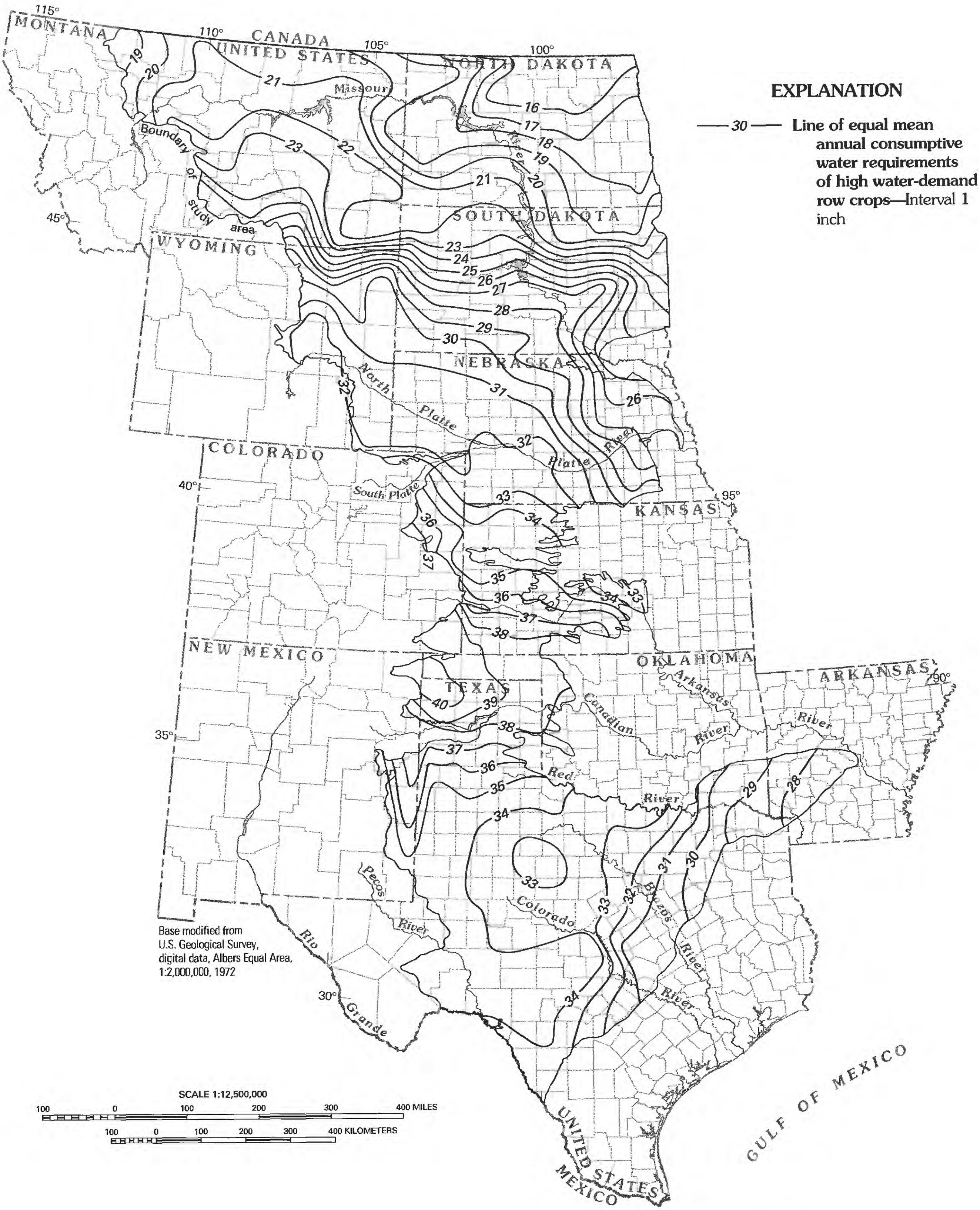


Figure 32. Mean annual consumptive water requirements for high-water-demand row crops, 1951–80.

as measured by CWR. If the soil water available is less than CWR, the shortage is the soil-water deficit (SWD). Conceptually, AET can be expressed in SWASP by the following equation:

$$AET = CWR - SWD, \qquad (2)$$

where SWD = CWR – infiltration.

Equation 2 is incomplete because it applies only to discrete points in time. Infiltration in actual SWASP computations equals AET plus deep percolation for nonirrigated conditions (DPD) over time because at any point in time, if AWC is reached, any excess soil water becomes DPD and is no longer available for AET. Furthermore, the underlying principal relation is that under nonirrigated conditions, long-term AET cannot exceed long-term infiltration. Also, the smaller the water-storage capacity of the soil (AWC times thickness of root zone), the greater the probability and size of the soil-water deficit.

The examination of AET in this report applies to nonirrigated conditions only. Under irrigated conditions, AET would increase by a quantity approximately equal to CIR. AET is computed for all possible soil-vegetation combinations (app. B) and represents the average net water returned to the atmosphere through evapotranspiration under nonirrigated conditions in a given area.

Because available soil water largely limits AET, AET (fig. 33) closely corresponds to infiltration (fig. 31) in most parts of the study area. Mean annual AET ranges from about 11 inches in north-central Montana, where infiltration is less than 12 inches, to more than 34 inches in parts of Arkansas, where infiltration exceeds 42 inches. In the area of the Oklahoma and Texas Panhandles, where annual PET (fig. 17) and CWR (fig. 32) are highest, AET is less than 15 inches as a result of limited infiltration (less than 16 inches). The difference between infiltration and AET is the soil water that is potentially available as recharge, which would be about 1 inch in north-central Montana and the area of the Oklahoma and Texas Panhandles, and about 8 inches in Arkansas.

Deep Percolation for Nonirrigated Conditions

Simulation of the quantity of water available for ground-water recharge is essentially an end product of the soil-water variables simulated in SWASP. SWASP does not compute the actual quantity of water reaching the saturated zone but simulates the volume of water moving beyond the soil-root zone (zone of active evapotranspiration) that becomes potentially available for recharge.

The interpretation of DPD as ground-water recharge is premised on basic assumptions that the immediate underlying aquifer is unconfined and true water-table conditions exist; all water that passes through the root zone into the unsaturated zone ultimately reaches the zone of saturation or water table.

Conceptually, in SWASP, DPD is expressed as:

$$DPD = \text{infiltration} - AET. \qquad (3)$$

However, this equation does not consider antecedent soil water within the soil-root zone. In SWASP, DPD for a specific time period would be:

$$DPD = \text{infiltration} - AET - \text{water storage capacity of the soil } (AWC \times \text{root-zone thickness}). \qquad (4)$$

DPD applies only to nonirrigated conditions; thus, all potential recharge or deep percolation is from precipitation. Under irrigated conditions, soil water in storage is partially derived from applied irrigation water, which affects the resultant soil-water balance.

The simulated spatial patterns of DPD (fig. 34) demonstrate the significance of climate, particularly precipitation, to potential ground-water recharge. Computed values of mean annual DPD range from less than 0.25 inch in much of the semiarid area, where mean annual precipitation (fig. 20) is generally less than 16 inches, to more than 10 inches in areas where mean annual precipitation generally exceeds 42 inches. Area-weighted DPD averages about 1 inch, and large sections of the study area average less than 0.50 inch.

The effect of soils (fig. 26) on DPD is apparent in selected areas. The well-defined extension of the 2-inch contour (fig. 34) westward in north-central Nebraska, and 2-inch outliers in southwestern Nebraska, northeastern Colorado, and southwestern Kansas coincide with areas of sandy soils. Conversely, DPD is less than 0.50 inch in the southeastern Texas Panhandle, where soils are steep and have low permeability (soil 3).

The role of vegetation (fig. 28) in DPD is less apparent in figure 34 because regional vegetation changes are usually gradual. However, under similar precipitation and soils, potential recharge tends to be

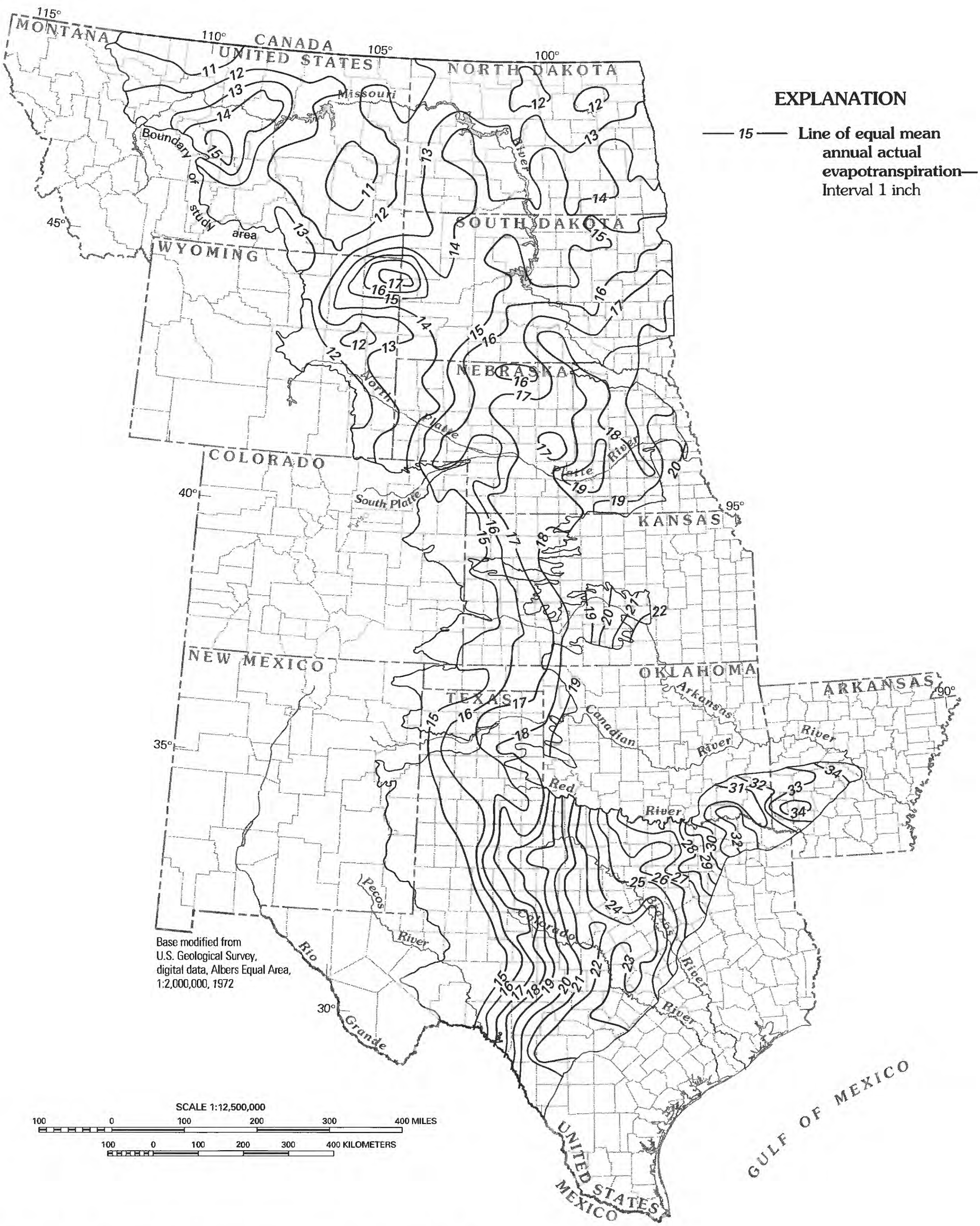


Figure 33. Mean annual actual evapotranspiration, 1951–80.

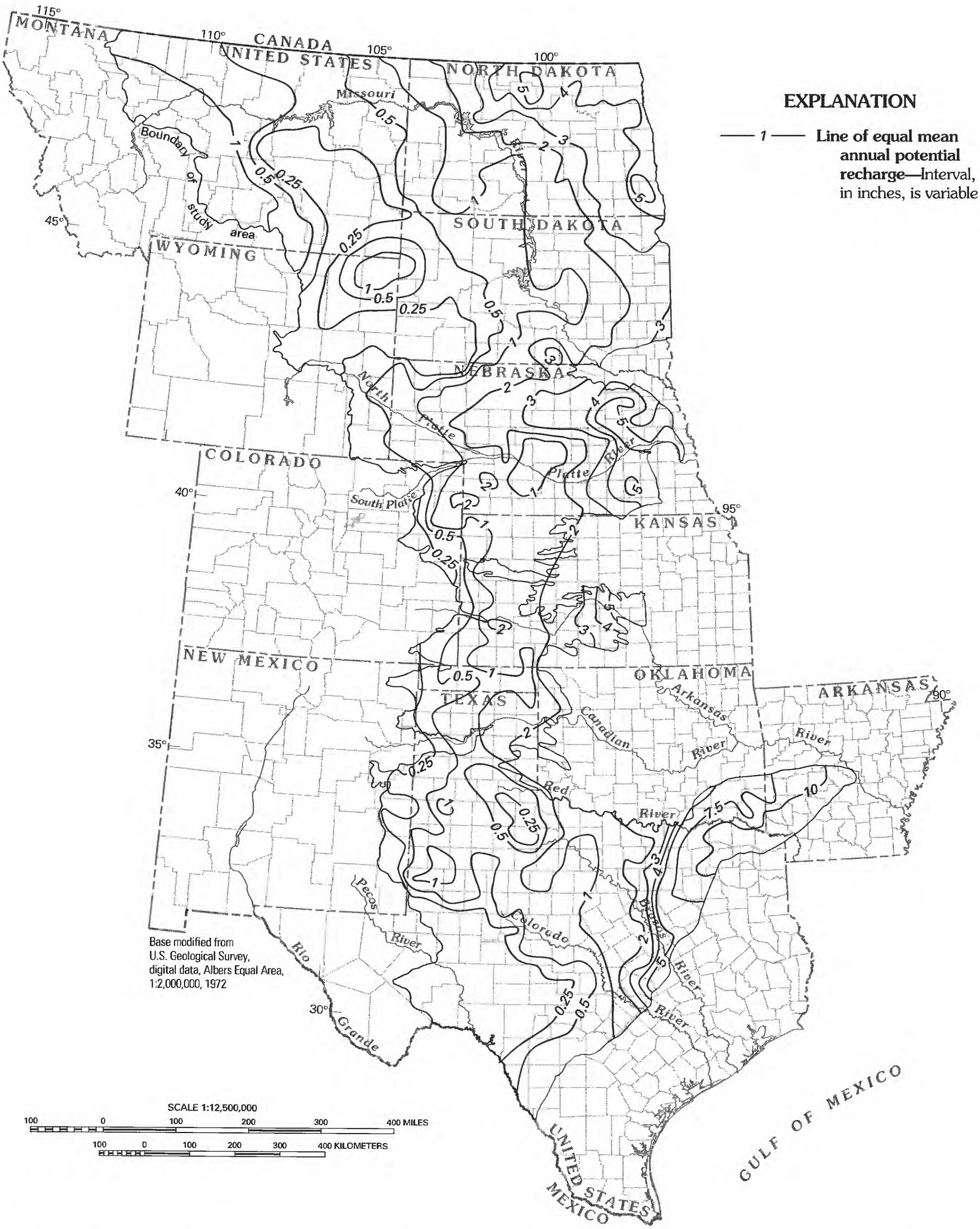


Figure 34. Mean annual potential ground-water recharge or deep percolation under nonirrigated conditions, 1951–80.

larger for cropland than natural vegetation. A large percentage of land is fallow, associated with wheat production in eastern North Dakota, western Kansas, and the southwestern Texas Panhandle, which increases DPD substantially in relation to precipitation in those areas. The large CWR and areal extent of grasslands and their dominance in the western parts of the northern Great Plains and in western and central Texas contribute to less DPD in those areas.

The relative efficiency of precipitation at recharging an underlying aquifer tends to increase as annual precipitation increases. Mean annual DPD as a percentage of mean annual precipitation (fig. 35) ranges from less than 1 percent in parts of southwestern Texas, eastern New Mexico, eastern Wyoming, and southwestern South Dakota, in areas where mean annual precipitation is generally 16 inches or less, to more than 25 percent in parts of the area extending into northeastern Texas and southwestern Arkansas, where mean annual precipitation exceeds 44 inches (fig. 20). Annual precipitation, however, is not the only factor that determines the relative efficiency of precipitation as recharge.

The seasonal distribution of precipitation (figs. 23 and 24) is probably as important as annual precipitation totals for recharge. Potential recharge expressed as DPD (fig. 34), and DPD as a percentage of mean annual precipitation (fig. 35), appear to be closely associated with cool-season precipitation (fig. 23). Small DPD values (less than 0.50 inch, fig. 34) in much of the northern and western parts of the study area are associated with low cool-season precipitation, which is less than 25 percent of the mean annual precipitation in those areas (fig. 20). The area of northeastern Texas extending into Arkansas, with DPD exceeding 10 inches (fig. 34), receives nearly half (more than 20 inches) of its annual precipitation during the cool season (fig. 23).

The percentage of a given quantity of precipitation that is potentially available as recharge is quite variable and dependent on several factors other than precipitation totals and seasonal distribution. DPD percentages can vary substantially as a result of differences in soils and vegetation. Recharge in sandy soil areas (soils 7, 8, and 9, fig. 26) frequently is more than 10 percent of the mean annual precipitation as compared to less than 5 percent for silty and clay soils under similar precipitation regimes. Sandy soils contribute DPD exceeding 25 percent of mean annual precipitation in small areas of eastern North Dakota and northeastern Nebraska. Large areas of fallow land (fig. 28) appear to contribute to increased percentages of recharge in much of eastern and north-central North Dakota and in central and western Kansas.

The effect of PET or CWR is apparent in percentages of potential recharge. The comparatively small PET and CWR values (figs. 17 and 32) in an area extending from northeastern Nebraska to north-central North Dakota contribute to the larger percentages of rechargeable precipitation (fig. 35). In certain parts of southwestern Texas, where mean annual precipitation exceeds 20 inches (fig. 20), potential recharge is less than 1 percent, partly as a result of large PET and CWR values.

Deep Percolation for Irrigated Conditions

DPI tends to be larger than DPD for similar crops and soils. This increase does not result from excess irrigation but from a larger soil-water balance in the root zone at the end of the irrigation season. In SWASP, meeting the CIR of crops requires that the soil-water balance in the root zone be maintained at 50 percent of the AWC of the soil throughout the irrigation season. Maintaining the soil water at 50 percent of capacity throughout the irrigation season normally results in greater carryover in the root zone at the end of the growing season. With increased carryover, a smaller quantity of infiltration of precipitation would be needed following the growing season to saturate the root zone, which would result in a greater soil-water surplus available for deep percolation. A comparison of DPI and DPD for similar soils and crop types at two selected sites is shown in table 3. Although the absolute variations between DPD and DPI are small, the percentage differences can be considerable, particularly when DPD is small. The average percentage difference between DPI and DPD for all soil- and crop-type combinations is 13 percent at Kearney and 24 percent at Holyoke.

The analysis of DPI in this report is confined to those crop types shown in table 3. The values for DPI on figure 36 are weighted toward high-water-demand row crops, which represent about two-thirds of the irrigated cropland in the study area. Irrigation of small grains, largely winter wheat, is substantial in various parts of the study area but is excluded from this analysis because data regarding irrigation of winter wheat are not available.

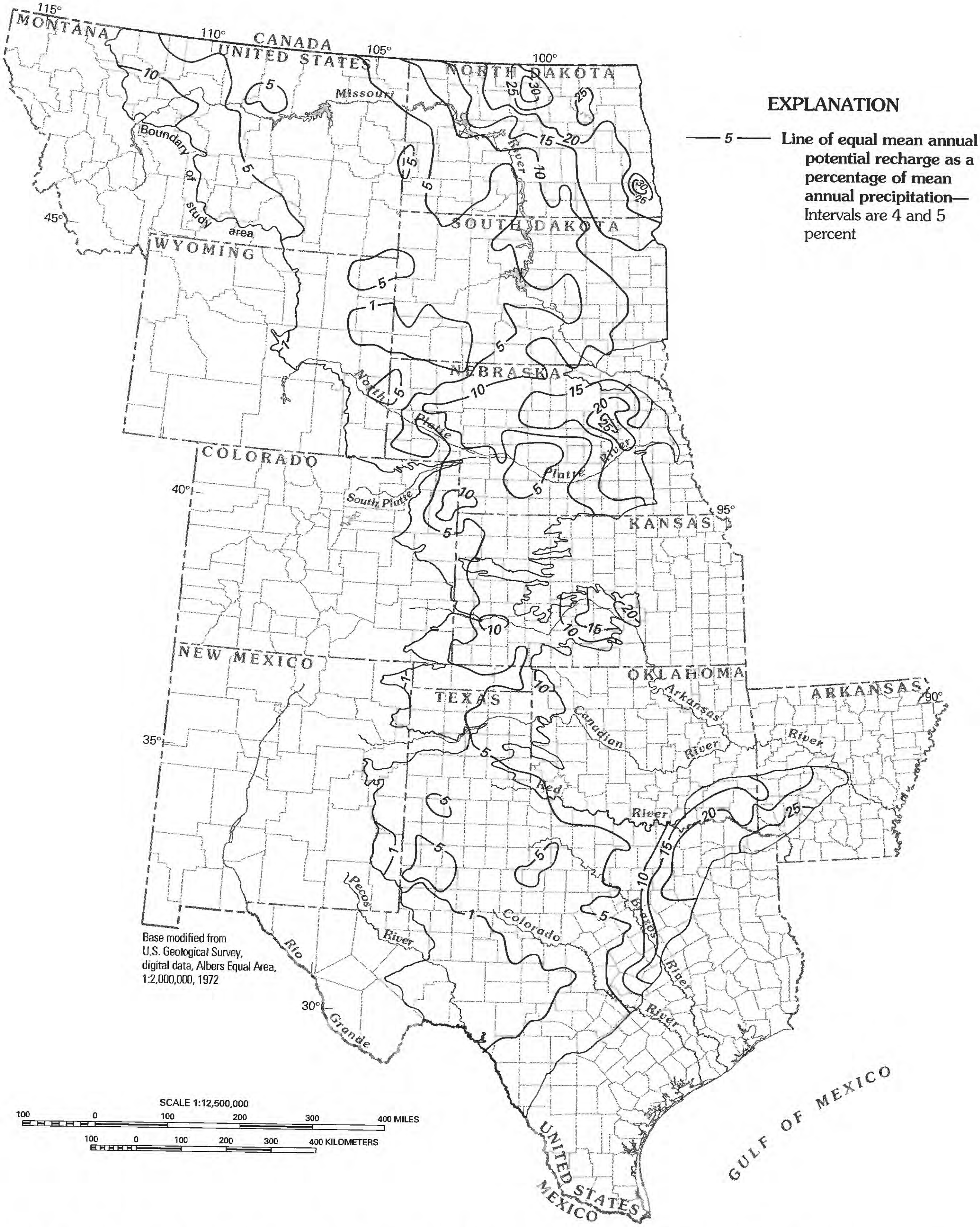


Figure 35. Mean annual potential ground-water recharge or deep percolation under nonirrigated conditions as a percentage of mean annual precipitation, 1951–80.

Table 3. Comparison of deep percolation for irrigated conditions with deep percolation for nonirrigated conditions for selected soils and crop types at Kearney, Nebraska, and Holyoke, Colorado, 1951–80

[Values in inches; DPI, deep percolation for irrigated conditions; DPD, deep percolation for nonirrigated conditions; HRC, high-water-demand row crops (corn and cotton); LRC, low-water-demand row crops (grain sorghum and soybeans). See also fig. 36]

Crop type	Soil 1		Soil 2		Soil 4		Soil 7	
	DPI	DPD	DPI	DPD	DPI	DPD	DPI	DPD
Kearney (mean annual precipitation = 24.52 inches)								
HRC	2.97	2.75	2.66	2.45	4.36	4.17	4.97	4.84
LRC	4.70	4.40	4.23	3.95	6.31	6.03	6.84	6.65
Hay (alfalfa)	.98	.73	.83	.60	1.20	.99	1.62	1.45
Holyoke (mean annual precipitation = 17.63 inches)								
HRC	0.81	0.71	0.70	0.62	1.41	1.29	1.81	1.73
LRC	1.78	1.62	1.51	1.44	2.77	2.61	3.29	3.16
Hay (alfalfa)	.07	.04	.05	.03	.13	.09	.22	.16

DPI is significant to overall potential recharge only where large areas are under irrigation. This area coincides with the High Plains part of the study area, which encompasses nearly all the major irrigated areas (fig. 29). DPI is not strictly comparable to DPD (fig. 34), which represents all vegetation types. However, a useful comparison between potential recharge for all vegetation under nonirrigated conditions and irrigated cropland can be made in given areas.

DPI is greater than DPD throughout most of the High Plains area, except where DPD is large as a result of extensive areas of fallow conditions. Areas where DPI exceeds DPD do not necessarily coincide with a net gain by the underlying aquifer under ground-water-irrigated conditions. This gain, derived from an increase of water in the root zone, is at the expense of ground water in storage. An examination of net fluxes from the water table under irrigated conditions (NFI) clarifies the relation between ground-water irrigation and potential recharge.

In actual ground- and surface-water irrigation practices, the water applied to the soil may substantially exceed the CIR. The soil-water simulations from SWASP, including DPI, however, do not address the disposition of this excess applied water. Some of the excess water may flow into drainage systems or become ponded where it can evaporate; however, most excess water infiltrates the ground and becomes additional soil water. Once excess water becomes additional soil water and the CWR of the crop has already been met, this excess water will move on through the root zone as deep percolation. A large, unmeasured part of the excess pumpage eventually returns to the aquifer. Additional data for both localized site and regional conditions are needed, including actual pumpage and measurement of runoff and ponding and surface evaporation, to accurately determine the rate of return under various soil, vegetation, and climatic conditions.

Deep Percolation for Combined Nonirrigated and Irrigated Conditions

A more comprehensive assessment of potential recharge is provided by DPW, a weighted combination of DPD and DPI (app. A). DPW represents deep percolation more realistically in parts of the study area than DPD alone because the effects of irrigation on the soil-water balance, particularly in areas of intense irrigation development, are included. Except in those areas of substantial irrigation, DPW patterns (fig. 37) are similar to those of DPD (fig. 34).

An assessment of the effects of soils (fig. 26) and vegetation type (fig. 28) on potential recharge is indicated by DPW patterns on figure 37. Soils exhibiting hydrologic properties that are either inhibiting or conducive to potential recharge are clearly evident. Soils 3 and 6, having moderate to low permeability and steep slopes, decrease potential recharge for the given climatic conditions in much of southeastern

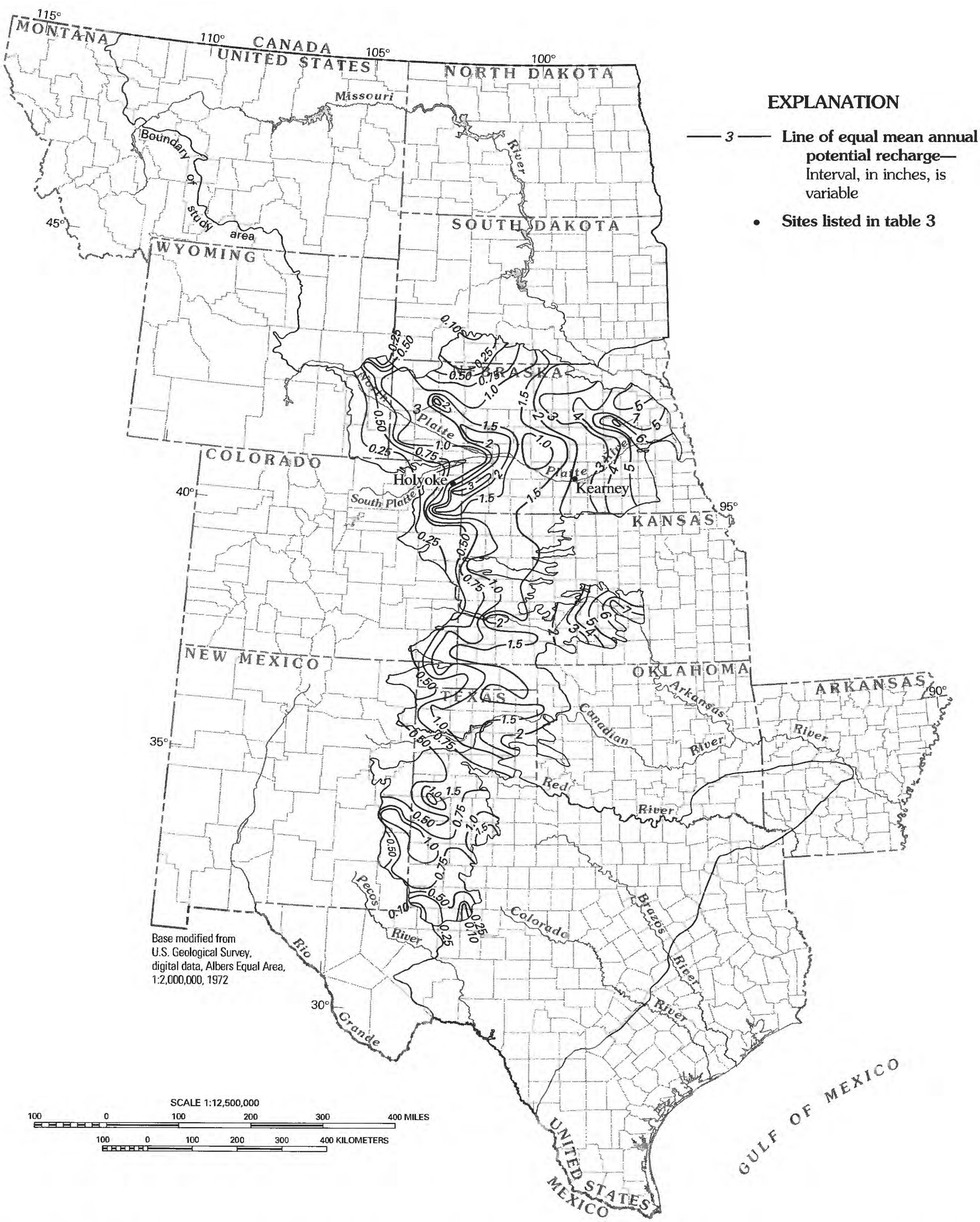


Figure 36. Mean annual potential ground-water recharge or deep percolation weighted for selected irrigated crops in the High Plains area of the Great Plains, 1951–80.

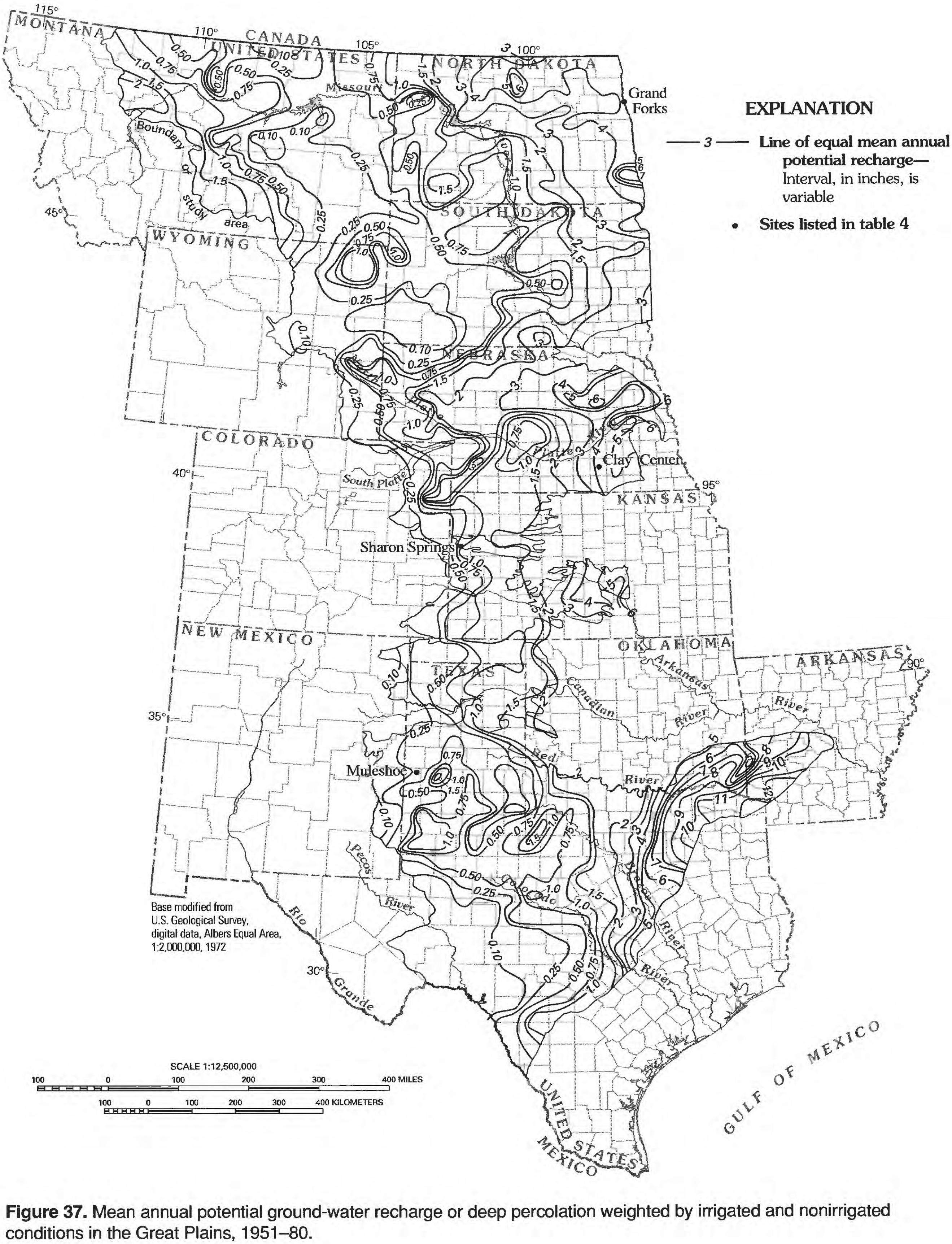


Figure 37. Mean annual potential ground-water recharge or deep percolation weighted by irrigated and nonirrigated conditions in the Great Plains, 1951–80.

Table 4. Comparison of deep percolation for combined nonirrigated and irrigated conditions for actual vegetation with deep percolation for nonirrigated conditions for grassland for soil 1 at selected sites, 1951–80

[DPW, deep percolation for combined nonirrigated and irrigated conditions; DPD, deep percolation for nonirrigated conditions; PET, potential evapotranspiration; SG, small grain; HRC, high-water-demand row crops. See also fig. 37]

Site	Predominant vegetation types	Mean annual precipitation (inches)	Mean annual PET (inches)	DPW mean annual potential recharge (inches)	DPD mean annual potential recharge for grassland (inches)
Grand Forks, North Dakota	Fallow, SG	18.28	28	4.01	1.58
Clay Center, Nebraska	Grassland, HRC	26.68	45	4.30	3.61
Sharon Springs, Kansas	Fallow, SG	18.29	58	.60	.33
Muleshoe, Texas	Fallow, HRC	16.08	68	.28	0

Montana, western North and South Dakota, and central Texas. Sandy soils (soils 7, 8, and 9) are associated with increased potential recharge in north-central and southwestern Nebraska, northeastern Colorado, discontinuous areas of southern Kansas, and parts of western Texas.

The effect of vegetation on potential recharge is not as apparent on figure 37 as is the effect of soil, but considerable differences occur as a result of cultivated agriculture. Areas where cultivated crops are prevalent have greater potential recharge than areas in grassland with similar climatic and soil conditions.

Table 4 compares DPW for actual vegetation or crops at four sites that are in areas predominantly in cultivation with DPD for grassland only at these sites for soil 1. Clay Center, Nebr., and Muleshoe, Tex., represent irrigated cropland and Grand Forks, N. Dak., and Sharon Springs, Kans., represent nonirrigated cropland. All sites show that substantially greater potential recharge occurs under actual cultivated conditions than under grassland conditions alone. Fallow conditions, which are the predominant vegetation or cover type at all sites but Clay Center, tend to increase the differences between the two potential recharge conditions (table 4). The low potential recharge for both conditions at Sharon Springs and Muleshoe, as compared to those at Grand Forks and Clay Center, is a result of the larger PET and, consequently, CWR at these sites.

The various factors that contribute to either high or low rates of potential recharge commonly are interrelated. For example, soils having more gradual slopes and moderate permeability (conditions conducive for greater potential recharge) are also favorable for cultivation of crops, which generally increases potential recharge. Conversely, steeply sloping soils are not suitable for cultivation and remain as grassland or woodland, which are not conducive to higher potential recharge as a result of their large CWR.

Climatic limitations also tend to reinforce certain potential-recharge conditions. Semiarid climates are marginal for cultivated crops because of inadequate precipitation, which results in more area remaining as grassland and in larger regional CWR. However, as precipitation increases in quantity and reliability, cultivated crops become more prevalent, which is more conducive to higher potential recharge.

An examination of soil patterns (fig. 26), vegetation (fig. 28), and DPW (fig. 37) substantiates that factors independently contributing to large or small DPW commonly occur in conjunction with one another. Much of the semiarid part of the study area, principally in the north-central and southwestern Great Plains, is occupied by steeply sloping, slight permeability soils (soil 3). These areas have little precipitation, have large potential runoff, and are more than 90 percent grassland or scrub, all of which contribute to mean annual potential recharge rates of less than 0.25 inch in much of the north-central area and less than 0.10 inch in the southwest (fig. 37).

In the area extending from eastern Nebraska to northeastern North Dakota, all the factors favorable for potential recharge tend to be present. These factors include sufficient precipitation, particularly in the cool season (figs. 20 and 23), low PET, a large percentage of cultivated crops (including considerable fallow land) (fig. 28), gradual slopes for most soils, and substantial areas having moderate to rapidly permeable soils (fig. 26). In this area, except for east-central

South Dakota, potential recharge generally exceeds 3 inches.

The combined effects of soils and vegetation, particularly cultivated crops, on potential-recharge rates can be considerable under certain conditions. If soil 3, a soil having steep slopes and grasslands (not shown) replaced soil 1 and cultivated crops (table 4) at Grand Forks and Clay Center, potential recharge would be much smaller. At Grand Forks, potential recharge for soil 3 and grassland would be 1.58 inches (DPD) compared to 4.01 inches for soil 1 and mostly small grains. At Clay Center, DPD would be 1.82 inches for soil 3 and grassland compared to 4.30 inches for soil 1 and high-water-demand row crops.

Where precipitation exceeds about 40 inches, with nearly half of that occurring in the cool season, the effects of vegetation and soils are secondary. In spite of the relatively larger CWR of woodland vegetation (fig. 26) and large simulated runoff (fig. 30) associated with the steep slopes of soil 6 (fig. 26), potential recharge (DPW) in southeastern Oklahoma and the area extending into Arkansas averages between 5 and 10 inches annually (fig. 37).

Consumptive Irrigation Requirement

CIR provides an estimate of the net quantity of supplemental water needed to meet the water needs of a particular crop during the critical stages of its growth cycle. In SWASP, CIR is a computational product of CWR, AWC, and infiltration during the period immediately before and during the assigned irrigation period (app. A).

Fixed criteria based on antecedent soil-water conditions for given soils, root-zone depths, and crop type are used to determine the timing and quantity of water required during the predetermined irrigation period. Soil water in the assigned root zone is considered to be deficient when it is less than 50 percent of the assigned AWC of the soil. When the 50-percent limit is reached, irrigation occurs until the AWC is reached. If the soil water again decreases to less than 50 percent of the AWC, additional irrigation is required.

With this method of computing CIR, the soil can be maintained at a relatively uniform moisture level for a given AWC, thus minimizing long-term soil-water deficits. CIR is based on monthly soil-water balances, which differ from typical irrigation-scheduling procedures that monitor daily or weekly soil-moisture conditions. CIR is not synonymous with irrigation pumpage, which is the gross quantity of water pumped to meet the requirement. CIR is generally proportional to pumpage, but variability in conveyance losses and efficiencies of water application make comparisons difficult. However, CIR does consider all evapotranspiration losses from the soil under irrigated conditions.

In this report, CIR is presented for only a single crop type, high-water-demand row crops, which is primarily corn or cotton in the study area. A CIR value weighted on the basis of all irrigated crops would not be spatially comparable because of the spatial variability of irrigated crop types. The objective is to provide a regional comparison of CIR based on variable soil and PET patterns under relatively uniform growth and water requirements. The CWR:PET ratios (crop coefficients) and potential length of the irrigation season vary for three subregional model configurations (see app. A).

The CIR of high-water-demand row crops, which account for nearly 65 percent of the irrigated cropland in the study area, averages about 10 percent less than that of hay, principally alfalfa, but about 30 to 40 percent greater than that computed for low-water-demand row crops. CIR for hay would be considerably larger than for high-water-demand row crops if the designated irrigation season were extended to additional months of the growing season for hay. Although wheat is irrigated in the semiarid areas of the central and southern subregions, the soil-water simulations were not configured to yield CIR for winter small grains.

As a result of the combined effects of CWR, precipitation, and soils, CIR of high-water-demand row crops (fig. 38) ranges from less than 4 inches in northeastern North Dakota to more than 21 inches in the Oklahoma and Texas Panhandle area. In the major areas of irrigated high-water-demand row crops, CIR values range from less than 10 to about 15 inches in Nebraska, from 18 to 19 inches in southwestern Kansas, and from 15 to 17 inches in the southern Texas Panhandle. The smaller values of CIR in the northern subregion reflect the assignment of a shorter irrigation season (July and August), smaller CWR, and shallower root zone in June (app. A). The effects of CWR (fig. 32) and warm-season precipitation (fig. 24) on CIR are quite evident. Although CWR represents the total annual water demand for all vegetation, the patterns are similar to those of CIR for high-water-demand row crops.

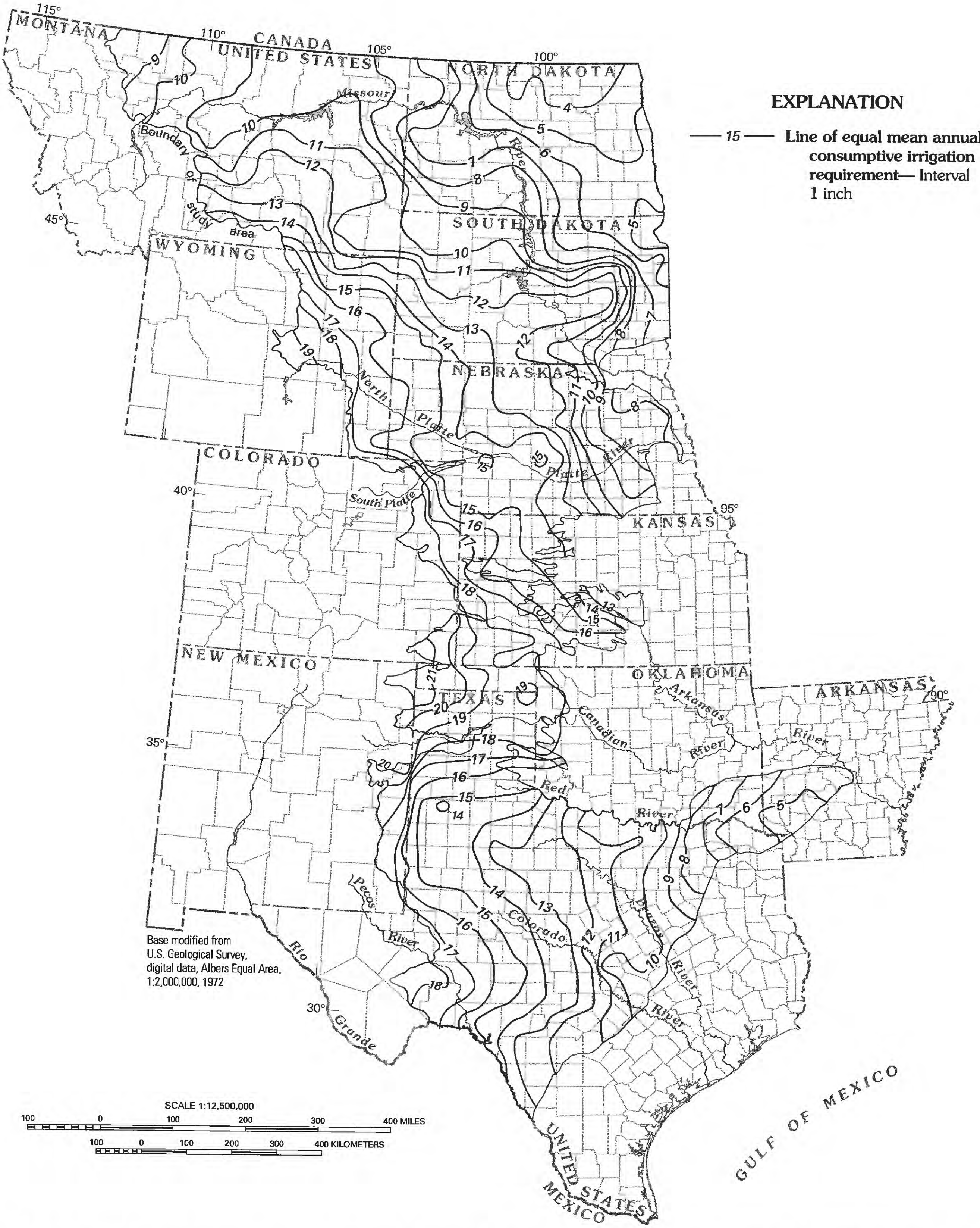


Figure 38. Mean annual consumptive irrigation requirements for high-water-demand row crops in the Great Plains, 1951–80.

Warm-season precipitation (April–September) reflects available moisture during both the antecedent and irrigation periods, whereas figure 39 indicates mean precipitation during the June-through-August irrigation season. Areas having large CWR also tend to be areas of limited growing season and particularly limited irrigation-season precipitation. There is no direct cause-and-effect relation between precipitation and CWR, but these joint tendencies contribute to large CIR in the central subregion of the study area. The west-to-east gradient of June-through-August precipitation (fig. 39) also is evident in the CIR patterns. The effects of the principal hydrologic properties of the soil on CIR—infiltration and AWC—are not readily apparent on figure 38.

Net Fluxes from the Ground-Water System Under Irrigated Conditions

In areas of extensive irrigation development, the long-term availability of ground water depends on the relation between net ground-water withdrawals and recharge. Development of ground-water models for simulating future changes requires accurate estimates of these net fluxes to or from the ground-water system. In this study, the relation between CIR and DPW provides an approximate estimation of these net fluxes.

Net flux (NFI) in this application is the rate that water is removed from ground-water storage to fulfill the CIR in relation to the rate of potential recharge as measured by DPW, or:

$$NFI = CIR - DPW. \quad (5)$$

A principal assumption of this equation is that CIR represents the total loss or withdrawal from the underlying ground-water system; any pumpage or withdrawal in excess of CIR is returned to the aquifer. As indicated previously, runoff or evaporation (in addition to evapotranspiration losses already computed in SWASP for the soil water) of excess pumpage that may occur is not considered.

The analysis of NFI in the study area is confined to the High Plains where ground-water irrigation development occurs in several large, continuous areas. The average annual net flux on irrigated lands is approximately 14 inches and ranges from less than 2 inches in parts of northeastern Nebraska to more than 21 inches in southeastern Colorado and northeastern New Mexico (fig. 40). Small NFI values (less than 6–7 inches) occur in areas of sandy soils in northeastern Nebraska where mean annual precipitation exceeds 25 inches, with 10 inches or more occurring during the irrigation season (June–August). Large potential recharge rates often occur in areas of small CIR, although there is not necessarily a causal relation. Conversely, small potential recharge rates often accompany large CIR, which result in large net fluxes.

NFI reflects only the mean annual net demand on underlying ground-water resources under irrigated conditions, not resultant water-level changes. The effect upon water levels and saturated thicknesses of underlying aquifers is beyond the scope of this study. Studies conducted as part of the High Plains RASA, however, provide useful comparisons. Gutentag and others (1984) examined previous effects of ground-water pumpage on the High Plains aquifer. Luckey and others (1988) simulated future aquifer changes for the same area using various irrigation-development conditions.

Substantial water-level declines occurred in those areas of intensive irrigation development and large NFI. Declines greater than 50 feet from predevelopment to 1980 occurred in parts of southwestern Kansas and the Texas Panhandle (Gutentag and others, 1984) where 30 to 60 percent of the farmland is irrigated (fig. 29) and NFI exceeds 15 inches. Additional declines exceeding 15 feet occurred in these areas from 1980 to 1990 (Dugan and Schild, 1992). Another area of intensive irrigation development, southeastern Nebraska, has had only a few small areas where water-level declines have exceeded 20 feet from predevelopment to 1990 (Steele and Wigley, 1991). These smaller declines in southeastern Nebraska are probably related to smaller NFI, 5 to 12 inches.

Simulated water-level declines as large as 200 feet between 1980 and 2020 in parts of southwestern Kansas and the northern Texas Panhandle by Luckey and others (1988) correspond to annual NFI of 16 to 20 inches. Similar declines projected for parts of eastern Nebraska, however, do not correspond well with a NFI that averages only about 5 inches annually in this area. The methods used by Luckey and others (1988) to compute fluxes or pumpage are substantially different from those used to compute NFI, which may account for the difference.

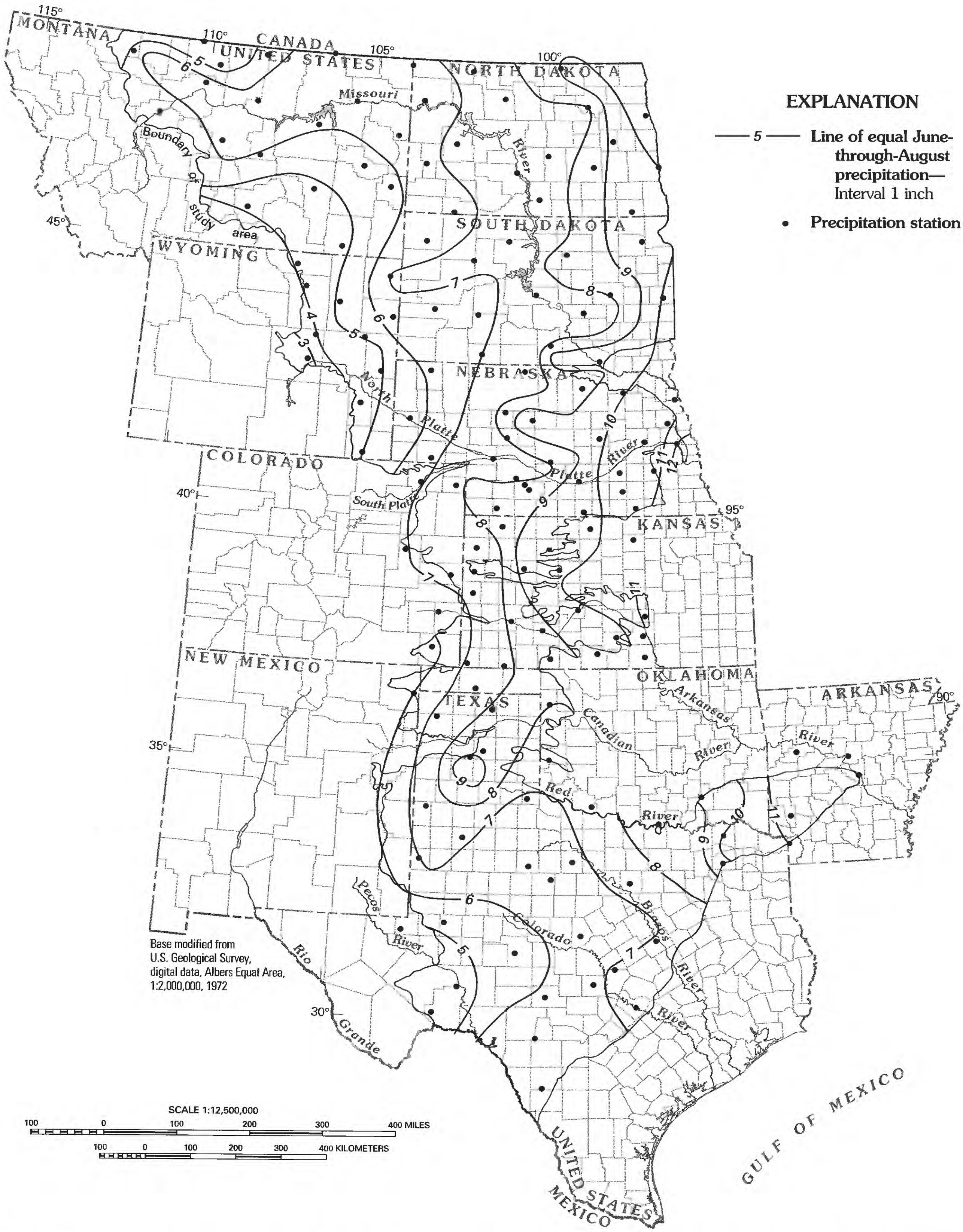


Figure 39. Mean irrigation-season (June–August) precipitation, 1951–80 (compiled from data provided by the National Climatic Data Center, Asheville, N.C.).

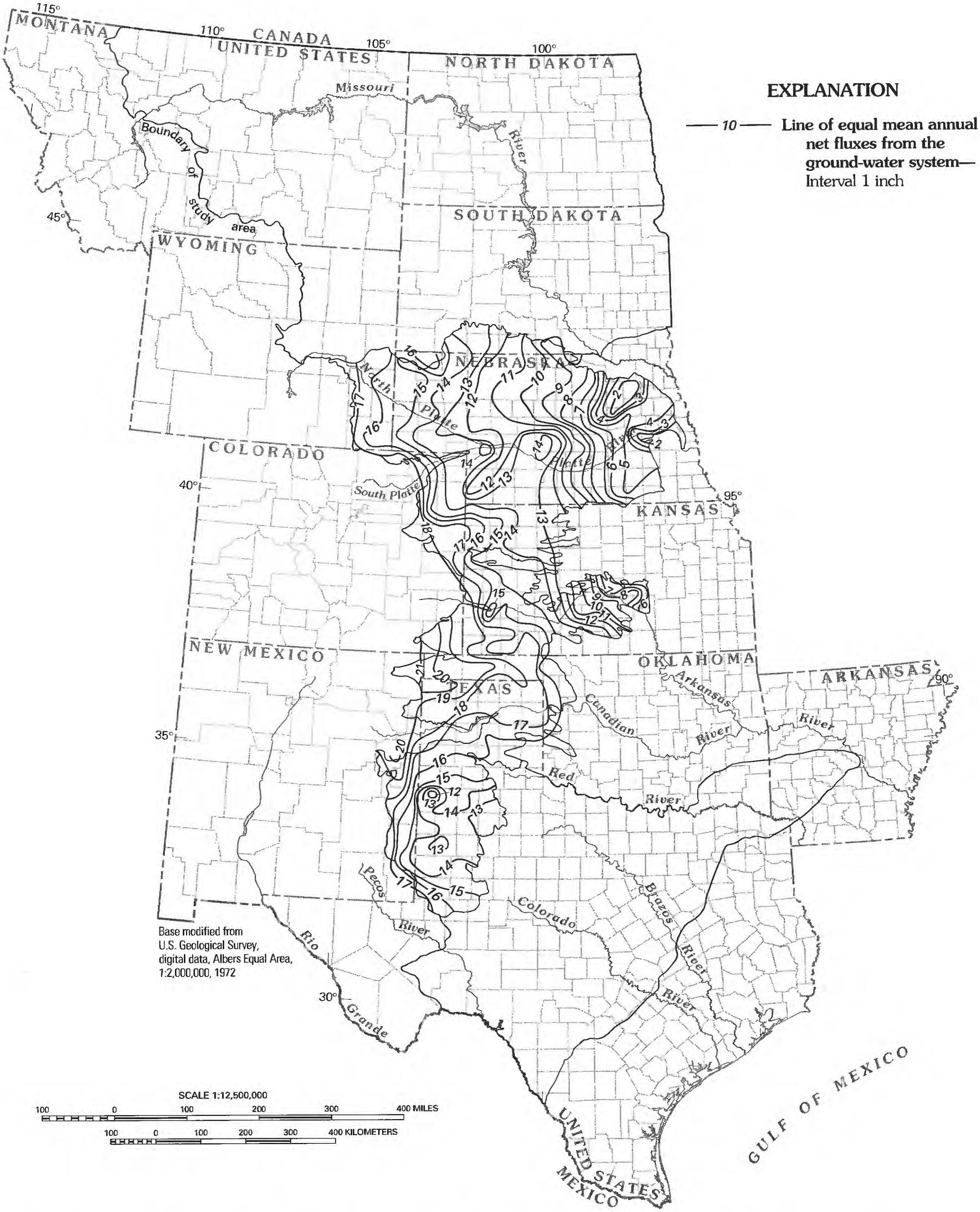


Figure 40. Mean annual net fluxes from the ground-water system under irrigated conditions in the High Plains area of the Great Plains, 1951–80.

Limitations of Simulation Program

Certain soil and topographic conditions limit the interpretations of the soil-water simulations from SWASP. In areas where these conditions are limiting, interpretations of the simulation results are not necessarily invalid but must be qualified.

Thin soils that are developed on subsurfaces that restrict complete root development may have root zones that fail to meet the criteria of SWASP. SWASP requires a root zone that ranges from 15 to 48 inches, depending on the season and vegetation type (app. A). If the actual root zone is less than the minimum root zone required by the vegetation type, then soil-water simulations from SWASP are not applicable, because the calculated soil-water content of the soil would exceed the actual total storage capacity. Substantial parts of the Great Plains and adjacent areas have soils that are less than 60 inches thick (fig. 3). These soils generally are on steep slopes (soils 3 and 6, fig. 26) that have been severely eroded. In a few cases, these soils have developed on less steep slopes on weathered bedrock (soil 2). Typically, the bedrock underlying soil 2 is resistant to weathering and relatively impervious to water movement.

The soils in figure 3 that do not actually meet the root-zone thickness criteria in SWASP cannot be differentiated. Therefore, soil-water conditions were simulated and mapped in these areas as though no thickness limitation existed. Simulation results are valid only for those soils that meet the minimum-thickness requirement for the seasonal root zone of the designated vegetation type in SWASP.

Topographic limitations imposed by the mountainous topography in the study area are closely associated with soil-thickness limitations. Steeply sloping topography generally results in soils that are very thin or absent, which would not meet root-zone thickness criteria in SWASP. The ability to simulate infiltration of precipitation and represent climatic conditions in these mountain areas also is severely restricted. Equations used to estimate infiltration (fig. 25 and app. A) were not developed for the extremely steep slopes and soils in mountainous terrain. The spatial complexity of precipitation and PET in these areas, resulting from the topographic relief and altitude differences, could not be represented with available data.

Simulation and mapping procedures followed in the mountain areas differ from those applied to thin soil areas. No soil-water simulations were made in the mountain areas, and values simulated in the surrounding lowlands were interpolated across them as if the mountains were not present. The relatively small size of most of these mountain areas permitted this interpolation. The assumptions are that these mountain areas have a minimal effect on soil-water conditions in the surrounding lowlands and that, if the mountain areas were not present, conditions in these areas would approximate those of the surrounding lowlands.

SUMMARY

An aspect of ground-water hydrology that often is given limited consideration is the effect of the extrinsic environment on the ground-water system. This environment, which includes climate, soils, and vegetation, largely determines the quantity of soil water available for ground-water recharge and the quantity of water needed for irrigation. The report describes the results of an analysis of long-term potential ground-water recharge and consumptive irrigation requirements (CIR) in the Great Plains and adjacent areas using soil-water simulations. In addition, the report provides a detailed examination of the characteristics of the extrinsic environment in the study area.

A computer program, SWASP, simulates the soil-water balance from selected elements representing the extrinsic environment. The soil-water characteristics derived from simulation, including potential recharge and CIR, are completely independent of underlying hydrogeologic conditions. The geographic extent of the study area and the distinct climatic transition associated with its midlatitude location contribute to the diversity in the various elements representing the extrinsic environment. Large differences in climate, soils, and vegetation, including crops, make the study area suitable for a regional analysis of long-term soil-water conditions.

The energy-balance component of the climate, represented by solar radiation, temperature, and potential evapotranspiration (PET), largely determines the evapotranspiration demands on available soil water. Generally well-defined northeast-to-southwest gradients exist among these energy-balance characteristics. Mean annual PET ranges from about 26 inches in northeastern North Dakota to about 68 inches in eastern New Mexico. Regional contrasts in PET are even greater during the cool season (October through March) and range from about 2 inches in northeastern North Dakota to about 20 inches in Texas.

Precipitation, the principal source of soil water for plant requirements and potential recharge, is variable geographically and seasonally throughout the study area. The quantity and seasonal distribution of precipitation affect soil-water characteristics. Potential recharge is largely dependent on cool-season precipitation, but irrigation needs are largely determined by warm-season precipitation (April–September).

Mean annual precipitation ranges from about 10 inches in north-central Montana to about 48 inches in central Arkansas. About 75 percent of the annual precipitation occurs during the warm season in most of the study area, except in Arkansas, where nearly 50 percent, or more than 20 inches, occurs in the cool season. Precipitation variability tends to increase as mean annual precipitation decreases. Cool-season precipitation varies considerably from year to year in the drier western parts of the study area.

Soil variations under similar climatic conditions can have a substantial effect on the soil-water balance. The hydrologic characteristics of the soil, including slope, permeability, and available water capacity (AWC), affect infiltration and the water-storage capacity of the soil. Sandy soils tend to have a much larger potential recharge rate than finer textured soils because of greater permeability and a smaller AWC. Large parts of the study area are covered by soils of low permeability (clay and silt) on steep slopes that tend to have smaller potential recharge because of less infiltration (more runoff) and increased water-storage capacity (larger AWC).

The soil-water balance varies substantially for different vegetation types. The distinctive growth characteristics of each vegetation type cause different seasonal consumptive water requirements (CWR) and root-zone thicknesses. Grassland, the dominant vegetation in the study area, has substantially larger annual CWR than most cultivated crops. Potential recharge tends to be greater in many areas under extensive cultivation as a result of smaller CWR of crops and larger percentages of fallow land.

Various soil-water characteristics were simulated by SWASP or derived through post-processing procedures. Among those characteristics were runoff, infiltration, consumptive water requirements (CWR), actual evapotranspiration (AET), deep percolation for nonirrigated conditions (DPD), deep percolation for irrigated conditions (DPI), potential recharge for combined nonirrigated and irrigated conditions (DPW), consumptive irrigation requirements (CIR), and net fluxes under irrigated conditions (NFI). Mapping of these soil-water characteristics in the study area was performed through a geographic information system (GIS).

Simulated runoff and infiltration closely reflect precipitation and soil factors. Runoff ranges from about 0.50 inch in the drier western part of the study area to more than 10 inches in southeastern Oklahoma and Arkansas, with most of the study area averaging from 1 to 3 inches. Infiltration generally averages from 90 to 95 percent of the annual precipitation in most of the study area.

CWR and AET, which are measures of water demand, vary considerably across the study area. Mean annual CWR for high-water-demand crops ranges from 16 inches in northeastern North Dakota to about 40 inches in an area that includes the extreme northwestern Texas Panhandle. Mean annual AET closely reflects soil-water availability and ranges from about 11 inches in north-central Montana to about 34 inches in parts of Arkansas.

DPD, a measurement of potential recharge under nonirrigated conditions, ranges from about 0.25 inch annually in much of the drier western areas to about 10 inches in part of Texas and Arkansas. The area-weighted average annual DPD for the study area is about 1 inch. Although CWR and precipitation appear to govern the general patterns of DPD, certain soil and vegetation conditions are evident locally. DPD substantially increases under sandy soil conditions, such as those that occur in north-central Nebraska, because of increased infiltration and smaller AWC. Areas of extensive cultivation, such as in eastern North Dakota, eastern Nebraska, western Kansas, and the southwestern Texas Panhandle, also show increases in potential recharge because of smaller overall CWR.

DPD, expressed as a percentage of mean annual precipitation, ranges from about 1 percent in several areas of the drier western part of the study area to about 25 percent in parts of eastern North Dakota and in Texas and Arkansas. Very large or very small percentages in given areas tend to show the effects of certain soil and vegetation types.

DPI, a measurement of potential recharge under irrigated conditions, generally is larger than DPD for comparable crops because methods of calculation provide for increased carryover of soil water at the end of the growing season. DPW provides a more realistic assessment of potential recharge in the study area than

DPD by averaging DPD and DPI in irrigated areas. In nonirrigated areas, DPW is identical to DPD; however, in intensively irrigated areas, such as south-central Nebraska and the southern Texas Panhandle, DPW is considerably larger than DPD.

CIR provides an estimate of minimum irrigation requirements and closely reflects CWR and warm-season precipitation. In the study area, CIR for high-water-demand row crops ranges from about 4 inches in northeastern North Dakota to about 21 inches in the Oklahoma and Texas Panhandles. Among the areas of intensive irrigation, CIR ranges from about 10 to 15 inches in Nebraska, from 18 to 19 inches in southwestern Kansas, and from 15 to 17 inches in the southern Texas Panhandle.

NFI, which was computed by subtracting DPW from CIR, provides an estimate of net losses or gains from the ground-water system in irrigated areas. NFI ranges from about 2 inches in parts of northeastern Nebraska to more than 21 inches in southeastern Colorado and northeastern New Mexico.

SWASP is not well suited for mountainous terrain or areas where soil thicknesses are less than the required minimum root zone. Restricted interpretation of simulation results was necessary in those parts of the study area where these environmental limitations were present.

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APPENDIXES A AND B

APPENDIX A. SOIL-WATER SIMULATION PROGRAM (SWASP)

The principal analytical tool of this study is the soil-water simulation program, SWASP, briefly described in the section on methods. Because of the variety of data and numerous operational steps required for the implementation of this program, the procedures and actual program setups are placed in this section. The actual documentation and verification of SWASP is outlined here to provide continuity and a more thorough understanding of the methodology as applied to this study. The results from the soil-water program are the product of several programs or subroutines executed in sequence. These include the programs PET and SWASP and a major subroutine within PET, SOLARR, that computes total radiation.

PET Program and SOLARR Subroutine

Potential evapotranspiration (PET) is a theoretical measure of the energy available for evapotranspiration and must be simulated from other climatic data, including solar radiation, temperature, and humidity. A modified Jensen-Haise energy-balance approximation method of computing PET (Jensen and others, 1970; Cady and Peckenpaugh, 1985) is used with SWASP.

The basic variables in the Jensen-Haise equation are (1) monthly mean daily solar radiation (langleys or inches of evaporation equivalent), (2) mean monthly temperature (degrees Fahrenheit), (3) mean July maximum and minimum temperature (degrees Fahrenheit), and (4) altitude (feet). Values of the last three variables are readily available from published data. The key variable in the Jensen-Haise equation, solar radiation, is available for the period of study at only a few sites in or near the study area. A subroutine within the PET program, SOLARR, computed solar-radiation values at 68 sites and temperature data with the following linear equation derived from multiple regression:

$$SR = 37.74570 \times DL + 253.7580 \times PSS + 3.55281 \times AI + 0.005655 \times ALT - 411.410, \quad (A1)$$

where

- SR = calculated monthly mean daily solar radiation, in langleys,
- DL = mean monthly day length, in hours,
- PSS = monthly percent of possible sunshine,
- AI = mean monthly angle of solar incidence, in degrees,
- ALT = altitude of site, in feet above sea level, and
- -441.410 = constant or intercept.

The sources of data for the independent variables are as follows:

(1) *DL*, by latitude, is available from various astronomical tables and was interpolated for each of the 68 sites in the study area.

(2) *PSS*, monthly percent of possible sunshine for 1951–80, is available for 28 sites in and around the study area from U.S. Department of Commerce, National Climatic Data Center (1951–80). A separate linear interpolation computer program, based on a simple distance-decay function, was used to estimate values at the 68 sites.

(3) *AI* was computed at each of the 68 sites with a separate computer program that interpolates daily solar-aspect or angle for each site on the basis of latitude for the middle of each month.

(4) *ALT* was obtained from U.S. Department of Commerce, National Climatic Data Center (1951–80).

The basic equation in SOLARR used to derive *SR* was based on solar radiation (682 observations) from eight sites in or near the study area. The multiple-regression analysis that derived the *SR* equation had a coefficient of explanation (R^2) of 0.94. The advantage of estimating solar radiation by this method is that it can be computed for any location with readily available data.

Output from the PET program consists of monthly PET values and mean monthly temperatures for 1951 through 1980 for the 68 sites. These values serve as direct inputs to SWASP.

Data Requirements and Program Variables for SWASP

The version of SWASP implemented in this study is modified from Cady and Peckenpaugh (1985) and Peckenpaugh and others (1987). Among the modifications are (1) more flexible input and output specifications, (2) additional options for irrigation or pumpage, (3) refined infiltration coefficients and computational methods, (4) revised crop coefficients, and (5) addition of seasonally variable root-zone depths.

In addition to the site-specific climatic input, which includes monthly PET, temperature, and precipitation, SWASP requires setting various programming variables that specify the parameters for a given simulation. These programming variables typically set the initial physical boundaries of the calculation of the soil-water balance. Calibration of SWASP is accomplished through modification of these programming variables. The programming variables are shown below in the SWASP program setups for the three subregions. The programming variables are—

(1) Irrigation threshold as proportion of the available water capacity (AWC) of the soil (FHCAP). This variable affects both the consumptive irrigation requirement (CIR) and recharge under irrigated conditions by predetermining at what point soil water must be depleted before irrigation is required. In all simulations for this study, FHCAP was set at 50 percent of AWC, an average value used in irrigation scheduling.

(2) Initial soil-water content at the beginning of simulation as a proportion of the AWC of the soil (FSMDP). In this study, FSMDP was 25 percent for each simulation. This parameter normally has minimal effect on long-term simulations but can be modified on the basis of known antecedent soil-water conditions.

(3) Length of irrigation season in months (monthly irrigation option). This variable restricts irrigation application to those months selected. Normally, it is based on the irrigation period of the principal irrigated crops of the region and has a significant effect on total seasonal or annual CIR.

(4) Infiltration-curve coefficients. This variable defines the equations that determine the amount of monthly precipitation permitted to infiltrate the soil and become available to meet CWR and provide soil water for potential ground-water recharge. This variable also determines the quantity of monthly precipitation that is surface runoff and not available as soil water.

Selection of the correct infiltration curve or equation, based on soil, topography, vegetative cover, and soil-conservation practices, is critical to estimating the potential water available within the soil system (see fig. 25). Infiltration-curve coefficients are essentially fixed, having been precisely developed from observed basin conditions; therefore, they should not be modified. Adjustments are best accomplished by selecting different curve numbers for given soil, vegetative cover, and topographic conditions.

(5) Crop coefficients. This variable, more properly termed CWR:PET ratio, determines monthly consumptive water requirements (CWR) or the rate at which a certain plant or crop type could potentially consume water as a proportion of the computed monthly PET. The variable is based on the growth and phenological characteristics of the plant under various climatic conditions. These coefficients are specifically derived to fit only PET values generated by the Jensen-Haise PET method.

Different sets of crop coefficients (see fig. 27) were developed for each of the three subregions from published data for various plant types (U.S. Soil Conservation Service, 1967; Stegman and others, 1977; Wright, 1982) and adjusted to reflect average regional phenological conditions. A basal coefficient of 0.150 or 0.200 was used to account for possible evaporation from the soil during normal dormancy periods of the various vegetation types (Wright, 1982). CIR and potential recharge are sensitive to modification of crop coefficients.

The crop coefficients represent general vegetation groups and not necessarily individual plant types. Because of computing and logistical limitations, the numerous plant types in the study area were categorized into the seven generalized vegetation groups evident in the subregional program setups shown in figure 27. Grouping of individual crop or plant types was based on their similar growth and phenological characteristics; therefore, they have comparable CWR (U.S. Soil Conservation Service, 1967). Coefficients, however, were computed largely on the basis of principal crop or plant types for which sufficient data were available. The seven generalized vegetation groups and the principal plant or crop types are listed in table A1.

Table A1 is not all inclusive but accounts for nearly all vegetation and crop types throughout the study area. Miscellaneous or minor crops were grouped in the appropriate vegetation type according to available data on their growth characteristics (Wilsie, 1962; U.S. Soil Conservation Service, 1967).

(6) Monthly effective root-zone depth by vegetation type. This variable determines the soil depth from which plants can extract soil water in a given month to meet evapotranspiration requirements. This variable modifies only the soil zone from which these requirements can be fulfilled, not the CWR of a plant. The effective soil-water extraction zone of a given plant type is based on its seasonal root development and is a reflection of its growth stage.

Seasonal root-development data for a large number of crop types are not readily available; therefore, the values were determined from a variety of sources and adjusted for regional phenological variations (Mitchell, 1970; Stegman and others, 1977). These root-zone values do not necessarily represent the maximum depth that roots can develop but rather represent the average-weighted depth at which all available soil water can be extracted by the given plant and consumed in the evapotranspiration process. Normally, a basal value of 15 inches was selected for both dormant-season and fallow conditions and reflects the maximum depth at which direct evaporation from the soil normally occurs.

(7) AWC by soil type. This variable is a critical factor because it determines the quantity of water a soil can hold and be subject to evapotranspiration. It is principally a function of the texture of the soil but can vary considerably for similar soils as a result of other physical characteristics of the soil, including structure and organic-matter content. Typically, silty soils have the largest AWC, sandy soils the smallest, and clayey soils are intermediate (Brady, 1974). The ranges of AWC

Table A1. Crop coefficient assignments by general vegetation type and by representative crops and vegetation
[CWR, consumptive water requirement; PET, potential evapotranspiration]

Crop coefficient number (CWR:PET)	General vegetation type	Representative crops and vegetation
1	High-water-demand row crops.	Corn, cotton, sugar beets, potatoes, horticultural field crops.
2	Low-water-demand row crops.	Grain sorghum, soybeans, dry beans.
3	Small grains	Winter wheat, spring wheat, oats, barley, rye.
4	Pasture and range	All grassland vegetation not harvested for hay.
5	Woodland	All species of trees and shrubs, including horticultural trees and scrubland (mesquite, sage brush).
6	Fallow	All unvegetated cultivated land, principally in summer fallow or clean tilled.
7	Hay	Alfalfa, clover, lespedeza, and all grassland, domesticated or native, harvested for hay.

values by soil texture used in the subregional program setups are shown in table A2.

The total water storage of the soil in terms of AWC is the root-zone thickness times the assigned AWC. For example, a root zone 30 inches thick with an AWC of 0.15 inch per inch would have a total water-storage capacity of 4.5 inches. In SWASP, this entire quantity remains in storage indefinitely and is subject to consumption through evapotranspiration. Any amount exceeding 4.5 inches of water at any given time would move out of the root zone and become deep percolation or potential recharge. This approach allows for the soil-water model to function as a simple accounting system, with the soil-root zone as semipermanent storage.

The actual process of soil-water movement or downward transfer beyond the root zone is a dynamic process that occurs under both saturated and unsaturated conditions. However, the complex simulation of saturated and unsaturated movement of soil water is not readily adaptable to long-term regional analysis of soil-water conditions. Thus, SWASP has been designed to permit deep percolation under less than saturated soil conditions by seasonally varying the root-zone thickness.

(8) Precipitation stations, the last entry in subregional program setups, are the sites at which soil-water simulations were performed. The one- or two-digit number to the immediate right of the entry is the PET site assigned to that precipitation site. Some precipitation sites did not have the temperature data required to compute PET. Therefore, PET data from nearby sites were used. These PET reassignments were based on geographic proximity and spatial analysis of seasonal PET (see figs. 17–19).

Model Calibration and Sensitivity Testing

Regional differences in climate, soils, and vegetation in the study area required that SWASP be calibrated to adjust for these varying conditions. SWASP is designed for the entire calibration to be achieved in the program variables. An important process in this calibration is sensitivity testing of those program variables selected for modification.

Calibration of SWASP occurred under the following constraints: (1) modifications were limited only to those program variables physically related to the desired adjustment in simulation results, (2) modifications of the appropriate program variables were limited to the observable range of that variable in the study area, and (3) calibration was performed only in relation to observed and comparable hydrologic data, which included comparisons of simulation results to observed streamflow (base flow and overland runoff), water-level changes, and ground-water pumpage.

Sensitivity testing of selected input variables of SWASP was conducted at selected sites within the study area. The variables that were the most sensitive and amenable to modification were AWC and root-zone thickness. Available data confirmed that these two variables are most suitable for flexible interpretation within their potential ranges. Other factors, including evapotranspiration coefficients and infiltration equations, are somewhat less sensitive and are less amenable to modification. Selecting different infiltration equations for a given soil-vegetation combination is quite acceptable, within limits, and can have a substantial effect on net water available as soil water.

Subregion Program Variations

The large differences in climate and vegetation within the study area made it necessary to perform soil-water simulations for three subregional units (see fig. 1). Although the data input to the programs SWASP and PET and subroutine SOLARR accounted for most climatic differences, certain calibrations and adjustments of the program variables within SWASP were required to account for certain phenological patterns. The SWASP input differs substantially among the three subregions. The major differences are in the vegetation (crop) types, the associated crop coefficients (ET/EP), and seasonal root-zone thicknesses, which reflect phenological differences among the subregions.

Vegetation Differences

Most apparent are the regional differences in principal crops representing certain general vegetation types. High-water-demand row crops differ for each subregion, changing from corn and sugar beets in the northern subregion to strictly corn in the central and to corn and cotton in the southern subregion. Low-water-demand row crops are rep-

Table A2. Permeability, available water capacity, slope ranges, and infiltration curve assignments of simulation soil groups
[AWC, available water capacity; do., ditto; >, greater than]

Simulation soil group number	Hydrologic soil groups[1]	Texture	Topographic description	Permeability range (inches per hour)	AWC range (inches per inch)	Slope range (percent)	Infiltration curve assignment (see fig. 25)
1	112, 122, 122s, 211, 212, 212s, 222, 222s	Clay to silty clay loam.	Flat to undulating	0.05–1.5	0.16–0.19	0–7	1, 2, or 3
2	132, 132s, 232, 232s	do.	Undulating to rolling	0.05–1.5	0.16–0.19	7–15	2, 3, or 4
3	142, 142s, 152, 152s, 242, 242s, 252, 252s	do.	Rolling to very steep	0.05–1.5	0.16–0.19	>15	3 or 4
4	311, 312, 322	Silt loam to loam	Flat to undulating	1.5–3.0	0.12–0.18	0–7	1 or 2
5	332, 332s	do.	Undulating to rolling	1.5–3.0	0.12–0.18	7–15	1 or 3
6	342, 342s, 352, 352s	do.	Rolling to very steep	1.5–3.0	0.12–0.18	>15	2 or 3
7	412, 422, 522	Loam to loamy sand	Flat to undulating	3.0–12.0	0.08–0.15	0–7	1
8	431, 432, 432s, 532, 552, 552s	do.	Undulating to very steep.	3.0–12.0	0.08–0.15	>7	1 or 2
9	652	Sand to dune sand	All slopes	>12.0	0.06–0.09	>0	1

[1]Dugan, Hobbs, and Ihm (1990).

resented largely by soybeans in the northern subregion, grain sorghum and soybeans in the central, and grain sorghum in the southern subregion. Spring wheat represents small grains in the northern subregion, and winter wheat represents small grains in the central and southern subregions. All other vegetation types are represented by the same specific vegetation or crops in all three subregions.

Crop Coefficients and Root-Zone Thickness

Differences in crop coefficients and root-zone thickness assigned to represent the three subregions are more important than the actual change in specific vegetation or crops representing general vegetation types. Although these changes partially reflect the differences in subregional crop types, they also reflect phenological or climatic progressions. The increased length and earlier start of the growing season (and shorter dormancy period) from the northern to southern subregions are evident in the crop coefficients and root-zone thickness. Changes in the crop coefficient and root-zone thickness ultimately express a general north-to-south increase in net consumptive water demand.

Irrigation Seasons

The months in which irrigation is permitted to occur in SWASP also differ among the subregional program setups. The irrigation season is July through August in the northern subregion and June through August in the central and southern subregions. The later beginning of the growing season and the subsequent lag in the developmental stages of certain crops (such as corn) in the north typically would defer the beginning of an irrigation season to July. Even in the northern parts of the central subregion, such as Nebraska, irrigation of the principal irrigated crop, corn, generally does not begin until very late June or early July. However, throughout most of the central subregion, the irrigation season for most irrigated crops typically begins in June. The differences in length of the irrigation season among the three subregions are not as important to total seasonal CIR as other program variables because soil-water deficits in the period preceding the actual irrigation period are carried over and accounted for during the irrigation season.

Other Subregional Considerations

The other program variables, namely (1) irrigation threshold (FHCAP), (2) initial soil-water content, (3) infiltration equations, and (4) AWC of the soil, remained the same in all subregions. Sufficient data indicating substantial regional differences related to these variables did not exist to warrant any regionally based modifications.

The three subregional program setups imply distinct regional climatic, phenological, and crop or vegetation boundaries, which are reflected in differences of assigned values for the program variables from SWASP. These phenomena, however, exhibit quite gradual transitions that cannot be expressed by regionalizing simulations for discrete sites. Interpolation of these data across subregional boundaries with the GIS procedures discussed in the following section partially smooths these transitions, but some simulation results remain somewhat regionalized and abrupt.

The results of the SWASP simulation require post-processing to convert the discrete data to a form that simulates continuous surfaces. SWASP generates results at each climatic (precipitation) site, reflecting all 63 potential combinations of soils and vegetation, which then must be processed further to reflect the actual patterns of soils, vegetation, and climate in the study area.

Subregion Program Setups

The following are SWASP setups for the three subregions of the study area (see fig. 1) and include the precipitation sites where simulations were generated.

DEFINITION OF VARIABLES IN OUTPUT LISTINGS FOR ALL THREE SUBREGIONS

TPERL	Number of pumping periods
PPER(12,2)	Pumping periods, beginning and last months
RXXX	Precipitation by month, in inches
SNOW	Cumulative amount of snow, in inches
EP	Monthly infiltration, in inches
RO	Monthly runoff, in inches
CWR	Actual monthly evapotranspiration (CWR=PET*CCOEF(J,MO)), in inches
PET	Potential monthly evapotranspiration, in inches
DPI	Deep percolation for irrigated lands, in inches
SHTI	Water shortage for irrigated lands, in inches
CIR	Consumptive irrigation requirements for irrigated lands, in inches
CSMI	Current soil moisture on irrigated lands, in inches
DPD	Deep percolation for drylands, in inches
SHT	Water shortage for drylands, in inches
CSMD	Current soil moisture on drylands, in inches
QIR	Net recharge or discharge for irrigated lands by pumping period, land use, soil, and year, in inches
QDY	Net recharge for drylands by pumping period, land use, soil, and year, in inches

NORTHERN SUBREGION

GREAT PLAINS STUDY AREA---SOIL-MOISTURE PROBLEM #1
TEST RUN 1 08-12-88 NORTHERN GREAT PLAINS
SOILM
DATE: 08-12-88 TEST RUN 1 STUDY AREA: NORTHERN GREAT PLAINS

NUMBER OF PRECIPITATION STATIONS (NST)	:	41
NUMBER OF TEMPERATURE STATIONS OR TPET SITES (IT)	:	18
PRINT SOIL-MOISTURE PARAMETERS FOR EACH PUMPING PERIOD (IF PRTPP>0)	:	1
SAVE SOIL-MOISTURE PARAMETERS FOR EACH PUMPING PERIOD (IF FILPP>0)	:	1
LISTINGS OF OUTPUT RESULTS BASED UPON PCODE>OR = (1,2,3,4)	:	4
SAVE OUTPUT ON TAPE OR DISK BASED UPON FCODE>OR = (1,2,3,4)	:	4
DATA CHECK (DATACK) IF DATACK .GT. 0, PRINT INPUT DATA FILES	:	0
(COMB)INATION OF PRECIPITATION STATION AND SOIL EXISTS--IF COMB>0	:	0
NUMBER OF PUMPING PERIODS PER YEAR (TPERL)	:	1
FIRST AND LAST MONTH OF PUMPING PERIODS: 1 12		
MINIMUM TEMPERATURE BEFORE SNOW STORAGE OCCURS (TMIN)	:	27°F
MAXIMUM NUMBER OF DAYS IN SNOW STORAGE (SNDAY)	:	40
NUMBER OF LAND USES (NCR)	:	7
NUMBER OF SOILS (NSC)	:	9
FIRST YEAR OF TIME PERIOD (NFYR)	:	1951
NUMBER OF YEARS IN TIME PERIOD (NYR)	:	30
USER SUPPLIED FACTOR FOR FIELD CAPACITY (FHCAP)	:	.50
USER SUPPLIED FACTOR - PREVIOUS SOIL MOISTURE, DRYLAND CROPS (FSMDP)	:	.25

FMTPPT :(2A3,I4,12F5.2,10X)
FMTPET :(2A3,4I4,F6.1,F8.2)

FMTCOM :(2I2,I4)

MONTHLY IRRIGATION OPTION -IF IRMO(I)=0, THEN IRRIGATION DOESN'T OCCUR AND
IF IRMO(I)=1, THEN IRRIGATION DOES OCCUR :

0 0 0 0 0 0 1 1 0 0 0 0

INDEX LAND USE (CROP IDENTIFICATION)

1 CORN-SUGAR BEETS
2 SOYBEANS
3 SPRING WHEAT
4 RANGE AND PASTURE
5 WOODLAND
6 FALLOW
7 ALFALFA

INDEX SOIL-TOPOGRAPHIC DESCRIPTION

1 CLAY TO SILTY CLAY LOAM (PERM. 0.5 TO 1.5) FLAT TO UNDULATING (0-7%)
2 CLAY TO SILTY CLAY LOAM (PERM. 0.5 TO 1.5) UNDULATING TO ROLLING (7-15%)
3 CLAY TO SILTY CLAY LOAM (PERM. 0.5 TO 1.5) ROLLING TO V. STEEP(15-30%)
4 SILT LOAM TO LOAM (PERM. 1.5 TO 3.0) FLAT TO UNDULATING (0-7%)
5 SILT LOAM TO LOAM (PERM. 1.5 TO 3.0) UNDULATING TO ROLLING (7-15%)
6 SILT LOAM TO LOAM (PERM. 1.5 TO 3.0) ROLLING TO V. STEEP (15-30%)
7 LOAM TO LOAMY-SAND (PERM. 3.0-12.0) FLAT TO UNDULATING (0-7%)
8 LOAM TO LOAMY-SAND (PERM. 3.0-12.0) UNDULATING TO V. STEEP (>7%)
9 SAND TO DUNE SAND (PERM. 12.0) ALL SLOPES

INFILTRATION CURVE COEFFICIENTS (I=A1+A2*RAIN+A3*RAIN**2 WHEN RAIN>AO)

CURVE NO.	AO	A1	A2	A3
1	1.77	0.0127	1.00825	–0.00871
2	1.12	–0.02102	1.05157	–0.02939
3	0.94	0.0332	1.00255	–0.04080
4	0.93	0.0435	0.99824	–0.04821

CROP COEFFICIENTS (CWR/PET)

CROP NO.	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1	.150	.150	.150	.150	.175	.404	.7701	1.058	.748	.150	.150	.150
2	.150	.150	.150	.150	.150	.257	.4201	1.090	.810	.200	.150	.150
3	.150	.150	.150	.280	.8801	1.020	.730	.230	.150	.150	.150	.150
4	.200	.200	.200	.387	.513	.783	.828	.810	.675	.450	.200	.200
5	.200	.200	.200	.440	.680	.9601	1.010	.990	.660	.400	.200	.200
6	.150	.150	.150	.150	.300	.400	.400	.400	.400	.150	.150	.150
7	.150	.150	.200	.300	.7751	1.0901	1.100	.960	.400	.150	.150	.150

ROOT DEPTH

CROP NO.	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1	15.	15.	15.	15.	15.	25.	48.	48.	30.	15.	15.	15.
2	15.	15.	15.	15.	15.	20.	30.	35.	35.	25.	15.	15.
3	15.	15.	15.	20.	25.	40.	40.	30.	15.	15.	15.	15.
4	15.	15.	15.	25.	30.	30.	30.	30.	30.	20.	15.	15.
5	15.	15.	24.	36.	48.	48.	48.	48.	48.	36.	24.	15.
6	15.	15.	15.	15.	15.	15.	15.	15.	15.	15.	15.	15.
7	15.	15.	24.	36.	48.	48.	48.	48.	48.	36.	24.	15.

SOIL-MOISTURE PROPERTIES

SOIL NO.	AVAIL. WATER	INFILTRATION CURVE FOR CROP NO. 1	2	3	4	5	6	7
1	.180	3	3	2	1	1	3	1
2	.180	4	4	3	2	2	4	2
3	.180	4	4	4	3	3	4	3
4	.150	2	2	2	1	1	2	1
5	.150	3	3	3	1	1	3	1
6	.150	3	3	3	2	2	3	2
7	.115	2	2	1	1	1	2	1
8	.115	2	2	2	1	1	2	1
9	.060	1	1	1	1	1	2	1

PRECIPITATION STATIONS:

240770 BIG SANDY	4
240807 BILLINGS AP	1
242173 CUTBANK	2
243013 FLAT WILLOW	1
243099 FORSYTH	1
243751 GREAT FALLS AP	3
243994 HAVRE AP	4
244004 HAXBY	5
244020 HAYES-ZORTMAN	5
244985 LEWISTON AP	3
245869 MOORHEAD	17
246233 OPHEIM 10N	7
246601 PLEVNA	6
247382 SAVAGE	10
247620 SIMPSON 6NW	4
248165 TERRY	6
248413 TURNER	7
248777 WESTBY	8
249103 WOLFPOINT	5
280961 BOWBELLS	8
281766 COOPERSTOWN	9
282158 DEVILS LAKE	14
282365 DUNN CENTER	10
282859 FARGO WBAP	9
283117 FORMAN	11
283616 GRAND FORKS AP	9
284178 HETTINGER	17
284413 JAMESTOWN AP	9
285210 LINTON	12
285479 MANDAN EXP	12
285813 MEDORA 3NNE	10
285988 MINOT AP	14
286947 PEMBINA	13
287664 ROLLA	14
288850 TUTTLE	10
289425 WILLISTON	8
412852 FAITH	15
416282 0NAKA	18
417062 REDIG 11NE	17
418307 TIMBER LAKE	15
418980 WAUBAY WILDLIFE	11

CENTRAL SUBREGION

GREAT PLAINS STUDY AREA---SOIL-MOISTURE PROBLEM #1
RUN 2 09-08-88 CENTRAL GREAT PLAINS
SOILM
DATE: 09-08-88 RUN 2 STUDY AREA: CENTRAL GREAT PLAINS

NUMBER OF PRECIPITATION STATIONS (NST)	:	80
NUMBER OF TEMPERATURE STATIONS OR TPET SITES (IT)	:	33
PRINT SOIL-MOISTURE PARAMETERS FOR EACH PUMPING PERIOD (IF PRTPP>0)	:	1
SAVE SOIL-MOISTURE PARAMETERS FOR EACH PUMPING PERIOD (IF FILPP>0)	:	1
LISTINGS OF OUTPUT RESULTS BASED UPON PCODE>OR = (1,2,3,4)	:	4
SAVE OUTPUT ON TAPE OR DISK BASED UPON FCODE>OR =(1,2,3,4)	:	4
DATA CHECK (DATACK) IF DATACK .GT. 0, PRINT INPUT DATA FILES	:	0
(COMB)INATION OF PRECIPITATION STATION AND SOIL EXISTS--IF COMB>0	:	0
NUMBER OF PUMPING PERIODS PER YEAR (TPERL)	:	1

FIRST AND LAST MONTH OF PUMPING PERIODS: 1 12

MINIMUM TEMPERATURE BEFORE SNOW STORAGE OCCURS (TMIN)	:	27°F
MAXIMUM NUMBER OF DAYS IN SNOW STORAGE (SNDAY)	:	40
NUMBER OF LAND USES (NCR)	:	7
NUMBER OF SOILS (NSC)	:	9
FIRST YEAR OF TIME PERIOD (NFYR)	:	1951
NUMBER OF YEARS IN TIME PERIOD (NYR)	:	30
USER SUPPLIED FACTOR FOR FIELD CAPACITY (FHCAP)	:	.50
USER SUPPLIED FACTOR - PREVIOUS SOIL MOISTURE, DRYLAND CROPS(FSMDP)	:	.25

FMTPPT :(2A3,I4,12F5.2,10X)
FMTPET :(2A3,4I4,F6.1,F8.2)
FMTCOM :(2I2,I4)

MONTHLY IRRIGATION OPTION -IF IRMO(I)=0, THEN IRRIGATION DOESN'T OCCUR AND
IF IRMO(I)=1, THEN IRRIGATION DOES OCCUR :
0 0 0 0 0 1 1 1 0 0 0 0

INDEX LAND USE (CROP IDENTIFICATION)
1 CORN
2 GRAIN SORGHUM
3 WINTER WHEAT
4 PASTURE AND RANGE
5 WOODLAND
6 FALLOW
7 ALFALFA

INDEX SOIL-TOPOGRAPHIC DESCRIPTION
1 CLAY TO SILTY CLAY LOAM (PERM. 0.5 TO 1.5) FLAT TO UNDULATING (0-7%)
2 CLAY TO SILTY CLAY LOAM (PERM. 0.5 TO 1.5) UNDULATING TO ROLLING (7-15%)
3 CLAY TO SILTY CLAY LOAM (PERM. 0.5 TO 1.5) ROLLING TO V. STEEP(15-30%)
4 SILT LOAM TO LOAM (PERM.1.5 TO 3.0) FLAT TO UNDULATING (0-7%)
5 SILT LOAM TO LOAM (PERM. 1.5 TO 3.0) UNDULATING TO ROLLING (7-15%)
6 SILT LOAM TO LOAM (PERM. 1.5 TO 3.0) ROLLING TO V. STEEP (15-30%)
7 LOAM TO LOAMY-SAND (PERM. 3.0-12.0) FLAT TO UNDULATING (0-7%)
8 LOAM TO LOAMY-SAND (PERM. 3.0-12.0) UNDULATING TO V. STEEP (>7%)
9 SAND TO DUNE SAND (PERM. 12.0) ALL SLOPES

INFILTRATION CURVE COEFFICIENTS (I=A1+A2*RAIN+A3*RAIN**2 WHEN RAIN>AO)

CURVE NO.	AO	A1	A2	A3
1	1.77	0.0127	1.00825	–0.00871
2	1.12	–0.02102	1.05157	–0.02939
3	0.94	0.0332	1.00255	–0.04080
4	0.93	0.0435	0.99824	–0.04821

CROP COEFFICIENTS (CWR/PET)

CROP NO.	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1	.200	.200	.200	.200	.396	.5801	1.000	.957	.775	.440	.200	.200
2	.200	.200	.200	.200	.200	.355	.820	.945	.666	.450	.200	.200
3	.200	.200	.600	.9501	1.0001	1.000	.360	.150	.360	.702	.990	.200
4	.200	.200	.200	.450	.639	.792	.828	.819	.729	.340	.200	.200
5	.200	.200	.300	.585	.775	.9601	1.010	.990	.837	.585	.200	.200
6	.150	.150	.150	.150	.300	.400	.400	.400	.400	.150	.150	.150
7	.200	.200	.460	.900	.980	.708	.985	.708	.704	.405	.270	.200

ROOT DEPTH

CROP NO.	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1	15.	15.	15.	15.	20.	30.	48.	48.	30.	20.	15.	15.
2	15.	15.	15.	15.	15.	25.	35.	40.	40.	24.	15.	15.
3	25.	25.	25.	30.	40.	40.	20.	15.	15.	20.	25.	25.
4	15.	15.	20.	25.	30.	30.	30.	30.	30.	25.	15.	15.
5	15.	15.	24.	36.	48.	48.	48.	48.	48.	36.	24.	15.
6	15.	15.	15.	15.	15.	15.	15.	15.	15.	15.	15.	15.
7	15.	15.	36.	48.	48.	48.	48.	48.	48.	36.	24.	15.

SOIL-MOISTURE PROPERTIES		INFILTRATION CURVE FOR CROP NO.						
SOIL NO.	AVAIL. WATER	1	2	3	4	5	6	7
1	.180	3	3	2	1	1	3	1
2	.180	4	4	3	2	2	4	2
3	.180	4	4	4	3	3	4	3
4	.150	2	2	2	1	1	2	1
5	.150	3	3	3	1	1	3	1
6	.150	3	3	3	2	2	3	2
7	.115	2	2	1	1	1	2	1
8	.115	2	2	2	1	1	2	1
9	.060	1	1	1	1	1	2	1

PRECIPITATION STATIONS:

051564 CHEYENNE WELLS	6
053258 GENOA	3
054082 HOLYOKE	17
054750 LAMAR	2
057871 SPRINGFIELD	4
057950 STERLING	1
120365 ASHLAND	20
120439 ATWOOD	6
121769 CONCORDIA AP	13
122164 DODGE CITY AP	5
122432 ELKHART	4
122452 ELLIS	8
122980 GARDEN CITY AP	5
123153 GOODLAND AP	6
123175 GOVE	8
123660 HILL C.	8
124313 KINGMAN	7
124530 LARNED	8
124695 LIBERAL	20
125173 MEDICINE LODGE	7
125744 NEWTON	9
127397 SHARON SPRINGS	6
127542 SMITH CENTER	13
128235 TRIBUNE	6
128670 WELLINGTON	7
128828 WICHITA AP	9
250420 ATKINSON	18
250445 AURORA	11
251575 CHADRON AP	10
251680 CLAY CENTER	11
251825 COLUMBUS	14
251990 CREIGHTON	26
252100 CURTIS	12
253035 FRANKLIN	13
253050 FREMONT	14
253425 GREELEY	15
253540 HALSEY	16
253735 HEBRON	11
253950 HOMER	26
254335 KEARNEY	13
255700 MULLEN	16
256165 OCONTO	12
256585 PAXTON	12
257715 SEWARD	14
257665 SCOTTSBLUFF	17
257835 SIDNEY 6NNW	17
258215 STOCKVILLE	12
258255 STRATTON	12
258650 TRYON	16
258760 VALENTINE AP	18

259115 WELLFLEET	12
259200 WEST POINT	14
271887 CLAYTON, NM	19
342944 ERICK	21
343407 GAGE AP	20
343628 GOODWELL	28
411076 BROOKINGS	22
411972 COTTONWOOD 2E	25
414127 HURON AP	33
415281 MARTIN 5NNE	23
416574 PICKSTOWN	26
416597 PIERRE AP	24
416937 RAPID CITY AP	25
419367 WINNER	18
430211 AMARILLO	27
432240 DALHART AP	19
436785 PANHANDLE	27
438523 SPEARMAN	28
490200 ALVA 5SE	32
491165 BUFFALO	31
491570 CASPER AP	29
491675 CHEYENNE AP	30
492725 DULL CENTER 1SE	31
493865 GILLETE 18SW	31
495830 LUSK	10
496195 MIDWEST	29
496660 NEWCASTLE	32
498155 SHERIDAN AP	31
499615 WHEATLAND	30
413217 GANN VALLEY	33

SOUTHERN SUBREGION

GREAT PLAINS STUDY AREA---SOIL-MOISTURE PROBLEM #1
RUN 2 09-08-88 SOUTHERN GREAT PLAINS AND TEXAS CARBONATES
SOILM
DATE: 09-08-88 RUN 2 STUDY AREA: SOUTHERN GREAT PLAINS AND TEXAS CARBONATES

NUMBER OF PRECIPITATION STATIONS (NST)	:	31
NUMBER OF TEMPERATURE STATIONS OR TPET SITES (IT)	:	18
PRINT SOIL-MOISTURE PARAMETERS FOR EACH PUMPING PERIOD (IF PRTPP>0)	:	1
SAVE SOIL-MOISTURE PARAMETERS FOR EACH PUMPING PERIOD (IF FILPP>0)	:	1
LISTINGS OF OUTPUT RESULTS BASED UPON PCODE>OR = (1,2,3,4)	:	4
SAVE OUTPUT ON TAPE OR DISK BASED UPON FCODE>OR =(1,2,3,4)	:	4
DATA CHECK (DATACK) IF DATACK .GT. 0, PRINT INPUT DATA FILES	:	0
(COMB)INATION OF PRECIPITATION STATION AND SOIL EXISTS--IF COMB>0	:	0
NUMBER OF PUMPING PERIODS PER YEAR (TPERL)	:	1
FIRST AND LAST MONTH OF PUMPING PERIODS: 1 12		
MINIMUM TEMPERATURE BEFORE SNOW STORAGE OCCURS (TMIN)	:	27°F
MAXIMUM NUMBER OF DAYS IN SNOW STORAGE (SNDAY)	:	40
NUMBER OF LAND USES (NCR)	:	7
NUMBER OF SOILS (NSC)	:	9
FIRST YEAR OF TIME PERIOD (NFYR)	:	1951
NUMBER OF YEARS IN TIME PERIOD (NYR)	:	30
USER SUPPLIED FACTOR FOR FIELD CAPACITY (FHCAP)	:	.50
USER SUPPLIED FACTOR - PREVIOUS SOIL MOISTURE, DRYLAND CROPS (FSMDP)	:	.25

FMTPPT :(2A3,I4,12F5.2,10X)
FMTPET :(2A3,4I4,F6.1,F8.2)
FMTCOM :(2I2,I4)
MONTHLY IRRIGATION OPTION -IF IRMO(I)=0, THEN IRRIGATION DOESN'T OCCUR AND
IF IRMO(I)=1, THEN IRRIGATION DOES OCCUR :
0 0 0 0 0 1 1 1 0 0 0 0
INDEX LAND USE (CROP IDENTIFICATION)
1 COTTON
2 GRAIN SORGHUM
3 WINTER WHEAT
4 RANGE AND PASTURE
5 WOODLAND

6 FALLOW
7 ALFALFA

INDEX SOIL-TOPOGRAPHIC DESCRIPTION

1 CLAY TO SILTY CLAY LOAM (PERM. 0.5 TO 1.5) FLAT TO UNDULATING (0-7%)
2 CLAY TO SILTY CLAY LOAM (PERM. 0.50-1.5) UNDULATING TO ROLLING (7-15%)
3 CLAY TO SILTY CLAY LOAM (PERM. 0.5-1.5) ROLLING TO VERY STEEP (15-30%)
4 SILT LOAM TO LOAM (PERM.1.5-3.0) FLAT TO UNDULATING (3-7%)
5 SILT LOAM TO LOAM (PERM. 1.5-3.0) UNDULATING TO ROLLING (7-15%)
6 SILT LOAM TO LOAM (PERM. 1.5-3.0) ROLLING TO V. STEEP (15-30%)
7 LOAM TO LOAMY-SAND (PERM. 3.0-12.0) FLAT TO UNDULATING (0-7%)
8 LOAM TO LOAMY-SAND (PERM. 3.0-12.0) UNDULATING TO V. STEEP (>7%)
9 SAND TO DUNE SAND (PERM. 12.0) ALL SLOPES

INFILTRATION CURVE COEFFICIENTS (I=A1+A2*RAIN+A3*RAIN**2 WHEN RAIN>AO)

CURVE NO.	AO	A1	A2	A3
1	1.77	0.0127	1.00825	–0.00871
2	1.12	–0.02102	1.05157	–0.02939
3	0.94	0.0332	1.00255	–0.04080
4	0.93	0.0435	0.99824	–0.04821

CROP COEFFICIENTS (CWR/PET)

CROP NO.	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1	.200	.200	.200	.200	.243	.423	.792	.918	.774	.576	.270	.200
2	.200	.200	.200	.200	.324	.783	.936	.702	.486	.200	.200	.200
3	.200	.310	.6851	1.000	1.000	.360	.200	.200	.200	.702	.990	.200
4	.270	.450	.540	.702	.792	.819	.828	.819	.792	.720	.603	.490
5	.200	.400	.585	.702	.840	.9631	1.020	.990	.927	.837	.720	.585
6	.150	.150	.150	.150	.300	.400	.400	.400	.400	.150	.150	.150
7	.200	.330	.680	.940	.844	.846	.846	.846	.846	.711	.337	.240

ROOT DEPTH

CROP NO.	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1	15.	15.	15.	20.	30.	40.	40.	40.	40.	30.	15.	15.
2	15.	15.	15.	15.	20.	30.	35.	35.	35.	35.	15.	15.
3	25.	25.	25.	35.	40.	20.	15.	15.	15.	15.	20.	25.
4	20.	25.	30.	30.	30.	30.	30.	30.	30.	30.	25.	20.
5	20.	25.	36.	48.	48.	48.	48.	48.	48.	48.	36.	20.
6	15.	15.	15.	15.	15.	15.	15.	15.	15.	15.	15.	15.
7	20.	36.	48.	48.	48.	48.	48.	48.	48.	48.	36.	20.

SOIL-MOISTURE PROPERTIES / INFILTRATION CURVE FOR CROP NO.

SOIL NO.	AVAIL. WATER	1	2	3	4	5	6	7
1	.180	3	3	2	1	1	3	1
2	.180	4	4	3	2	2	4	2
3	.180	4	4	4	3	3	4	3
4	.150	2	2	2	1	1	2	1
5	.150	3	3	3	1	1	3	1
6	.150	3	3	3	2	2	3	2
7	.115	2	2	1	1	1	2	1
8	.115	2	2	2	1	1	2	1
9	.060	1	1	1	1	1	2	1

PRECIPITATION STATIONS:

031596	CONWAY	1
034248	LITTLE ROCK	1
035112	NASHVILLE	2
035576	PARIS	3
037048	TEXARKANA	2
340391	ATOKA	6
343709	GRANDFIELD	5
345563	MARIETTA	5
430016	ABILENE AP	7
430394	ASPERMONT	7
430428	AUSTIN AP	8
431138	BROWNWOOD	15
431398	CAMP WOOD 2S	11
431698	CHILDRESS AP	10
432160	CRYSTAL CITY	9
434671	JUNCTION	11
435018	LAMPASAS	8
435272	LLANO	11
435411	LUBBOCK AP	14
435890	MIDLAND	12
436135	MULESHOE 1	14
437074	PLAINS	14
436794	PARIS	13
437943	SAN ANGELO AP	15
438027	SANDERSON	16
438252	SHEFFIELD	12
438743	SULPHUR SPRINGS	13
439014	THROCKMORTON	9
439419	WACO	17
439532	WEATHERFORD	18
439830	WINK AP	12

APPENDIX B. POST-PROCESSING CONVERSION OF DISCRETE SWASP OUTPUT INTO SIMULATED CONTINUOUS SURFACES USING A GEOGRAPHIC INFORMATION SYSTEM

Data collected or derived at nonuniformly distributed points in space (discrete information) can be interpreted better when they are represented as continuous phenomena in a multidimensional framework. Representing the data continuously is potentially of greatest concern in simulation studies in which the results are a product of synthesizing many types of independently derived data. As in this study, the spatial characteristics of such data as climate, soils, and vegetation are inherently different both in their natural occurrence and methods of representation. The purpose of the following discussion is to provide both a conceptual and methodological understanding of the post-processing procedures implemented to convert these various phenomena to compatible surfaces in order to represent the soil-water characteristics as continuous surfaces.

Conceptual Considerations

The general assumption of the soil-water simulation program (SWASP) is that all 63 possible combinations of soils (9 types) and vegetation (7 types) occur at each selected climatic site (152) within the study area. The soil-water program can be modified to compute only those soil-vegetation combinations that may occur in a given area, but this does not weight the output on the basis of proportions of selected soils and vegetation occurring in a given area. Therefore, it was necessary to post-process the data to reflect variable soil and vegetation conditions and to interpolate point data to simulate a continuous distribution.

Use of the ARC/INFO geographic information system (GIS) software enables information about different characteristics to be converted to a uniform format and then analyzed as a series of geographically superimposed surfaces or layers. The layers then may be combined to create new information, such as by statistically weighting existing variables or producing entirely different variables.

Previous approaches for converting discrete output from SWASP to spatially continuous surfaces relied either on Theissen polygons or on interpolation of site results to grid points using a fixed distance-decay function (Peckenpaugh and Dugan, 1983; Peckenpaugh and others, 1987). With Theissen polygons, the values were fixed over an entire area depending on polygon size. Although interpolation based on fixed distance-decay relations provides more continuity for a given surface, it has limitations that require manual distance measurements, and only a few sites can be considered per grid point.

In addition to limitations of the earlier methods of converting the discrete data of SWASP to spatially continuous distributions, there were limitations in the spatial-weighting procedures. The soil classification required manual coding of soil groups on a proportional basis for each grid element. Also, the vegetation classification, normally derived from crop and land-use statistics by county units, required manually proportioning vegetation classes if a grid element occurred in more than one county.

The methodology for converting discrete simulation results from SWASP to continuous patterns with the post-processing procedures using a GIS can potentially affect the interpretations of the results. Therefore, the methodology used within this phase of the analysis was carefully designed to minimize any inherent biases that might result from design error. This design requires an initial conceptualization of the spatial and measurement characteristics of the individual phenomena used in the post-processing and determines how they can be interrelated without compromising the original data.

The basis of the post-processing procedures using a GIS is the interpolation or assignment of all data to the centers of elements in a gridded format. Climatic and soil-water simulation data are interpolated to these center points from the climatic sites used for the simulation in SWASP. This interpolation presents few problems for these data because they represent phenomena that are continuously distributed in nature and normally follow a relatively smooth transition with few breaks when the data are long term and collected at closely spaced points.

Soil and vegetation, although continuously distributed in nature, typically exist or are mapped as discrete spatial units with abrupt transitions among types. Therefore, these unitized data must be converted to a form in which the given soil and vegetation characteristics can be assigned to the centroid of each element in a gridded format compatible with the interpolated climatic and soil-water data. Two methods may be used to accomplish this.

In the first method, all the soils and vegetation types within a particular grid element on an areal basis are proportionally weighted, which generates an averaged value for a particular soil-water characteristic. In a sense, the weighted soil-vegetation characteristics that are assigned to the centroid of a particular grid element represent hybridized characteristics and not a single soil-vegetation combination. This method has the advantage of considering all soil-vegetation conditions within the grid element. The disadvantage is that proportional weighting of all soils and vegetation by grid element requires either laborious hand coding or large amounts of computer time (if the capability is available). The potential gain in precision for broad-scale studies may not be cost effective.

The second method determines the particular soil or vegetation type that occurs at the centroid of the element and assigns the value of that type to the entire grid element. This method has the advantage of being well suited for accurate and efficient processing by computer. The disadvantage is that the soil or vegetation type occurring at the centroid may be an isolated unit not representative of the grid element.

The latter method of assigning a single soil type to a grid element was selected to input the soil component into the GIS on the basis of the following reasons: (1) the soil map (Dugan, Hobbs, and Ihm, 1990) is sufficiently generalized that single mapping units commonly occupy several contiguous grid elements, with most elements containing only one soil type; (2) the quantitative characteristics assigned to a particular soil type already represented a spatially weighted average of several individual soil series in a given area (Dugan, Hobbs, and Ihm, 1990); and (3) subjectively, the efficiency and accuracy of this method outweigh the potentially greater precision provided by proportional weighting.

Vegetation data in this study are represented by percentages of counties occupied by the seven vegetation types and, therefore, are already spatially weighted data similar to the soils input. Furthermore, because the county vegetation unit is analogous to the soil mapping unit in that they both represent statistical entities, similar criteria may be applied for post-processing within a GIS. In the post-processing of vegetation data, the county occupying the center of each grid element serves to represent the entire element.

The potential consequence in assigning vegetation by this method is similar to that of the soil mapping unit in that a county that occupies most of the grid element may not occur at the center and, therefore, may not be represented in that element. An examination of the relation between the configuration of counties and the grid system indicates that this problem rarely occurs, because the element size representing 625 square miles is approximately the same size as the smallest county in the study area (about 550 square miles). Furthermore, the use of county-unit percentage data to represent broad vegetational types tends to minimize abrupt transitions. Again, the efficiency and accuracy of data sampled by computer at a single point, the centroid, more than compensate for the slight loss in precision.

Methodological Considerations

While the methodology used in the GIS to convert discrete data to simulated continuous data relies on concepts similar to those in previous studies, it has the obvious potential advantages of speed and improved accuracy (Peckenpaugh and Dugan, 1983; Peckenpaugh and others, 1987). Also, post-processing using a GIS provides more flexibility in combining and manipulating variables, as well as permitting the inclusion of a larger number of variables in the analysis. The rather broad nature of this study permitted, and in some respects required, a more simplistic implementation of a GIS to be used, which will be discussed in the following paragraphs. The variables derived from SWASP that were selected for spatial analysis with a GIS are listed in table B1.

The characteristics of each soil-water variable can be quite different and can determine how they are manipulated within the post-processing procedures. Most variables are both vegetation and soil dependent and can occur in all 63 possible combinations. Some variables, however, are independent of soil conditions or logically apply only to certain vegetation or crop types, such as irrigated conditions.

The consumptive water requirement (CWR) is dependent on vegetation type but is independent of soil type. The actual evapotranspiration (AET) is a function of CWR but also is dependent on soil type (and the soil's available water capacity, AWC) and is computed for all 63 soil-vegetation combinations. AET is CWR minus a computed soil-moisture deficit (SWD) value. Runoff and infiltration both are determined from the infiltration equations in SWASP. Four infiltration equations can represent any of the 63 possible combinations. Equation assignments were determined individually for each of the 63 soil-vegetation combinations (see infiltration curves in SWASP subregional setups, fig. 25). Therefore, combinations had to be processed through a GIS.

Certain soil-water variables that potentially may have 63 values per site are only meaningful for selected soil-vegetation combinations. The consumptive irrigation requirement (CIR) could not be averaged or weighted logically for all or several of the potentially irrigated crop types because this would have created a variable that could not be compared spatially. Therefore, the most commonly irrigated crop type, high-water-demand row crops, was selected to represent CIR, which resulted in only nine combinations based on only the soil types. DPI (deep percolation for irrigated conditions) simulations also were limited to only those crops commonly irrigated from June through August (high-water-demand row crops, low-water-demand row crops, and hay), which limited the combinations to 27.

DPW, which is a weighted average of DPD (deep percolation for nonirrigated conditions) and DPI, uses a rather simplistic method to weight DPI on the basis of area irrigated. DPW is expressed in the following equation:

$$DPW = IRF \times DPI + (1 - IRF) \times DPD, \qquad \text{(B1)}$$

where

DPW = deep percolation, weighted, in inches,

IRF = proportion of county land area irrigated,

Table B1. Soil-water variables spatially analyzed with a geographic information system
[HRC, high-water-demand row crop; LRC, low-water-demand row crop; SWASP, soil-water simulation program; Do., ditto]

Code	Variable	Soil types	Vegetation types	Input source
DPD	Deep percolation, nonirrigated	All	All	SWASP output.
DPI	Deep percolation, irrigated	All	HRC, LRC, and hay.	Do.
DPW	Deep percolation, weighted	All	([1])	DPD and DPI weighted by irrigated land.
AET	Actual evapotranspiration	All	All	SWASP output.
EP	Infiltration (effective precipitation)	All	All	Do.
RO	Overland runoff	All	All	Do.
CWR	Consumptive water requirement	([2])	([3])	Do.
CIR	Consumptive irrigation requirement	All	HRC	Do.
NFI	Net flux in irrigated conditions	All	([1])	DPW – CIR.
None	DPD:precipitation ratio	All	([1])	DPD/mean annual precipitation.

[1]Computed secondarily from indicated soil-water variables.
[2]Independent of soil type.
[3]Computed for all vegetation types, but only high-water-demand row crops illustrated.

DPI = deep percolation for irrigated crops by specific soil, in inches, and

DPD = deep percolation for nonirrigated conditions by soil-vegetation type, in inches.

The net flux for irrigated conditions (NFI) was generated within the GIS by subtracting DPW from CIR, which provides an estimate of net gain or loss from the ground-water system under irrigated conditions. This procedure provides only an approximation of NFI because it is derived from CIR computed only for high-water-demand row crops and DPW computed for all vegetation types. NFI, however, provides a spatial comparison of relative differences in net ground-water withdrawals from aquifers beneath irrigated areas.

A relative measure of the proportion of precipitation that is available as recharge is the DPD:precipitation ratio. It is calculated in the GIS as simply the mean annual DPD grid-node values divided by mean-annual-precipitation values interpolated to those nodes. Because the ratio is calculated from DPD, it reflects all the possible vegetation-soil combinations.

Post-Processing Procedures

The following is the sequential approach used in the GIS generation of the geographic distribution of the nine selected variables:

(1) The variables required for inclusion in the post-processing procedures were identified within the 30-year mean output of SWASP for the 152 sites and converted into 63 separate input files on the basis of potential soil-vegetation combinations.

DPD, DPI, CWR, CIR, runoff, and infiltration values were output directly from SWASP and required no external modifications. AET values were generated outside of SWASP from the CWR and the soil-water deficit before input into the GIS. DPW was generated within the GIS as a product of DPI and DPD values weighted by county irrigation statistics. The DPD:precipitation ratio also was generated within the GIS.

(2) The 152 sites were indexed by their latitude and longitude and their National Weather Service codes for georeferencing with the 7 input variables (DPD, DPI, CWR, CIR, runoff, infiltration, and AET) in the 63 separate files external to the GIS.

(3) Using the capabilities of the GIS, a continuous spatial distribution was interpolated for each of the 7 variables for each of the 63 potential soil-vegetation combinations. These continuous surfaces were constructed by using the triangulated irregular network (TIN) procedure of ARC/ INFO in which the triangle vertices are located at the 152 sites. A linear interpolation procedure was selected to estimate the distribution of values between nodes.

(4) For each of the 7 variables, the subsequent weighting of the 63 TIN surfaces was determined by superimposing soil and vegetation layers. The soil units were digitized as polygons from Dugan, Hobbs, and Ihm (1990) at the map scale of 1:3,168,000. The 34 hydrologic soil groups from the map were consolidated further into 9 groups to coincide with the soil groups in SWASP. Mountains and

water bodies were placed in separate nonsoil classes for exclusion from the simulation.

(5) The vegetation or land-cover layer was derived on the basis of county statistical units from 1982 census of agriculture data (U.S. Bureau of the Census, 1984). The raw data required considerable manipulation with a statistical package to remove data inconsistencies and to group the data into the seven vegetation types. The original units were converted from acres to percentages of each vegetation type occupying a given county. Thus, the vegetation layer actually consisted of seven attributes for each county unit or polygon, which coincided with the seven vegetation types in SWASP.

Digital data for the county boundaries were obtained from the U.S. Geological Survey's National Digital Cartographic Data Base National Atlas series (1:2,000,000 scale). The county-proportional vegetation data then were related to the cartographic boundary data using an identification code for each county.

(6) At this point in the post-processing, a method for integrating the several data surfaces or layers was required. Among the options available with the ARC/INFO GIS were (1) creation of a polygon overlay of the soil and county (vegetation) polygons, with subsequent sampling of the 63 potential soil-water surfaces at the centroid of each resulting soil-vegetation polygon or (2) systematic sampling at grid nodes using a regular grid. The latter option was selected because it provided better resolution.

The resultant grid was generated in the Albers conic equal-area projection with equal grid spacing of 25 miles, which created 625-square-mile grid elements. The study area is composed of 873 grid elements. Although the grid is oriented precisely to the cardinal directions along only one meridian, it provides consistent distances for the grid intervals in relation to the GIS data layers.

(7) Using the gridded sample points or nodes, a GIS overlay with both the soil groups and county boundaries was created, thereby attaching to each point the necessary information about its soil-group polygon and county (for vegetation attributes). Then using the same set of grid points, sampling of the 63 potential continuous TIN surfaces generated from the soil-water-program output was performed. The soil and vegetation information associated with each grid point then was used to calculate a weighted value for each of the 7 soil-water variables at each of the 873 grid points. The calculating procedure for the seven variables is expressed in the following general equation:

$$SMV_{ij} = \sum (SMV_{ijkl} W_{jl}), \qquad \text{(B2)}$$

where

SMV = value of soil-water variable, in inches of water,
W = proportion of land area covered by vegetation type,
i = soil-water variable,
j = sample point location,
k = soil type coincident with location j, and
l = vegetation type.

This equation fully applies only to DPD, runoff, infiltration, and AET. As previously indicated, CIR and DPI are based only on selected vegetation types, whereas DPW, NFI, and DPD:precipitation ratios are products of modifications requiring data external to SWASP. CWR is soil independent; therefore, it is generated with an equation that disregards the soil type (k).

The output from the GIS was either plots of the grid values or contour maps derived from the grid values. These plots and contour maps served as analytical tools and the preliminary drafts of the final illustrations. The actual boundary formed by the bounding polygons of the GIS surface is not identical to the study-area boundary because ARC/INFO cannot use data assigned to points outside of an assigned boundary. A few of the soil-water sites were immediately outside the study-area boundary, which required extending the polygon boundary to include these data points in the data base. Some extrapolation of results was required along parts of the boundary where no sites were available immediately outside the study area.