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Selected Approaches to Estimate Water-budget Components of the High Plains, 1940 through 1949 and 2000 through 2009

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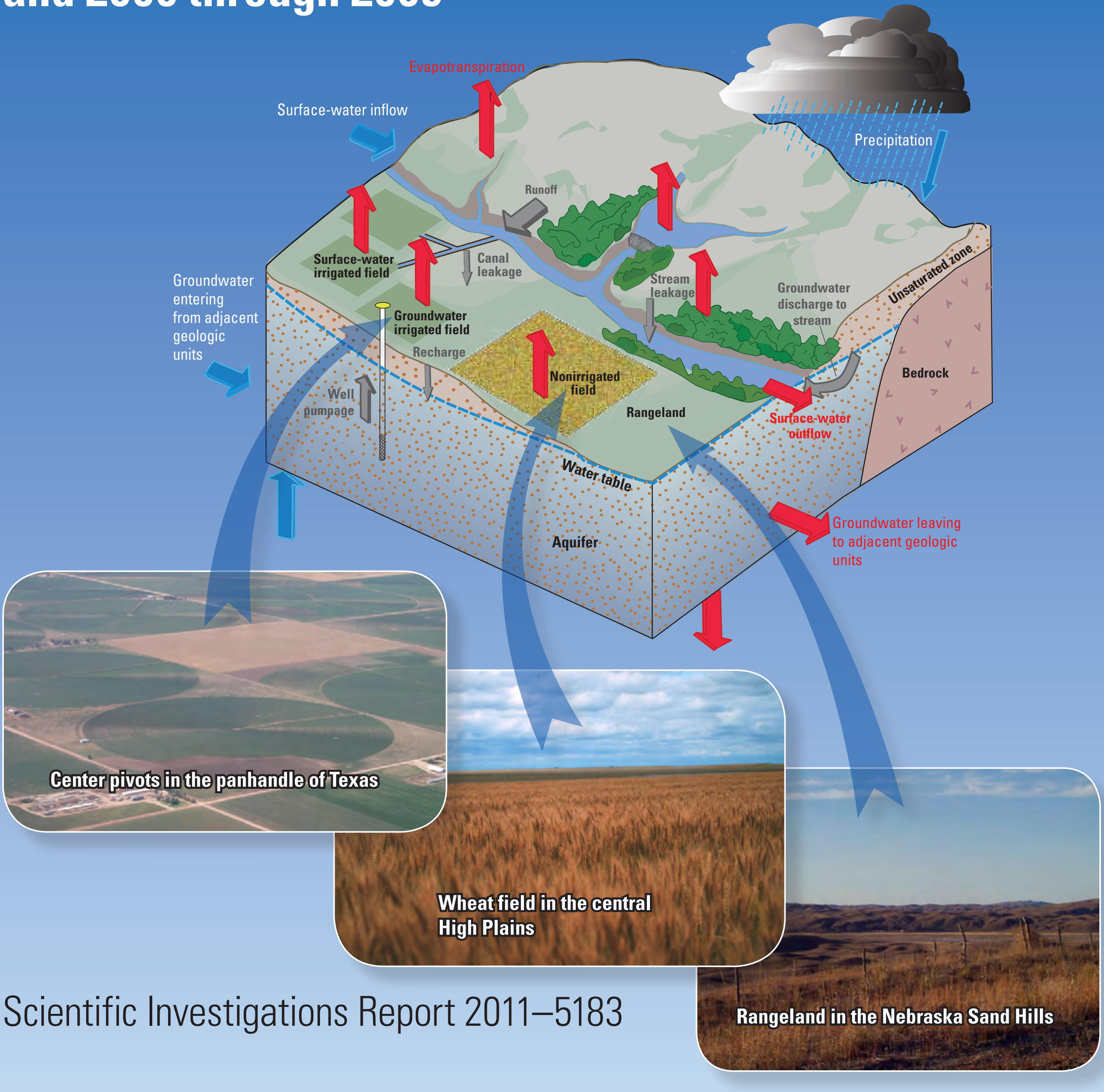
GROUNDWATER RESOURCES PROGRAM

Selected Approaches to Estimate Water-Budget Components of the High Plains, 1940 through 1949 and 2000 through 2009



Scientific Investigations Report 2011–5183

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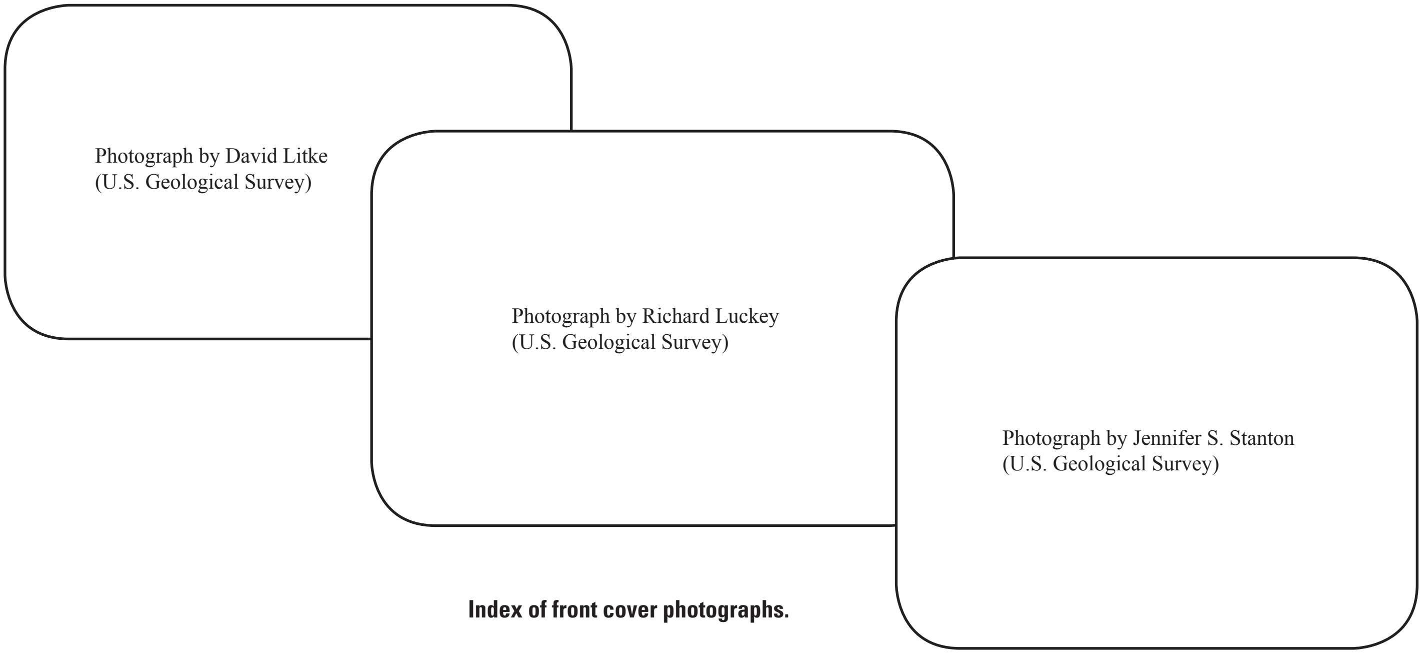

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U.S. Department of the Interior
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Conversion Factors and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
acre-foot (acre-ft)	1,233	cubic meter (m^3)
Flow rate		
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per hour (in/hr)	25.4	millimeter per hour (mm/hr)
inch per day (in/day)	25.4	millimeter per day (mm/day)
Crop-water usage per unit area; Recharge, Evaporation, Evapotranspiration		
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
Slope		
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Acronyms

AET	Actual Evapotranspiration
AWC	Available-Water Capacity
BFI	Base-Flow Index
CHP	Central High Plains
CN	Curve Number
ET	Evapotranspiration
GIS	Geographic Information System
IDW	Inverse-Distance Weighted
MODIS	Moderate Resolution Spectroradiometer
NEXRAD	Next Generation Weather Radar
NHP	Northern High Plains
NRCS	Natural Resources Conservation Service
PET	Potential Evapotranspiration
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
SAC-SMA	Sacramento-Soil Moisture Accounting
SHP	Southern High Plains
SOWAT	SOil-WATer Balance
SSEB	Simplified-Surface-Energy Balance
SWB	Soil-Water Balance
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

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By Jennifer S. Stanton, Sharon L. Qi, Derek W. Ryter, Sarah E. Falk, Natalie A. Houston, Steven M. Peterson, Stephen M. Westenbroek, and Scott C. Christenson

Abstract

The High Plains aquifer, underlying almost 112 million acres in the central United States, is one of the largest aquifers in the Nation. It is the primary water supply for drinking water, irrigation, animal production, and industry in the region. Expansion of irrigated agriculture throughout the past 60 years has helped make the High Plains one of the most productive agricultural regions in the Nation. Extensive withdrawals of groundwater for irrigation have caused water-level declines in many parts of the aquifer and increased concerns about the long-term sustainability of the aquifer.

Quantification of water-budget components is a prerequisite for effective water-resources management. Components analyzed as part of this study were precipitation, evapotranspiration, recharge, surface runoff, groundwater discharge to streams, groundwater fluxes to and from adjacent geologic units, irrigation, and groundwater in storage. These components were assessed for 1940 through 1949 (representing conditions prior to substantial groundwater development and referred to as "pregroundwater development" throughout this report) and 2000 through 2009. Because no single method can perfectly quantify the magnitude of any part of a water budget at a regional scale, results from several methods and previously published work were compiled and compared for this study when feasible. Results varied among the several methods applied, as indicated by the range of average annual volumes given for each component listed in the following paragraphs.

Precipitation was derived from three sources: the Parameter-Elevation Regressions on Independent Slopes Model, data developed using Next Generation Weather Radar and measured precipitation from weather stations by the Office of Hydrologic Development at the National Weather Service for the Sacramento-Soil Moisture Accounting model, and precipitation measured at weather stations and spatially distributed using an inverse-distance-weighted interpolation method. Precipitation estimates using these sources, as a 10-year average annual total volume for the High Plains, ranged from 192 to 199 million acre-feet (acre-ft) for 1940 through 1949 and from 185 to 199 million acre-ft for 2000 through 2009.

Evapotranspiration was obtained from three sources: the National Weather Service Sacramento-Soil Moisture Accounting model, the Simplified-Surface-Energy-Balance model using remotely sensed data, and the Soil-Water-Balance model. Average annual total evapotranspiration estimated using these sources was 148 million acre-ft for 1940 through 1949 and ranged from 154 to 193 million acre-ft for 2000 through 2009. The maximum amount of shallow groundwater lost to evapotranspiration was approximated for areas where the water table was within 5 feet of land surface. The average annual total volume of evapotranspiration from shallow groundwater was 9.0 million acre-ft for 1940 through 1949 and ranged from 9.6 to 12.6 million acre-ft for 2000 through 2009.

Recharge was estimated using two soil-water-balance models as well as previously published studies for various locations across the High Plains region. Average annual total recharge ranged from 8.3 to 13.2 million acre-ft for 1940 through 1949 and from 15.9 to 35.0 million acre-ft for 2000 through 2009.

Surface runoff and groundwater discharge to streams were determined using discharge records from streamflow-gaging stations near the edges of the High Plains and the Base-Flow Index program. For 1940 through 1949, the average annual net surface runoff leaving the High Plains was 1.9 million acre-ft, and the net loss from the High Plains aquifer by groundwater discharge to streams was 3.1 million acre-ft. For 2000 through 2009, the average annual net surface runoff leaving the High Plains region was 1.3 million acre-ft and the net loss by groundwater discharge to streams was 3.9 million acre-ft.

For 2000 through 2009, the average annual total estimated groundwater pumpage volume from two soil-water-balance models ranged from 8.7 to 16.2 million acre-ft. Average annual irrigation application rates for the High Plains ranged from 8.4 to 16.2 inches per year. The USGS Water-Use Program published estimated total annual pumpage from the High Plains aquifer for 2000 and 2005. Those volumes were greater than those estimated from the two soil-water-balance models.

Total groundwater in storage in the High Plains aquifer was estimated as 3,173 million acre-ft prior to groundwater

development and 2,907 million acre-ft in 2007. The average annual decrease of groundwater in storage between 2000 and 2007 was 10 million acre-ft per year.

Introduction

The High Plains aquifer, underlying almost 112 million acres in the central United States (fig. 1), is one of the largest aquifers in the Nation. It is the primary source for drinking water, irrigation, animal production, and industry in the region. In 2000, the High Plains aquifer supplied drinking water for about 80 percent of the High Plains regional population (Sharon Qi, U.S. Geological Survey, written commun., 2005). In this report, the term “High Plains” refers to the landscape and aquifer system corresponding to the geographic extent of the High Plains aquifer system. Development of this region for agriculture began during the late 1800s with nonirrigated cropland and cattle grazing; however, low precipitation and high evaporation rates limited the production of nonirrigated crops for most of the area. Expansion of irrigated agriculture in the past 60 years has helped make the High Plains one of the most productive agricultural regions in the Nation. The High Plains region supplies approximately one-fourth of the Nation’s agricultural production (McMahon and others, 2007). As of 2007, there were 50 million acres of cropland, of which 15.4 million acres were irrigated, in the High Plains (U.S. Department of Agriculture, variously dated). Extensive withdrawals of groundwater for irrigation have caused water-level declines in many parts of the aquifer and increased concerns about the long-term sustainability of the aquifer.

This study is part of a series of regional studies funded by the U.S. Geological Survey (USGS) to evaluate the availability and sustainability of major aquifers across the Nation. These studies are designed to assist State and local agencies who manage groundwater resources and to assess the status of groundwater resources from a national perspective. The High Plains Groundwater Availability Study updates the High Plains Regional Aquifer System Assessment (Weeks and others, 1988). That study compiled information about the hydrogeologic framework, water-quality characteristics, hydrologic budget, and stresses to the aquifer system.

Purpose and Scope

This report describes selected approaches to estimate pregroundwater development (1940 through 1949) and current (2000 through 2009) water-budget components of the High Plains aquifer and overlying landscape. The report emphasizes the groundwater part of the budget but also includes several land-surface budget components because of their connection with the groundwater system. Because no single method can perfectly quantify the magnitude of any part of a water budget at a regional scale, results from several methods and previously published work are compared when feasible. Effects of land use, landscape, climate, and modeling methods on individual water-budget components are discussed. This report provides information that can be used to guide the construction and evaluate individual water-budget components of regional hydrologic models of the High Plains area, but does not present a complete water budget or comprehensive evaluation of groundwater availability or sustainability.

Water Budgets and Sustainability

A water budget is an accounting of hydrologic components of the water cycle, transfers between the components, and their relative contributions within a water system. Water budgets help define how much water is available, how much water is used, where the water comes from, and at what rate water is replenished. In its simplest form, a water budget defines the amount of water entering and leaving a water system. A schematic showing water inputs and outputs for the water system in the High Plains, referred to as the landscape and aquifer system, are shown in figure 2.

Under undisturbed or undeveloped conditions, the only sources of water to the High Plains landscape and aquifer system are from precipitation, streamflow from outside the High Plains, or subsurface water entering from underlying geologic units. Water entering the High Plains can follow many routes through the system. Precipitation can be lost to the atmosphere through interception or evapotranspiration (ET), which includes evaporation from soil or water bodies and plant transpiration; flow to streams or reservoirs; or percolate downward where it either is stored in the unsaturated zone or becomes aquifer recharge. Incoming streamflow can infiltrate into the aquifer, evaporate, or continue to flow out of the High Plains. Water entering the aquifer from subsurface sources or as infiltration from surface sources (recharge or stream leakage) can be stored there, discharge to streams or springs, or become ET (if the water table is close enough to land surface). Once an area is developed for irrigated agriculture, water is transported from streams or the aquifer to irrigated fields where it becomes ET, surface runoff, or recharge (from irrigation return flow or canal leakage).

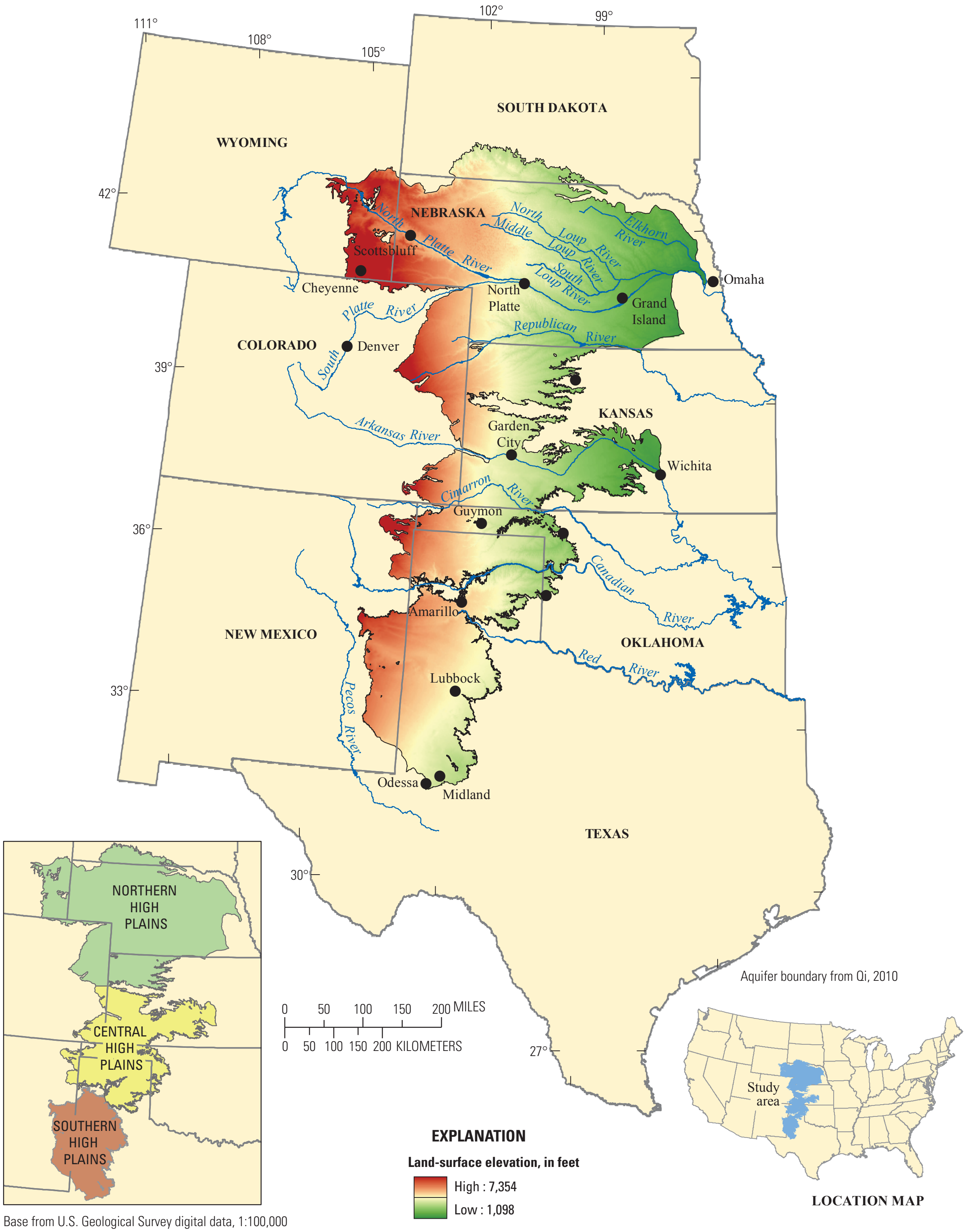
Water-Budget Equations

A simplified water-budget equation for a hydrologic system can be expressed as the following equation:

$$P + Q_{in} = ET + Q_{out} + \Delta S \quad (1)$$

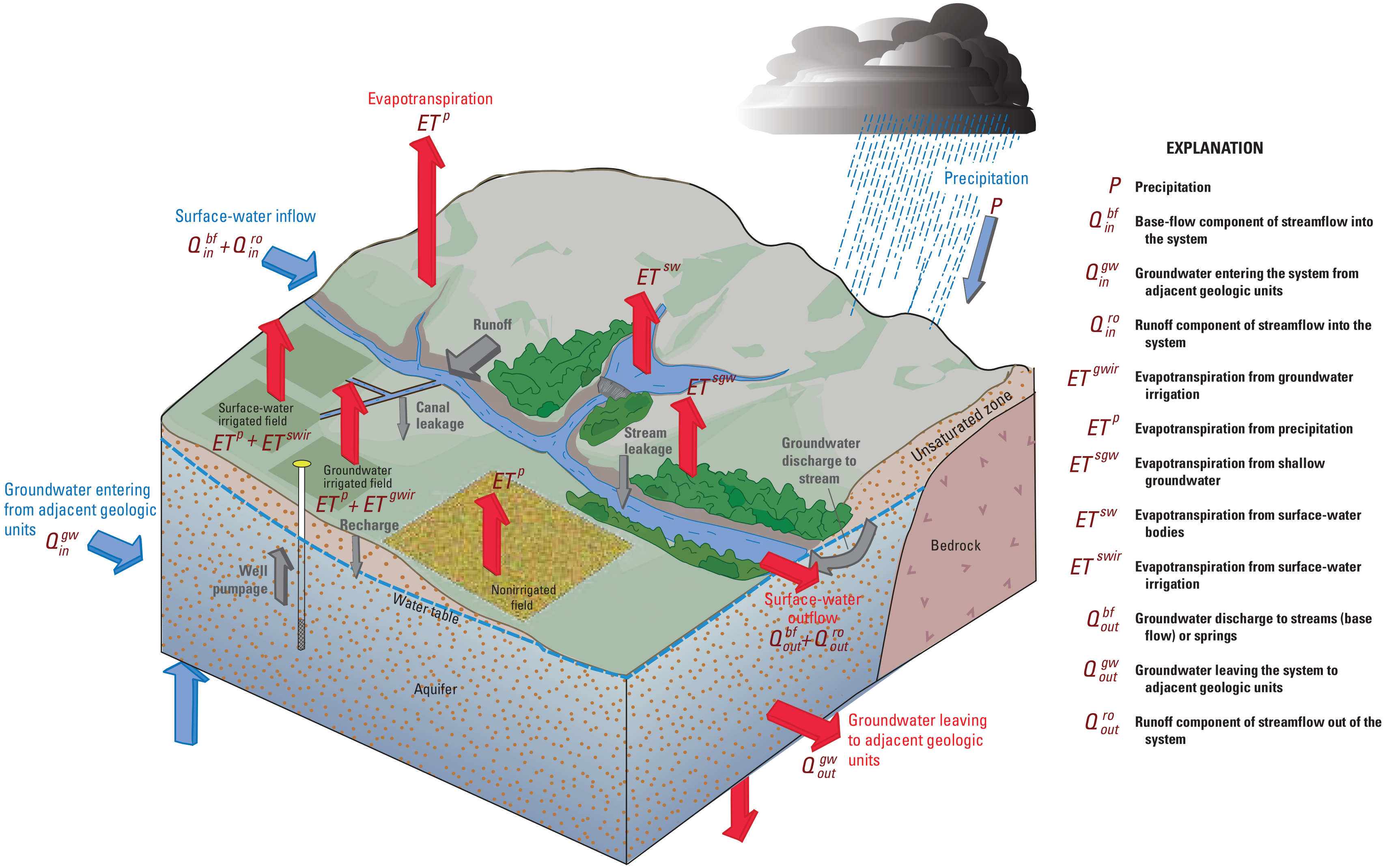
where

P is precipitation,
Q_{in} is flow into the system,
ET is evapotranspiration,
Q_{out} is flow out of the system, and
ΔS is the change in storage.



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983
North American Vertical Datum of 1988

Figure 1. Location of the High Plains aquifer.



EXPLANATION

P	Precipitation
Q_{in}^{bf}	Base-flow component of streamflow into the system
Q_{in}^{gw}	Groundwater entering the system from adjacent geologic units
Q_{in}^{ro}	Runoff component of streamflow into the system
ET^{gwir}	Evapotranspiration from groundwater irrigation
ET^{p}	Evapotranspiration from precipitation
ET^{sgw}	Evapotranspiration from shallow groundwater
ET^{sw}	Evapotranspiration from surface-water bodies
ET^{swir}	Evapotranspiration from surface-water irrigation
Q_{out}^{bf}	Groundwater discharge to streams (base flow) or springs
Q_{out}^{gw}	Groundwater leaving the system to adjacent geologic units
Q_{out}^{ro}	Runoff component of streamflow out of the system

Figure 2. Water-budget components of the High Plains landscape and aquifer system.

Precipitation and flow into the system represent inputs, and *ET* and flow out of the system represent outputs. Change in storage results from an imbalance between inputs and outputs. In the general system described by equation 1, the groundwater system is not treated as a separate hydrologic compartment.

For the High Plains landscape and aquifer system, these water-budget components can be expanded to:

$$P+Q_{in}^{bf}+Q_{in}^{gw}+Q_{in}^{ro}=ET^{gwir}+ET^{P}+ET^{sgw}+ET^{sw}+ET^{swir}+ Q_{out}^{bf}+Q_{out}^{gw}+Q_{out}^{ro}+\Delta S^{gw}+\Delta S^{sw}+\Delta S^{uz} \qquad (2)$$

where

P is precipitation,

Q_{in}^{bf} is the base-flow component of streamflow into the system,

Q_{in}^{gw} is groundwater entering the system from adjacent geologic units,

Q_{in}^{ro} is the runoff component of streamflow into the system,

ET^{gwir} is evapotranspiration of water from groundwater irrigation (groundwater pumpage minus return flow and runoff),

ET^{P} is evapotranspiration from precipitation,

ET^{sgw} is evapotranspiration from shallow groundwater,

ET^{sw} is evapotranspiration from surface-water bodies,

ET^{swir} is evapotranspiration of water from surface-water irrigation (diverted water minus canal leakage, return flow, and surface runoff),

Q_{out}^{bf} is groundwater discharge to streams (base flow) or springs,

Q_{out}^{gw} is groundwater leaving the system to adjacent geologic units,

Q_{out}^{ro} is the surface-runoff component of streamflow out of the system,

ΔS^{gw} is the change in groundwater storage,

ΔS^{sw} is the change in surface-water storage, and

ΔS^{uz} is the change in unsaturated-zone storage.

This equation illustrates that in addition to precipitation, water can enter the system from outside the High Plains as the base flow or surface-runoff components of streamflow or from subsurface sources. Water leaves the system primarily by *ET* of water from precipitation, shallow groundwater, irrigation water (originating from surface water or groundwater), or directly from surface-water bodies. Water also flows out of the system as groundwater discharge to streams or springs, surface runoff to streams, or to adjacent geologic units. Imbalances between inputs and outputs will change the amount of water stored in groundwater, the unsaturated zone, or surface-water bodies.

A water budget can be created for any part of the hydrologic system, such as for a lake, the soil zone, the unsaturated zone, or the aquifer. The water budget specific to the High Plains aquifer system can be expressed by the following equation:

$$R^{gwir}+R^{P}+R^{sw}+R^{swir}+Q_{in}^{gw}=ET^{sgw}+Q_{out}^{bf}+Q_{out}^{gw}+Q_{out}^{pump}+\Delta S^{gw} \qquad (3)$$

where

R^{gwir} is recharge from groundwater-irrigation return flow [groundwater withdrawal (Q_{out}^{pump}) minus evapotranspiration of water from groundwater irrigation (ET^{gwir}) minus groundwater-irrigation water runoff to streams],

R^{P} is recharge from precipitation ($P - Q_{out}^{ro} - ET^{P}$),

R^{sw} is recharge from surface-water seepage ($Q_{in}^{ro} + Q_{in}^{bf} - Q_{out}^{ro} - Q_{out}^{bf}$),

R^{swir} is recharge from surface-water-irrigation return flow and canal leakage [diverted surface water minus diverted surface water that returns to streams minus evapotranspiration of water from surface-water irrigation (ET^{swir})], and

Q_{out}^{pump} is groundwater withdrawal, and other terms are as defined previously.

The aquifer-specific budget components are linked closely to the budget components in equation 2, particularly precipitation and *ET*. Recharge has been divided into several components to reflect the different sources of water that can become available for recharge: precipitation, groundwater-irrigation return flow, surface-water-irrigation return flow and canal leakage, and seepage from naturally occurring surface-water features. In addition to the terms listed in the equation explanation, each of the recharge components is related to changes in the amount of water stored in the unsaturated zone. Groundwater withdrawals also are related to landscape processes because the amount of water needed for irrigation is determined by *ET* demand of the crops grown at the land surface. Much of the groundwater withdrawn for other purposes likely returns to the aquifer or becomes surface-water runoff. For example, a portion of water withdrawn for public-water supplies will eventually end up in sewer systems and discharge to streams (Westerhoff and Crittenden, 2009).

Current and historical data describing the water-budget components for an aquifer often are not available and need to be estimated. These estimates are subject to uncertainties and limitations. Recharge and ET from groundwater can be particularly difficult to quantify (Healy and others, 2007). Groundwater withdrawals for irrigation can be measured directly but only have been measured for limited areas in the High Plains. Groundwater-flow models are used to help verify estimates of these budget components by comparing model results with observable hydrologic conditions such as groundwater levels and discharge to streams. Hydrologic models that determine the fate of precipitation and estimate the amount of additional water needed for irrigation are available to quantify these components, as well as other land-surface water-budget components, such as the fate of water diverted from streams and reservoirs for irrigation. Coupling land-surface and subsurface processes can provide a comprehensive assessment of groundwater and landscape water-budget components and a tool for evaluating the effects of changes in various water-budget components. Even though hydrologically defensible models are calibrated by adjusting water-budget components and other model parameters so that model results match hydrologic measurements (such as groundwater levels and streamflows), it is still useful to compare modeled water-budget components with results from independent studies as an evaluation of model performance.

Sustainability

Groundwater sustainability was defined by Alley and others (1999) as the "development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences." Understanding the components of the water budget is a prerequisite for assessing the sustainability of a hydrologic system. Under average long-term conditions in an undeveloped system, the amount of water leaving will be balanced by water entering the system. Climate change, geologic shifts, or human disturbances such as groundwater pumpage can cause an imbalance between inputs and outputs. For a groundwater system to be sustainable, water leaving the aquifer from pumpage must be balanced by increased recharge, reduced evapotranspiration from groundwater, or reduced discharge to streams. If water leaving the aquifer is not balanced by other hydrologic components, water stored in the aquifer will decline, and groundwater mining occurs.

Water budgets help define the balance between water entering and leaving an aquifer but do not account for other factors that affect the long-term sustainability of an aquifer. These additional factors include physical limitations on how much groundwater can be extracted; deterioration of groundwater quality; effects of groundwater depletions on streams, lakes, wetlands, and land subsidence; future climatic conditions; economic costs associated with extracting groundwater; and public policy goals.

Description of Study Area

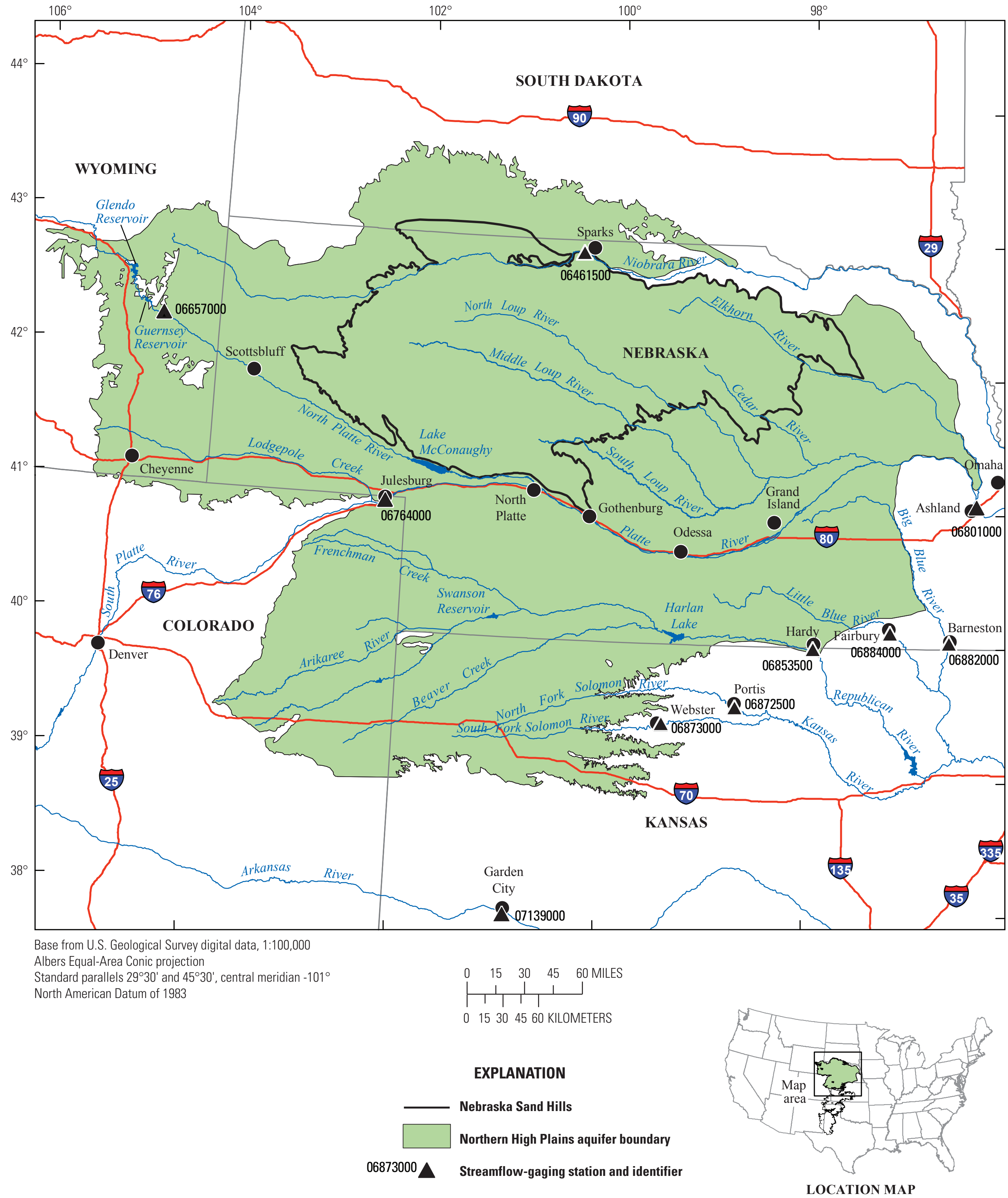
The High Plains landscape and aquifer system extent coincides with the boundary of the underlying High Plains aquifer that recently was updated to reflect changes in the understanding of the boundary location in Kansas, Colorado, Oklahoma, Texas, and New Mexico (Qi, 2010). The High Plains covers parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 1, table 1) and was divided into three geographic regions in previous studies—northern High Plains (NHP), central High Plains (CHP), and southern High Plains (SHP) (figs. 3, 4, and 5) (Weeks and others, 1988; McMahon and others, 2007). These regions were defined using natural aquifer boundaries, air-temperature gradients, and logistical considerations associated with water-quality sample collection. The bounds of those regional areas and their naming convention are used in this report.

Table 1. Area of High Plains within each region and State.

	Area, in million acres
Region	
Northern	61.7
Central	31.4
Southern	18.8
State	
Colorado	8.5
Kansas	19.7
Nebraska	41.4
New Mexico	6.0
Oklahoma	4.7
South Dakota	3.1
Texas	23.2
Wyoming	5.2
High Plains	111.8

Landscape

The High Plains is within the Great Plains physiographic province, which lies between the Rocky Mountains (not shown) on the west and the Central Lowlands (not shown) on the east (Fenneman and Johnson, 1946). Land-surface elevation is highest in the northwest, trending from about 7,400 feet (ft) along the northwestern boundary to about 1,000 ft along the eastern boundary. Most of the High Plains is composed of flat plains or gently rolling hills. Grasses are the dominant natural vegetation of the landscape, ranging from short-grass prairies in the west to tall-grass prairies in the east. Streams have dissected the plains, producing a drainage network and escarpments that in many places define the boundary of the High Plains. Wind-blown sand has formed dunes across parts of the High Plains. The largest sand dune region, the Nebraska Sand Hills, in north-central Nebraska (fig. 3), is one of the largest grass-stabilized dune regions in the world. Its unique topography consists of dunes as high as 400 ft and as long as 20 miles (mi) (Bleed and Flowerday, 1989). Numerous lakes and meadows are located between the dunes, where groundwater is at or near land surface. In other parts of the High Plains, ephemeral shallow lakes have formed in shallow depressions called playas. Most playa lakes are not connected to the groundwater and contain surface runoff from precipitation events. Playas are most common south of the Arkansas River (Gutentag and others, 1984).



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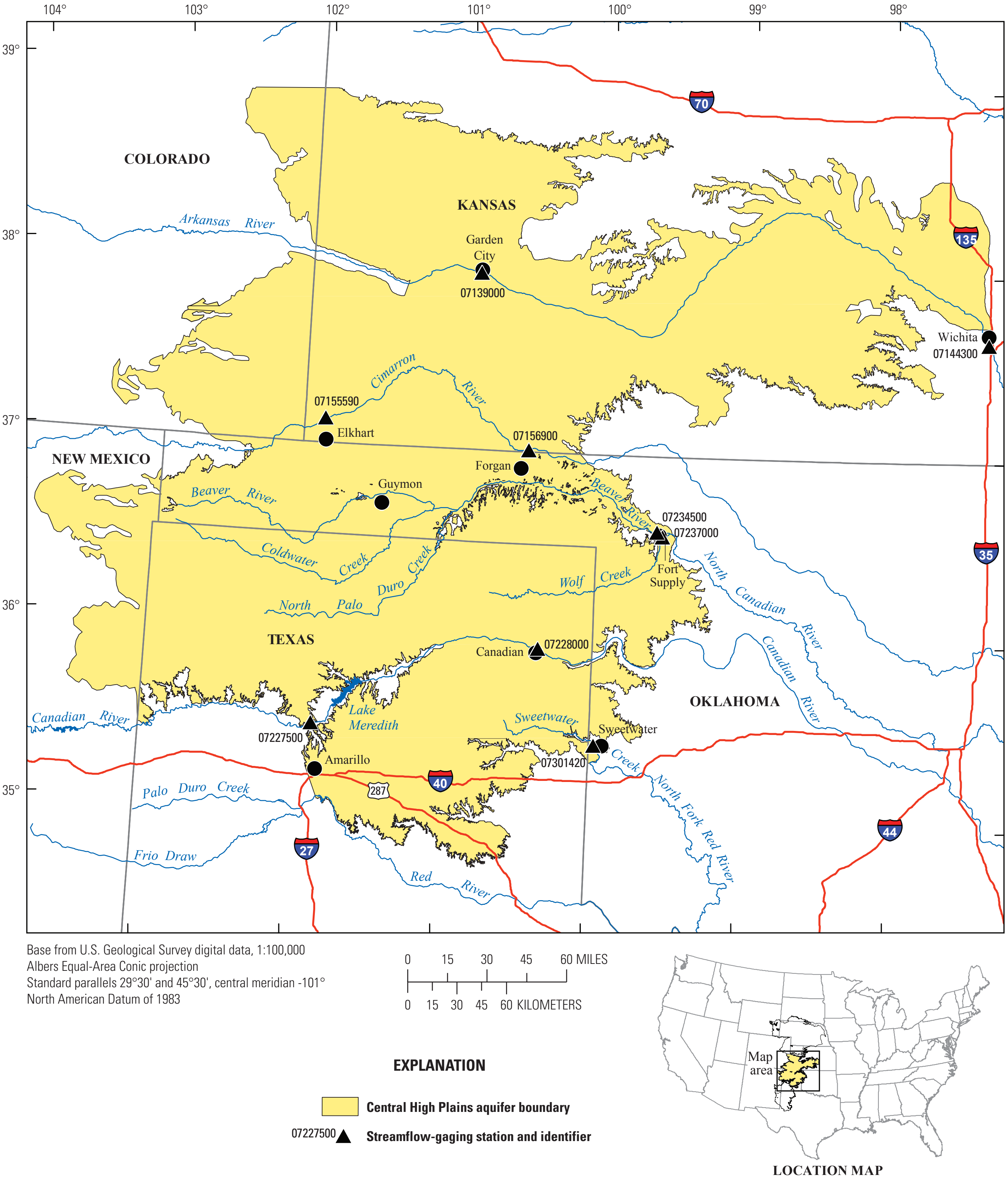
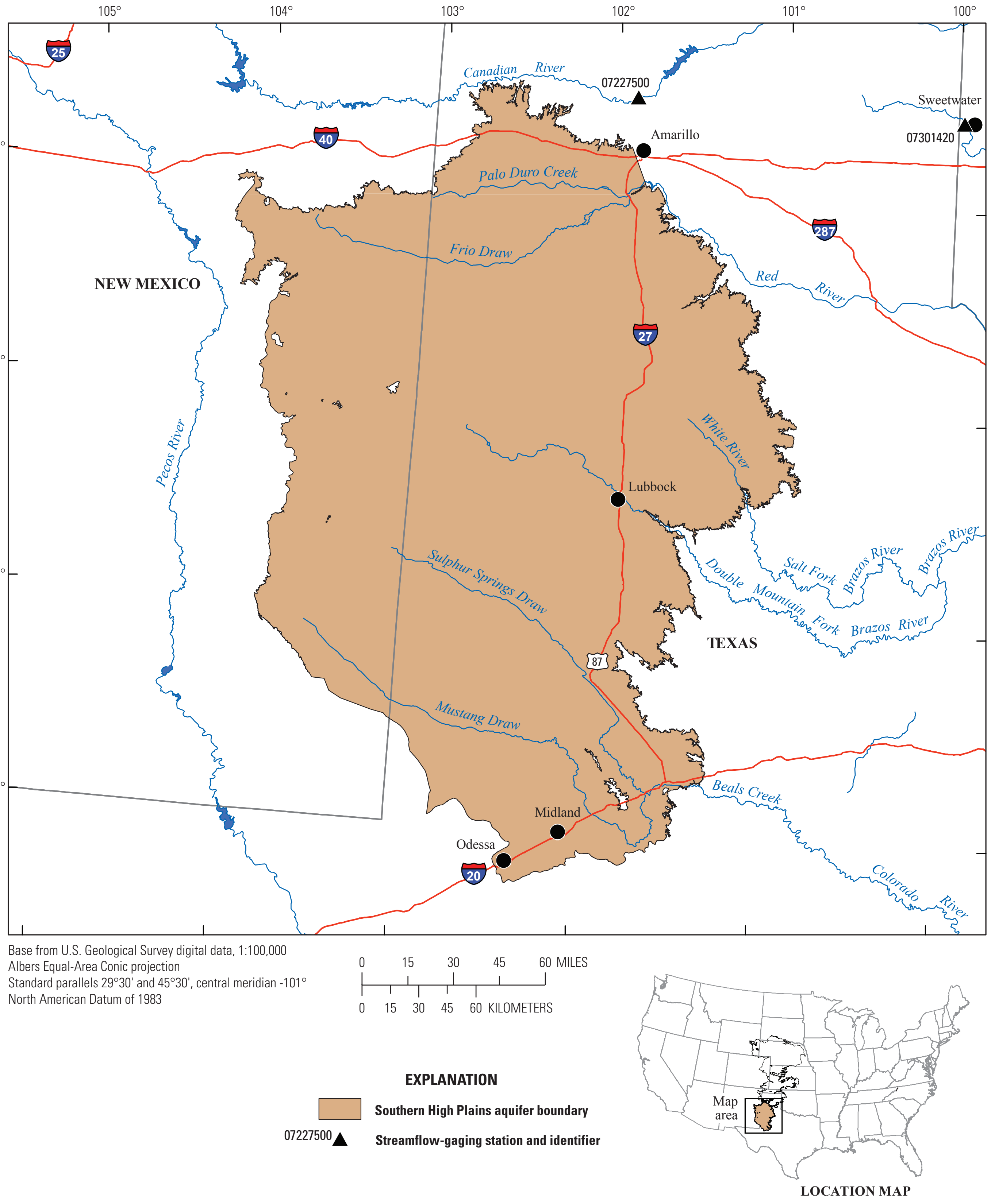
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

Figure 3. Location of the northern High Plains.



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

Figure 4. Location of the central High Plains.



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North American Datum of 1983

Figure 5. Location of the southern High Plains.

Climate

The High Plains has a continental climate with strong seasonality of temperature extremes. Air temperatures generally increase from north to south (fig. 6). Average air temperatures for 14 weather stations (fig. 7) across the High Plains measured during 1905 through 2009 ranged from 47.4 to 76.8 degrees Fahrenheit (°F) (U.S. Historical Climatology Network, 2010). Average air temperature from 2000 through 2009 (55.6°F) was almost 1 degree warmer than the mean temperature from 1940 through 1949 (54.7°F). An increase in mean air temperature has probably affected the water budget in recent years because potential evapotranspiration (PET) is affected by temperature. Greater PET rates will increase the demand for irrigation water if precipitation also does not increase.

Near-surface air is cooled as liquid water is turned to vapor by the process of ET. Irrigated fields lose more water through ET converting water to vapor than do nonirrigated cropland and rangeland. This process may have at least partially counteracted temperature trends, and it is possible that recent temperatures would have been warmer without the development of irrigation in the High Plains (Kueppers and others, 2007).

Average annual precipitation rates generally increase from west to east in the High Plains (Thornton and others, 1997). Average precipitation rates for 14 weather stations (fig. 7) measured during 1905 through 2009 ranged from 16.3 to 29.6 inches per year (in/yr) (U.S. Historical Climatology Network, 2010). Average precipitation for 2000 through 2009 (21.1 in/yr) was 1.0 inch less than average precipitation for 1940 through 1949 (22.1 in/yr). Precipitation rates as a component of the water budget are discussed in more detail in the “Precipitation” section of this report.

The frequent winds and high temperatures of the High Plains cause large evaporation rates (Gutentag and others, 1984). Potential evaporation rates measured from Class A evaporation pans ranged from 60 in/yr in the north to 105 in/yr in the south (Gutentag and others, 1984). Throughout the High Plains, potential evaporation rates are greater than precipitation rates, creating conditions that limit aquifer recharge.

The climatic record from the last century may not be representative of future conditions. Climate changes could affect future recharge rates, frequency and duration of droughts, ET rates through vegetation shifts, and demands for groundwater through changes in the availability of surface water for irrigation (Alley and others, 1999).

Surface Water

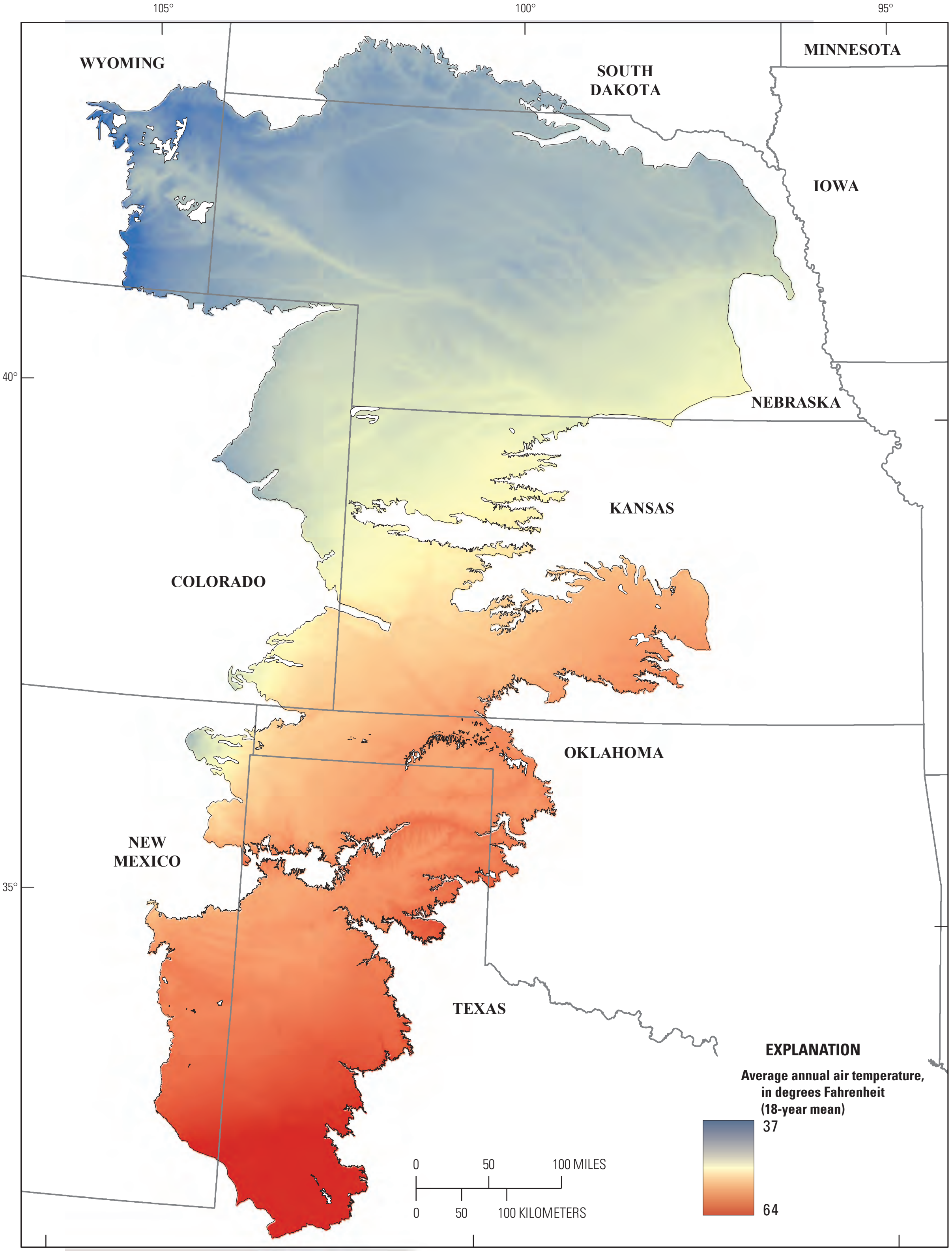
Perennial streams are more prevalent in the north than the south. Major streams draining the NHP are the Niobrara, Platte, Little Blue, Big Blue, Republican, and Solomon Rivers (fig. 3). The Arkansas and Canadian Rivers drain the CHP (fig. 4). No perennial streams drain the SHP (Blandford and others, 2003). Within the High Plains, streamflow in the Canadian, Kansas, Niobrara, Platte, and Republican River Basins (basins not shown) is controlled by reservoirs and canal diversions that provide water to agricultural land (Bureau of Reclamation, 2011).

The Nebraska Sand Hills (fig. 3) are an important recharge area for the High Plains. This recharge contributes to the regional flow system and base flow to several rivers that are tributaries of the Platte and Niobrara Rivers. Annual streamflow from the Sand Hills averages approximately 14 percent of annual precipitation (Bentall, 1998). Runoff to streams over most of the Sand Hills is limited by the dune landscape and permeable topsoil (Bentall and Shaffer, 1979). Vegetation is dominated by mixed-prairie grasses, which take up water during a moderately short growing season. These two characteristics allow much of the water that infiltrates the soil profile to become available for groundwater recharge, which contributes to reliable base flow of streams. As streams leave the Sand Hills, base flow ranges from about 80 to 95 percent of total streamflow (Stanton and others, 2010). As these streams cross the dissected and loess-covered plains to the south and east, however, they receive less base flow, more surface runoff, and the base-flow fraction of streamflow drops to between about 60 and 80 percent.

Though naturally occurring lakes are a minor component of the surface-water system on the High Plains, with most effects on the groundwater system local in scope, numerous small lakes and marshes in the Nebraska Sand Hills are closely connected to groundwater (Bleed and Ginsberg, 1998). Several large, artificial reservoirs in the NHP cause local groundwater mounding and increase water storage locally. Because the source of water in reservoirs is predominantly impoundment of surface runoff (or snowmelt from outside the High Plains), the net flux is from reservoirs to the High Plains aquifer. Although there is no quantitative estimate of water flux from surface reservoirs to the High Plains, it is considered minor because of the limited number and relatively small surface area of reservoirs on the High Plains. Several large storage reservoirs upstream from the western boundary of the High Plains are a dominant factor in the surface-water hydrology of the North and South Platte Rivers.

Agriculture

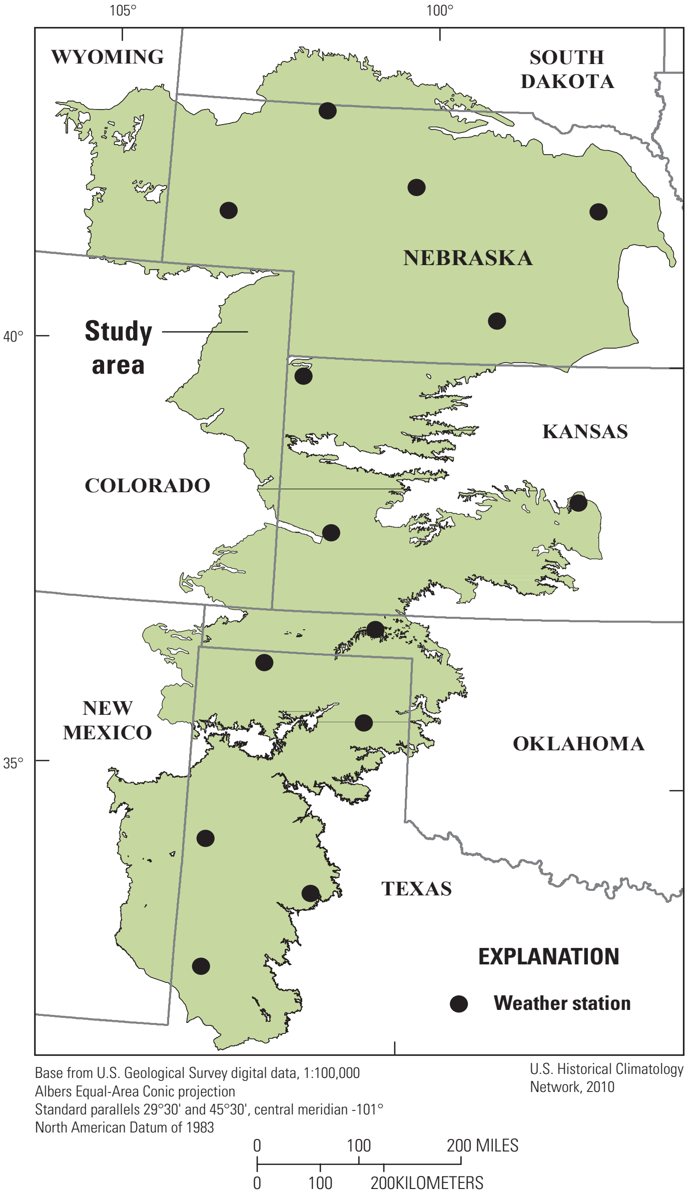
Most of the High Plains landscape is composed of flat plains or gently rolling hills, making it well-suited for growing crops. In 2007, almost one-half of the land area within the High Plains was used for growing crops (U.S. Department of Agriculture, variously dated). The principal crops grown in the High Plains in 2008 were corn, wheat, hay, alfalfa, soybeans, cotton, and sorghum, with primarily corn grown in the NHP, wheat in the CHP, and cotton in the SHP (U.S. Department of Agriculture, 2008). To support crop production, the aquifer has undergone extensive development for irrigation. The number of irrigated acres has increased from about 3 million in 1949



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

From Thornton and others, 1997

Figure 6. Distribution of average air temperature in the High Plains, 1980 through 1997.



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U.S. Historical Climatology Network, 2010

Figure 7. Weather stations used for assessing average annual air temperature and precipitation 1905 through 2009.

to about 15.4 million in 2007 (U.S. Department of Commerce, variously dated; U.S. Department of Agriculture, variously dated) (fig. 8*A*). Before the 1930s, irrigation generally was limited to areas where surface water could be diverted to crop fields, but advancements in well drilling and pumping equipment increased development of the aquifer as a source of irrigation water for fields in relatively flat areas after the drought periods of the 1930s and 1950s (Weeks and others, 1988). Later development of the center-pivot irrigation system in the 1960s further expanded irrigation to areas previously not suitable for irrigation because of their rolling topography.

In 2005, water for irrigation accounted for approximately 95 percent of total pumpage from the High Plains aquifer (Kenny and others, 2009). Groundwater pumpage for irrigation increased from approximately 4 million acre-ft in 1950 to about 20 million acre-ft in 1975 and was approximately 18 million acre-ft in 2005 (fig. 8*B*) (U.S. Geological Survey, variously dated). Several periods of time have had smaller-than-average precipitation that correlated with increased irrigated acres in the High Plains (fig. 8*A*). Conversely, a reduction in the number of irrigated acres in the 1980s corresponds to a period of greater-than-average precipitation.

Agriculture affects the water budget of a water system in several important ways. Greater recharge rates are associated more with nonirrigated cropland than with rangeland (Scanlon and others, 2005b; Sophocleous, 2004). The greater recharge is caused by changes to soil structure, vegetation coverage, wilting point, and rooting depth. Irrigation of agricultural fields further affects the hydrologic budget. Irrigation water increases ET and deep percolation, or potential recharge. If surface water is the source for irrigation, water is redistributed from streams, through canals, and finally to agricultural fields. Diverted water reduces streamflow and may increase recharge along the distribution system. If groundwater is the source for irrigation, groundwater pumpage increases and groundwater in

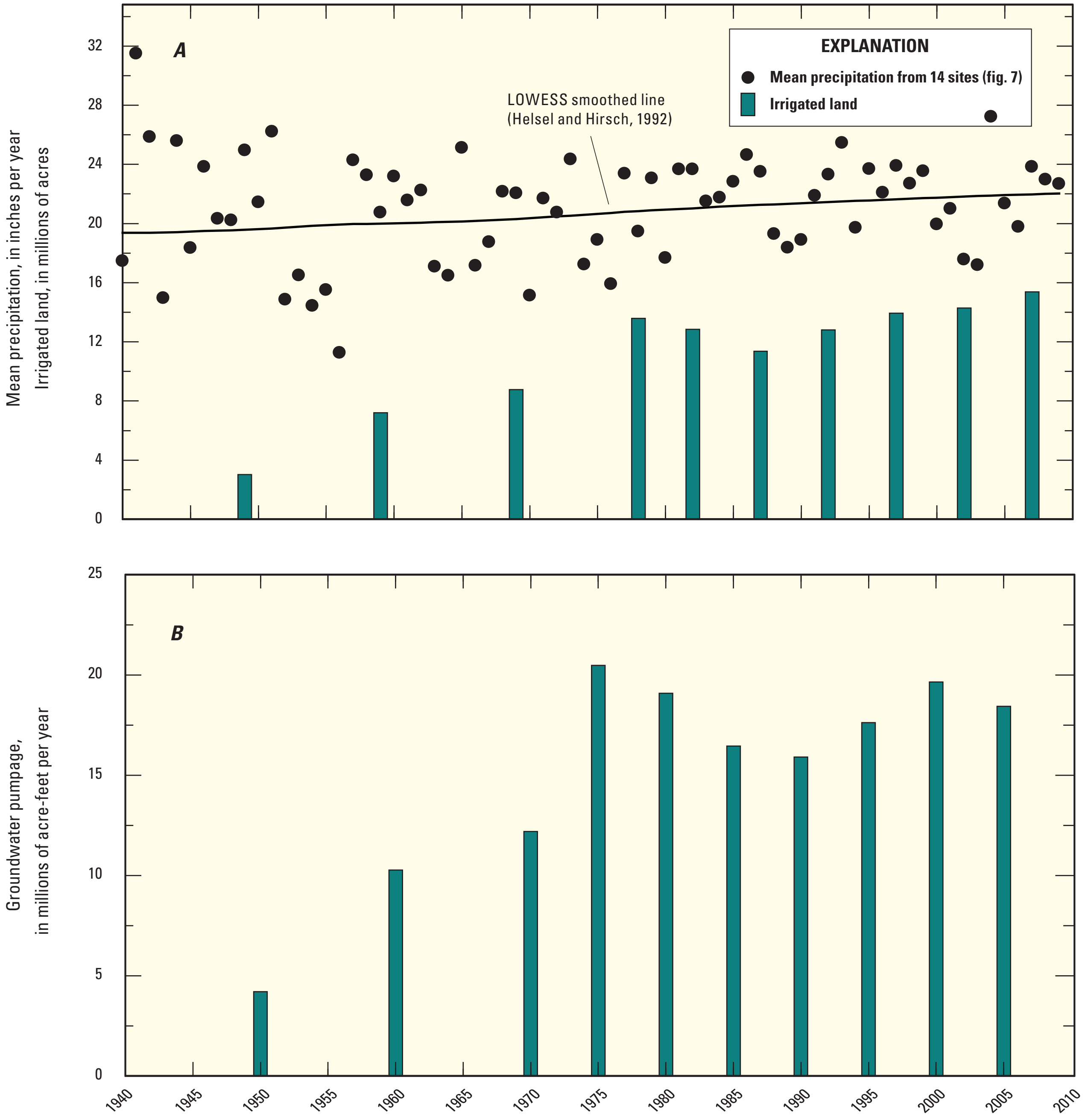
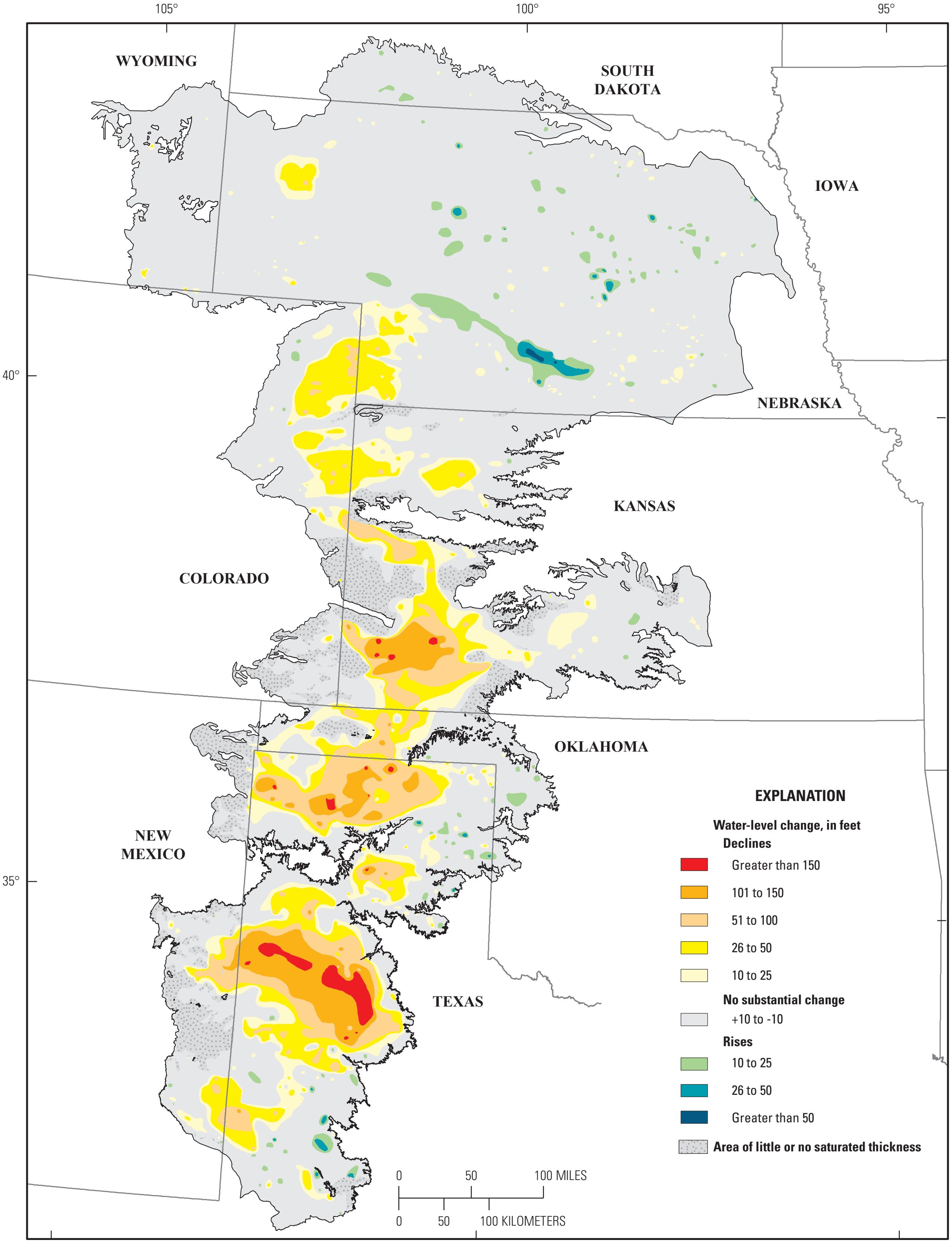


Figure 8. (*A*) Groundwater and surface-water irrigated acres, 1949 through 2007, and average annual precipitation, 1940 through 2009; (*B*) groundwater pumpage for irrigation in the High Plains, 1950 through 2005 (U.S. Department of Commerce, variously dated; U.S. Department of Agriculture, variously dated; U.S. Geological Survey, variously dated).

storage can be reduced. Groundwater-level declines have been observed in parts of the High Plains as a result of groundwater pumpage for irrigation (McGuire and others, 2003; McGuire, 2007) (fig. 9).

Irrigation methods also can affect the water budget. Center-pivot systems have improved irrigation efficiency by reducing deep-percolation rates associated with gravity-flow irrigation (Musick and others, 1990). The combination of center-pivot systems with low-energy, precision-application methods further improves irrigation efficiency by reducing water losses associated with droplet evaporation and drift (Howell and others, 1995). Center-pivot systems have been replacing gravity-flow systems since about the 1950s (Musick and others, 1990). According to estimates from the USGS Water-Use Program, most of the irrigated fields in High Plains States were irrigated primarily with sprinkler systems, such as center-pivot systems, in 2005 (U.S. Geological Survey, variously dated) (figs. 10*A*, 10*B*, and 10*C*).



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Albers Equal-Area Conic projection
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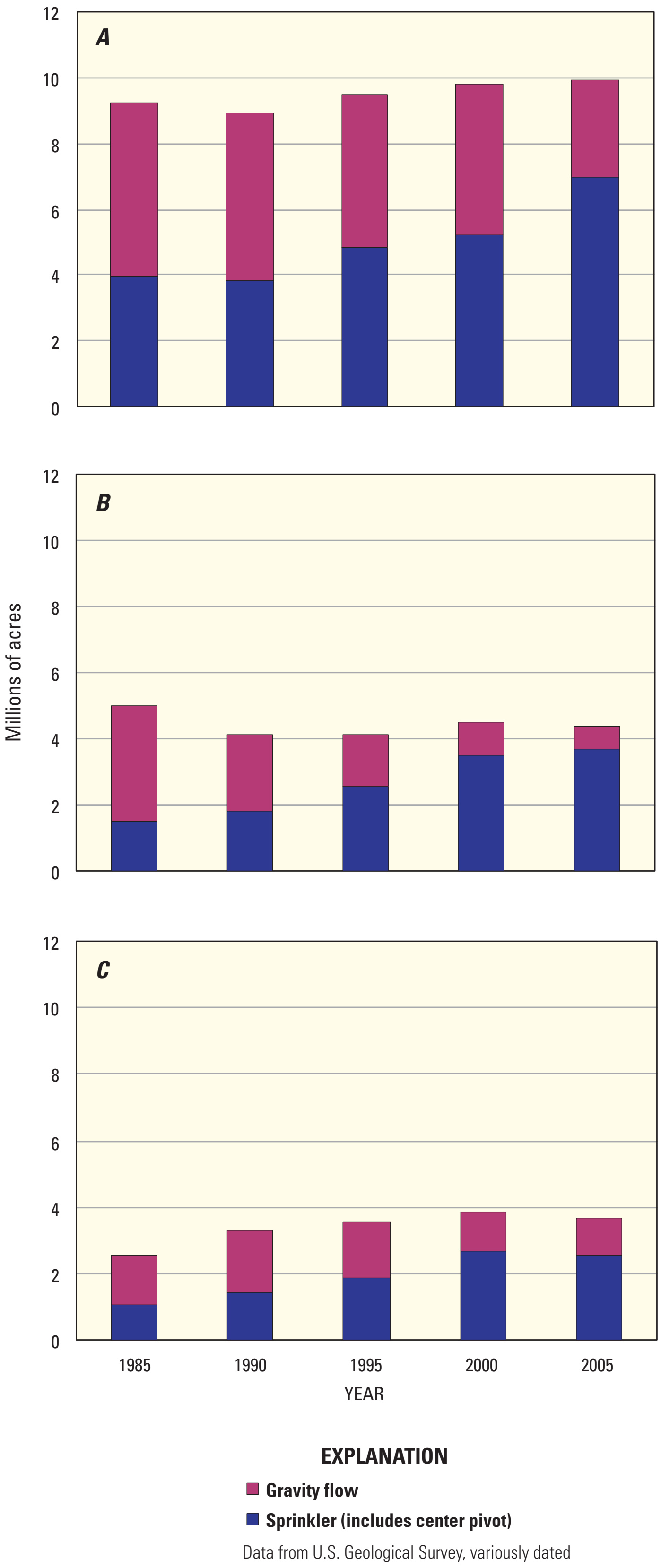
North American Datum of 1983

From McGuire (2007)

Figure 9. Groundwater-level changes in the High Plains aquifer, pregroundwater development (about 1950) to 2005.



Data from U.S. Geological Survey, variously dated

Figure 10. Number of acres irrigated by gravity-flow and sprinkler methods in the (*A*) northern High Plains, (*B*) central High Plains, and (*C*) southern High Plains.

Hydrogeologic Framework

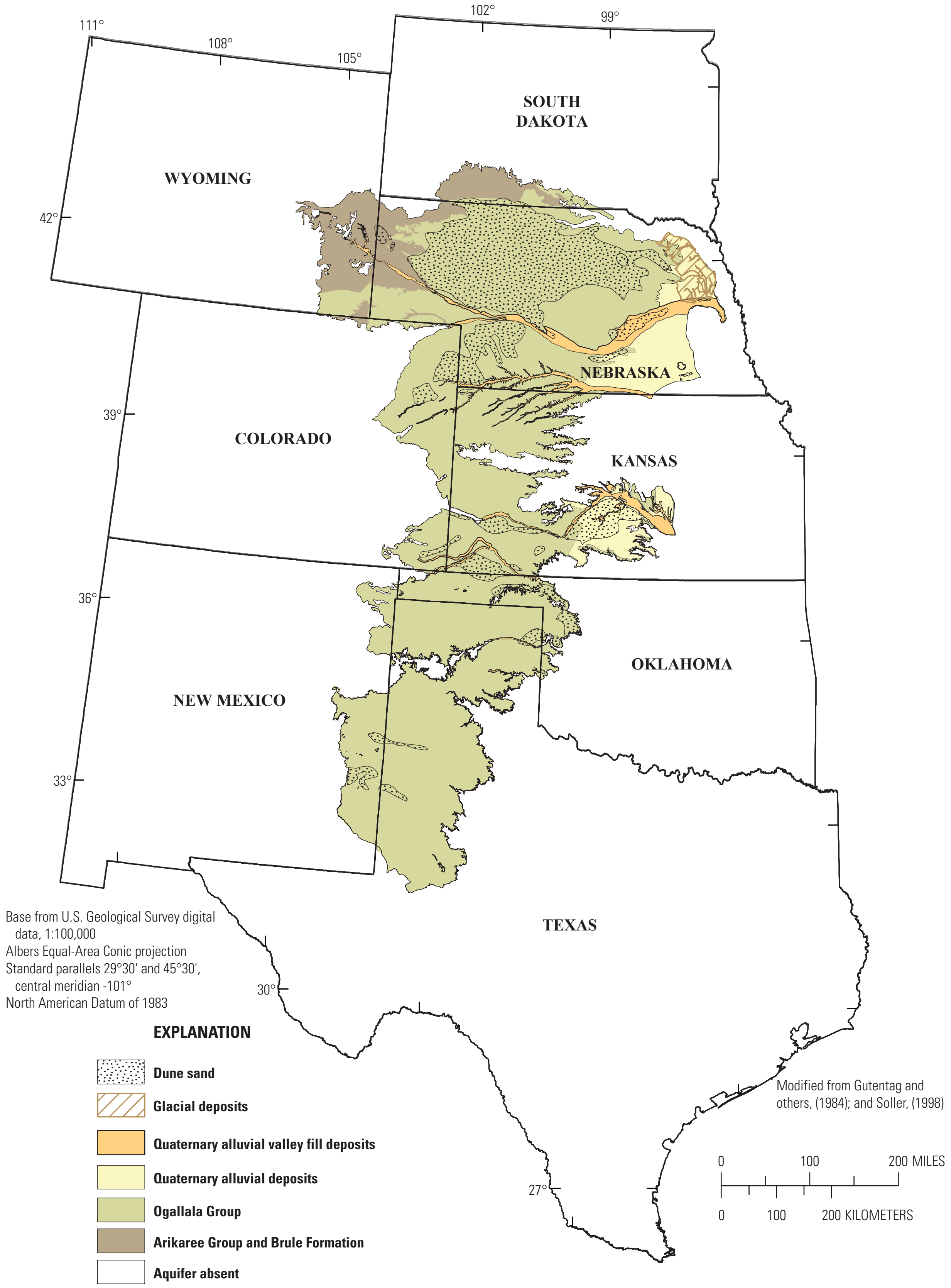
Although the hydrogeologic framework is not the subject of this report, a discussion of the basic framework is needed before discussing water budgets. Much of the description of geologic units is derived from the thorough description provided in Gutentag and others (1984).

Major Geologic Units

The High Plains aquifer consists of hydraulically connected deposits of late Tertiary and Quaternary age (Gutentag and others, 1984). Late Tertiary-age deposits, from oldest to youngest, include the Brule Formation of the White River Group, Arikaree Group, Ogallala Group, and Broadwater Formation (not shown) (Gutentag and others, 1984; Diffendal, 1995) (fig. 11). Quaternary-age deposits include alluvial, valley-fill, eolian sand, and glacial deposits. The Ogallala Group makes up most of the High Plains aquifer and underlies about 134,000 square miles (mi^2) of the study area (Gutentag and others, 1984). The paleosurface upon which the High Plains aquifer material was deposited slopes gently from west to east at 5 to 7 feet per mile (ft/mi), though local variations and buried valleys exist throughout the area. Geologic units underlying the High Plains aquifer are poorly permeable, middle-Tertiary-age or older deposits (Weeks and Gutentag, 1981). Groundwater flow between the High Plains aquifer and the underlying units is minimal.

The Brule Formation of the White River Group, together with the Arikaree Group, constitute the oldest geologic units of the High Plains aquifer, and both are present along the northwestern extent of the NHP aquifer. The Brule Formation is mainly a massive, poorly permeable siltstone, though locally containing coarser-grained deposits such as sandstone beds or channel deposits. It is considered part of the High Plains aquifer only where the permeability of the Brule Formation has been increased by secondary porosity such as joints, fractures, and solution openings (Gutentag and others, 1984). Areas containing coarser deposits, or where the permeability of the Brule Formation has been increased through secondary porosity, are difficult to map on a regional scale (Cannia and others, 2006). Where it was not enhanced through secondary porosity, the top of the Brule Formation forms the base of the High Plains aquifer. In the western part of the NHP region, the Brule Formation is overlain by the younger Arikaree Group (fig. 11), mainly composed of very fine to fine-grained sandstone. The Arikaree has a maximum thickness of about 1,000 ft in western Nebraska and eastern Wyoming.

Where both are present, the Arikaree Group is overlain by the Ogallala Group (Gutentag and others, 1984). The Ogallala Group is a heterogeneous deposit of interlayered stream sediments, lakebeds, and windblown sand, silt, and clay. The Ogallala Group varies greatly in sediment size and character over short distances (Cannia and others, 2006). Though highly variable, one consistent feature found at the top of the Ogallala Group in most areas of the High Plains is the Ogallala cap



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

Modified from Gutentag and others, (1984); and Soller, (1998)

Figure 11. Major geologic units in the High Plains.

rock, a caliche deposit, which is also called mortar beds. These deposits are cemented with calcium carbonate, are resistant to weathering, and form ledges when in outcrop (Weeks and Gutentag, 1984). The Ogallala Group is generally coarser than the underlying Arikaree Group, but less coarse than the overlying Quaternary alluvial and valley-fill deposits; gravel is not abundant within the Ogallala Group (Lawton, 1984). The maximum thickness of the Ogallala Group is about 800 ft (Swinehart and others, 1988).

The Broadwater Formation, a late-Tertiary alluvial sand and gravel deposit, overlies the Ogallala Group and underlies younger Quaternary-age deposits across the north-central part of the NHP (Swinehart and others, 1985). The Broadwater Formation has a maximum thickness of 300 ft and contains more silt eastward, though generally it is only distinguished from overlying Quaternary-age alluvial deposits because of its age, whereas the character and physical characteristics of both units are similar. Though not necessarily called Broadwater Formation in eastern Nebraska, equivalent late-Tertiary-age sand and gravel are present there as well.

Unconsolidated Quaternary-age alluvial gravel, sand, silt, and clay overlie and are in hydrologic connection with the Ogallala Group in the eastern parts of the CHP and NHP (fig. 11). Eastward of the margin of where both units are present, the Ogallala Group is absent, and Quaternary alluvial and valley-fill deposits directly overlie poorly permeable bedrock. The Quaternary-age alluvial deposits generally are thinner than areas dominated by the Ogallala Group, and maximum thicknesses are around 300 ft (Gutentag and others, 1984). Quaternary-age valley-fill deposits (fig. 11) are similar in character and deposition to the Quaternary-age alluvial deposits, and are distinguished because the valley-fill deposits are related to erosion and deposition by current-day stream systems rather than ancient streams. These valley-fill deposits are as much as 60 ft thick and are present near most major rivers that cross the High Plains aquifer. Across the SHP and partly into the CHP, the Ogallala Group is overlain by the Quaternary-age Blackwater Draw Formation consisting of sandy to clayey eolian sediments (Holliday, 1989).

Quaternary-age dune sand deposits overlie the Ogallala Group in large parts of the NHP and over some of the CHP, but only exist in small areas in the SHP (fig. 11). The largest contiguous area, known as the Nebraska Sand Hills, covers approximately 20,000 mi^2 of the NHP (fig. 3) and was undergoing dune formation and migration as recently as about 700 years ago (Miao and others, 2007). The dune sands range from very fine to medium sand and, where saturated, are considered part of the High Plains aquifer (Gutentag and others, 1984). The dune sand deposits are as much as 300 ft thick, but probably average closer to 100 to 150 ft, and actually are a relatively thin veneer on top of the underlying deposits of the Ogallala Group (Lawton, 1984). Ogallala Group deposits underlie all dune sands present in the High Plains (Muhs, 2007).

Though not always acknowledged in discussions regarding the High Plains aquifer, glacial deposits overlie the eastern end of the NHP (Condra and others, 1950). Whereas glacial deposits have been removed through erosion in major stream valleys, glacial till remains in intervalley areas of the NHP north of the Platte River (Soller, 1998). The glacial deposits consist of till and outwash overlain with eolian loess, with possible buried valley-fill deposits of sand and gravel. The distribution and occurrence of buried-valley deposits within or underlying the till is not well-known. Though the fine-grained till is only poorly permeable, groundwater may flow through local deposits of sand and gravel within the till and through underlying or intervening glacial valley-fill deposits. Eastern Nebraska glacial deposits are currently under study (Smith and others, 2008; Divine and others, 2009), but the interaction between groundwater within the glacial deposits and other aquifers is still poorly understood. However, groundwater-flow modeling studies of a sub-area of the NHP (Peterson and others, 2008; Stanton and others, 2010) used the western edge of the glacial till (fig. 11) as a no-flow or fixed-water-level model boundary. Both models calibrated favorably with minimal groundwater discharge across these boundaries, from the Quaternary alluvial deposits into the till deposits (west to east), supporting the concept that the High Plains aquifer may not be continuous through the area overlain with till.

Surficial deposits of eolian loess overlie parts of the NHP and CHP (Muhs and Bettis, 2000). Loess is defined as wind-blown sediment primarily of silt-size particles (Pye, 1995). The fine-grained loess deposits can be as thick as 325 ft (Condon, 2006; Johnson, 1960; Richmond and others, 1994).

Saturated and Unsaturated Zones

The proximity of saturated subsurface deposits to the land surface can affect the water budget. When saturated deposits are close to the land surface (thin unsaturated zone), shallow groundwater is available for plant transpiration; discharge to lakes where it can eventually evaporate; or discharge to streams where it can later evaporate, recharge groundwater downstream, or flow out of the system. In some cases, water that would otherwise become recharge will instead become surface runoff because sediments are already saturated and potential recharge rates exceed the rate of infiltration to the subsurface. In these areas, the recharge rate will decrease as the depth to saturated sediment decreases, and groundwater flow will be predominately horizontal instead of vertical (Sophocleous, 2004). In areas where saturated sediments are deeper, typically in arid or semiarid settings, they are less well-connected hydrologically with surface-water features, and recharge is more likely to occur where surface runoff collects in topographic depressions, such as playas or dry streambeds. Water moving downward through thick unsaturated zones can take decades or millennia to reach the aquifer (McMahon and others, 2006).

The boundary between the saturated and unsaturated zones is the water table. Water-table elevations for 2000 (fig. 12*A*) (McMahon and others, 2007; V.L. McGuire, U.S. Geological Survey, written commun., 2002) were used to calculate the thickness of saturated and unsaturated zones in the High Plains (figs. 12*B* and 12*C*). The saturated thickness was calculated as the difference between the water-table and the base-of-aquifer elevations (McGuire and others, 2003). The saturated thickness of the High Plains aquifer ranges from less than 50 ft in much of the SHP and near the edges of the aquifer to about 1,200 ft in the NHP. Flow of water through the saturated zone from recharge to discharge areas is controlled by the hydraulic conductivity of the aquifer material and the hydraulic gradient between the recharge and discharge areas. In the High Plains, sediments in the Broadwater Formation and Quaternary deposits generally are coarser and have greater hydraulic conductivity values than older deposits. As a result, water flows more freely through the younger deposits. Hydraulic gradients indicate that regional groundwater movement is generally from west to east with localized flow towards streams (fig. 12*A*).

The unsaturated zone thickness was calculated as the difference between the land-surface and water-table elevations. The thickness of the unsaturated zone ranges from 0 to greater than 300 ft (fig. 12*C*). The composition of the unsaturated zone can affect the movement of water through the system. Composition of the unsaturated zone in the High Plains is variable, consisting of unconsolidated clay, silt, sand, and gravel with localized zones of cemented calcium carbonate and silica (Gurdak and others, 2007). The fine-grained loess deposits present in parts of the NHP and CHP can restrict water flow; however, where fractures are present, downward flow could be substantial (Flury and others, 1994; McMahon and others, 2006). Conversely, flow downward through dune sand deposits is uniformly rapid.

Soil represents the shallowest part of the unsaturated zone. Most soils in the High Plains developed from loess or dune-sand deposits (Gutentag and others, 1984). Soil permeability ranges from less than 1 to greater than 9 inches per hour (in/hr) (Schwarz and Alexander, 1995) (fig. 13). Average permeability is 5.41 in/hr in the NHP, 2.73 in/hr in the CHP, and 1.87 in/hr in the SHP. Soil permeability can affect surface runoff, recharge, and irrigation components of the water budget. Soils that are more permeable will result in reduced surface runoff, increased recharge, and increased amounts of irrigation water needed to maintain adequate soil moisture for crop growth.

Soil-Water-Balance Models

Soil-water-balance models assist estimation of several components of the High Plains aquifer water budget by simulating processes in the soil profile, thus linking landscape conditions such as precipitation and ET to aquifer budget components such as recharge and irrigation pumpage. In the following sections, methods used to calculate water-budget component values by the SOil-WATer-Balance (SOWAT) and Soil-Water-Balance (SWB) models for this study are described. Although both the SOWAT and SWB models use a soil-water-budget equation to estimate unknown components of the soil-water budget, the models are formulated differently with respect to model inputs such as time-step length, ET, runoff, soil-moisture dynamics, and precipitation.

SOil-WATer-Balance (SOWAT) Model

The SOil-WATer-Balance (SOWAT) model, developed by the Columbia Plateau Water-Availability Study (Kahle and others, 2011), uses information about precipitation, *ET*, soil properties, land cover, and irrigation practices to compute two unknown quantities: groundwater withdrawals for irrigation and potential recharge. Estimates of the unknown quantities of groundwater withdrawals for irrigation and potential recharge were made on a monthly time scale at 449,504 cells across the High Plains for the period of 2000 through 2009. Model cells were 0.62 mi by 0.62 mi in extent. The soil profile water-budget equation solved by the SOWAT model for each model cell is:

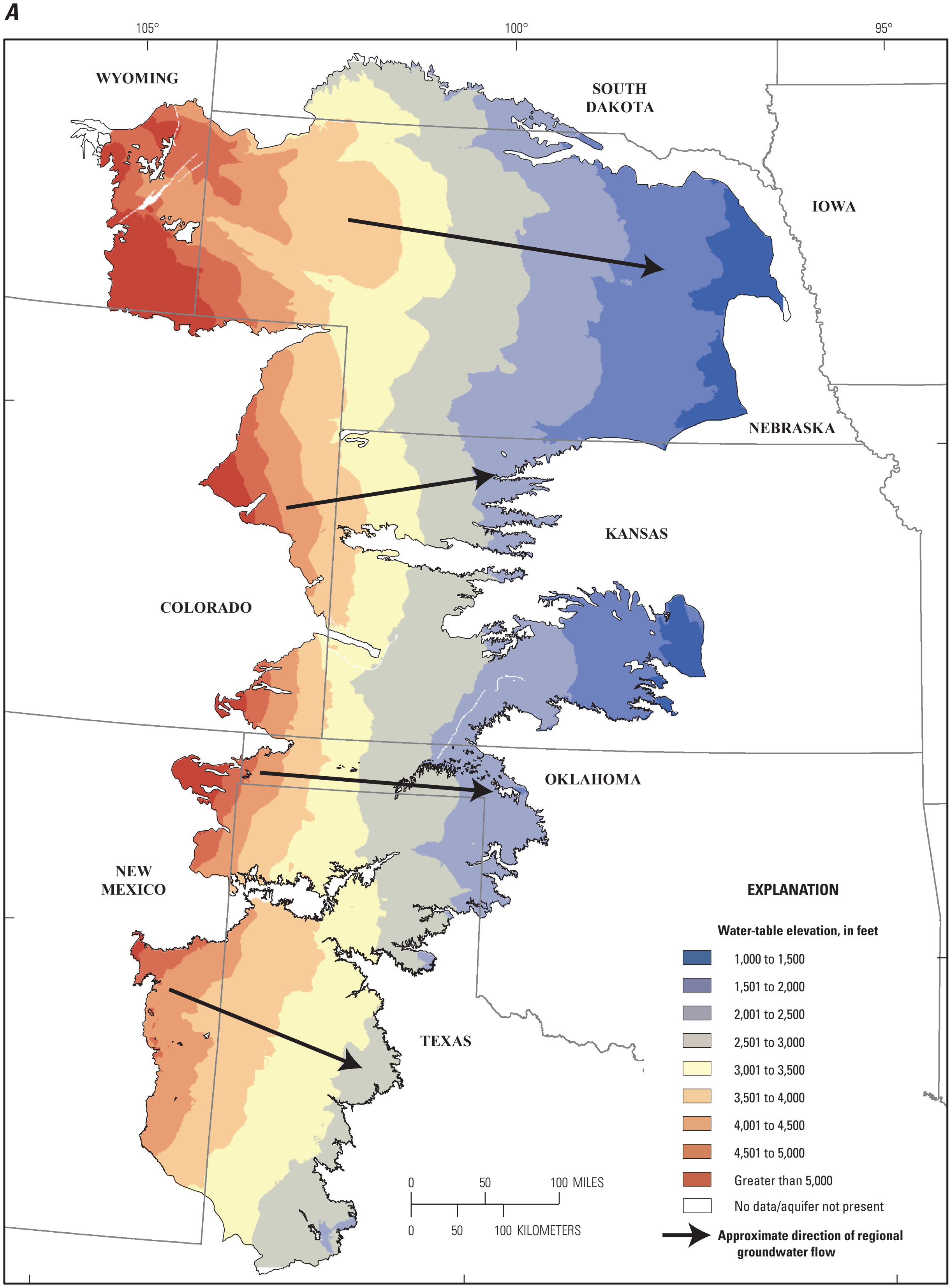
$$\Delta S^{soil} = P^{eff} + IR - ET - R \qquad (4)$$

where

ΔS^{soil} is the change in soil-water storage, in inches,
P^{eff} is precipitation plus snowmelt minus surface runoff, in inches,
IR is irrigation application, in inches,
ET is evapotranspiration, in inches, and
R is potential recharge, or deep percolation, in inches.

Precipitation and Evapotranspiration

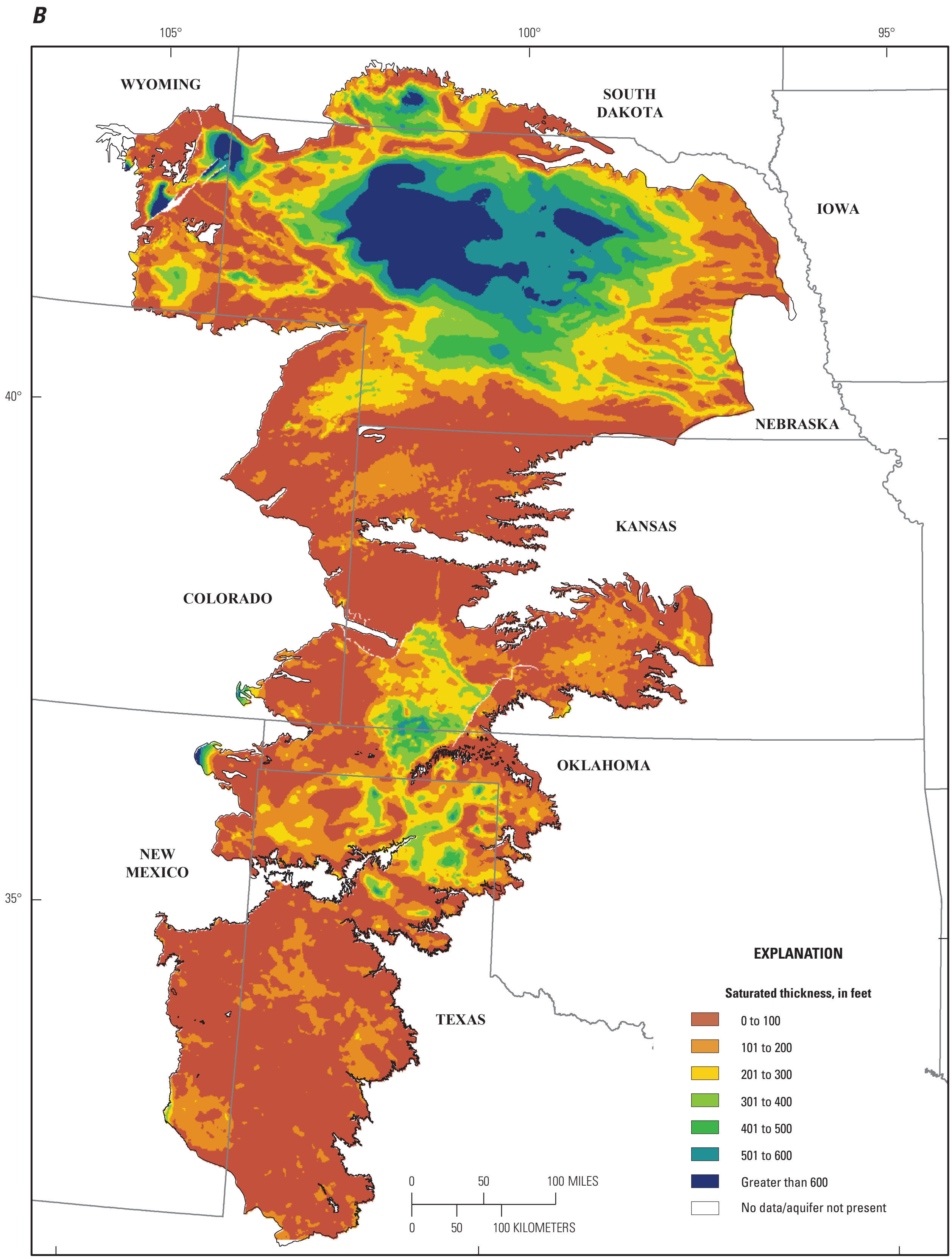
The SOWAT model was designed to accept precipitation data and a single pre-determined direct-runoff factor defined as a percentage of precipitation (Kahle and others, 2011). The model does not account for snowmelt directly in the soil-moisture calculations. Because the High Plains is such a large area with substantial climatic gradients and variations in soil texture, a single runoff factor is not adequate to describe conditions in the model area. Moreover, moisture input from snowmelt must be a consideration for much of the High Plains area. To accommodate these realities in view of model limitations, a combination parameter was calculated called “effective precipitation.” Effective precipitation represents the amount of natural (not irrigation) water available for infiltration into the soil and was calculated using precipitation (National Weather Service, written commun., 2010), snowmelt (Anderson, 2006), and surface-runoff (National Weather Service, written commun., 2010) data generated from a National Weather Service (NWS) hydrologic model called the Sacramento-Soil Moisture Accounting (SAC-SMA) model (described in the “Precipitation” section of this report). Effective precipitation was



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

From McMahon and others, 2007

Figure 12. (*A*) Water table, (*B*) saturated thickness, and (*C*) unsaturated thickness in the High Plains, 2000.



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
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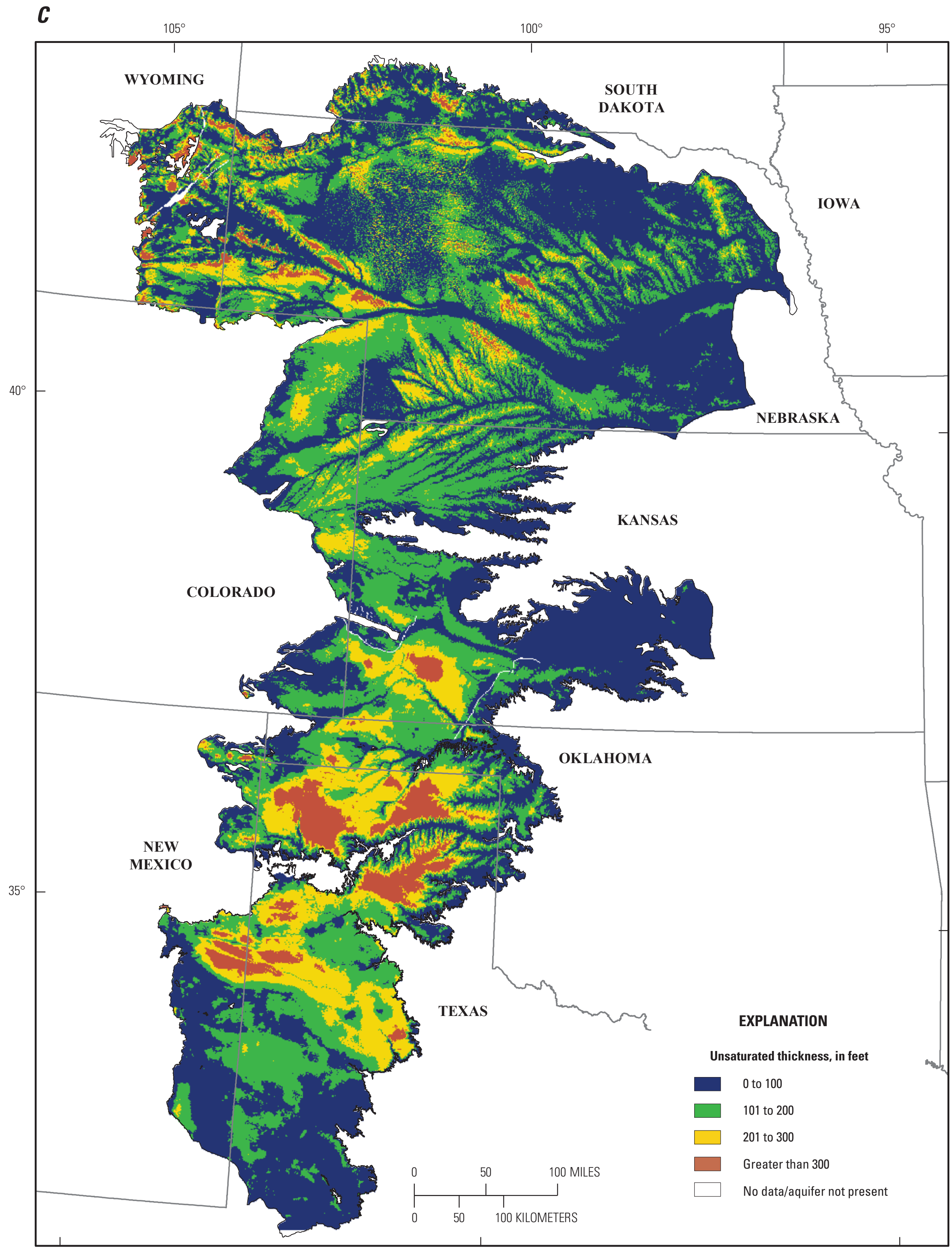
From McMahon and others, 2007

Figure 12. (*A*) Water table, (*B*) saturated thickness, and (*C*) unsaturated thickness in the High Plains, 2000.—Continued



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

From McMahon and others, 2007

Figure 12. (*A*) Water table, (*B*) saturated thickness, and (*C*) unsaturated thickness in the High Plains, 2000.—Continued

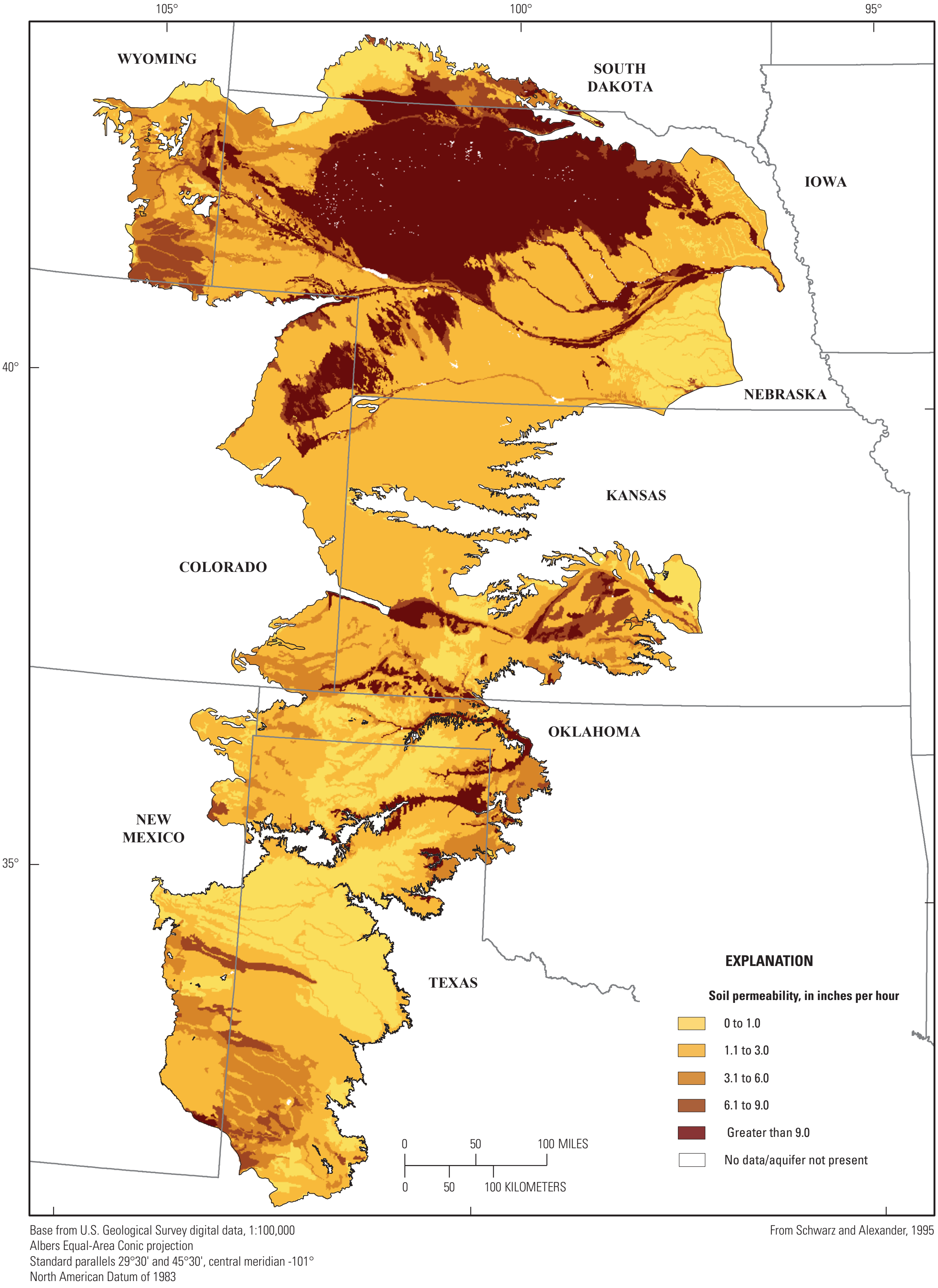


Figure 13. Permeability of soils in the High Plains.

calculated for each model cell as the sum of precipitation and snowmelt minus surface runoff.

The Simplified-Surface-Energy-Balance (SSEB) model estimates actual evapotranspiration (AET) from remotely sensed land-surface-temperature data. Specific details about the SSEB model are described in the "Evapotranspiration" section of this report.

Soil Properties, Land Cover, and Irrigation Practices

In the SOWAT model, simulated soil moisture is compared with the estimated soil moisture required to support crops (Kahle and others, 2011). If simulated soil moisture in a model cell is less than the soil moisture required, then irrigation is supplied until the soil moisture in that model cell fills to the water-storage capacity of the soil. The amount of water the soil is able to store also is known as the available-water capacity (AWC) of the soil. The AWC of the upper 59 in. of soils in the High Plains was derived from the General Soil Map (STATSGO) (Miller and White, 1998) (fig. 14). For this study, the minimum soil-moisture requirement was set in the model to 50 percent of the AWC of the soil. This percentage was based on water requirements for crops common to the High Plains (corn, wheat, sorghum, and cotton) (Kirkpatrick and others, 2006; McMahon and others, 2007). The initial moisture content of the soil for the month before the start of the simulation (February 2000) was estimated by running the model from March 2000 to December 2009 using an estimated initial condition and computing the average February soil moisture for 2001 through 2009.

Three land-cover classes were used as input for the SOWAT model: (1) irrigated agriculture, (2) nonirrigated agriculture and native vegetation, and (3) built-up land and water bodies. Because the National Land Cover Database (NLCD) for 2001 (Multi-Resolution Land Characteristics Consortium, 2001) only identified agricultural land and not irrigated fields, the irrigated cells were identified using the NLCD and delineated irrigated land for 2002 from remotely sensed satellite imagery (Brown and others, 2008). Thus, the NLCD and irrigated-land data sets were combined in this study. If a model cell identified as agricultural land from the NLCD also was identified as irrigated, then the cell was classified as irrigated agriculture in the SOWAT model (fig. 15). The irrigated agricultural cells in the land-cover grid identify where SOWAT allowed irrigation when a soil-moisture deficit existed for that cell during a simulation. Land identified in the NLCD as either built-up area or open water was reclassified as urban land/water bodies, and all other NLCD land-use classes were lumped into the native/nonirrigated-land class in the SOWAT model input.

The SOWAT model requires values for irrigation efficiencies (for groundwater and surface-water irrigation), the length of the irrigation season, and the fraction of groundwater and surface-water irrigation within a cell (Kahle and others, 2011). Irrigating with surface water is considered less efficient than with groundwater for this model because gravity-flow systems typically are used for irrigating with surface water, and sprinklers are more often used for irrigating with groundwater. Less irrigation efficiency means more water needs to be delivered to supply the crop-water requirements. Gravity-flow irrigation efficiencies can range from 35 to 90 percent (with tailwater reuse), and sprinkler irrigation efficiencies range from 55 percent to 95 percent (U.S. Department of Agriculture, 1997; Melvin and Yonts, 2009). Conservative estimates for mean irrigation efficiencies of 75 percent for groundwater and 65 percent for surface-water delivery were used in the High Plains SOWAT model.

Because there are substantial climate gradients across the High Plains, the length of the irrigation season can differ from the NHP to the SHP. Irrigation season lengths were estimated from an analysis of the monthly AET data (2000 through 2009). The beginning of the irrigation season was selected to be the month when mean monthly AET begins to rise rapidly in the spring; the end of the irrigation season was selected to be the month when AET decreases rapidly in the fall. The irrigation season estimated for the NHP and CHP regions was May through September. For the SHP, it was estimated as April through September. The same irrigation season was used for all years of the simulation.

Finally, the model requires an estimate of the fraction of irrigated acres in each model cell receiving irrigation water that is supplied by groundwater. This value is used to determine how much of the crop-water demand will be supplied by surface-water and groundwater sources. The values for each cell may range from 0.0 (100 percent supplied by surface water) to 1.0 (100 percent supplied by groundwater). For the High Plains, substantial surface-water irrigation occurs only in the NHP (Buchanan and others, 2009; Colaizzi and others, 2008). The fraction of groundwater irrigation in each cell for the NHP was determined using the location of surface-water irrigated fields within Nebraska, northwestern Kansas (Amanda Saunders, U.S. Geological Survey, written commun., 2010), and Wyoming (Matt Hoobler, Wyoming State Engineer's Office, written commun., 2010).

Model Calculations

The amounts of water needed for irrigation or potentially available for recharge are determined in the SOWAT model by comparing the simulated soil moisture with the AWC and applying an adjustment for irrigation efficiency. Simulated soil moisture (SM), in inches, is calculated by SOWAT (Kahle and others, 2011) as:

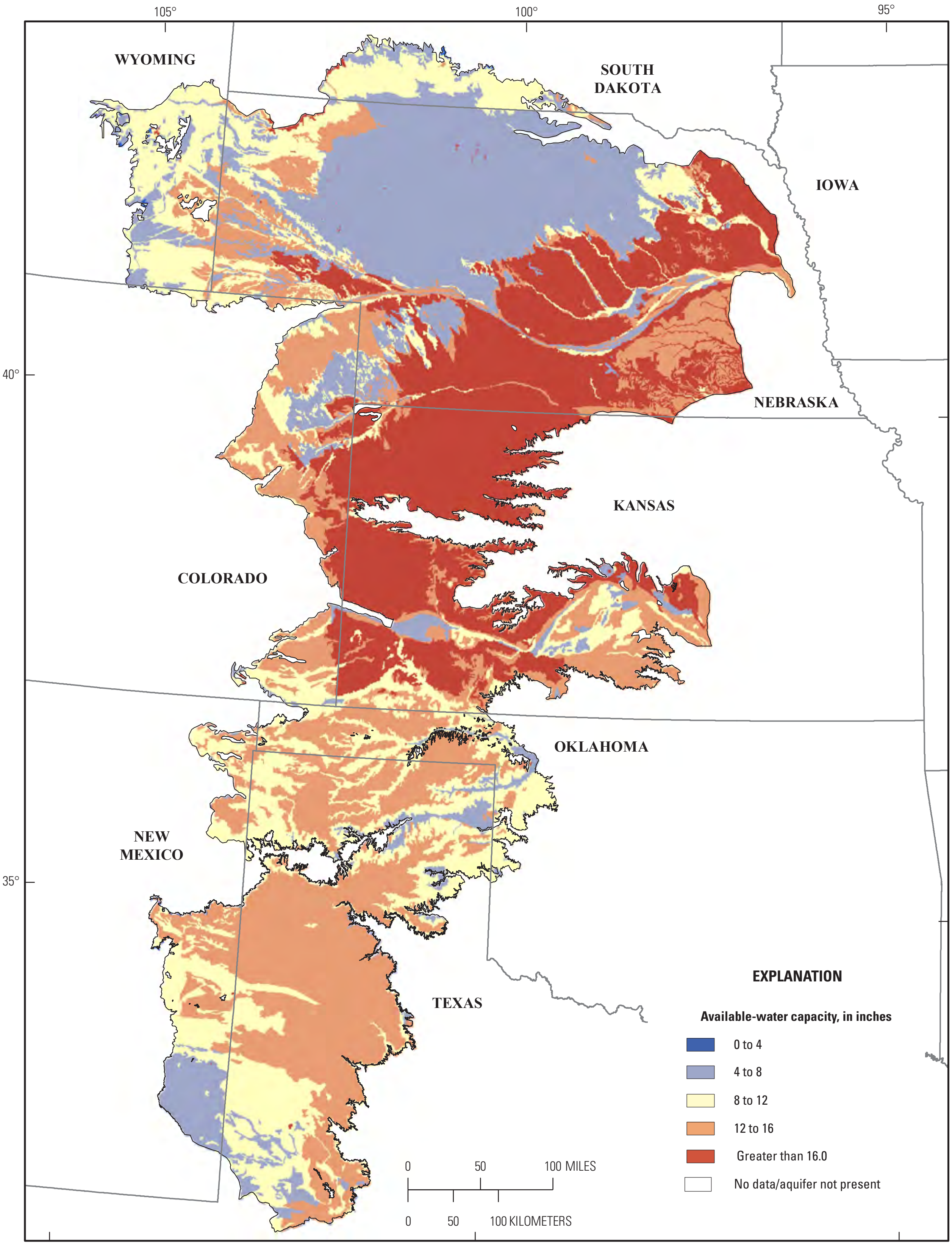
$$SM = SM' + P^{eff} - AET \tag{5}$$

where

SM' is soil moisture from the previous month, in inches,

P^{eff} is effective precipitation, in inches, and

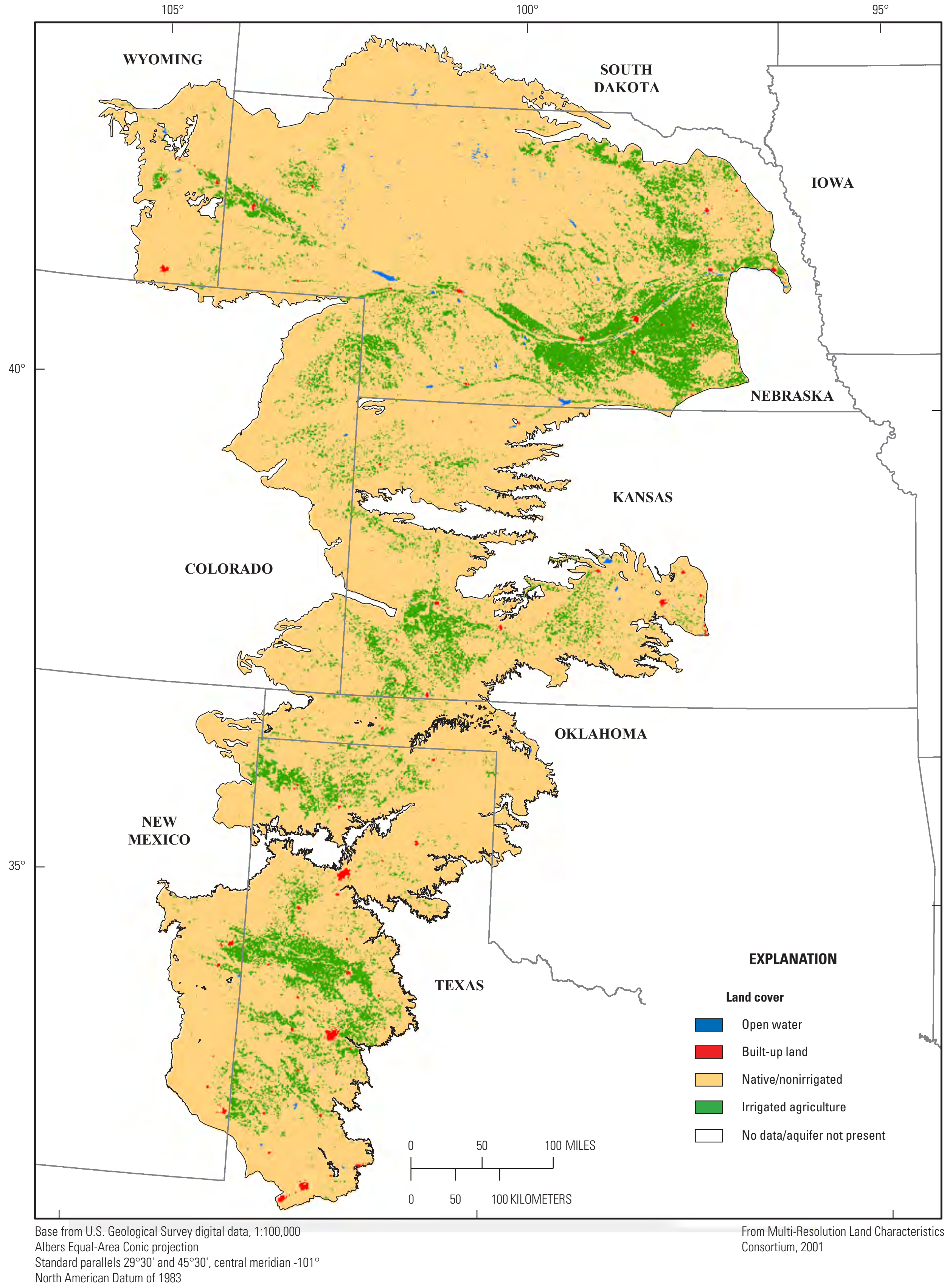
AET is actual evapotranspiration, in inches.



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

From Miller and White, 1998

Figure 14. Available-water capacity of upper 59 in. of soils in the High Plains.



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

From Multi-Resolution Land Characteristics Consortium, 2001

Figure 15. Land-cover classification in the High Plains.

Effective precipitation in the SOWAT model is added to the previous month's soil moisture, and *AET* is subtracted to determine the current month's soil moisture (Kahle and others, 2011). For irrigated cells during the irrigation season, the irrigation demand or amount of water potentially available for recharge is calculated from the soil moisture, *AWC*, and irrigation efficiencies. If soil moisture is greater than the *AWC*, excess moisture becomes available for potential recharge. If soil moisture is equal to or greater than the minimum soil-moisture requirement but less than the *AWC*, then no irrigation is applied for the current month. If soil moisture is less than the minimum soil-moisture requirement, irrigation water is added to the cell so that the soil moisture is equal to the *AWC*. The amount of irrigation water supplied to a model cell (Q^{irr}), in inches, is calculated as,

$$Q^{irr} = (AWC - SM) / IE \qquad (6)$$

where

AWC is the available-water content of the soil, in inches,

SM is simulated soil moisture, in inches, and

IE is irrigation efficiency, expressed as a fraction.

Supplied irrigation water is apportioned among groundwater and surface-water sources using a user-supplied fraction of irrigated acres in each model cell that is supplied by groundwater. If less than 100 percent of a model cell is groundwater irrigated, the remainder of the irrigation demand is supplied by surface water.

For nonirrigated model cells or non-irrigation-season months in the SOWAT simulation, irrigation water is not supplied to satisfy the ET demands of crops or native vegetation when soil moisture is less than the soil-moisture target. This can result in negative potential-recharge values. A possible interpretation of negative values is that water is supplied by other sources (deeper unsaturated zones, shallow groundwater, or surface water) to meet *AET*. If the simulated soil moisture is greater than the *AWC*, excess moisture becomes available for potential recharge.

Sensitivity Analysis

A sensitivity analysis determines the effect of changing model input values on model output values. Because model values (parameters) input into the soil-water-balance models can be uncertain, a range of values were tested in the model to determine how simulated recharge and irrigation pumpage might be affected by that uncertainty. To test sensitivity of recharge and irrigation pumpage to changes in SOWAT model inputs, groundwater and surface-water irrigation efficiencies, initial soil moisture, minimum soil-moisture requirement as a percentage of the AWC, effective precipitation, and AET were systematically and individually increased and decreased by 10 and 20 percent of the original parameter values for the duration of the 2000 through 2009 simulation period. The sensitivity of each parameter was tested separately for each region by varying each parameter individually while keeping all other parameters the same as the original simulation for that region.

Simulated recharge and irrigation pumpage were most sensitive to changes in effective precipitation and AET (fig. 16). Average annual simulated recharge was most sensitive to changes within the CHP, where a 20-percent decrease in effective precipitation caused a 214-percent decrease in recharge, and a 20-percent increase in AET caused a 192-percent decrease in simulated recharge. Decreases in recharge greater than 100 percent indicate that the AET demand would be satisfied by shallow groundwater or moisture in the unsaturated zone deeper than 59 in. below land surface if those sources of water were available. Average annual simulated irrigation pumpage changed the most in the NHP, where simulated irrigation pumpage increased by 46 percent in response to a 20-percent decrease to effective precipitation, and increased 72 percent in response to a 20-percent increase in AET. These sensitivity results highlight the need for reliable estimates of effective precipitation and AET when using water-balance models, because small errors in effective precipitation or in the model can cause large errors in simulated results. Simulated recharge and pumpage were much less sensitive to changes in irrigation efficiencies, initial soil moisture, and minimum soil-moisture requirement. The largest change to simulated recharge from a change to one of those three parameters was a 14-percent increase in response to a 20-percent decrease in irrigation efficiencies in the CHP. The largest change to simulated irrigation pumpage from a change to one of those three parameters was a 25-percent increase in response to a 20-percent decrease in irrigation efficiencies.

Soil-Water-Balance (SWB) Model

The Soil-Water-Balance (SWB) model (Dripps and Bradbury, 2007; Westenbroek and others, 2010) uses spatially distributed soil and landscape properties with daily weather data to calculate spatial and temporal variations in potential recharge and the estimated amount of irrigation water needed to sustain crops (appendix 1).

The SWB model layout (Westenbroek and others, 2010) consists of a grid, with soil properties and daily climate data attributed to each model cell. SWB calculates the fractions of precipitation and snowmelt that become surface runoff, AET, and recharge using a modified Thornthwaite-Mather soil-water accounting method to track the soil water in each cell through time (Thornthwaite and Mather, 1957; Westenbroek and others, 2010). Potential recharge, represented in SWB by deep percolation, is surplus water in the soil column between the land surface and the bottom of the root zone. Surplus water is calculated by subtracting the sum of the outputs (AET, surface runoff, plant interception) from the inputs (precipitation, snowmelt, surface runoff from adjacent cells).

Physical factors that control flow and loss of water on the ground surface and within the soil include the soil AWC,

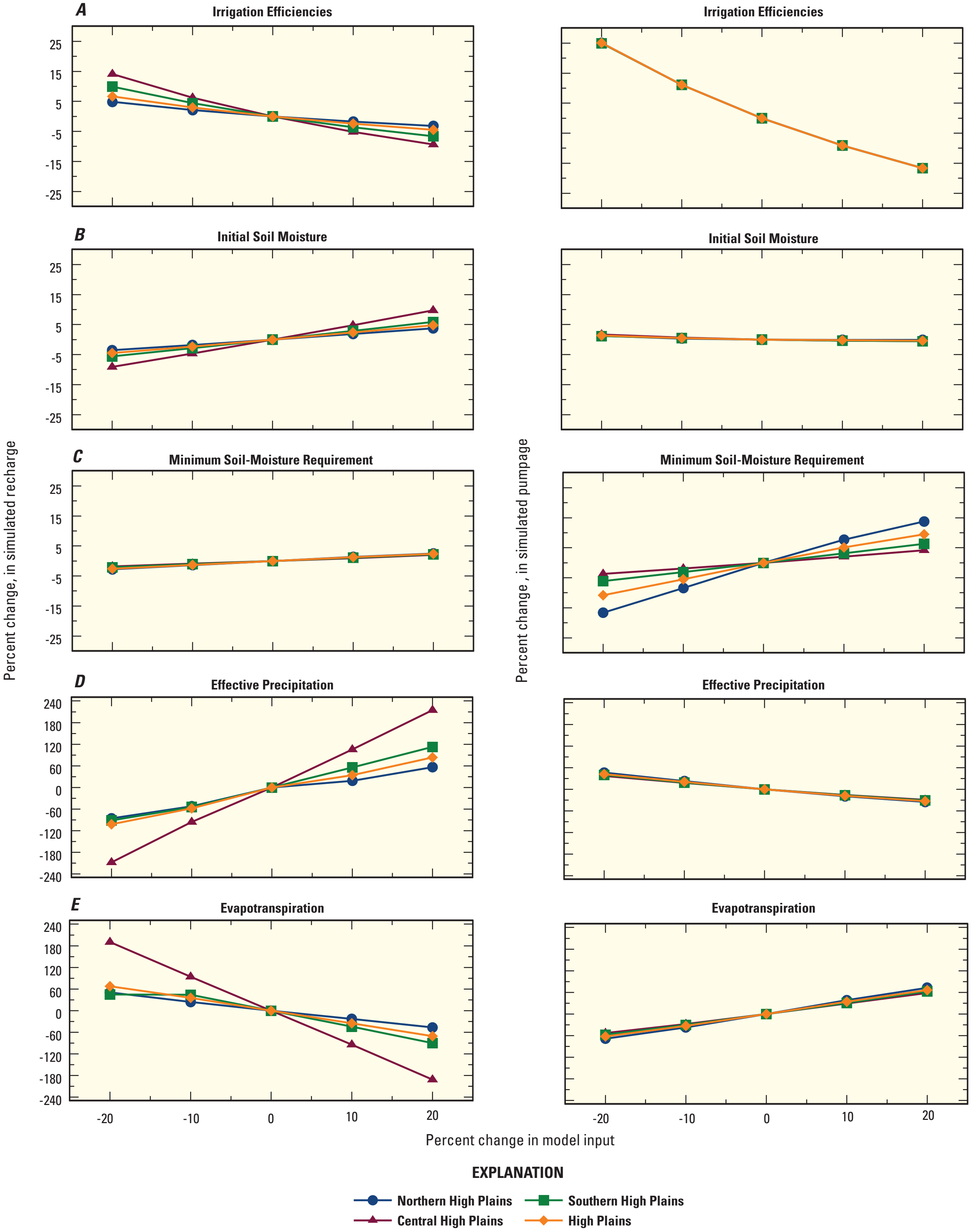


Figure 16. Sensitivity of average annual recharge and irrigation pumpage simulated by the SOil-WATer-Balance (SOWAT) model to changes in (*A*) irrigation efficiencies, (*B*) initial soil moisture, (*C*) minimum soil-moisture requirement, (*D*) effective precipitation, and (*E*) evapotranspiration.

hydrologic soil group, land use, and direction of surface-water flow, which is used for routing runoff. Soil properties were derived from the General Soil Map (STATSGO2) (U.S. Department of Agriculture, 2006). Land-use classes used to assign each cell included agricultural, urban, forest, and grassland (Multi-Resolution Land Characteristics Consortium, 2001). Characteristics assigned according to land use, such as the Natural Resources Conservation Service (NRCS) runoff-curve number for estimating the potential for surface runoff, plant interception values, and root-zone depth, were obtained from the USDA National Engineering Handbook (U.S. Dept. of Agriculture, 2004), Cronshey and others (1986), and Thornthwaite and Mather (1957).

To represent climatic conditions, the SWB code requires, at minimum, precipitation and temperature for each day. These data can either be from a single weather station and applied uniformly to the model grid, or from daily grids of weather data, interpolated from multiple stations located throughout and just outside the study area. For the geographically extensive High Plains, daily precipitation values were interpolated using inverse-distance weighting of weather-station data (National Climatic Data Center, 2010) for 1940 through 1949 and 2000 through 2009 (see the “Precipitation Methods” section of this report for more information). Daily air-temperature values were interpolated using a kriging method with weather-station data (National Climatic Data Center, 2010) for 1940 through 1949 and 2000 through 2009.

The model grid consisted of 452,979 grid cells across a rectangular area that extended beyond the boundaries of the High Plains. Grid cells were 5,000 ft by 5,000 ft in size. The SWB code processes the soils grids and daily weather grids to calculate the daily soil-water content from precipitation, potential ET (PET) and AET, surface runoff into and from adjacent cells, snowmelt, and potential recharge that passes below the root zone, on a cell-by-cell basis.

Initial soil-moisture values for the model were estimated by running the model for the year previous to each period of interest. Simulated soil-moisture values for the end of 1939 were used as initial conditions for 1940 through 1949, and simulated soil-moisture values for the end of 1999 were used as initial conditions for 2000 through 2009.

The only water source used as input to the soil profile in the published SWB code (Westenbroek and others, 2010) is precipitation. For this High Plains study, irrigation water was a substantial source for many areas from the 1950s to present (2011). To include irrigation water in the analysis, the model code was modified to allow irrigation to maintain soil moisture in irrigated agricultural areas (Brown and others, 2008; Multi-Resolution Land Characteristics Consortium, 2001) above a minimum level during the growing season (appendix 1). The volume of water necessary to maintain that level of soil moisture was assumed to be the volume of water entering the soil profile from irrigation, and was calculated as equal to the part of crop demand beyond that available from infiltrated precipitation plus stored soil water above the specified minimum level. Some parts of the High Plains were irrigated in the 1940s, but those areas composed a small percentage of the High Plains area (McGuire and others, 2003); therefore, irrigation water was not applied to the simulation during the 1940s.

Surface runoff is calculated using the NRCS curve-number method (Cronshey and others, 1986) and is affected by soil properties, moisture content, and air temperature. If surface runoff water is routed to a closed surface depression, available water can exceed AET and soil-moisture demands. In these cases, unrealistic recharge values can occur. To limit excessive recharge, a maximum recharge rate was set to 2, 0.6, 0.24, and 0.12 in/day for hydrologic soil group A, B, C, and D, respectively. The extra water that was not allowed to infiltrate was not carried into the following day. Precipitation that falls as snow is accounted by SWB as being stored on the surface until daily air temperature indicates it would melt (Westenbroek and others, 2010). The rate of snowmelt is determined from a temperature-index method where 0.059 in. of snow melts per day per average degree Celsius that the daily maximum temperature is above the freezing point. Infiltration and surface runoff also are affected by frozen ground, which is tracked continuously using a frozen-ground index (Molnau and Bissell, 1983). Runoff that is transferred between cells is tracked as inflow and outflow.

There are several methods available in the SWB code to estimate PET, but for this study the Hargreaves and Samani (1985) method was used, which uses the daily high and low temperatures to calculate PET. The SWB model then calculates AET from PET and the available soil moisture in storage as determined from a series of nonlinear relations (for combinations of soil type and vegetation categories) between soil moisture and the accumulated potential water loss (Thornthwaite and Mather, 1957). If precipitation exceeds PET, AET is equal to PET; if PET exceeds precipitation, AET is equal to precipitation plus the amount of water that can be extracted from the soil (up to but not exceeding the PET). Updates to the SWB code for this study include effects of crop-water use on AET and the availability of irrigation water to satisfy crop-water use requirements in irrigated areas (appendix 1).

Root-zone depths are an important parameter in the SWB model. Values are assigned based on hydrologic soil group and land-cover classification because the same vegetation type will send roots to different depths for different soil types. Digital elevation models were processed to determine the surface-water-flow direction for each grid cell, as described in Westenbroek and others (2010). Irrigation efficiency, the source of irrigation water, and the availability of shallow groundwater to satisfy crop-water demands are not defined in the model formulation.

Model Calculations

Potential recharge is equivalent to the surplus water in the soil profile and is calculated as the difference between the change in soil moisture and water inputs and outputs. Sources include precipitation, snowmelt, and inflow from adjacent cells. Outputs include interception by plants, outflow to adjacent cells, and *AET*. In equation form, the daily soil-water budget is expressed as:

$$recharge = (precipitation + snowmelt + inflow) - (interception + outflow + AET) - change\ in\ soil\ moisture \quad (7)$$

Estimation of the amount of irrigation required to sustain crop growth was calculated using the methods discussed in appendix 1.

Sensitivity Analysis

To test sensitivity of simulated recharge, crop-irrigation demand, and AET to changes in SWB model inputs, root-zone depth, runoff-curve number values, and precipitation, were systematically and individually increased and decreased over the entire High Plains by 10 and 20 percent for the 2000-through-2009 time period (fig. 17). The sensitivity of each parameter also was tested separately by varying each parameter individually while keeping all other parameters the same as the original model parameters.

Simulated results from the SWB model were less sensitive to changes in model inputs than were results from the SOWAT model. Changes to the runoff-curve number value by as much as 20 percent had the least effect on the simulation results, causing at most a 7-percent reduction in average annual simulated AET in the SHP (fig. 17*B*). A 20-percent change in root-zone depth caused average annual simulated recharge to change by as much as 15 percent in the NHP, 20 percent in the CHP, and 17 percent in the SHP (fig. 17*A*). Changes to root-zone depth had a smaller effect on simulated crop-irrigation demand and AET, causing as much as a 3.3-percent change in simulated crop-irrigation demand (NHP) and as much as a 2.3-percent change in simulated AET (SHP). Changes to precipitation had the largest effect on simulated results (fig. 17*C*). A 20-percent change to precipitation caused simulated recharge to change by as much as 42 percent in the NHP, 47 percent in the CHP, and 39 percent in the SHP. Simulated crop-irrigation demand changed by as much as 12 percent (NHP) and simulated AET changed by as much as 14 percent (CHP) in response to a 20-percent change in precipitation values.

As with the SOWAT model sensitivity results, the SWB model sensitivity results highlight the need for reliable precipitation values when using water-balance models, because small errors in precipitation inputs to the model can cause large errors in simulated results. If weather-station data or the method for estimating precipitation at locations between weather stations does not accurately represent precipitation occurring in the environment, then simulated recharge results will be less reliable. Though the SWB model is sensitive to changing root-zone depth, the most common land-use types were grassland and agriculture, which have well-constrained root-zone depths.

Limitations of SOWAT and SWB Models

Hydrologic models are necessarily a simplification of the hydrologic system and inherently have limitations. In addition, each type of model will have specific limitations depending upon the types of simplifications that are used. Many of the same limitations are applicable to the SOWAT and SWB models. These include:

1. The models do not simulate subsurface flows or physical properties below the root zone. The models provide estimates of water potentially available for groundwater recharge, but the path to the water table is not known and further analysis of the unsaturated zone is required to determine the fate of deep percolation.
2. The models are not calibrated to hydrologic measurements, such as groundwater levels and streamflows, to verify that they produce recharge and pumpage values that are consistent with observable hydrologic conditions.
3. As with other water-balance models, it was demonstrated in the sensitivity analysis results that the accuracy of the model outputs depends on the accuracy of the model inputs, particularly when the magnitude of the model output is much smaller than the magnitude of the model inputs. Precipitation and ET are much greater than recharge and pumpage and also have substantial uncertainties associated, particularly with their estimation at locations distant from measurement stations. These uncertainties could cause substantial errors in simulated recharge and groundwater withdrawals for irrigation.
4. When aggregating land-cover information, each model cell is assigned a land-cover class that represents the dominant cover type within that model cell, but subdominant cover types are a source of uncertainty. For example, a cell may encompass rangeland and agricultural land; if the agricultural land covers at least 50 percent of the cell, then the entire cell is assigned this class, and information about the rangeland is ignored. The same occurs for the determination of irrigated-agriculture cells. If the amount of irrigated land within a model cell is 50 percent or greater, then the entire cell is classified as irrigated. These situations could potentially overestimate or underestimate not only the amount of irrigated agriculture within the modeled area, but the water-budget components affected by land-cover and irrigation status.
5. The models are only applicable where the soil-root zone is above the water table and deep percolation can exit the soil profile.

SOWAT Model

The SOWAT model is a simplified soil-water-balance model specifically designed to determine monthly irrigation

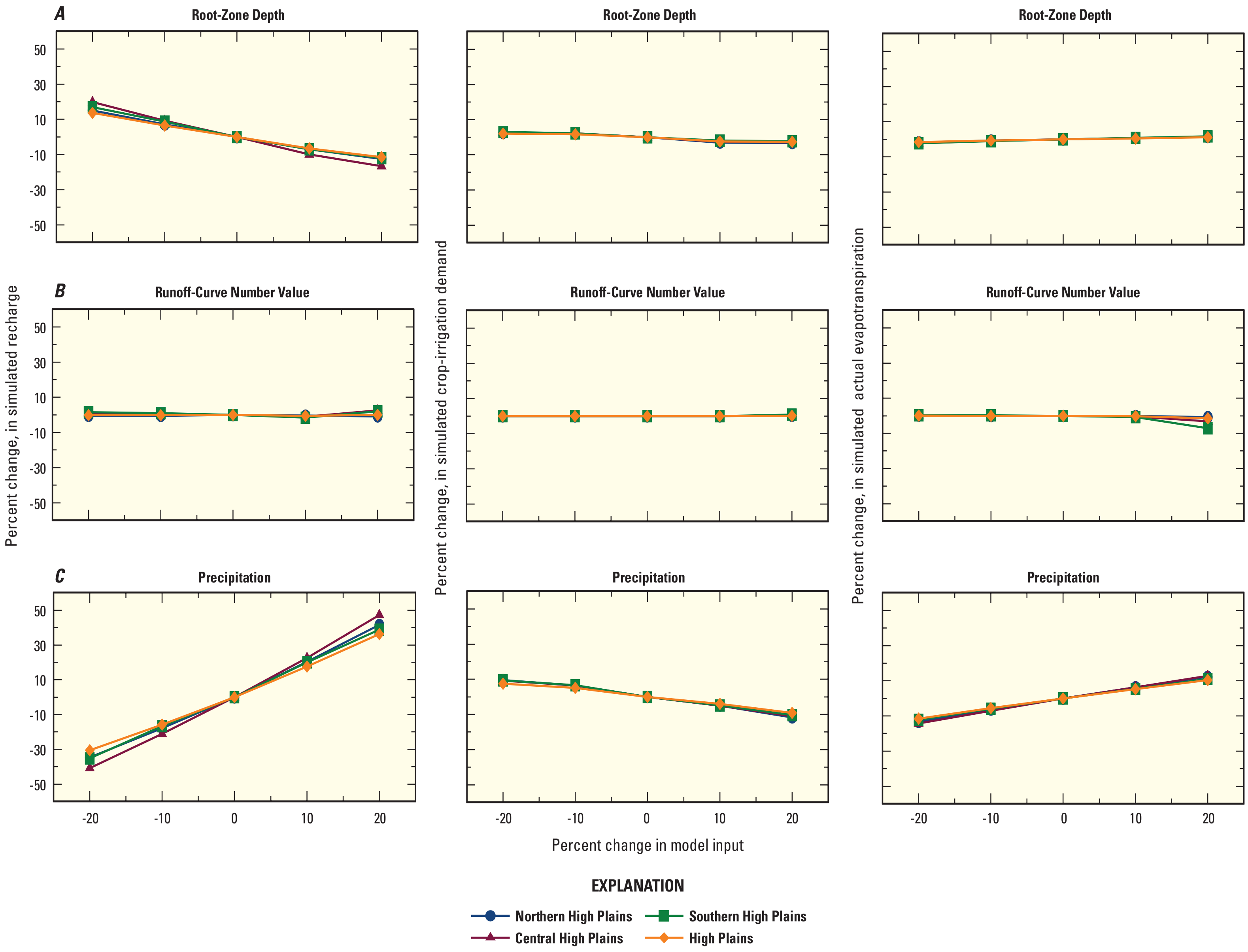


Figure 17. Sensitivity of average annual recharge, crop-irrigation demand, and actual evapotranspiration simulated by the Soil-Water-Balance (SWB) model to changes in (*A*) root-zone depth, (*B*) runoff-curve number value, and (*C*) precipitation, 2000 through 2009.

amounts based on soil and climate information. The model is fairly easy to use as a result of the necessary simplifications employed for model construction; however, this means that there are inherent limitations. Some specific limitations of the model include:

1. The monthly time steps used in this study may not capture the effects of short-term events. For example, most recharge processes are not linear with respect to time, and recharge results become less accurate as time steps increase in length (Sophocleous, 2004). The likely result is that the SOWAT model may underestimate recharge.

2. Although SOWAT allows the user to designate different irrigation-efficiency factors for groundwater and surface water, irrigation efficiency can vary for groundwater-irrigated fields depending on the irrigation method employed. For example, center-pivot sprinkler systems typically cause less deep percolation than gravity-flow systems (Musick and others, 1990). For the SOWAT model, the distribution of sprinkler and gravity-flow systems across the High Plains was unknown, and an estimated average-efficiency factor was chosen to reflect the estimated average efficiencies of both system types. If irrigation efficiency is underestimated in the SOWAT model, pumpage and recharge will be overestimated.

3. The irrigation-efficiency routine, as formulated in SOWAT, allows all extra water pumped because of inefficiencies to be available as extra soil moisture or deep percolation. However, for most irrigation systems, some water also is lost to droplet or interception evaporation before it reaches the soil. Thus, the SOWAT model likely underestimates evaporation and overestimates deep percolation.

4. Recharge simulated by SOWAT was somewhat sensitive to initial soil-moisture values (fig. 16*B*). If the initial soil-moisture value used as input to the SOWAT model is 10 percent different than actual soil-moisture conditions, the error in simulated recharge values would be about 2 to 5 percent.

SWB Model

Although the SWB model provides a general accounting of the water that infiltrates below the root zone as a function of spatial variation in soil properties, land use, and climate, model simplifications cause limitations. These limitations include:

1. SWB is not formulated to account for the source of irrigation water. Users must estimate the portion of irrigation water that is from groundwater if surface water also is used for irrigation.

2. Daily precipitation and temperature data are distributed between weather stations using a simple interpolation method. Although more robust methods are available for distributing precipitation (see the “Precipitation” section of this report), results from those methods were not available for 1940 through 1949.

3. Processing daily precipitation and temperature data for multiple years for a large area is labor intensive. Therefore, a small number of weather stations were used to define precipitation and temperature (see the “Precipitation” section of this report). Increasing the number of weather stations could decrease the uncertainty associated with interpolating climate values between stations that have large distances between them.

4. The NRCS curve-number method was designed to evaluate flood events and may not accurately estimate runoff for average rainfall events (Garen and Moore, 2005).

5. No water losses associated with irrigation inefficiencies are included when calculating irrigation water requirements; the estimated irrigation-water withdrawal amounts are likely biased low as a result.

6. SWB tracks the mean depletion of soil moisture for each combination of land-use and soil type. If the mean depletion percentage of soil moisture for all cells of a land-use/soil-type category is greater than the maximum allowable depletion defined by the modeler, a uniform amount of water is added to all grid cells sharing that same land-use-soil type combination. Some cells will thus receive water in excess of field capacity, whereas others do not receive enough water to completely erase the soil-moisture deficit. This simple approach to estimating irrigation-water requirements represents a compromise between ease of calculation, accuracy, and available data.

7. All irrigated crops were assigned the same growing-season profile of crop water-use coefficients, regardless of crop type or location. The model could better represent irrigation requirements if irrigated crops were assigned crop-coefficient values specific to crop type and location.

Selected Approaches to Estimate Water-Budget Components

Water-budget components estimated as part of this study were precipitation, ET, recharge, surface runoff, groundwater discharge to streams, groundwater discharge to springs, groundwater fluxes to and from adjacent geologic units, irrigation-water applications, and groundwater in storage.

The average annual amounts of water associated with individual components of the water budget of the High Plains landscape and aquifer system were estimated for 1940 through 1949 (representing conditions prior to groundwater development), and 2000 through 2009 (representing recent conditions of groundwater development). Magnitudes of water-budget components were obtained from the following sources (fig. 18):

- Precipitation was derived from three sources: the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (Daly and others, 1994), data developed by the Office of Hydrologic Development at the National Weather Service (NWS) using Next Generation Weather Radar (NEXRAD) data and measured precipitation from weather stations as part of the Sacramento-Soil Moisture Accounting (SAC-SMA) model (Burnash, 1995), and precipitation data from weather stations that were spatially interpolated using an inverse-distance-weighted (IDW) method.
- Evapotranspiration was obtained from three sources: the NWS SAC-SMA model, the SSEB model (Senay and others, 2007; Senay and others, 2011) using remotely sensed data from the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Soil-Water-Balance (SWB) model (Westenbroek and others, 2010).
- Recharge was estimated using the SOil-WATer-Balance (SOWAT) (Kahle and others, 2011) and SWB models as well as 43 studies previously published for various locations across the High Plains aquifer (citations in appendix 2).
- Surface runoff and groundwater discharge to streams were determined using discharge records from streamflow-gaging stations near the edges of the High Plains and the Base-Flow-Index (BFI) program (Wahl and Wahl, 2007).
- Groundwater discharge to springs was obtained from previously published information (Blandford and others, 2003; Brune, 1975; Dutton and others, 2001; McKusick, 2003).
- Groundwater flow to and from adjacent geologic units was obtained from previously published information (Blandford and others, 2008; McMahon, 2001; McMahon and others, 2004).
- Irrigation applications were estimated using the SWB and SOWAT models, or obtained from the USGS Water-Use Program (U.S. Geological Survey, variously dated).
- Groundwater in storage was obtained from the USGS High Plains Water-Level Monitoring Study (McGuire and others, 2003; McGuire, 2009).

The following sections present methods and results for these estimated components for 1940 through 1949 and 2000 through 2009.

Precipitation

Precipitation is defined as water that falls from the atmosphere in the form of rain, snow, sleet, or hail. It is the primary natural source of water to the landscape and the most important natural source of recharge to the High Plains aquifer (Alley and others, 1999; Blandford and others, 2003; Sophocleous, 2004).

Precipitation Methods

Spatially distributed precipitation models have been developed to interpolate measured precipitation data between weather stations. In this section of the report, results obtained using three sources of precipitation information are presented: (1) the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) data developed by the PRISM Climate group at Oregon State University, (2) data developed by the National Weather Service (NWS) Office of Hydrologic Development for the Sacramento-Soil Moisture Accounting (SAC-SMA) model (Burnash, 1995) using Next Generation Weather Radar (NEXRAD) data and measured precipitation from weather stations, and (3) precipitation data from weather stations that were spatially interpolated using an inverse-distance-weighted (IDW) method.

The PRISM model uses point measurements of monthly and annual precipitation and develops statistical relations with land-surface elevation to estimate precipitation across regional scales (Daly and others, 1994). The method yielded a grid of 28,057 precipitation values across the study area at a 2.49-mi (4-kilometer (km)) horizontal resolution.

Precipitation data were provided by the NWS from the SAC-SMA model (Burnash, 1995). The NWS precipitation data were developed as model-input data using NEXRAD data and measured precipitation from weather stations (National Weather Service Office of Hydrologic Development, oral commun., 2010). Total precipitation then was separated into liquid and solid components (rain and snow) in the model using temperature and elevation (National Weather Service Office of Hydrologic Development, oral commun., 2010). The available model inputs did not include data for the 1940-through-1949 period.

An IDW interpolation method was used to spatially distribute daily precipitation amounts from as many as 82 weather stations across and near the High Plains for 1940 through 1949 and 2000 through 2009 (table 2, fig. 19) (National Climatic Data Center, 2010). Data were interpolated between the weather stations for each day during those time periods. This yielded daily grids of 196,901 precipitation estimates spaced 5,000 ft apart across the High Plains for every day of the simulation period. The interpolated daily precipitation data were then summed through each year to yield annual totals of precipitation. This method is less sophisticated than methods used in the PRISM or NWS models, but provided an effective means to obtain daily precipitation information across the High Plains for the SWB model.

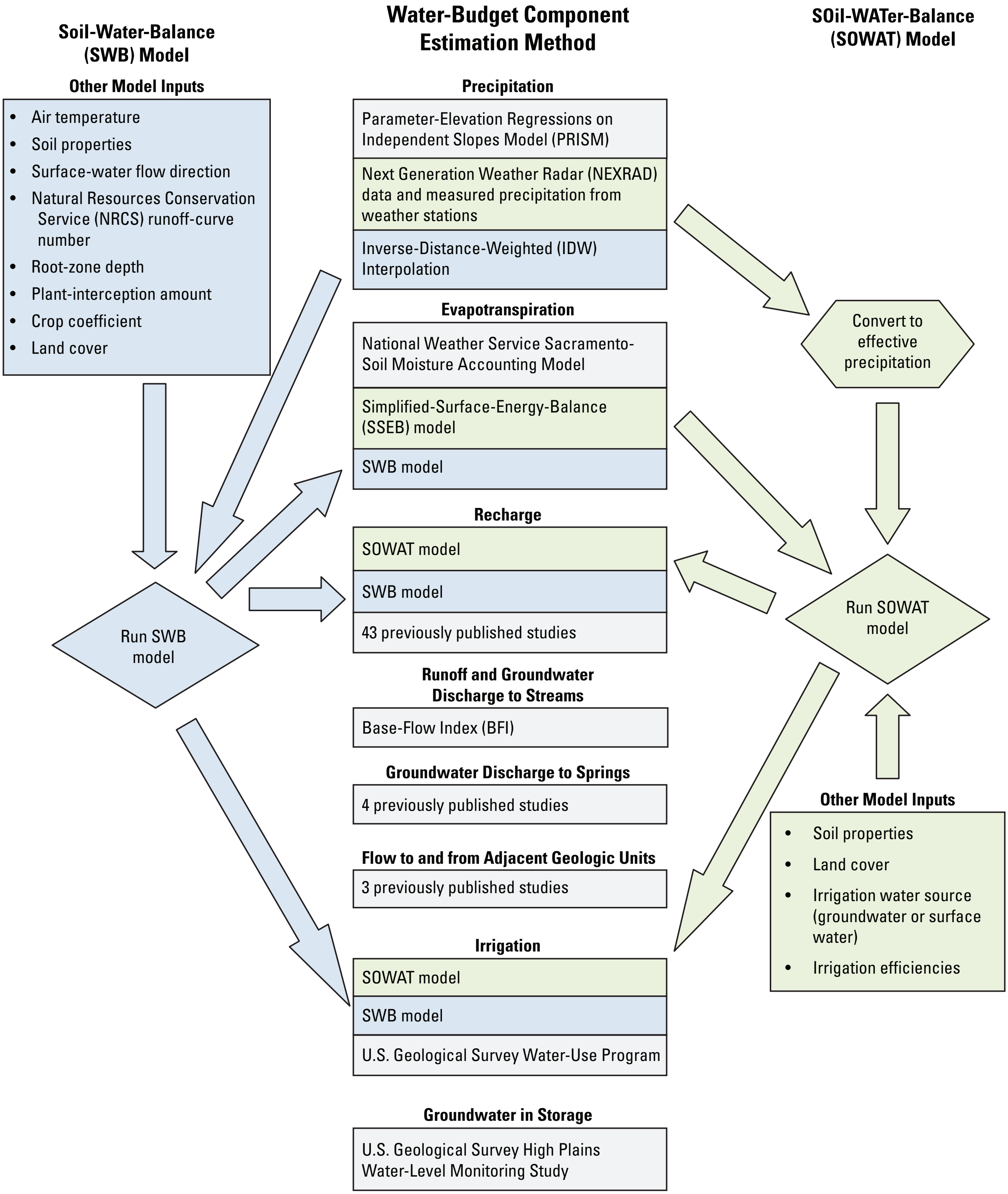


Figure 18. Water-budget component estimation methods and their relation to the SOil-WATer-Balance (SOWAT) and Soil-Water-Balance (SWB) models.

Precipitation volumes for the High Plains and for each region and State within the High Plains were calculated by multiplying the average precipitation rate specific to those zones with the total area of those zones. As a result, regions and States with larger areas typically will have greater volumes.

Precipitation Results

Precipitation patterns from the three methods indicate that precipitation increases from west to east (fig. 20 *A–E*) and that average precipitation rates for the High Plains were greater for 1940 through 1949 than for 2000 through 2009 (table 3).

Average annual total precipitation from the PRISM model for 1940 through 1949 ranged from 13 to 35 in. (fig. 20*A*), with the average for the High Plains equal to 20.6 in. (table 3). The average annual volume of precipitation for the 1940s was 192 million acre-ft for the High Plains (table 3). For 2000 through 2009, average annual precipitation ranged from 12 to 35 in. (fig. 20*B*). The average for the High Plains was 19.9 in. (table 3), yielding an average annual total volume of 185 million acre-ft. Precipitation was more than one-half inch less for 2000 through 2009 than for 1940 through 1949. Differences in average annual precipitation between the two time periods were only 0.2 to 0.3 in. for the NHP and SHP, but the CHP had a 2 in. smaller (10 percent less) average annual precipitation in the 2000s. Nebraska and South Dakota were the only states with greater precipitation in the 2000s compared with the 1940s.

Precipitation values from the National Weather Service data were available for 2000 through 2009 but not for 1940 through 1949. Average annual precipitation for the 2000s ranged from 12 to 37 in. (fig. 20*C*). Averaged for the High Plains, precipitation was 21.3 in., yielding an annual volume of 199 million acre-ft (table 3).

The average annual precipitation for the High Plains from the interpolated weather-station data for 1940 through 1949 ranged from 17 to 33 in. (fig. 20*D*), with the average precipitation equal to 21.2 in., or 199 million acre-ft (table 3). Average annual precipitation for 2000 through 2009 ranged from 15 to 29 in. (fig. 20*E*). Annual precipitation averaged for the High Plains was 20.3 in. and the volume was 190 million acre-ft (table 3). Similar to the PRISM model, the largest difference between the two time periods was in the CHP, where precipitation was almost 3 in. (12 percent) larger for the 1940s than for the 2000s.

Average 2000 through 2009 total precipitation values from the three methods were compared to determine variability. Precipitation for the High Plains from PRISM was smaller than the other two methods by as much as 7 percent. However, average precipitation calculated for each State differed by as much as 11 percent between PRISM and IDW-interpolated data and as much as 12 percent between PRISM and NWS data. The difference between precipitation from NWS and IDW-interpolated data for the High Plains was almost 5 percent. However, differences were greater for specific areas. Differences were greatest for Kansas (12 percent) and South Dakota (8 percent).

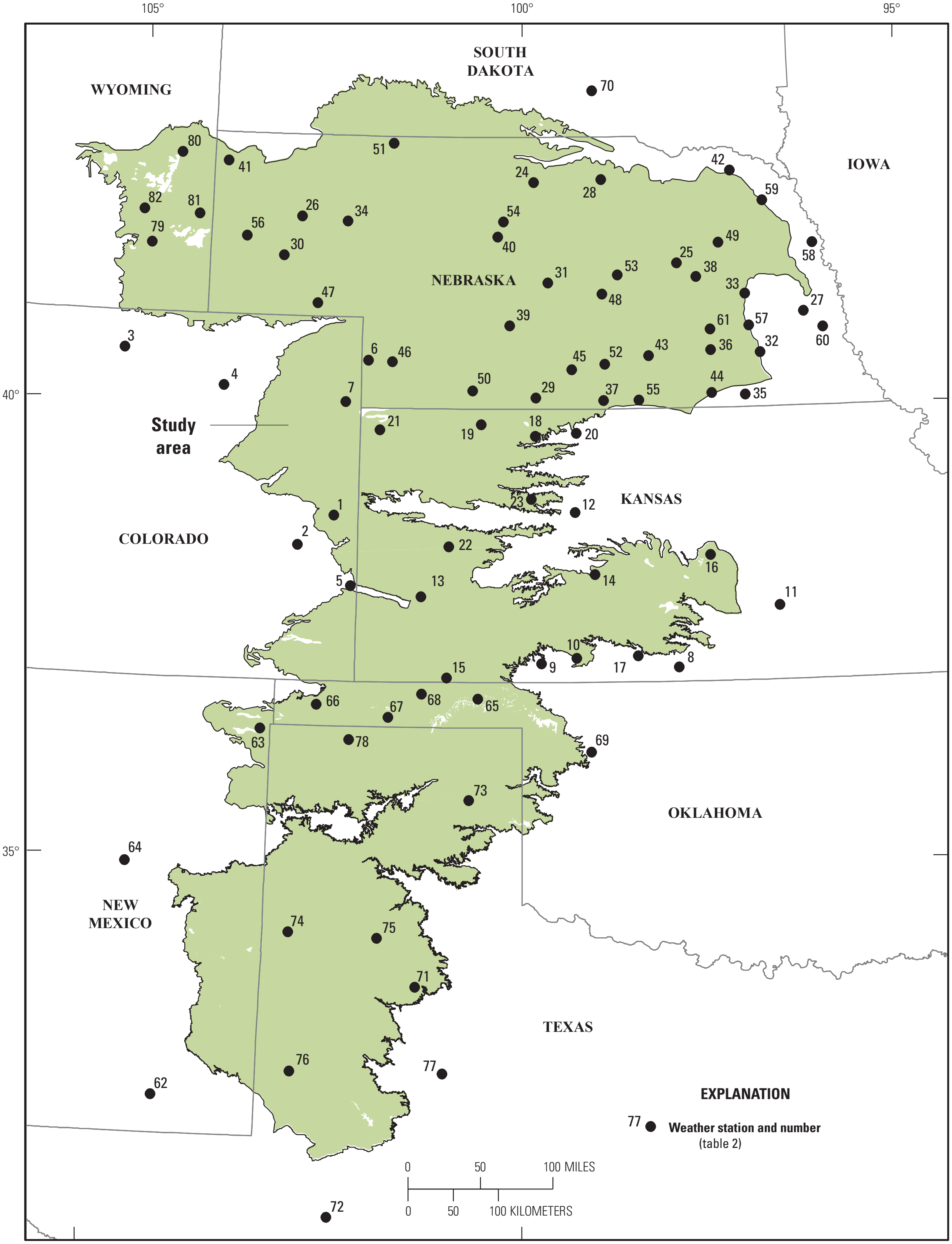
Although the three methods commonly are used and generally accepted as appropriate methods for estimating precipitation, there are inherent limitations associated with all methods. Variability can be introduced when estimating values for locations between measurement points, and for this study each of the compared methods used a unique approach to interpolation. As discussed in the “Soil-Water-Balance Models” section of this report, these differences have implications for hydrologic models and water-balance calculations that are sensitive to changes in precipitation.

Evapotranspiration

Evapotranspiration (ET) is the combined process of evaporation and transpiration by plants. Estimates of ET are critical for understanding the water budget of the High Plains aquifer because ET affects the amount of water from precipitation that can infiltrate below the root zone, potentially to become recharge. In semi-arid areas like the western part of the High Plains, the actual ET is limited by the availability of water, such that the actual ET (AET) rate is less than the potential ET (PET) rate (the evaporative demand of the atmospheric conditions). The amount of ET that occurs is a function of crop characteristics, management, soil characteristics, environmental conditions that affect crop development, and weather conditions including radiation, temperature, humidity, and wind speed (Allen and others, 1998).

The three primary sources of water that supply ET in the High Plains are precipitation, irrigation water, and shallow groundwater. In areas without irrigation or shallow groundwater, AET is limited to water derived from precipitation that is not lost to surface runoff. In areas with irrigation or shallow groundwater, additional water can be evaporated or transpired by plants, but limited to the PET demand. The estimated amount of water applied to meet the ET demand of crops in irrigated areas is discussed in the “Irrigation” section of this report. AET can be estimated using direct and indirect methods. Direct methods for estimating ET include using measurements of precipitation and soil-moisture storage. Direct estimation of ET is costly, time consuming, and only provides measurements of ET on a small, local scale (Payero and Irmak, 2008).

Indirect methods for estimating ET include water budgets, hydrometeorological equations (such as Penman-Monteith (Allen and others, 1998), Blaney-Criddle (Blaney and Criddle, 1966), and Hargreaves equations (Hargreaves and Samani, 1985)), and calculating the energy budget at land surface. Estimates of ET as a residual term from a water budget can be calculated on various scales, but are dependent on the accuracy of measurements of the various water-budget components such as precipitation, runoff, deep infiltration, and groundwater outflow. Hydrometeorological equations



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

From National Climatic Data Center, 2010

Figure 19. Distribution of weather stations used by the inverse-distance-weighted (IDW) interpolation method to estimate precipitation across the High Plains, 1940 through 1949 and 2000 through 2009.

Table 2. Weather-station data used by the inverse-distance-weighted (IDW) interpolation method to estimate daily precipitation in the High Plains, 1940 through 1949 and 2000 through 2009.

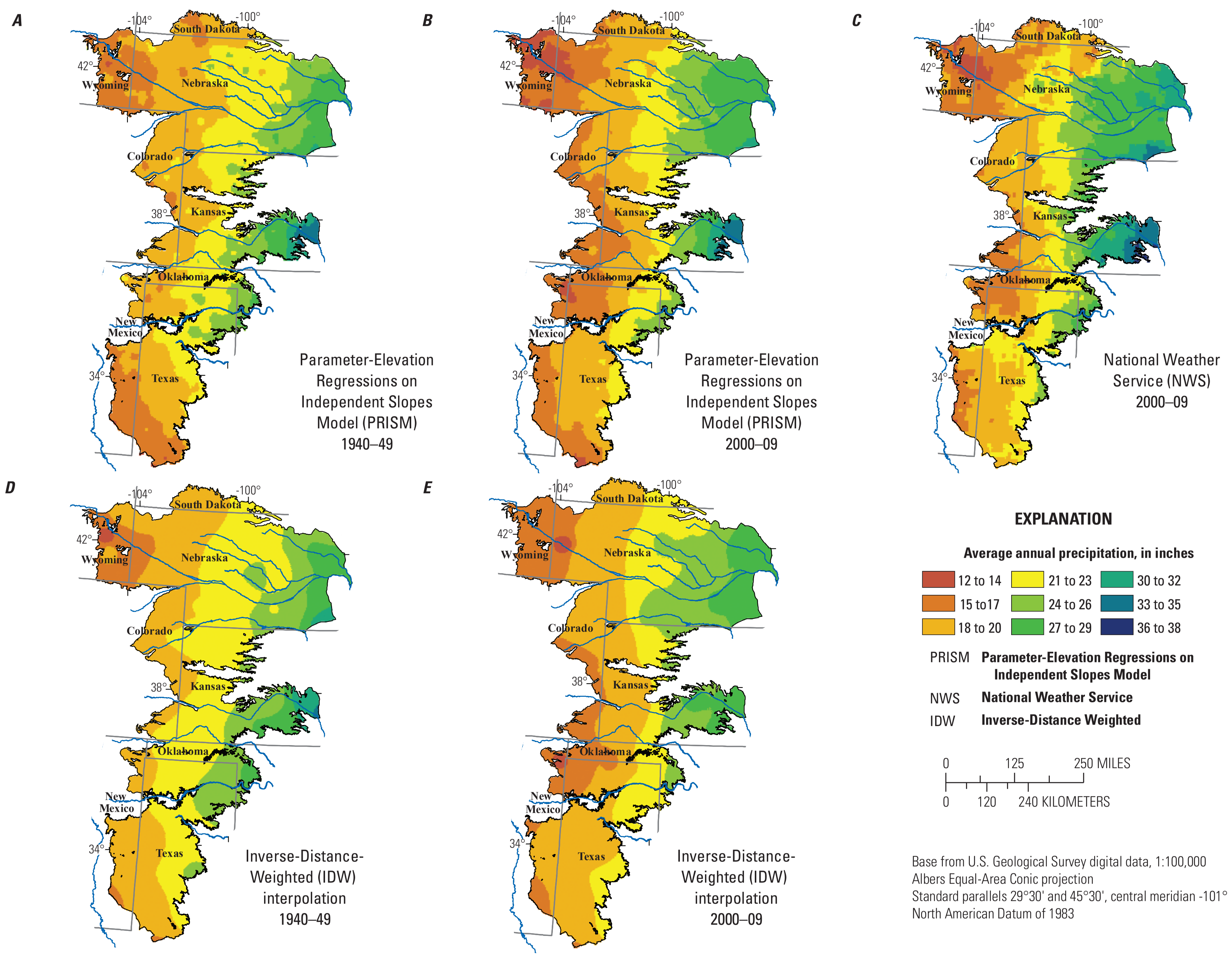
[Stations with short periods of record had no effect on inverse-distance-weighted (IDW) interpolation for days with no data]

Map identifier (fig. 19)	Cooperative station identifier	National Climatic Data Center (NCDC) station name	Years used for this study	Percentage of decade with precipitation data	
				1940–49	2000–09
1	051564	CHEYENNE WELLS	1940–49, 2000–09	95	99
2	052446	EADS 2S	1940–49, 2000–09	100	100
3	053005	FORT COLLINS	1940–49, 2000–01	100	20
4	053038	FORT MORGAN 2S	1948–49, 2000–01	14	20
5	054076	HOLLY	1940–45, 1948–49, 2000–09	70	92
6	054770	LAMAR	1940–49, 2000–01	100	20
7	059243	WRAY	1940–49, 2000–01	96	20
8	140264	ANTHONY	1940–49, 2000–01	100	20
9	140365	ASHLAND	1940–49, 2000–01	100	20
10	141704	COLDWATER	1940–49, 2000–09	93	100
11	142401	EL DORADO	1940–49, 2000–01	100	20
12	143527	HAYS 1S	1940–49, 2000–09	100	99
13	144464	LAKIN	1940–49, 2000–09	100	100
14	144530	LARNED	1940–49, 2000–08	100	82
15	144695	LIBERAL	1940–49, 2000–01	99	20
16	145152	MCPHERSON	1940–49, 2000–01	100	20
17	145173	MEDICINE LODGE	1940–49	100	0
18	145856	NORTON 9SSE	1940–49, 2000–01	100	20
19	145906	OBERLIN 1E	1940–49, 2000–01	95	20
20	146374	PHILLIPSBURG 1SSE	1940–49	99	0
21	147093	SAINT FRANCIS	1940–49, 2000–09	100	100
22	147271	SCOTT CITY	1940–49, 2000–09	99	100
23	148495	WAKEENEY	1948–49, 2000–09	14	99
24	250050	AINSWORTH	1948–49, 2000–09	13	97
25	250070	ALBION	1940–49, 2000–01	100	20
26	250130	ALLIANCE	1940–49, 2000–09	100	91
27	250375	ASHLAND 2	1948–49, 2000–09	16	99
28	250420	ATKINSON	1940–49, 2000–09	86	86
29	250640	BEAVER CITY	1948–49, 2000–01	16	20
30	251145	BRIDGEPORT	1940–49, 2000–09	100	93
31	251200	BROKEN BOW	1940–49, 2000–07	100	70
32	252020	CRETE	1948–49, 2000–01	16	18
33	252205	DAVID CITY	1940–49, 2000–09	97	99
34	252645	ELLSWORTH	1943–49, 2000–09	62	98
35	252820	FAIRBURY	1940–49, 2000–01	100	20
36	252840	FAIRMONT	1948–49, 2000–01	16	20
37	253035	FRANKLIN	1940–49	100	0
38	253185	GENOA	1948–49, 2000–01	16	20
39	253365	GOTHENBURG	1940–49, 2000–01	100	20
40	253540	HALSEY	1940–49	99	0
41	253615	HARRISON	1940–49, 2000–09	100	99

Table 2. Weather-station data used by the inverse-distance-weighted (IDW) interpolation method to estimate daily precipitation in the High Plains, 1940 through 1949 and 2000 through 2009.—Continued

[Stations with short periods of record had no effect on inverse-distance-weighted (IDW) interpolation for days with no data]

Map identifier (fig. 19)	Cooperative station identifier	National Climatic Data Center (NCDC) station name	Years used for this study	Percentage of decade with precipitation data	
				1940–49	2000–09
42	253630	HARTINGTON	1940–49, 2000–01	100	20
43	253660	HASTINGS	1940–49, 2000–09	99	100
44	253735	HEBRON	1948–49, 2000–01	16	20
45	253910	HOLDREGE	1948–49, 2000–01	16	20
46	254110	IMPERIAL	1940–49, 2000–03, 2006–09	95	72
47	254900	LODGEPOLE	1940–49, 2000–09	95	91
48	254985	LOUP CITY	1948–49, 2000–09	16	95
49	255080	MADISON	1940–49, 2000–09	100	87
50	255310	MCCOOK	1940–49, 2000–09	96	95
51	255470	MERRIMAN	1940–49, 2000–06, 2008–09	88	70
52	255565	MINDEN	1940–49, 2000–09	97	100
53	256040	NORTH LOUP	1940–49, 2000–09	95	96
54	256970	PURDUM	1940–49, 2000–09	98	91
55	257070	RED CLOUD	1940–49, 2000–09	97	100
56	257665	SCOTTSBLUFF HEILIG AP	1940–49, 2000–09	98	100
57	257715	SEWARD	1948–49, 2000–01	16	20
58	258480	TEKAMAH	1948–49, 2000–01	16	19
59	258915	WAKEFIELD	1948–49, 2000–01	14	20
60	259090	WEEPING WATER	1948–49, 2000–01	16	20
61	259510	YORK	1948–49, 2000–08	16	85
62	291469	CARLSBAD	1940–49, 2000–09	94	96
63	291887	CLAYTON WSO AP	1940–49, 2000–09	98	100
64	298107	SANTA ROSA	1940–49, 2000–09	83	88
65	340593	BEAVER	1945–49, 2000–09	45	97
66	340908	BOISE CITY 2E	1940–49, 2000–09	94	96
67	343628	GOODWELL RESEARCH STATION	1940–49, 2000–09	89	97
68	344298	HOOKER	1940–49, 2000–09	95	89
69	346139	MUTUAL	1940–49, 2000–09	96	100
70	390043	ACADEMY 2NE	2000–09	0	97
71	412121	CROSBYTON	1940–49, 2000–09	95	100
72	415707	MCCAMEY	1940–49, 2000–09	100	75
73	415875	MIAMI	1940–49, 2000–06	99	61
74	416135	MULESHOE 1	1940–49, 2000–09	100	87
75	417079	PLAINVIEW	1940–49, 2000–09	100	100
76	418201	SEMINOLE	1940–49, 2000–09	79	98
77	418433	SNYDER	1940–49, 2000–09	97	94
78	418692	STRATFORD	1940–49, 2000–09	90	97
79	481730	CHUGWATER	1940–49, 2000–09	100	97
80	485830	LUSK 2SW	1940–49, 2000–07	100	66
81	488995	TORRINGTON EXP FARM	1940–49, 2000–01	100	20
82	489615	WHEATLAND 4N	1940–49, 2000–09	100	97



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

Figure 20. Distribution of average annual total precipitation in the High Plains from the (*A*) Parameter-Elevation Regressions on Independent Slopes Model (PRISM) for 1940 through 1949, (*B*) PRISM for 2000 through 2009, (*C*) National Weather Service (NWS) for 2000 through 2009, (*D*) Inverse-Distance-Weighted (IDW) interpolation for 1940 through 1949, and (*E*) IDW interpolation for 2000 through 2009.

Table 3. Average annual precipitation in the High Plains, 1940 through 1949 and 2000 through 2009.

[Volumes calculated as the average annual precipitation multiplied by summarized area. NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains; NA, not available]

	Average precipitation, inches		Average annual volume of precipitation, million acre-feet		Average precipitation, inches		Average annual volume of precipitation, million acre-feet		Average precipitation, inches		Average annual volume of precipitation, million acre-feet	
	1940–49	2000–09	1940–49	2000–09	1940–49	2000–09	1940–49	2000–09	1940–49	2000–09	1940–49	2000–09
	Parameter-Elevation Regressions on Independent Slopes Model (PRISM)				National Weather Service (NWS)				Inverse-Distance-Weighted (IDW) Interpolation			
NHP	20.6	20.3	106	105	NA	21.7	NA	111	21.0	20.9	108	107
CHP	22.2	20.2	58	53	NA	22.0	NA	58	22.7	19.9	60	53
SHP	17.9	17.7	28	28	NA	19.1	NA	30	19.6	18.7	31	30
Colorado	18.4	16.5	13	12	NA	17.6	NA	13	19.1	17.2	14	12
Kansas	23.1	21.6	38	36	NA	24.3	NA	40	23.2	21.4	38	35
Nebraska	21.5	21.8	74	75	NA	23.2	NA	80	21.8	22.2	75	77
New Mexico	16.7	16.0	8.3	7.9	NA	16.9	NA	8.4	18.5	16.9	9.3	8.5
Oklahoma	22.0	19.9	8.7	7.9	NA	20.7	NA	8.2	23.2	19.8	9.3	7.9
South Dakota	18.2	18.3	4.7	4.7	NA	18.0	NA	4.7	19.1	19.5	5.0	5.1
Texas	19.7	18.6	38	36	NA	20.1	NA	39	20.9	19.1	41	37
Wyoming	16.1	14.1	7.0	6.1	NA	15.3	NA	6.6	16.3	15.9	6.9	6.8
High Plains[1]	20.6	19.9	192	185	NA	21.3	NA	199	21.2	20.3	199	190

[1] Volume calculated for the High Plains does not always equal the sum of region or State volumes because of rounding.

use various climatological properties measured on the earth's surface to calculate the PET. Hydrometeorological equations have varying levels of complexity and accuracy and generally require climatological inputs such as temperature, wind speed, relative humidity, and solar radiation to calculate PET. The AET for an area is then determined by applying a crop-coefficient factor to the calculated PET. Estimates of ET from energy budgets are calculated from incoming and outgoing radiation, changes in heat storage, and sensible heat flux to estimate the latent heat flux. AET is calculated from the latent heat flux using the latent heat of vaporization and the density of water.

Evapotranspiration from groundwater can occur when the water table is near land surface, allowing water to evaporate or plant roots to access groundwater for transpiration. The limited published data quantifying ET demand satisfied by shallow groundwater indicate that rates ranged from 30 to 50 percent of PET, and model calibrations resulted in groundwater-supplied ET rates of 2 to 96 percent of total groundwater discharge (Scanlon and others, 2005a).

Evapotranspiration Methods

This study estimated ET from all water sources using four indirect methods. PET and AET were compiled from the NWS SAC-SMA model (Burnash, 1995), AET was compiled from the Simplified-Surface-Energy-Balance (SSEB) model using remotely sensed data (Senay and others, 2007; Senay and others, 2011), and AET was computed from the Soil-Water-Balance (SWB) model as part of the water budget (Westenbroek and others, 2010). Estimates of ET calculated with the energy-balance method were available for two riparian study sites (Landon and others, 2009). As with precipitation, the average annual volumes of PET and AET were calculated as a product of the ET rate and summarized area.

PET and AET were estimated as part of simulations using the NWS SAC-SMA model (Burnash, 1995). PET, an input to the SAC-SMA model, was a climatological estimate of free-water surface evaporation with a monthly adjustment factor to account for the effects of vegetation (Zhang and others, 2004; Michael Smith, National Weather Service, written commun., 2010). The PET rate was assumed to be a conservative variable and did not vary interannually. This assumption is consistent with studies by Calder and others (1983) and Fowler (2002). The AET rate was calculated as a component of the water budget in the SAC-SMA model as a function of evaporative demand (PET) and the fraction of that demand that is available from simulated soil layers (Burnash, 1995). Irrigation water was not included as a potential source of moisture in the soil layers. The SAC-SMA simulation period did not include 1940 through 1949; therefore, PET and AET estimates were only available for 2000 through 2009.

The SOWAT model was designed to use AET estimates based on the Simplified-Surface-Energy-Balance (SSEB) model (Senay and others, 2007; Senay and others, 2011). The SSEB model uses remotely sensed land-surface temperature data acquired at a 0.62-mi (1-km) resolution by the Moderate Resolution Spectroradiometer (MODIS) satellite-borne sensor (U.S. Geological Survey, 2008) and reference ET derived from local weather data. Reference ET is a measure of the amount of water a hypothetical reference crop (usually grass or alfalfa) will transpire if soil water is not limiting. The SSEB model identifies "cold pixels" in intensively irrigated areas (where AET is presumed equal to reference ET) and "hot pixels" in fallow or barren-soil areas (where AET is near zero). For each pixel, AET is calculated as a fraction of reference ET using the ratio of the difference between the temperature of the measured pixel and the hot pixels to the total temperature range between the hot and cold pixels. Calculated AET values also are corrected for land-surface elevation and vegetation status from the Normalized Difference Vegetation Index ratio. The SSEB model was used to produce monthly estimates of AET from satellite images acquired every 8 days from March 2000 (when data acquisition by the MODIS sensor began) to December 2009 for each grid cell in the SOWAT model.

The SWB model calculates AET as the amount of precipitation and soil moisture that are available to meet the PET demand. The SWB model estimated the PET demand using the Hargreaves-Samani method (Hargreaves and Samani, 1985), using daily maximum and minimum air temperature, which produces a spatially variable PET (Westenbroek and others, 2010). If the daily precipitation value exceeds the PET demand, then AET is defined as equal to PET. In most cases, the daily AET is limited by soil-moisture availability as calculated by means of the Thornthwaite-Mather soil-moisture retention tables (Thornthwaite and Mather, 1957). The tables use a nonlinear relation of AET to soil-moisture in recognition that soil moisture is more tightly held (soil-water tension or suction) as the soil-moisture deficit increases. Specific details about the SWB model are described in the "Soil-Water-Balance Models" section of this report.

The estimated average annual AET rate for two riparian sites (near Odessa and Gothenburg, Nebraska; fig. 3) located along the Platte River in Nebraska was compiled from Landon and others (2009). Objectives of the study were to understand ET rates, the factors affecting them, and to estimate the amount of shallow groundwater needed to satisfy ET demand by riparian vegetation. At each of the study sites, daily AET was computed from measured meteorological data using eddy-covariance (Businger and others, 1967) and energy-balance methods. AET from shallow groundwater was estimated using a water-balance approach. Riparian vegetation was primarily composed of cottonwood forest and deciduous shrubs at the Odessa site; whereas, cottonwood forest and eastern redcedars dominated the Gothenburg site.

Evapotranspiration from Shallow Groundwater

To estimate the amount of groundwater that potentially could be lost to ET for this study, AET values from the NWS approach and from the SSEB and SWB models (table 4) were selected for areas where the water table was within 5 ft of land surface in 2000 (McMahon and others, 2007; water-table elevation from Virginia McGuire, USGS, written commun., 2006). AET volumes were calculated by multiplying the average AET rate within areas with shallow groundwater by the total area with shallow groundwater. Although some plants can access water at greater depths (Scanlon and others, 2005a), most ET typically occurs within several feet of land surface. Therefore, 5 ft was considered reasonable as the maximum depth for ET from groundwater to occur. If depths to groundwater for 2000 do not represent conditions for other years of the study (1940 through 1949 and 2001 through 2009), the resulting estimates of AET will be biased too high or too low. However, with all things being equal, depth to groundwater is generally more stable in groundwater discharge areas near surface-water bodies where groundwater is shallow, compared to upland areas, and annual changes to water-table elevations should be minimal (Freeze and Cherry, 1979).

Evapotranspiration Results

Rates of ET in the High Plains generally correspond to temperature and precipitation gradients. Mean annual air temperatures are greatest in the south and east and decrease northward and westward (fig. 6). Annual precipitation rates are greatest in the east and decrease westward (figs. 20*A*–*E*). Similarly, the AET rates in the High Plains are greater in the east and decrease westward. Larger AET rates also were observed in areas of irrigated agriculture in models that included irrigation water as a source of additional soil moisture.

The NWS PET generally increased from west to east and north to south with the highest PET rates in the eastern parts of the CHP and SHP and the lowest PET rates in western NHP (fig. 21*A*). The average annual rate of PET for 2000 through 2009 in the High Plains was 32.5 in. (table 4). The NWS rate of AET compared to the rate of PET is an indication of the deficit of water available to meet the PET demand. Distribution of AET rates in the High Plains are shown on figure 21*B*. Average AET for the High Plains was 20.7 in/yr, about 36 percent less than PET. As would be expected from temperature and precipitation gradients, AET rates were closer to PET rates in the NHP than in the CHP or SHP. The average volume of AET for the 2000s in the High Plains was 193 million acre-ft/yr.

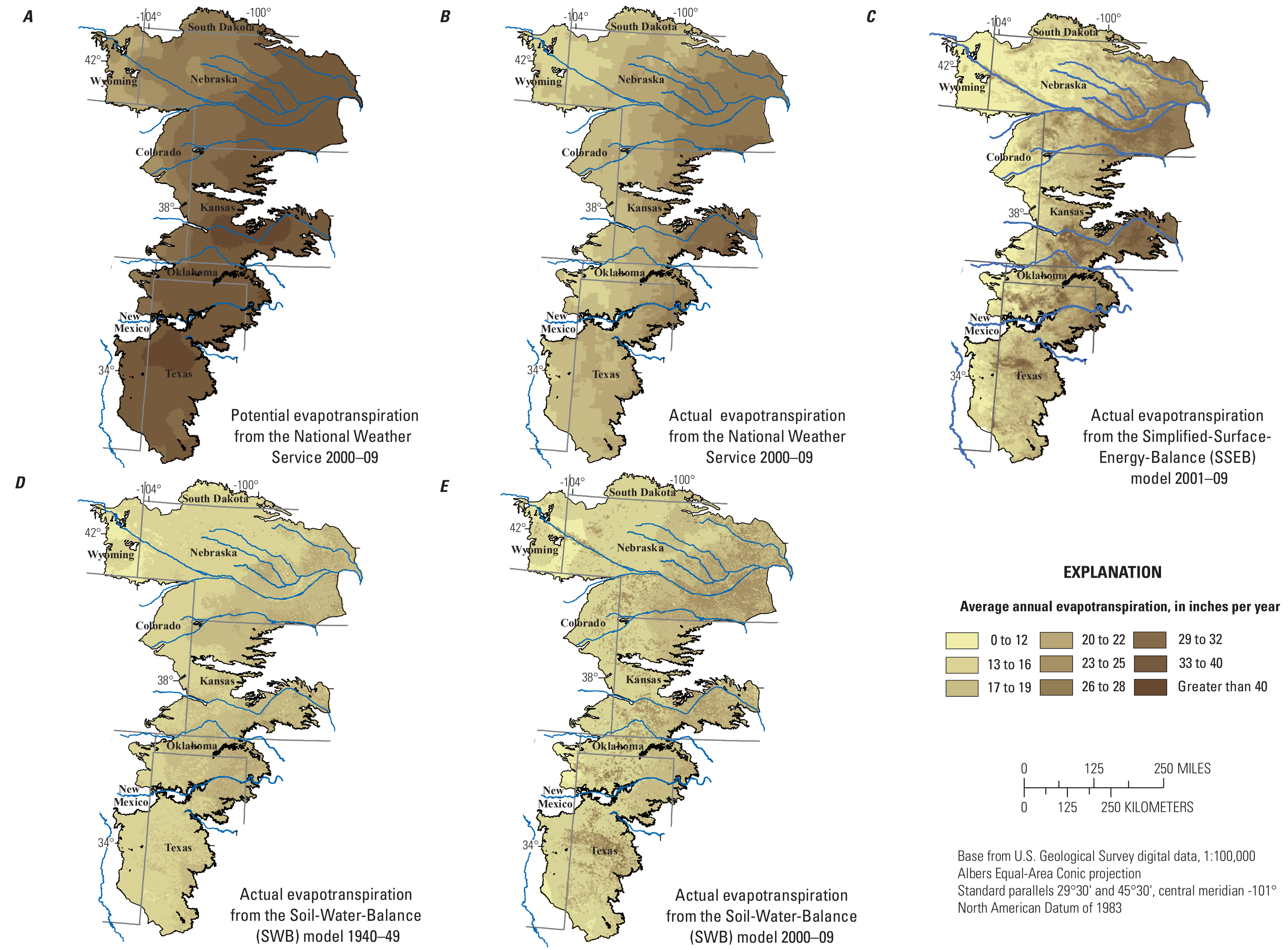
Because SSEB data were not available for the entire year of 2000, annual AET (fig. 21*C*) was averaged from 2001 through 2009. AET generally increased from west to east and the highest AET rates occurred in eastern Nebraska and eastern Kansas, in areas with irrigated agriculture, and along riparian corridors. Average annual AET rates for that time period ranged from less than 12 in/yr to greater than 40 in/yr, with an average of 18.6 in/yr for the High Plains (table 4). As a volume, the average annual AET for the High Plains was 173 million acre-ft.

Annual AET (fig. 21*D*) averaged from 1940 through 1949 from the SWB model for the High Plains was 15.8 in/yr, or 148 million acre-ft (table 4). For 2000 through 2009, average annual AET (fig. 21*E*) compared to 1940 through 1949 increased in the NHP by 1.3 in. to 16.5 in., decreased in the CHP by 0.6 in. to 16.6 in., and increased in the SHP by 1.0 in. to 16.1 in. (table 4). Overall, average annual AET for the High Plains was 3.8 percent greater for 2000 through 2009 (16.4 in/yr) than for 1940 through 1949 (15.8 in/yr), as calculated with the SWB model. Differences in average AET rates from the SWB model between the 1940s and 2000s in each region reflect the combined effects of less precipitation (table 3) and warmer air temperatures during the 2000s and development of irrigated agriculture.

The average annual AET rate for the riparian study site near Odessa, Nebraska (fig. 3), was 21.7 in/yr and for the site near Gothenburg, Nebraska (fig. 3), was 22.6 in/yr, though these estimated rates likely represent minimum AET values (Landon and others, 2009). Landon and others (2009) also concluded that ET demand from riparian vegetation along a section of the Platte River measured from 2002 through 2005 was satisfied by available precipitation except in 2002 (the driest study year), and in most years (2003 to 2005), the part of ET demand satisfied by groundwater is balanced by recharge of excess precipitation.

The difference in AET results between the various methods used for the 2000s was greater than the temporal difference between the two periods simulated by the SWB model method, highlighting the potential uncertainty associated with estimating AET across large regions. These method-based differences are important because, as demonstrated in figures 16 and 17, small changes in the estimated ET rates used as input to hydrologic models can cause substantial changes in simulated recharge and irrigation pumpage. Average AET from the NWS method was about 10 percent greater than SSEB-modeled AET and about 20 percent greater than SWB-modeled AET. Differences were greatest between the NWS and SSEB results for New Mexico and Wyoming. Comparing the NWS and SWB AET results, the greatest differences were in Kansas, Nebraska, and South Dakota. AET results from SSEB were about 11 percent greater than SWB-modeled AET, where the greatest differences were in Wyoming. In Wyoming, the average SSEB-modeled AET rate was 42 percent less than the NWS model and 45 percent less than the SWB model, indicating that the SSEB results may be less reliable in that area.

The AET rates measured at the Platte River riparian study sites were compared with average annual AET rates from SSEB model cells coinciding with the riparian study sites during the years of the riparian study (2002 through 2005). The average AET rate from the SSEB model at the Odessa riparian study site was approximately 29.0 in/yr and was 30.1 in/yr at the Gothenburg site. Though the estimated rates of AET from Landon and others' sites (2009) are less than the minimum AET from the SSEB model, the authors note that the tower AET rates represent a minimum AET rate (Landon and others, 2009). In addition, the SSEB model is better-suited to estimate AET rates for basin-scale water-budget analysis, where highly



Potential evapotranspiration from the National Weather Service 2000–09

Actual evapotranspiration from the National Weather Service 2000–09

Actual evapotranspiration from the Simplified-Surface-Energy-Balance (SSEB) model 2001–09

Actual evapotranspiration from the Soil-Water-Balance (SWB) model 1940–49

Actual evapotranspiration from the Soil-Water-Balance (SWB) model 2000–09

Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

Figure 21. High Plains distribution of estimated average annual (*A*) potential evapotranspiration and (*B*) actual evapotranspiration from the National Weather Service (NWS) for 2000 through 2009, (*C*) actual evapotranspiration from the Simplified-Surface-Energy-Balance (SSEB) model for 2001 through 2009, (*D*) actual evapotranspiration from the Soil-Water-Balance (SWB) model for 1940 through 1949, and (*E*) actual evapotranspiration from the SWB model for 2000 through 2009.

Table 4. Estimated average annual potential and actual evapotranspiration in the High Plains, 1940 through 1949 and 2000 through 2009.

[Volumes calculated as the average evapotranspiration rate multiplied by summarized area. PET, potential evapotranspiration; AET, actual evapotranspiration; NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains]

	Average PET rate, inches per year	Average annual PET volume, million acre-feet	Average AET rate, inches per year	Average annual AET volume, million acre-feet	Average AET rate, inches per year	Average annual AET volume, million acre-feet	Average AET rate, inches per year		Average annual AET volume, million acre-feet	
	2000–09		2000–09		2001–09		1940–49	2000–09	1940–49	2000–09
	National Weather Service (NWS)				Simplified-Surface-Energy-Balance Model		Soil-Water-Balance (SWB) Model			
NHP	29.6	152	20.9	108	17.4	90	15.2	16.5	78	85
CHP	36.1	94	21.4	56	21.4	56	17.2	16.6	45	44
SHP	35.9	56	18.7	29	17.6	28	15.1	16.1	24	26
Colorado	27.3	19	17.3	12	13.0	9.2	14.5	14.1	10	10
Kansas	36.2	60	23.6	39	22.8	38	17.4	17.5	29	29
Nebraska	30.8	106	22.2	76	19.0	66	15.6	17.4	54	60
New Mexico	33.6	17	16.7	8.3	13.0	6.5	14.2	13.7	7.2	6.9
Oklahoma	36.1	14	20.3	8.0	21.1	8.3	18.0	16.6	7.2	6.6
South Dakota	27.7	7.2	18.2	4.7	15.6	4.0	13.5	14.3	3.5	3.7
Texas	36.3	70	19.6	38	19.6	38	16.2	16.5	32	32
Wyoming	21.9	9.4	15.0	6.5	8.7	3.8	12.3	12.8	5.2	5.5
High Plains[1]	32.5	303	20.7	193	18.6	173	15.8	16.4	148	154

[1] Volume calculated for the High Plains does not always equal the sum of region or State volumes because of rounding.

accurate AET estimates are not required (Senay and others, 2011).

Evapotranspiration from Shallow Groundwater

The estimated average annual maximum volume of groundwater lost to ET for the High Plains, based on SWB-model results, was 9.0 million acre-ft for 1940 through 1949 but increased about 6 percent to 9.6 million acre-feet for 2000-09 (table 5). These estimates are considered maximums because the methods assume that all of the ET demand is satisfied by groundwater; however, ET demand also will be satisfied by precipitation, particularly in more humid areas. Minimum values of groundwater lost to ET may be close to zero, according to conclusions of Landon and others (2009). Areas with shallow groundwater were more prevalent in the NHP (4.2 million acres), where ET is less and precipitation is greater, than in the CHP (2.1 million acres) or SHP (0.5 million acres) (table 5).

Recharge

Groundwater recharge can be defined as water that enters the saturated zone. Although information about recharge is critical for understanding long-term sustainability of an aquifer, local-scale methods provide information for a point location that is difficult to apply at regional scales. Estimating recharge for large areas also is challenging because of the many uncertainties associated with generalizing the factors that affect it over regional scales. These factors include climate, soil and subsurface-sediment characteristics, vegetation, land use, terrain slope, and depth to water table (Sophocleous, 2004).

The sources of water available for recharge in natural and undeveloped systems are precipitation and leakage from streams, playas, or other surface-water bodies. Playas are ephemeral, closed-basin wetlands that may serve as important sources of focused recharge, particularly in the SHP (Gurdak and Roe, 2009).

In areas developed for agriculture, recharge also can increase because of enhanced infiltration of precipitation, irrigation water applied in excess of crop-water requirements, or from irrigation canal leakage. Scanlon and others (2005b) and Sophocleous (2004) reported that recharge rates are lowest in natural rangeland areas, moderate in nonirrigated cropland areas, and moderate-to-high in irrigated agricultural areas. Tilled land allows precipitation to infiltrate more easily than areas that remain rangeland. Similarly, the practice of irrigation increases soil moisture and enhances recharge (McMahon and others, 2006). Excess irrigation water returning to the aquifer as recharge (irrigation return flow) can greatly enhance recharge in irrigated areas, but it is difficult to differentiate between natural recharge from precipitation, increased recharge resulting from tillage, and irrigation return water. The magnitude of irrigation return flow is not well-known, and estimates as a percentage of total irrigation pumpage vary widely, ranging from between 0 to 10 percent in recent years to as much as 55 percent in the 1940s through 1960s (Luckey and others, 1986; Myers and others, 1996; Luckey and Becker, 1999; Blandford and others, 2003). Irrigation return flow has probably decreased with time because of conversion from gravity-flow systems to sprinklers and adoption of even higher-efficiency system improvements in recent years. Return flow is dependent upon the same physical factors, such as soils and topography, that affect recharge. In addition, the length of time for return flow to reach the aquifer creates complications for recharge estimation, because it may take many years for deep percolation to reach the aquifer (Scanlon and others, 2010). Other minor sources of recharge to the High Plains aquifer include septic tanks, leaking underground water and sewage pipes, and excess irrigation in urban areas.

Water available for recharge will percolate downward to the saturated zone if the subsurface is not already saturated, as in groundwater-discharge or water-logged areas. In these cases, water available for recharge can instead become overland runoff or be subject to evapotranspiration. The time it takes for water to percolate through the unsaturated zone to the water table may take days or decades, depending on the depth of the water table and the porosity of the unsaturated zone. This time delay can add to the difficulty of estimating recharge rates for short time periods, particularly in arid regions where the water table can be hundreds of feet below land surface.

A variety of methods are available for estimating recharge. The methods can be categorized as water-budget, groundwater, streamflow, unsaturated-zone, or tracer methods (U.S. Geological Survey, 2009; Healy, 2010). Water-budget methods do not directly estimate recharge using independent hydrologic measurements, such as groundwater levels or streamflow measurements. Soil-water-balance models fall into the water-budget-method category and are used to estimate recharge as the residual term in the water-budget equation, where all other terms have been measured or estimated. Groundwater methods include groundwater-flow models and water-table-fluctuation methods. Unsaturated-zone methods, such as lysimeter and Darcian-flux measurements, rely on physical properties of the unsaturated zone to derive estimates of recharge. Streamflow methods such as watershed-rainfall/runoff models and recession-curve displacement estimate recharge using surface-water data. Streamflow methods are only valid where groundwater is in hydraulic connection with the stream. Tracer methods use chemical concentrations or temperature to infer the rate of infiltration or movement of recharge water in the unsaturated or saturated zones. Tracer methods used within the unsaturated zone are better suited for arid regions where the unsaturated zone is thick and disconnected from surface-water bodies.

Spatial scales of interest are important when making recharge estimates. Methods that measure physical properties or tracers in the unsaturated zone provide local-scale or point estimates of recharge, whereas watershed models yield estimates representative of larger areas. Each method is subject to uncertainties and limitations; however, more reliable recharge

Table 5. Estimated area and average annual maximum evapotranspiration of shallow groundwater in the High Plains, 1940 through 1949 and 2000 through 2009.

[Volumes calculated as the average evapotranspiration rate within areas with shallow groundwater multiplied by summarized area with shallow groundwater. NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains]

	Area of shallow groundwater, millions of acres	Average ET rate from shallow groundwater areas, in inches per year	Average annual ET from shallow groundwater, in million acre-feet	Average ET rate from shallow groundwater areas, in inches per year	Average annual ET from shallow groundwater, in million acre-feet	Average annual ET from shallow groundwater, in inches		Average annual ET from shallow groundwater, in acre-feet	
	2000	2000–09		2001–09		1940–49	2000–09	1940–49	2000–09
		National Weather Service (NWS)		Simplified-Surface-Energy-Balance (SSEB) Model		Soil-Water-Balance (SWB) Model			
NHP	4.2	21.4	7.5	20.0	7.0	15.1	16.9	5.2	5.9
CHP	2.1	25.1	4.4	24.5	4.3	17.9	17.5	3.1	3.0
SHP	.5	18.5	.82	17.3	.76	15.3	15.0	.67	.66
Colorado	.3	16.5	.35	11.8	.25	14.9	13.2	.31	.28
Kansas	1.6	27.0	3.6	26.0	3.5	18.2	18.5	2.4	2.5
Nebraska	2.8	23.3	5.4	22.9	5.3	15.7	18.0	3.7	4.2
New Mexico	.2	15.9	.29	11.2	.20	14.1	12.9	.26	.23
Oklahoma	.2	22.8	.47	24.2	.50	18.3	17.1	.38	.35
South Dakota	.3	18.0	.49	17.0	.46	13.8	14.6	.37	.39
Texas	.7	20.7	1.2	20.7	1.2	16.6	15.7	.93	.88
Wyoming	.7	14.9	.84	10.3	.58	12.2	13.5	.68	.76
High Plains[1]	6.8	22.3	12.6	21.1	12.0	15.9	16.9	9.0	9.6

[1] Volume calculated for the High Plains does not always equal the sum of region or State volumes because of rounding.

estimates can be obtained if multiple methods are used (Scanlon and others, 2002).

Recharge estimation methods report recharge as actual recharge, potential recharge, or net recharge (Scanlon and others, 2002). Actual recharge is a measure of the amount of water that reaches the water table, and its determination is the product of groundwater methods. Unsaturated-zone, water-budget, and some streamflow methods produce estimates of potential recharge, a measure of the amount of water that has infiltrated into the subsurface but may not reach the water table. Net recharge is a measure of the amount of recharged groundwater that eventually discharges to streams (actual recharge minus discharge to other sources such as well pumpage or evapotranspiration from the water table) and is the product of some types of streamflow methods.

Recharge Methods

Every method for estimating recharge has inherent uncertainties and limitations; therefore, using recharge estimates from a variety of methods can provide more reliable recharge estimates (Scanlon and others, 2002). For this study, recharge was estimated from the SWB model, the SOWAT model, and previously published studies (appendix 2). SWB and SOWAT models (described in the “Soil-Water-Balance Models” section of this report) provide potential-recharge estimates for the High Plains aquifer from two variations of the water-budget method, and the previously published studies provide actual- and potential-recharge estimates from a wide range of methods, spatial scales, and temporal scales.

Estimates from 43 previously published studies (appendix 2) were assembled to derive a composited-average recharge estimate across the High Plains aquifer, for the three subregions of the High Plains aquifer, and for several land-cover categories. Many of these recharge studies were compiled previously by Sophocleous (2004) and Gurdak and Roe (2009). However, recharge results reported herein do not include all available studies; a bias towards regional-scale studies was employed during the selection process. In some cases, an average recharge rate for a study was not available, so an average was calculated as the average of the minimum and maximum reported values. The composited-average recharge estimates from these previous studies should be used with caution because a field-scale study in a playa setting will have the same influence on the composited-average recharge rate as a regional-scale study covering primarily rangeland.

Recharge Results

Potential recharge was estimated from the SOWAT model across the High Plains aquifer for 2000 through 2009 (fig. 22*A*). The 1940 through 1949 time period was not assessed because AET data derived from satellite imagery were not available for those years. Estimated average annual potential recharge from precipitation and excess irrigation water was 3.8 in., for a total volume of 35.0 million acre-ft (table 6). As a percentage of precipitation, SOWAT-simulated recharge was 18 percent of precipitation from the NWS.

Average annual potential recharge during 1940 through 1949 for the High Plains aquifer, estimated using the SWB model, was 1.4 in., or 13.2 million acre-ft (table 6, fig. 22*B*). For 2000 through 2009, the estimated average annual recharge for the High Plains aquifer was 1.7 in., or 15.9 million acre-ft (fig. 22*C*). For the SWB model, average annual potential recharge rates from 2000 through 2009 were greater than from 1940 through 1949 (table 6) despite smaller precipitation (table 3) and greater AET rates (table 4) estimated by the SWB model. This result agrees with previous studies that indicate recharge rates increase after rangeland is converted to nonirrigated and irrigated cropland [for example, Scanlon and others (2005b) and Sophocleous (2004)]. Most increases in potential recharge were within Nebraska and Texas, the two States with the largest number of irrigated acres. SWB-simulated recharge was about 7 percent of precipitation (from IDW interpolation) in the 1940s and about 8 percent of precipitation in the 2000s.

The composited-average annual recharge rate from the previously published studies in the High Plains was 1.9 in. (table 6), yielding a volume of 17.7 million acre-ft of recharge. Average recharge was smallest in the SHP (1.1 in/yr) and largest in NHP (2.9 in/yr), corresponding to greater precipitation in the northeast and decreasing PET from south to north. Recharge rates differed between land uses. Rangeland and undeveloped land (considered to represent 1940 through 1949 conditions) had the smallest average recharge rate (0.9 in/yr), irrigated cropland had an average recharge rate of 3.1 in/yr, and nonirrigated cropland had an average recharge rate of 1.5 in/yr (table 7). This land-use-related recharge pattern agrees with an assessment of recharge reported by Scanlon and others (2005b). In the SHP, playas had a greater average recharge rate (3.6 in/yr) than other settings (0.1 to 1.4 in/yr). Sand-dune settings had the largest average recharge rate (4.2 in/yr) in the High Plains.

The various estimation methods yielded different recharge rates for the same area, reflecting uncertainties related to estimating recharge and underscoring the value of using multiple methods. Average potential recharge in the NHP during 1940 through 1949 (1.4 in/yr) from the SWB model was similar to composite-averaged recharge for undeveloped or rangeland areas (representing 1940 through 1949 conditions) reported by previous studies (1.6 in/yr) (table 6); however, 1940–49 SWB-estimated recharge rates for the CHP and SHP were much greater than those from previously published studies for undeveloped/rangeland areas (table 7).

For 2000 through 2009, average potential recharge based on the SOWAT model (3.8 in/yr) was more than twice as much as that based on the SWB model (1.7 in/yr) and was twice as large as the composite average of values reported by previous studies (1.9 in/yr) (table 6). Differences between the SWB and SOWAT models were evident where the SOWAT model simulated negative recharge values (representing areas where AET is greater than the available water from precipitation,

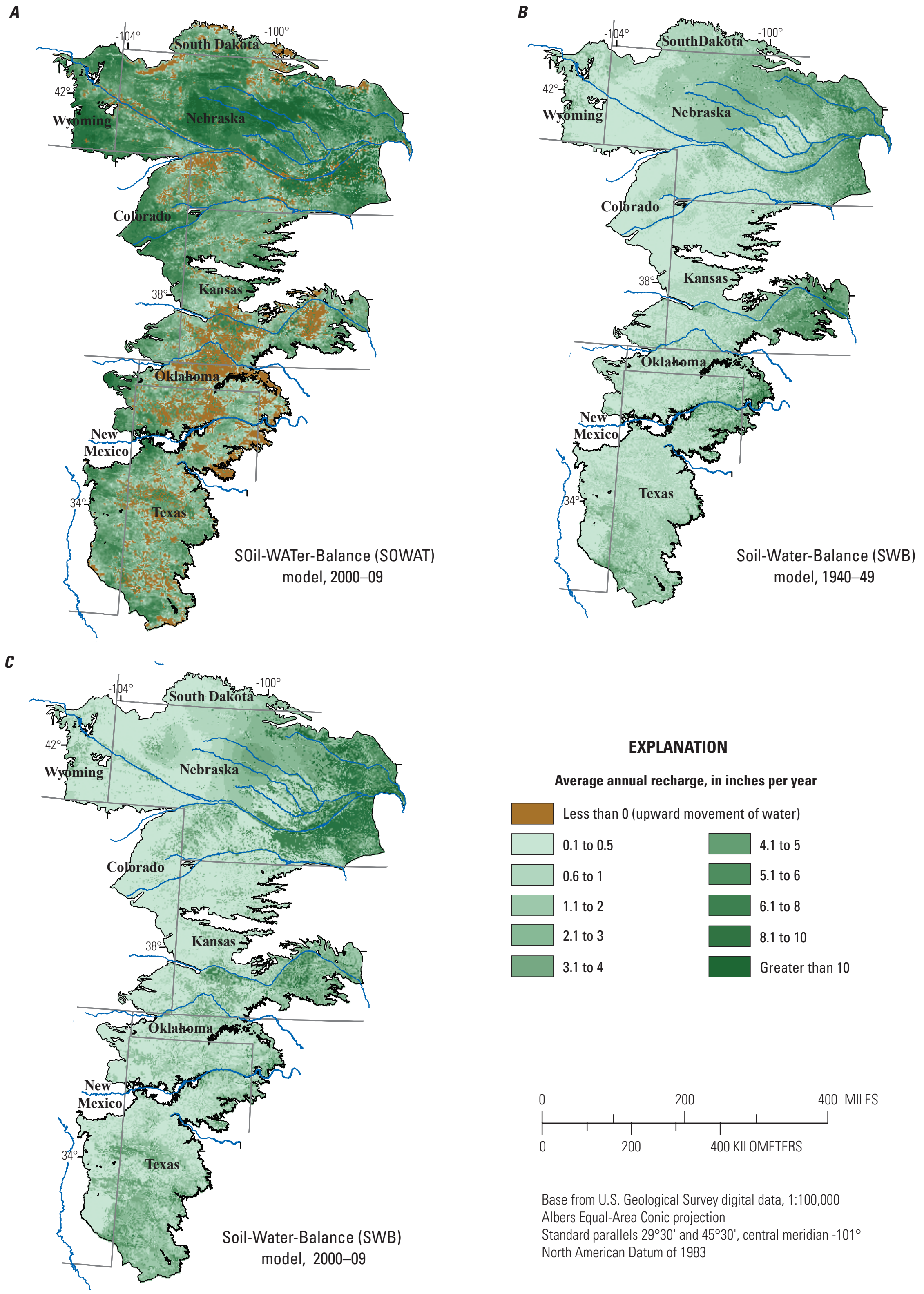


Figure 22. Distribution of estimated average annual potential recharge from (*A*) the SOil-WATer-Balance (SOWAT) model, 2000 through 2009, (*B*) the Soil-Water-Balance (SWB) model, 1940 through 1949, and (*C*) the SWB model, 2000 through 2009.

Table 6. Estimated average annual potential recharge for the High Plains aquifer, 1940 through 1949 and 2000 through 2009.

[Volumes calculated as the average annual recharge rate multiplied by summarized area. NHP, northern High Plains; NA, not analyzed; CHP, central High Plains; SHP, southern High Plains]

	Average potential recharge rate, inches per year		Average annual volume of potential recharge, million acre-feet		Average potential recharge rate, inches per year		Average annual volume of potential recharge, million acre-feet		Composited-average recharge rate, inches per year		Composited-average annual recharge volume, million acre-feet	
	1940–49	2000–09	1940–49	2000–09	1940–49	2000–09	1940–49	2000–09	Prior to groundwater development[1]	All years[2]	Prior to groundwater development	All years
	SOil-WATer-Balance (SOWAT) Model				Soil-Water-Balance (SWB) Model				Previously published recharge studies (appendix 2)			
NHP	NA	5.1	NA	26.1	1.4	1.9	7.4	10.0	1.6	2.9	8.2	14.9
CHP	NA	1.7	NA	4.5	1.6	1.3	4.2	3.5	.6	1.3	1.6	3.4
SHP	NA	2.8	NA	4.4	1.1	1.6	1.7	2.5	.1	1.1	.2	1.7
Colorado	NA	4.8	NA	3.4	.35	.32	.25	.23	NA	NA	NA	NA
Kansas	NA	2.5	NA	4.0	1.5	1.5	2.5	2.4	NA	NA	NA	NA
Nebraska	NA	5.4	NA	18.4	1.9	2.7	6.4	9.2	NA	NA	NA	NA
New Mexico	NA	4.2	NA	2.1	.74	.79	.37	.40	NA	NA	NA	NA
Oklahoma	NA	.18	NA	.07	1.6	1.0	.64	.40	NA	NA	NA	NA
South Dakota	NA	2.5	NA	.62	1.1	.64	.27	.17	NA	NA	NA	NA
Texas	NA	2.0	NA	3.7	1.2	1.5	2.4	2.9	NA	NA	NA	NA
Wyoming	NA	6.5	NA	2.8	.66	.53	.28	.22	NA	NA	NA	NA
High Plains[3]	NA	3.8	NA	35.0	1.4	1.7	13.2	15.9	0.9	1.9	[4]8.3	[4]17.7

[1] Represents recharge studies for rangeland and undeveloped areas in appendix 2 and approximates 1940–49 conditions.

[2] Represents all recharge studies listed in appendix 2.

[3] Volume calculated for the High Plains does not always equal the sum of region or State volumes because of rounding.

[4] Total does not equal sum of the three regions because the averaged recharge rates from individual studies are not area-weighted.

Table 7. Composited-average annual recharge determined by previously published studies in the High Plains.

[Values are in inches per year. NHP, northern High Plains; NA, not available; CHP, central High Plains; SHP, southern High Plains]

Region	All	Undeveloped or rangeland[1]	Irrigated cropland	Nonirrigated cropland	Nonirrigated land	Nonspecific	Playas	Sand dune
NHP	2.9	1.6	4.8	2.2	2.6	2.5	NA	6.5
CHP	1.3	.6	1.8	NA	1.0	1.1	NA	4.8
SHP	1.1	.1	1.4	.5	.4	.9	3.6	.8
High Plains	1.9	0.9	3.1	1.5	0.95	1.5	3.6	4.2

[1] Represents pregroundwater-development conditions.

irrigation, or moisture in the upper 59 in. of the soil profile) and in the western part of the study area where SOWAT simulated greater recharge values than the SWB model.

Differences in methodology, combined with sensitivity of the SWB and SOWAT models to changes in model input parameters, can help explain differing potential-recharge rates. For example, a 10-percent increase in effective precipitation in the SOWAT model increased simulated recharge by as much as 105.8 percent (fig. 16), whereas a 10-percent increase in total precipitation in the SWB model increased recharge by as much as 47 percent (fig. 17). Precipitation could vary by more than 10 percent when different precipitation-estimation methods are used (table 3). Additionally, recharge also changed by as much as 94.7 percent when ET was changed by 10 percent in the SOWAT model.

Although SWB and SOWAT are both soil-water-balance models, the methods differ in several ways. Differences are associated with time-step, AET, surface-runoff, soil-moisture calculations, and precipitation inputs:

1. SWB uses daily time steps and SOWAT uses monthly time steps. Because most recharge processes are not linear with respect to time, these disparate time-step lengths can affect recharge results (Healy, 2010; Sophocleous, 2004).

2. SOWAT accounts for irrigation-system inefficiencies, whereas SWB assumes that irrigation systems are 100 percent efficient and there is no surplus irrigation water for recharge. Irrigation efficiency, as formulated in SOWAT, assumes that extra water pumped because of inefficient systems is available as extra soil moisture or deep percolation, rather than accounting for substantial losses of the extra pumpage to droplet and crop canopy evaporation. The inclusion of irrigation efficiency in SOWAT tends to explain, at least partially, the general positive bias in recharge estimation as compared with SWB.

3. SWB calculates AET internally based on an empirical equation that calculates PET and soil moisture; as soil moisture decreases, AET also decreases. SOWAT uses AET derived from the SSEB model. As a result, if precipitation and soil moisture are not adequate to meet AET in the SOWAT model, additional water is obtained from below the soil profile. In addition, estimated AET from the SSEB model was less than AET from other methods in the western part of the study area (fig. 21), and could explain the relatively larger recharge values from the SOWAT model in that part.

4. Soil-moisture depletion was computed from the Thornthwaite-Mather soil-water-retention tables (Thornthwaite and Mather, 1957) for SWB and is calculated in SOWAT as the balance of water remaining after accounting for soil moisture from the previous month and the current month's infiltration and AET. The simplified calculation of soil-moisture depletion in the SOWAT model could cause differences in estimated recharge.

5. Precipitation for SWB was from interpolated daily precipitation measured at weather stations. SOWAT used the NWS-estimated precipitation, which uses NEXRAD data and measured precipitation from weather stations as model input data. Both models are sensitive to changes in precipitation, and differences in precipitation at the local scale could cause large differences in potential recharge rates.

6. Surface runoff is calculated as part of the SWB model from the NRCS curve number (Cronshey and others, 1986), whereas SOWAT used runoff data calculated externally by the NWS SAC-SMA model. The SAC-SMA model yielded surface-runoff values that were much smaller than those estimated by the Base-Flow-Index (BFI) method (see next section). If surface-runoff values used by the SOWAT model were too small, recharge rates could be too large, and this difference also explains, at least partially, the general positive bias in recharge estimates from SOWAT as compared with SWB.

Surface Runoff and Groundwater Discharge to Streams

Major sources of streamflow are surface runoff and groundwater discharge (base flow). The amount of water entering and leaving the High Plains from surface runoff and as base flow was determined using data from streamflow-gaging stations and the BFI program. Streamflow data were downloaded from the National Water Information System (NWIS) (U.S. Geological Survey, 2010a) and processed using the BFI program, version 4.15 (Wahl and Wahl, 2007), to separate streamflow originating from groundwater discharge to streams (base flow) from streamflow originating from surface runoff. The BFI method combines a local minimums approach with a recession slope test. The minimum daily streamflow is first identified for each 5-day period in the water year. These minimums are then compared with adjacent minimums to identify base-flow hydrograph turning points. A minimum is identified as a turning point if both the adjacent minimums are greater than the value of that minimum multiplied by 0.9. These turning points represent the base-flow hydrograph, from which base-flow volume is calculated. The program uses a linear base-flow recession if a base-flow turning point corresponds to zero streamflow.

The time period (*N*) used for identifying streamflow minimums can be manipulated by the user to account for characteristics of a particular stream. To adjust *N* for a streamflow-gaging station, a range of *N*-values is used in successive runs, and BFI is plotted for varying *N* as described in Wahl and Wahl (1995). As *N* is increased, the amount of flow separated into surface runoff increases, and the BFI decreases. The appropriate *N*-value is selected as the smaller value at which the relation of *N* to BFI becomes nearly linear.

Mean daily base-flow and surface-runoff components of each streamflow record were calculated by applying the BFI program for the months of April and October throughout the period of record. These two generally off-peak flow months were chosen because many of the streams that cross the High Plains have numerous flow-control structures such as diversions and dams that regulate streamflow, particularly during times of peak runoff. It also was assumed that the base flow during April and October is representative of the entire year at each site because diversions for irrigation generally are inactive during those months. The mean daily base flow for the months of April and October were then multiplied by the number of days in the calendar year to determine the average annual base flow and surface runoff.

Total streamflow, surface runoff, and base flow entering and leaving the High Plains were estimated for the Niobrara, Platte, Little Blue, Big Blue, Republican, Solomon, Arkansas, and Canadian Rivers (figs. 3–5, table 8). However, streamflow-gaging stations were not always located at the boundary of the High Plains or at smaller streams; therefore, it was not possible to precisely determine the amount of streamflow entering and leaving the High Plains. The amount of water leaving the High Plains in the major streams was greater than the amount entering during both study periods (table 8). The net amount of streamflow leaving the High Plains was about 4.9 million acre-ft/yr in the 1940s and about 5.3 million acre-ft/yr in the 2000s, which paralleled the results for the base-flow component of streamflow. Base flow also composed the majority of streamflow leaving the High Plains in both study periods, but the surface-runoff fraction of streamflow was substantially smaller for the 2000s (28 percent) than for the 1940s (42 percent). The net volume of base flow leaving the High Plains was greater in the 2000s (3.9 million acre-ft/yr) than in the 1940s (3.1 million acre-ft/yr). Most of the increases to base flow were from streams within the Platte River Basin. This study did not account for diverted flows or evaporative losses in storage facilities, but the BFI analysis yielded base-flow-index values similar to those calculated by Bentall and Shaffer (1979).

Streamflow records were available for several smaller streams that carry water outside the High Plains, but records were only collected during one of the study periods. Those results were not included in the comparisons above but have been included in table 8 for reference. These streams include the Cimarron River, Beaver River, Wolf Creek, and Sweetwater Creek (fig. 4). Flows from those sites were a small fraction of the total streamflow.

Groundwater Discharge to Springs

Along parts of the High Plains boundary, water leaves the aquifer through springs and seeps. In many areas, spring flow is not gaged and no study has estimated the total discharge. Brune (1975) reported that springs and seeps in the SHP were flowing at rates of 1 to 2 cubic feet per second (ft^3/s) each. However, falling groundwater levels have caused most spring flows to decrease, and they are now a negligible component of the water budget (Dutton and others, 2001). A regional groundwater flow model for the SHP estimated that springs and seeps discharged about 58,000 acre-ft/yr before 1940 and about 42,000 acre-ft in 2000 to salt lake basins and along the eastern escarpment (Blandford and others, 2003). Another regional groundwater-flow model for the Republican River Basin within the NHP estimated average outflows to springs of about 65,000 acre-ft/yr in the 1920s and 88,000 acre-ft/yr in the 1990s (McKusick, 2003).

Groundwater Flow to and from Adjacent Geologic Units

Geologic units that compose the High Plains aquifer are the youngest saturated deposits within the High Plains (Gutentag and others, 1984). Older deposits generally are much less permeable, and little water exchange is expected between them and the aquifer. However, some upward or downward flux is possible. Measurements of hydraulic head in nested wells indicated that vertical gradients in some areas cause upward movement of water from older deposits beneath the High Plains aquifer in the CHP (McMahon, 2001). Conversely, vertical gradients at some locations in the SHP indicated that water movement was downward from the High Plains aquifer into older, underlying deposits (McMahon and others, 2004). In addition, a groundwater-flow model constructed for the SHP simulated groundwater fluxes between the High Plains aquifer and the underlying Cretaceous-age

Table 8. Streamflow entering and leaving the High Plains, 1940 through 1949 and 2000 through 2009.

[Sources of streamflow values: U.S. Geological Survey, 2010a. Values are in acre-feet per year. NHP; northern High Plains; WY, Wyoming; CO, Colorado; CHP; central High Plains; KS, Kansas; TX, Texas; NE, Nebraska; OK, Oklahoma]

River Basin	Streamflow-gaging station(s)	Station number(s)	Region	Mean annual streamflow	Mean annual base flow	Mean annual surface runoff	Mean annual streamflow	Mean annual base flow	Mean annual surface runoff
				1940 through 1949			2000 through 2009		
				Streamflow Entering High Plains					
Niobrara	Headwaters within High Plains		NHP	0	0	0	0	0	0
Platte	North Platte River below Whalen Diversion Dam, WY; South Platte River at Julesburg, CO	06657000; 06764000	NHP	627,000	368,000	259,000	273,000	96,000	177,000
Little Blue	Headwaters within High Plains		NHP	0	0	0	0	0	0
Big Blue	Headwaters within High Plains		NHP	0	0	0	0	0	0
Republican	Headwaters within High Plains		NHP	0	0	0	0	0	0
Solomon	Headwaters within High Plains		NHP	0	0	0	0	0	0
Arkansas	Arkansas River at Garden City, KS	07139000	CHP	164,000	27,000	137,000	14,000	7,000	7,000
Canadian	Canadian River near Amarillo, TX	07227500	CHP	301,000	22,000	279,000	70,000	9,000	61,000
Total				1,092,000	417,000	675,000	357,000	112,000	245,000
				Streamflow Leaving High Plains					
Niobrara	Niobrara River near Sparks, NE[1]	06461500	NHP	612,000	580,000	32,000	562,000	509,000	53,000
Platte	Platte River near Ashland, NE	06801000	NHP	2,864,000	2,020,000	844,000	3,644,000	2,888,000	756,000
Little Blue	Little Blue River near Fairbury, NE	06884000	NHP	198,000	114,000	84,000	138,000	83,000	55,000
Big Blue	Big Blue River at Barneston, NE	06882000	NHP	366,000	116,000	250,000	419,000	187,000	232,000
Republican	Republican River near Hardy, NE	06853500	NHP	538,000	285,000	253,000	108,000	57,000	51,000
Solomon	North Fork Solomon River at Portis, KS[1]; South Fork Solomon River above Webster Reservoir, KS[1]	06872500; 06873000	NHP	185,000	33,000	152,000	80,000	40,000	40,000
Arkansas	Arkansas River at Wichita, KS	07144300	CHP	903,000	320,000	583,000	636,000	255,000	381,000
Canadian	Canadian River near Canadian, TX	07228000	CHP	359,000	25,000	334,000	56,000	34,000	22,000
Total				6,025,000	3,493,000	2,532,000	5,643,000	4,053,000	1,590,000
Net Water Balance (water entering minus water leaving)				-4,933,000	-3,076,000	-1,857,000	-5,286,000	-3,941,000	-1,345,000
		Streamflow Leaving the High Plains (only one time period available)							
Cimarron	Cimarron River near Forgan, OK	07155590	CHP	No data	No data	No data	25,000	21,000	4,000
Beaver River	Beaver River near Fort Supply, OK	07234500	CHP	151,000	19,000	132,000	No data	No data	No data
Wolf Creek	Wolf Creek near Fort Supply, OK	07237000	CHP	105,000	6,000	99,000	No data	No data	No data
Sweetwater	Sweetwater Creek near Sweetwater, OK	07301420	CHP	No data	No data	No data	18,000	11,000	7,000

[1] No data available before 1945.

deposits (Blandford and others, 2008). Groundwater movement primarily was downward from the High Plains aquifer to the underlying deposits but localized upward flows also occurred. The net volume of water lost from the High Plains aquifer to the underlying deposits was simulated to be less than 1 percent of the volume of recharge entering the High Plains aquifer in the modeled area.

Irrigation

The dominant use of groundwater in the High Plains is for irrigating crops. In 2005, approximately 95 percent of groundwater pumpage in the High Plains was for irrigation; withdrawals for public supply and industrial uses were 2 percent and 3 percent, respectively (Kenny and others, 2009). The process of irrigation includes the withdrawal of water from surface-water bodies or groundwater, followed by either its loss during conveyance, return to the atmosphere through evapotranspiration by plants, surface runoff to streams, or infiltration through the unsaturated zone (irrigation return flow) to become recharge.

Irrigation Methods

Although detailed water-use information is available from surface-water irrigation districts, groundwater pumpage for irrigation is measured in few parts of the High Plains. Therefore, the amount of water withdrawn is usually estimated using information about the number of acres irrigated with groundwater, the amount of water that was expected to be used by the crops grown on those acres, and the amount of the crop-water demand that was satisfied by precipitation (Kenny, 2004).

The estimated number of irrigated acres in the High Plains in 2002 ranged from 14.2 to 14.9 million acres (Brown and others, 2008; U.S. Department of Agriculture, variously dated) (table 9). Most fields are irrigated using groundwater; however, about 1 million acres are irrigated from surface-water sources. Surface-water-irrigated acres occur primarily within the NHP region in Kansas, Nebraska, and Wyoming (fig. 23) (Buchanan and others, 2009; Colaizzi and others, 2008; Colorado Department of Natural Resources, 2010). Readily available information on the location of surface-water irrigated fields were compiled using GIS data for Nebraska and Wyoming (Amanda Flynn, USGS, written commun., 2010; Matt Hoobler, Wyoming State Engineer's Office, written commun., 2010), but GIS for surface-water-irrigated acres in Kansas were not available. The surface-water-irrigation districts lie mainly along the North Platte River in Wyoming and Nebraska, and along the Platte, Republican, and Loup Rivers in Nebraska (fig. 23).

Estimates of the amount of water used for irrigation came from four main sources: the SOWAT model, the SWB model, the USGS National Water-Use Program (compiled at 5-year intervals from 1950 to 2005), and limited information from metered irrigation wells (Kenneth Kopp, Kansas Department of Agriculture, oral commun., 2010). All estimates reported herein are for 2000 through 2009. The SOWAT and SWB models constructed for this study are described fully in the "Soil-Water-Balance Models" section of this report.

Water-use estimates for the Nation from the USGS Water-Use Program have been published every 5 years beginning in 1950; hence, this source provides no estimates for the 1940s study period. Information on water use is compiled for all purposes (private, public, commercial, industrial, and agricultural) at the county, State, and Federal level every 5 years. Data from the Water-Use Program for 2000 and 2005 were used for this report (Hutson, 2007; Kenny, 2004).

Under the USGS Water-Use Program each state is responsible for the data compilation using methods specific to each State. Thus, the methods used for compiling estimates of groundwater pumpage for irrigation vary by State. Four of the eight States (Colorado, Nebraska, Texas, Wyoming) generally use crop acreages, estimated crop-water demand, irrigation system efficiency, and climate information to determine consumptive use and pumpage (Dana Barbie, USGS, written commun., 2009; Greg Boughton, USGS, written commun., 2009; Russ Dash, USGS, written commun., 2009; Natalie Houston, USGS, written commun., 2009; Jill Frankforter, USGS, written commun., 2009). The other States use a combination of direct measurement (meters attached to the irrigation systems),

Table 9. Irrigated acres in the High Plains, selected estimates, 2002.

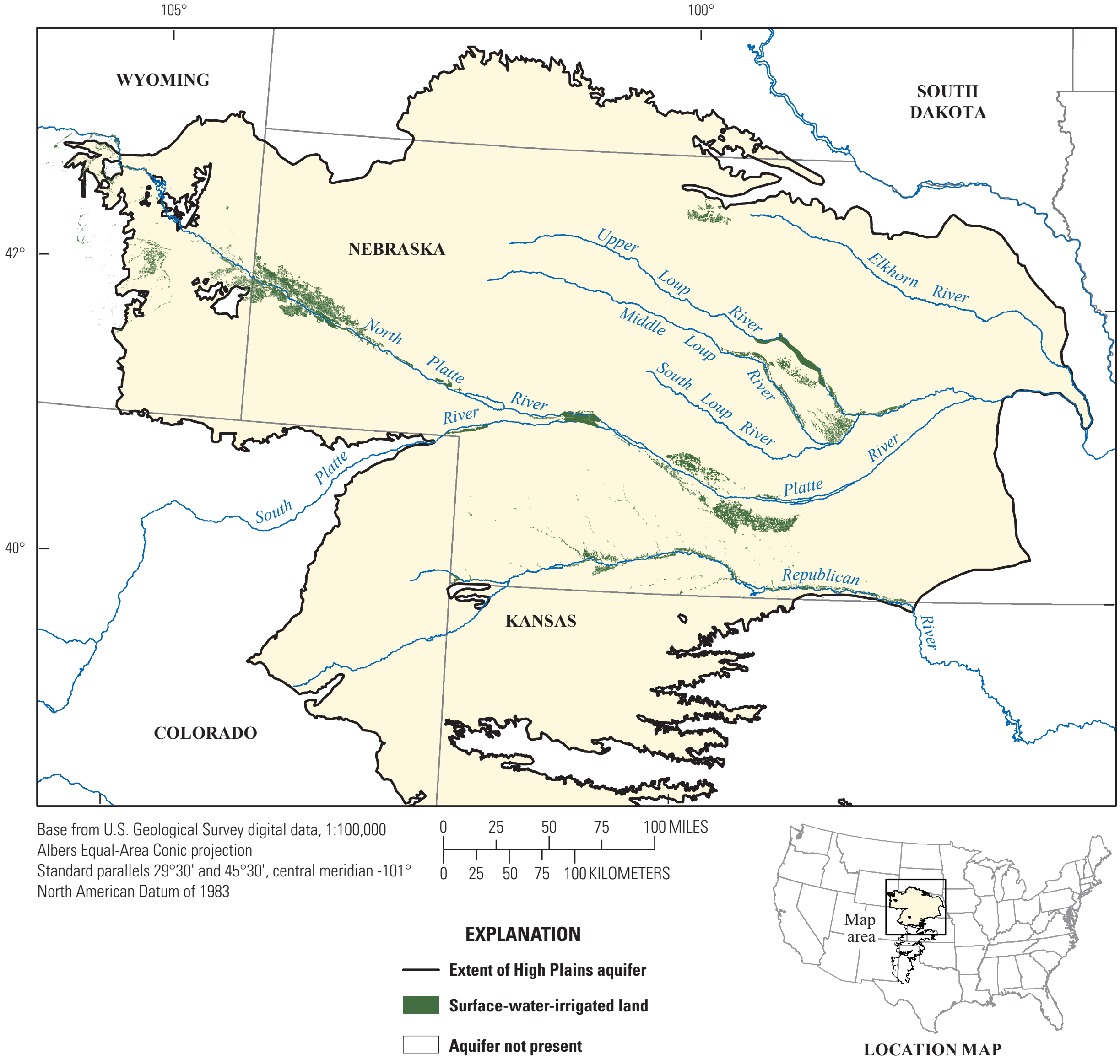
[Units are million acres. NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains]

	Remotely sensed data from satellite imagery[1]	Census of Agriculture report[2]
NHP	8.6	8.2
CHP	3.3	3.2
SHP	2.9	2.8
Colorado	0.7	0.7
Kansas	2.4	2.2
Nebraska	7.4	7.0
New Mexico	.3	.3
Oklahoma	.3	.3
South Dakota	0	0
Texas	3.6	3.5
Wyoming	.3	.3
High Plains[3]	14.9	14.2

[1] From Brown and others (2008).

[2] From U.S. Department of Agriculture (variously dated). Values are considered rough estimates because original data are reported at the county level and the exact number of irrigated acres within the High Plains were not available for counties along the edge of the High Plains.

[3] Area calculated for the High Plains does not always equal the sum of region or State areas because of rounding.



Base from U.S. Geological Survey digital data, 1:100,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -101°
North American Datum of 1983

Figure 23. Surface-water irrigated land in the northern High Plains region, 2000 through 2009.

questionnaires to land owners, and water-rights databases to compute irrigation pumpage (Robert Gold, USGS, written commun., 2009; Joan Kenny, USGS, written commun., 2009; Kathy Neitzert, USGS, written commun., 2009; Robert Tortorelli, USGS, written commun., 2009). Groundwater pumpage for irrigation was compiled for the counties that are completely within or touch the boundary of the High Plains. Because the data are by county and many counties are only partly within the High Plains, the county values were adjusted by the ratio of the amount of irrigated land in a county that fell within the aquifer. County pumpage values were then compiled for each State and region for 2000 and 2005.

There are few data available for the 2000-through-2009 period from direct measurements of groundwater pumpage for irrigation (metered irrigation wells) in the High Plains, and no data available for the 1940s. However, the State of Kansas has been progressively metering irrigation wells since 1987 and has had metering requirements in place for wells in northwestern and southwestern Kansas for the past 5 to 20 years. More recently, irrigation wells have begun to be metered in other areas of the High Plains, such as the Republican River Basin in the NHP (see, for example, Colorado Department of Natural Resources, 2009) and selected groundwater conservation districts in Texas (see, for example, North Plains Groundwater Conservation District, 2011), but those data were not used for this report.

Irrigation Results

The average annual total volume of water applied on cropland for irrigation (surface-water and groundwater sources) for 2000 through 2009 from the SOWAT model was 9.3 million acre-ft for the High Plains, yielding an average annual irrigation application rate of 8.4 in. on irrigated lands (fig. 24*A*). Total irrigation from groundwater sources only (pumpage) during 2000 through 2009 was approximately 8.7 million acre-ft/yr for the High Plains, for an average application rate of 8.4 in/yr (table 10). The average annual irrigation application rates for groundwater-irrigated acres were 7.8, 10.6, and 7.7 in. for the NHP, CHP, and SHP, respectively. The SOWAT estimated volume of surface water applied to fields in the NHP for 2000 through 2009 was approximately 650,000 acre-ft. Surface water was used to irrigate crops in some parts of the High Plains before 1950, but too little information was available to allow estimation of the amount of water used during the 1940s.

The average annual total volume of water used for irrigation (surface-water and groundwater sources), based on the SWB model results, was 17.6 million acre-ft for the High Plains, and the average annual irrigation application rate was 15.8 in. on irrigated lands (fig. 24*B*). For areas where surface-water irrigation occurred, the amount of groundwater pumped for irrigation was approximated by multiplying the total irrigated acres by the ratio of groundwater-irrigated acres to the total irrigated acres. Thus, average annual irrigation from groundwater for the High Plains was estimated as 16.2 million acre-ft, or 15.8 in. (table 10). Regional average groundwater-irrigation application rates generally were similar across the High Plains: 15.3 in/yr in the NHP, 17.0 in/yr in the CHP, and 16.1 in/yr in the SHP.

Average adjusted irrigation application volume estimated from the National water-use data for the year 2000 was 19.6 million acre-ft, for an average application rate of 17.8 in. (table 10). In 2005, the volume was 18.4 million acre-ft, for an average application rate of 16.7 in. Surface water used for irrigation in the NHP was estimated as 2.4 million acre-ft in 2000 and 2.0 million acre-ft in 2005, yielding average application rates of about 28 inches and 23 inches, respectively.

From metered irrigation wells in 2000, groundwater pumpage for irrigation was reported as 3.14 million acre-feet, for an average applied depth of 16.9 inches within the groundwater-irrigated High Plains part of Kansas (Kenneth Kopp, Kansas Department of Agriculture, oral commun., 2010). Metered pumpage values represent a total amount of water applied and include losses to system inefficiency.

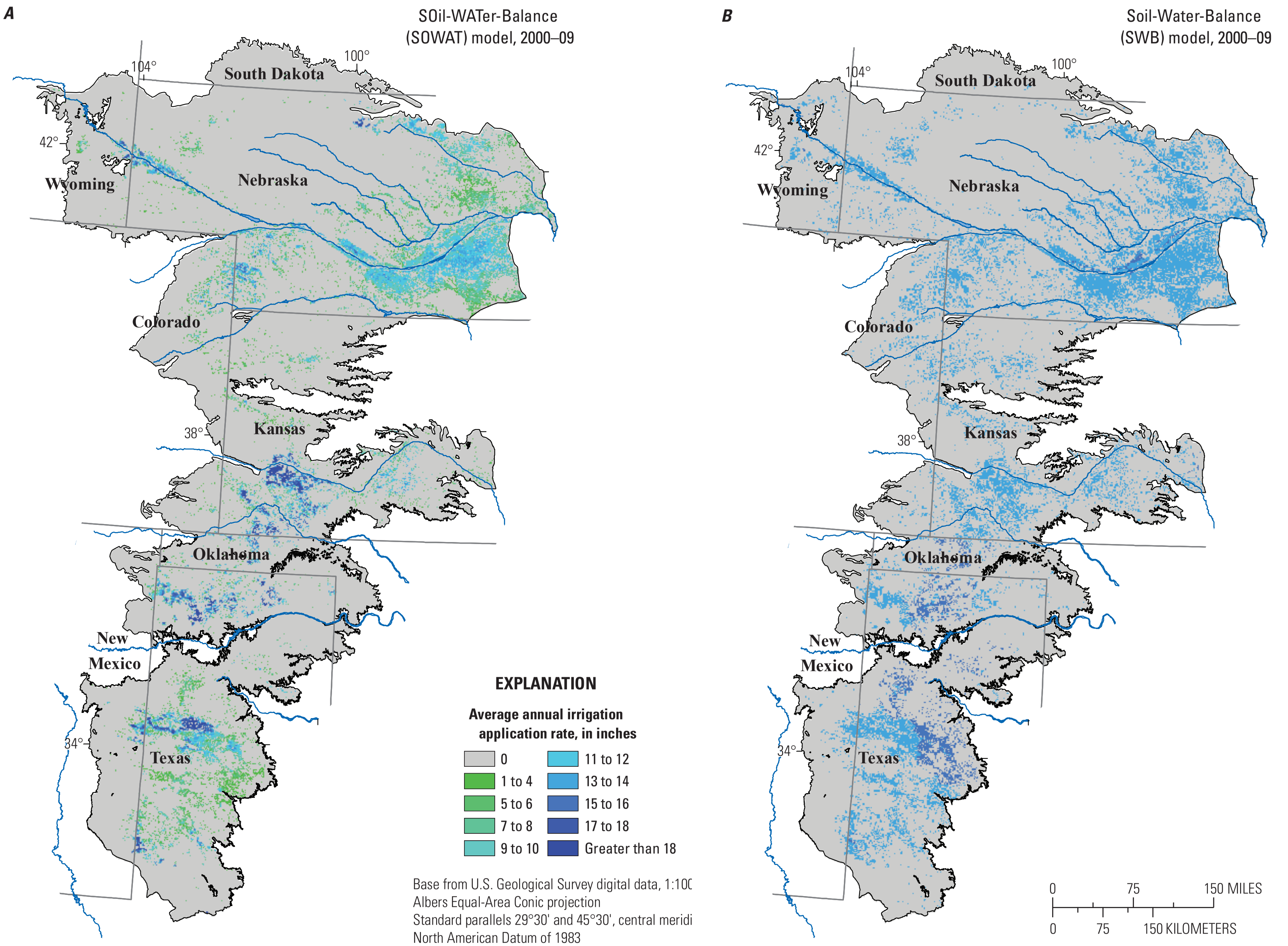
Temperature, precipitation, and PET gradients in the High Plains indicate that greater amounts of water likely are needed to be applied to irrigated fields in the SHP than in the NHP (fig. 6, tables 4 and 5). However, AET rates estimated from the SSEB and NWS SAC-SMA models indicate that there is more water uptake to the atmosphere in the CHP through ET than in the other regions (fig. 21*C*, table 4). In addition to temperature, precipitation, and PET, irrigation applications also depend on the crop type, soil characteristics, system efficiency, commodity prices, subsidies, and energy costs (Colaizzi and others, 2008), factors that would be included in the estimated AET rates that are derived from satellite imagery (SSEB model). In addition, the SHP has experienced substantial water-level declines since pregroundwater development (approximately 50 percent or more of the saturated thickness has been lost since pregroundwater development) (McGuire, 2009). This decline may have reduced the amount of groundwater that is available for irrigation and prompted the accelerated conversion to high-efficiency irrigation systems, thus reducing the amount of pumpage that otherwise would have been required for irrigation (Colaizzi and others, 2008). Estimated groundwater irrigation application rates from the SOWAT model and the USGS Water-Use Program were greatest in the CHP and about the same for the SHP and NHP (table 10). For the SWB model, groundwater irrigation application rates were greatest in the CHP, but differences between the three subregions were less substantial than for the SOWAT model and USGS Water-Use Program.

Apart from the excellent agreement between the estimated irrigation application rate from the SWB model and the metered irrigation-well data in Kansas, the estimation methods yielded different groundwater irrigation application rates for the same area, reflecting uncertainties related to estimating groundwater irrigation applications and underscoring the value of using multiple methods. Estimated pumpage for the High Plains from the SOWAT model was about 50 percent of that estimated for 2005 by the USGS Water-Use Program and the SWB model for 2000 through 2009 (table 10). Annual pumpage volumes from the Water-Use Program generally were larger than the volumes of irrigation applied that were estimated from the two soil-water-balance models. Differences between the methods cannot be summarized easily for the High Plains because the methods used for the Water-Use Program vary widely among the States. However, some possible explanations for the disparate results include:

1. Monthly time steps used by the SOWAT model may be too long for representing soil-moisture dynamics.

2. Different methods were used to estimate AET. The SOWAT model derives crop-water requirements from AET estimated from satellite data, whereas the SWB model uses daily temperature, soil-water holding capacity, and vegetation root depths to estimate AET, and the Water-Use Program used other methods including a calculated crop-water requirement, water rights information, or direct measurements (meters).

3. Results are sensitive to changes in AET and effective precipitation. It was demonstrated in the “Precipitation” section of this report that different sources of precipitation can vary by more than 10 percent for some areas (table 3), potentially causing a 20-percent change in SOWAT-simulated pumpage (fig. 16). AET values are also uncertain, and a 10-percent change in AET can cause pumpage simulated by SOWAT to change by more than 30 percent. Although a sensitivity analysis was not conducted as part of the USGS Water-Use Program, it is likely that those results also are sensitive to somewhat uncertain AET and effective precipitation estimates.



Base from U.S. Geological Survey digital data, 1:10
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridi
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Figure 24. Distribution of estimated average annual irrigation application rates for groundwater and surface water from (*A*) the SOil-WATer-Balance (SOWAT) model and (*B*) the Soil-Water-Balance (SWB) model in the High Plains, 2000 through 2009.

Table 10. Estimated irrigation from groundwater in the High Plains, 2000 through 2009.

[Volumes calculated as the average irrigation application rate multiplied by the irrigated area. NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains; <, less than]

	Average annual irrigation application rate, in inches[1]	Average annual pumpage volume, million acre-feet[2]	Average annual irrigation application rate, in inches[1]	Average annual pumpage volume, million acre-feet[2]	Average annual irrigation application rate, in inches[1 3]		Average annual pumpage volume, million acre-feet	
	2000–09		2000–09		2000	2005	2000	2005
	SOil-WATer-Balance (SOWAT) Model		Soil-Water-Balance (SWB) Model		U.S. Geological Survey Water-Use Program[4]			
NHP	7.8	4.4	15.3	8.6	16.7	16.3	10.0	9.8
CHP	10.6	2.5	17.0	4.0	21.4	18.3	5.6	4.8
SHP	7.7	1.7	16.1	3.6	16.7	16.0	3.9	3.8
Colorado	5.0	.22	17.4	.76	16.7	19.7	1.0	1.2
Kansas	9.9	1.6	16.9	2.8	19.4	14.8	3.6	2.7
Nebraska	8.2	4.1	14.8	7.4	15.6	15.3	7.9	7.7
New Mexico	8.6	.17	18.1	.35	22.2	20.1	.6	.5
Oklahoma	9.7	.15	20.2	.32	22.0	12.4	.5	.3
South Dakota	5.9	<.01	29.8	.01	16.7	19.7	<.1	<.1
Texas	8.5	2.4	16.3	4.5	19.5	18.9	5.7	5.5
Wyoming	8.9	<.04	21.6	.11	26.6	28.6	.4	.4
High Plains[5]	8.4	8.7	15.8	16.2	17.8	16.7	19.6	18.4

[1] Applied to groundwater-irrigated acres.

[2] Volumes calculated as the average irrigation application rate multiplied by the irrigated area.

[3] Application rates are calculated as the volume of irrigation divided by the irrigated area.

[4] Values from the USGS Water-Use Program are considered rough estimates because original data are reported for the county level and the exact amount of irrigation within the High Plains was not known for counties along the edge of the High Plains.

[5] Volume calculated for the entire High Plains does not always equal the sum of region or State volumes because of rounding.

4. Irrigation-application values from the SOWAT model and the USGS Water-Use Program include additional withdrawals to account for irrigation system inefficiencies, whereas the SWB model does not. Thus, the SWB model may underestimate the total amount of water pumped from the High Plains aquifer.

5. The USGS Water-Use Program estimated irrigation applications for only two years (2000 and 2005) of the 10-year period. If climate conditions for 2000 and 2005 were not representative of average conditions for 2000 through 2009, results from the USGS Water-Use Program will be biased.

The volume of surface water used to irrigate crops, as estimated from the SOWAT model, is substantially less than the amount reported by the Water-Use Program. Similar to the groundwater pumpage estimates, SOWAT uses stored soil water and effective precipitation to satisfy crop-water requirements, whereas the Water-Use Program used either effective precipitation or total precipitation as the only source of water. In addition, fewer surface-water irrigated acres were identified for SOWAT. Surface-water irrigated land for SOWAT represented acres within irrigation districts only (total of about 1 million acres). However, surface-water irrigated acres in areas outside of the irrigation districts also were included in the acreage tabulations for the USGS Water-Use Program (total of almost 2.5 million acres in 2005) (Jill Frankforter, USGS, written commun., 2008; Matt Hoobler, Wyoming State Engineer's Office, written commun., 2010).

Groundwater in Storage

The available groundwater in storage is the amount of water that can be extracted physically from the aquifer for use. The amount of water that can be removed from an aquifer varies by location and is dependent upon the well construction, saturated thickness, and aquifer properties such as the composition of the aquifer sediments, the amount of voids (space between the sediments), and the degree to which the voids are connected in the aquifer. Groundwater storage and water-table elevations will change as a response to changes in inputs to (such as recharge from precipitation and seepage from streams) and outputs from (such as pumpage, discharge to streams, or ET) the aquifer.

For water-resources-management purposes, the amount of groundwater in storage in the High Plains aquifer is an important component of the water budget. In many parts of the High Plains, crop yields are dependent upon supplemental irrigation from groundwater. Groundwater also is the primary source of drinking water (Dennehy, 2000). Understanding the status of groundwater storage can help guide decision makers about future use of the resource. However, the volume of groundwater in storage does not solely define the availability of water or the sustainability of the resource. Water availability and sustainability also are related to the cost of extracting groundwater, the quality of groundwater, the effects of groundwater withdrawals on surface water, and the definition of groundwater availability by policymakers. For example, policymakers can decide that only a fraction of the groundwater in storage should be extracted.

Groundwater in Storage Methods

The USGS High Plains Water-Level Monitoring Study (U.S. Geological Survey, 2010b) has analyzed historical groundwater levels and estimated changes to groundwater storage. Results from that study indicate that groundwater levels have been declining throughout the past 50 years as a response to groundwater withdrawals (table 11). When compared as State-level averages, the largest groundwater-level declines during the period of groundwater development through 2007 occurred in Texas (37 ft) and Kansas (23 ft). Almost no groundwater-level change occurred in Nebraska, South Dakota, and Wyoming (table 11).

The volume of groundwater in storage was estimated for 2000 by McGuire and others (2003) by multiplying the volume of saturated material by the area-weighted average specific yield of the aquifer. The change in storage for pre-groundwater development and 2007 was calculated by multiplying the change in the volume of saturated material between 2000 and 2007 by the average specific yield (McGuire, 2009). Storage volumes for pregroundwater development and 2007 then were determined by subtracting or adding, as appropriate, the change in storage as compared to 2000 with the volume of groundwater in storage for 2000.

Groundwater in Storage Results

Total groundwater in storage in the High Plains aquifer was estimated as 3,173 million acre-ft prior to groundwater development and 2,907 million acre-ft in 2007. The largest State-total decreases in groundwater storage were in Texas and Kansas (table 11). Groundwater in storage has declined since prior to groundwater development (before about 1950) by as little as 1 percent in Nebraska and South Dakota to as much as 29 percent in Texas. Reductions to groundwater in storage were greater in the CHP (117 million acre-ft) and SHP (100 million acre-ft) than in the NHP (50 million acre-ft), which means that the net groundwater discharge (outputs minus inputs) was greater in the CHP and SHP than in the NHP. The average annual decrease of groundwater storage between 2000 and 2007 in the High Plains aquifer was 10 million acre-ft/yr.

Uncertainty and Limitations

A water budget can be a useful management tool if water-budget components are accurately quantified and the balance between water inputs and water outputs can be determined without bias. In previous sections of the report, multiple

Table 11. Estimated volume of groundwater in storage in the High Plains aquifer, prior to groundwater development (before about 1950) and 2007 (McGuire and others, 2003; McGuire, 2009).

[NHP, northern High Plains; CHP, central High Plains; SHP, southern High Plains]

	Predevelopment volume of storage, million acre-feet	Change in storage, predevelopment through 2007, million acre-feet	Change in storage, predevelopment through 2007, percent	Average water-level change, predevelopment through 2007, feet[1]	2007 volume of storage, million acre-feet
NHP	2,337	-50	-2.1	-2.9	2,287
CHP	596	-117	-20	-26	479
SHP	240	-100	-42	-35	140
Colorado	95	-17	-18	-13	78
Kansas	321	-63	-20	-23	258
Nebraska	1,998	-21	-1.1	-1.0	1,977
New Mexico	46	-10	-22	-16	36
Oklahoma	117	-12	-10	-12	105
South Dakota	59	-0.60	-1.0	0	58
Texas	476	-140	-29	-37	336
Wyoming	61	-2.3	-3.8	-0.4	59
High Plains	3,173	-267	-8.4	-14	2,907

[1] Negative change of water level indicates a decreasing water-table altitude.

sources of information were compiled to estimate the average annual volumes of water associated with selected water-budget components of the High Plains landscape and aquifer system for 1940 through 1949 (representing conditions prior to groundwater development) and 2000 through 2009 time periods. The primary budget components of the aquifer for the 1940 through 1949 were recharge from precipitation, AET from shallow groundwater, and net discharge to streams (fig. 25*A*). For 2000 through 2009, primary budget components are expanded (fig. 25*B*) to include groundwater pumpage for irrigation and recharge associated with agricultural practices. Other components of the budget such as exchange of water with underlying geologic units, discharge to springs, and groundwater pumpage for other purposes (such as for public water supply) are small compared to the primary components.

As demonstrated in figure 25, water-budget-component values for the High Plains aquifer obtained from multiple methods as part of this study differed substantially, indicating uncertainty in the results. Even precipitation, a component that typically is considered to be well-known at weather stations, varied among the different methods by more than 10 percent in parts of the High Plains when values were interpolated between weather stations (table 3). These differences are important because relatively small changes in values used as input to hydrologic models can cause substantial changes to simulated amounts of recharge and irrigation pumpage (figs. 16 and 17), and present challenges for balancing water-budget inflows and outflows.

In addition to the limitations associated with the soil-water-balance models (see the “Soil-Water-Balance Models” section of this report), none of the methods used to estimate water-budget components for this study were designed to produce an integrated water budget for the landscape and subsurface. The methods also did not include calibration to independent hydrologic measurements, such as groundwater levels and streamflow, to verify that the water-budget values would reproduce hydrologic conditions. Without additional refinement of water-budget component estimates through an integrated hydrologic model calibrated to independent hydrologic measurements, these results cannot be used to define the sustainability of the High Plains aquifer. Results are intended to provide a comparison of water-budget component-estimation methods and an assessment of the range of values for the components that could be obtained from different methods. This information can be used to guide the selection and evaluation of model inputs or both for regional hydrologic models of the High Plains landscape and subsurface. Results can also help evaluate input values of previous models and why their results may differ from other models.

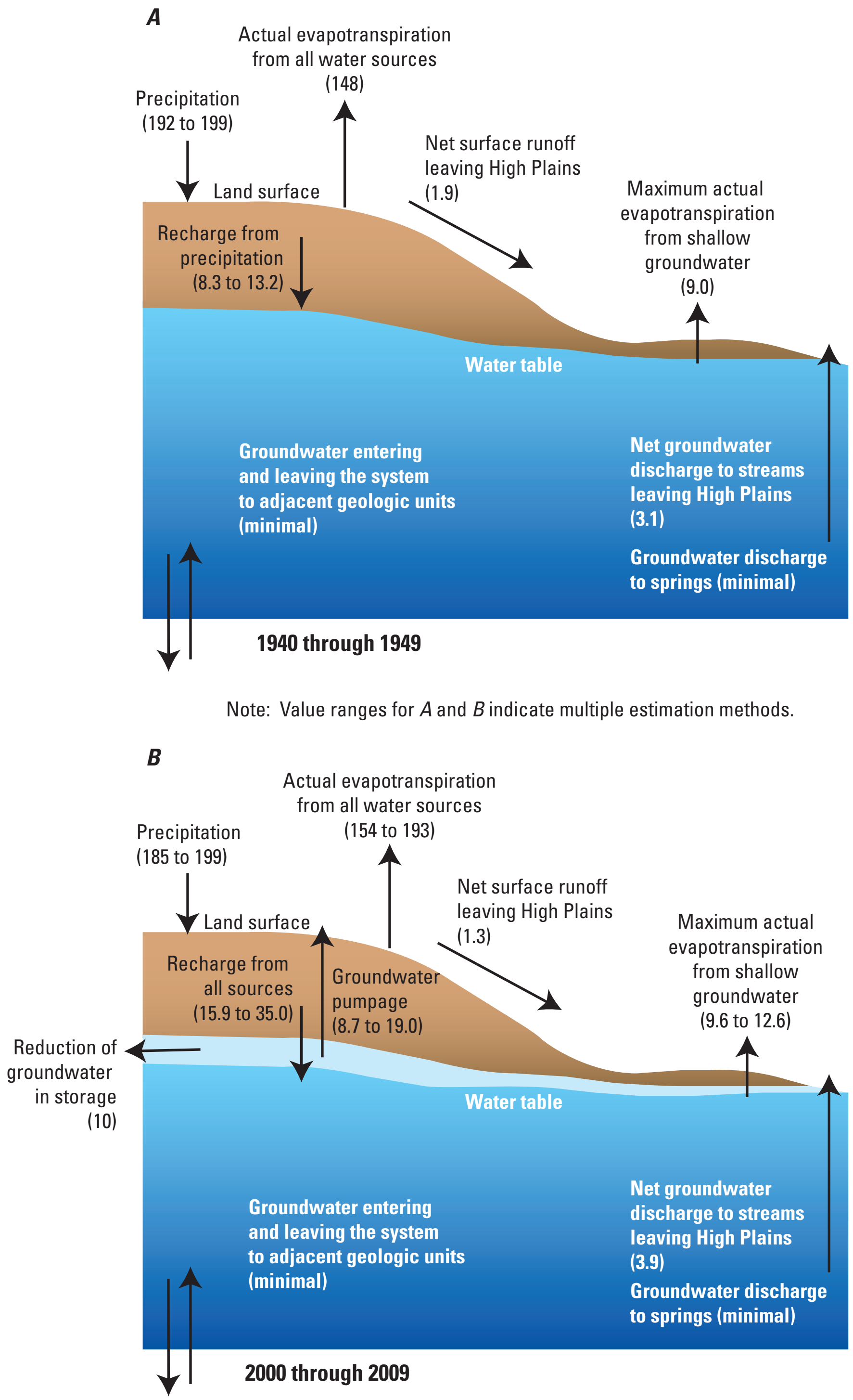

Figure 25. Ranges for selected water-budget components in the High Plains, (*A*) 1940 through 1949 and (*B*) 2000 through 2009. (Values enclosed by parentheses are given in million acre-feet per year.)

Summary

The High Plains aquifer, underlying almost 112 million acres in the central United States, is one of the largest aquifers in the Nation. It is the primary water supply for drinking water, irrigation, animal production, and industry in the region. Expansion of irrigated agriculture throughout the past 60 years has helped make the High Plains one of the most productive agricultural regions in the Nation. Extensive withdrawals of groundwater for irrigation have caused water-level declines in many parts of the aquifer and increased concerns about the long-term sustainability of the aquifer.

A water budget is an accounting of hydrologic components of the water cycle, transfers between the components, and their relative contributions within a water system. Water budgets help define how much water is available, how much water is used, where the water comes from, and at what rate water is replenished. In its simplest form, a water budget defines the amount of water entering and leaving a water system. Quantification of water-budget components is essential for effective water-resource management. Water-budget components analyzed as part of this study were precipitation, evapotranspiration (ET), recharge, surface runoff, groundwater discharge to streams, groundwater discharge to springs, groundwater fluxes to and from adjacent units, irrigation, and groundwater in storage. These components were described for 1940 through 1949 (representing conditions prior to groundwater-development) and 2000 through 2009.

Because no single method can perfectly quantify the magnitude of any part of a water budget at a regional scale, results from several methods and previously published work were compiled and compared for this study when feasible. Two spatially distributed soil-water-balance models were developed: the SOil-WATer-Balance (SOWAT) and Soil-Water-Balance (SWB) models. Although both models use a water-budget equation to estimate unknown components of the water budget, the models are formulated differently with respect to model inputs such as time-step length, ET, runoff, soil-moisture dynamics, and precipitation.

Precipitation was derived from three sources: the Parameter-Elevation Regressions on Independent Slopes Model (PRISM); data developed by the National Weather Service Office of Hydrologic Development (for the Sacramento-Soil Moisture Accounting model) using Next Generation Weather Radar data and measured precipitation from weather stations; and precipitation data from weather stations that were spatially interpolated using an inverse-distance-weighted (IDW) method. For 1940 through 1949, the 10-year average annual precipitation from the two estimation methods with data for that time period (PRISM and IDW interpolation) ranged from 20.6 to 21.0 in. for the northern High Plains (NHP), 22.2 to 22.7 in. for the central High Plains (CHP), and 17.9 to 19.6 in. for the southern High Plains (SHP). Average annual precipitation for the High Plains during the 1940s ranged from 20.6 to 21.2 in., and total precipitation as an average annual volume for the High Plains ranged from 192 to 199 million acre-ft. For 2000 through 2009, average annual precipitation from the three estimation methods ranged from 19.9 to 21.3 in. for the High Plains; 20.3 to 21.7 in. for the NHP, 19.9 to 22.0 in. for the CHP, and 17.7 to 19.1 in. for the SHP. The average annual volume of precipitation for the High Plains during the 2000s ranged from 185 to 199 million acre-ft. Average precipitation calculated for each State differed by as much as 12 percent. Although the three methods commonly are used and generally accepted as appropriate methods for estimating precipitation, there are inherent limitations associated with all models. The differences between methods have implications for hydrologic models, such as SOWAT and SWB, which are sensitive to changes in precipitation.

Evapotranspiration estimates were obtained from four methods: the National Weather Service Sacramento-Soil Moisture Accounting model, the Simplified-Surface-Energy-Balance model using remotely sensed data, the SWB model, and an energy-balance method applied to two riparian study sites. For 1940 through 1949, average annual actual ET (AET) estimated from the SWB model was 15.8 in. for the High Plains and 15.2, 17.2, and 15.1 in. for the NHP, CHP, and SHP, respectively. AET as an average annual volume was 148 million acre-ft for the High Plains. For 2000 through 2009, average annual AET estimated from all three estimation methods ranged from 16.4 to 20.7 in. for the High Plains (16.5 to 20.9 in. for the NHP, 16.6 to 21.4 in. for the CHP, and 16.1 to 18.7 in. for the SHP). The average annual volume of AET during the 2000s ranged from 154 to 193 million acre-ft for the High Plains. Differences between the estimation methods were substantial and were greater than the temporal difference between the two study periods, highlighting the potential uncertainty associated with estimating AET across large regions. As with precipitation estimates, this uncertainty can affect the outcome of hydrologic models that use ET as an input.

The amount of shallow groundwater lost to ET was estimated using AET rates from the NWS, SOWAT, and SWB models for areas where the water table was within 5 ft of land surface. The estimated average annual maximum volume of ET from shallow groundwater was 9.0 million acre-ft for 1940 through 1949 and ranged from 9.6 to 12.6 million acre-ft for 2000 through 2009. These estimates are considered maximum possible values because the calculated results rely on the assumption that all of the ET demand is satisfied by groundwater; however, ET demand also will be satisfied by precipitation, particularly in more humid areas.

Potential recharge was estimated using the SOWAT and SWB models as well as previously published studies of various locations across the High Plains. For 1940 through 1949, average annual recharge estimated from SWB and previously published studies ranged from 0.9 to 1.4 in. for the High Plains (1.4 to 1.6 in. for the NHP, 0.6 to 1.6 in. for the CHP, and 0.1 to 1.1 in. for the SHP). Recharge volume ranged from 8.3 to 13.2 million acre-ft/yr for the High Plains. For 2000 through 2009, average annual recharge estimated from the three methods ranged from 1.7 to 3.8 in. for the High Plains (1.9 to

5.1 in. for the NHP, 1.3 to 1.7 in. for the CHP, and 1.1 to 2.8 in. for the SHP). Average annual recharge volume during the 2000s ranged from 15.9 to 35.0 million acre-ft for the High Plains. The average potential recharge rates estimated for 2000 through 2009 were greater than for 1940 through 1949 despite smaller precipitation and greater AET rates across the High Plains. This result agrees with previous studies that indicate recharge rates increase after rangeland is converted to nonirrigated and irrigated cropland. Most increases in potential recharge were within Nebraska and Texas, the two States with the largest number of irrigated acres. Recharge results from the SOWAT model were much greater than those from either the SWB model or results averaged from previously published studies.

Surface runoff and aquifer discharge to streams were determined using discharge records from streamflow-gaging stations near the edges of the High Plains, together with the Base-Flow-Index program. For 1940 through 1949, net base flow leaving the High Plains was 3.1 million acre-ft/yr, and the net surface runoff leaving the High Plains was 1.9 million acre-ft/yr. For 2000 through 2009, net base flow leaving the High Plains was 3.9 million acre-ft/yr, and the net runoff leaving the High Plains was 1.3 million acre-ft/yr. Most streamflow leaving the High Plains was from the NHP. The amount leaving from springs along the eastern edge of the High Plains was small compared to other water-budget components.

Though little water exchange is expected to occur between the aquifer and older deposits, some upward or downward flux has been observed by previous studies. The net volume of water lost from the SHP aquifer to the underlying deposits was simulated by a groundwater-flow model to be less than 1 percent of the volume of recharge entering the High Plains aquifer in the modeled area.

Most groundwater withdrawn from the High Plains aquifer is used for irrigating crops. For 2000 through 2009, the average annual volume of applied irrigation estimated using the two soil-water-balance models ranged from 8.7 to 16.2 million acre-ft for the High Plains. Average annual irrigation application rates for the High Plains estimated by these two models for the 2000s ranged from 8.4 to 15.8 in. The U.S. Geological Survey Water-Use Program published estimated annual pumpage for 2000 and 2005. Annual pumpage volumes from the Water-Use Program generally were larger than the volumes of irrigation applied that were estimated from the two soil-water-balance models.

Estimated total groundwater storage in the High Plains aquifer as determined by the USGS High Plains Water-Level Monitoring Study was 3,173 million acre-ft before 1950 and 2,907 million acre-ft in 2007. The average annual reduction of groundwater storage between 2000 and 2007 was 10 million acre-ft/yr.

As demonstrated by these results, the estimates of individual water-budget components obtained from multiple methods can differ substantially. The methods, as applied herein, did not include calibration to independent hydrologic measurements, such as groundwater levels and streamflow records, to verify that the water-budget estimates would reproduce hydrologic conditions. The results have allowed a comparison of water-budget component estimation methods, and of the range of values that could be obtained by applying these different methods. This information can be used to guide the selection and evaluation of inputs for regional hydrologic models of the High Plains landscape and aquifer system.

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Appendix 1

Enhancements to the SWB Model —A Modified Thornthwaite-Mather Soil-Water-Balance Code for Estimating Groundwater Recharge

The Soil-Water-Balance (SWB) model was developed to calculate spatial and temporal variations in potential groundwater recharge (Westenbroek and others, 2010). The SWB model estimates potential recharge on the basis of a modified Thornthwaite-Mather (Thornthwaite and Mather, 1957) soil-water balance calculated for each grid cell in the model domain. Although the SWB model was designed to apply to a wide range of geographic and climatic conditions, it was not designed to calculate effects of crop-water use on evapotranspiration (*ET*) or estimate potential recharge in areas where irrigation is a substantial component of the water budget.

Adapting the SWB model to the needs of the High Plains study involved adding a simple algorithm to estimate amounts of crop-water demand and irrigation required to sustain crop growth. The new module performs two primary tasks. First, the new module increases or reduces the potential *ET* value calculated for each cell through application of a crop coefficient; the original version of SWB calculates potential *ET* as a function of latitude and air temperature. Through the use of crop coefficients, the potential *ET* is reduced during early stages of plant growth, and increased during peak growth stages. This modification to SWB provides a more accurate estimate of crop water needs throughout the growing season. Second, the new module adds water to irrigated areas whenever the soil-moisture deficit exceeds a maximum user-definable amount, where deficit thresholds are specified for unique combinations of land use and soil type.

The use of a crop coefficient is widely used to estimate crop-water requirements and is described in detail by Allen and others (1998). In that approach, crop *ET* is calculated by multiplying reference-crop *ET* by a crop coefficient:

$$ET_c = K_c \, x \, ET_0 \qquad \text{(A.1)}$$

where

ET_c is the crop *ET* (in/day),
K_c is the crop coefficient (dimensionless), and
ET_0 is the reference crop *ET* (in/day).

Reference crop *ET* was calculated by means of the method developed by Hargreaves and Samani (1985); the reference crop in this method is tall fescue grass (*Schedonorus phoenix* (Scop.) Holub).

For the present study, the methodology of Ojeda-Bustamante and others (2004) was used to simplify the specification of crop coefficients; rather than supplying data pairs (crop coefficient, growth stage) for initial, developmental, middle, and late growth periods, the user supplies an initial crop coefficient, a maximum crop coefficient, and the numbers of growing degree-days (*GDD*) associated with the maximum crop coefficient and the end of crop growth. The crop coefficient is calculated as:

$$K_c = K_{max} erfc\left(\left(\frac{x - x_{K_{max}}}{\alpha_1}\right)^2\right) \qquad \text{(A.2)}$$

where

K_c is the calculated crop coefficient (dimensionless) for a specific number of *GDD*,
K_{max} is the maximum value attained by K_c during the growing season,
$erfc$ is the complementary error function, derived by integrating a normalized Gaussian distribution function,
$x = \frac{GDD}{\alpha_0}$ is a unitless ratio quantifying the progression through the growing season (where *GDD* is the current point in the growing season, given in growing degree-days, and α_0 is the number of *GDD* at crop maturity),
$X_{K_{max}}$ is the value of *x* as defined above that corresponds to the point in the growing season when the crop coefficient is at a maximum, and α_1 is a unitless parameter controlling the shape of the K_c curve relative to the growing degree-day of the simulation. The initial crop coefficient value is substituted when the calculated K_c is less than the initial K_c.

Figure A1 illustrates how the value of the shape parameter (α_1) affects the resulting K_c-*GDD* curve. Larger α_1 values increase the crop coefficient, apart from K_{max} , and produce a longer growing season, resulting in greater crop-water use. The parameter α_1 may take on values in the range $0 < \alpha_1 \leq 1$; values closer to 1 result in a K_c-*GDD* curve with greater

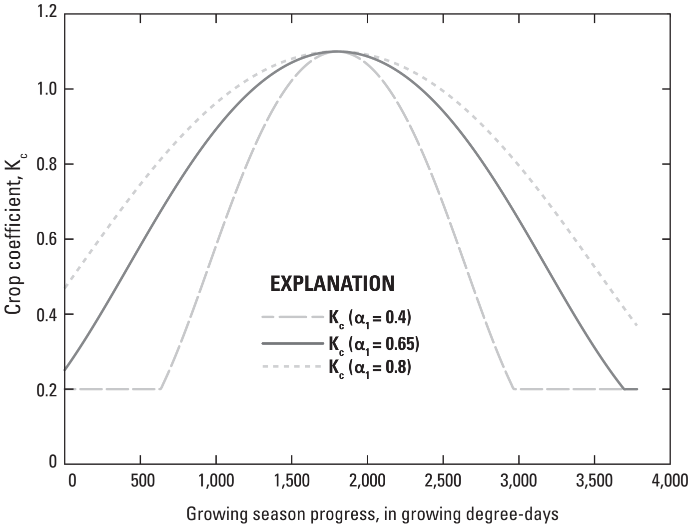

Figure A1. Example of mean crop coefficient generated for irrigated crops with three values of the crop coefficient shape parameter (α_1).

spread relative to a curve produced with α_l closer to 0. The crop coefficients applied in simulations are shown in table A1. The coefficients for irrigated crops (land-use code 125) were adapted from those developed for the High Plains by Stegman (1988). All irrigated crops were assigned the same crop coefficients to simplify calculations and because many irrigated crops in the High Plains have similar crop-coefficient patterns (Allen and others, 1998).

In addition to the model parameters described above, a maximum allowable soil-moisture depletion is specified for each land-use code. SWB tracks the mean percent soil-moisture depletion, averaged over the model domain, for each unique combination of land use and soil type. If the mean soil-moisture depletion for a combination is greater than the maximum allowable depletion, water is added to all grid cells with that land-use-soil-type combination. The amount of water added is assumed to be equal to the mean soil-moisture deficit; however, the distribution of soil-moisture conditions about the mean condition inevitably means that some cells will receive water in excess of field capacity, whereas others do not receive enough water to completely erase the soil-moisture deficit. Note that specifying a maximum allowable depletion of 100 percent effectively prevents any irrigation water from being applied to the given land use. In addition, it was assumed that irrigation would take place (if needed) between May 15 and August 24 on the irrigated cells. Actual dates or irrigation in the field depend on a variety of factors, including the irrigation strategy selected by an individual farmer, water-holding capacity of the soil, maturity group of the crop, and climate history.

No water transmission losses are included by SWB when calculating irrigation-water requirements; the estimated irrigation amounts likely are biased low as a result. Also, water-balance calculations within the modified SWB model treat applied irrigation water as though it was pumped from somewhere outside the model domain; and the model code currently does not track whether this applied irrigation water originates as surface water or as groundwater. This simple approach to estimating irrigation-water requirements represents a compromise between ease of calculation, accuracy, and available data.

The SWB model could calculate more accurately the effects of irrigation on potential recharge if complete field-by-field daily irrigation records existed, but at a much higher computational cost because it would require tracking applications at the field resolution. For the purposes of this study, the modifications as described here allowed potential recharge calculations to be kept relatively simple while recognizing and including the contributions of irrigation in the water budget.

Table A1. Crop coefficient table used for SWB model.

[GDD, growing degree-day; temperatures in degrees Fahrenheit; NA, not applicable]

Land-use code	Maximum crop coefficient	First-stage crop coefficient	α_1[1]	GDD maximum K_c[2]	GDD at maturity	GDD base temperature	GDD maximum temperature	Management allowable soil-moisture depetion (percent)	Date of first irrigation	Date of last irrigation	Landuse description
104	0.75	0.5	0.65	1,800	3,000	50	140	100	NA	NA	Low intensity (1/8 acre residential)
111	1.1	.4	.65	1,680	2,800	50	140	100	NA	NA	Nonirrigated herbaceous/field crops (close-seeded, contoured, good condition)
112	1.1	.4	.65	1,680	2,800	50	140	100	NA	NA	Nonirrigated row crops (straight row, good condition)
113	1.1	.3	.65	1,375.8	2,293	50	140	100	NA	NA	Nonirrigated corn (contoured, good condition)
118	1.2	.3	.65	1,800	3,000	50	140	100	NA	NA	Nonirrigated other row crops (sm grain, contoured, good condition)
125	1.2	.3	.65	1,375.8	2,293	50	140	40	15-May	24-Aug	All irrigated crops [3 4 5]
150	.95	.9	.65	2,100	3,500	50	140	100	NA	NA	Grassland (assume pasture, good condition)
161	1	.75	1	2,100	3,500	50	140	100	NA	NA	Coniferous forest
173	1	.75	1	2,100	3,500	50	140	100	NA	NA	Mixed/other coniferous forest
175	1	.75	1	2,100	3,500	50	140	100	NA	NA	Broad-leaved deciduous forest
200	1	1	.65	1,800	3,000	50	140	100	NA	NA	Open water
211	1.2	.3	.65	1,800	3,000	50	140	100	NA	NA	Emergent/wet meadow
212	1.2	.3	.65	1,800	3,000	50	140	100	NA	NA	Floating aquatic herbaceous vegetation
240	1	.2	.65	1,800	3,000	50	140	100	NA	NA	Barren
250	1	.2	.65	1,800	3,000	50	140	100	NA	NA	Shrubland

[1] α_1: controls the shape or spread of the error function used to estimate the K_c for a given GDD. (higher=greater spread; smaller=more pronounced peak)

[2] Error function K_c estimation method documented in Ojeda-Bustamante and others (2004).

[3] Corn parameters adapted from Stegman (1988).

[4] Primary source for other coefficients based on Allen and others (1998).

[5] The only land use allowed to receive irrigation is land use 125.

Appendix 2

Table A2. Recharge rates in the High Plains compiled from previously published studies.

[NHP, northern High Plains; P, precipitation; --, no notes; I, irrigation return flow; S, streamflow seepage; C, canal and reservoir seepage; U, unspecified; CHP, central High Plains; SHP, southern High Plains]

Method type	Method	Reference(s)	Scale[1]	Region	Location	Land cover	Water sources	Recharge rate, inches per year	Time period	Notes
Groundwater	Groundwater-flow model	McKusick (2003); Landon (2002)	Regional	NHP	Northeastern Colorado, Northwestern Kansas, Southwestern Nebraska	Undeveloped	P	1.03	Pre-1931	--
Groundwater	Groundwater-flow model	McKusick (2003); Landon (2002)	Regional	NHP	Northeastern Colorado, Northwestern Kansas, Southwestern Nebraska	Composite	P,I,S,C	1.81	1941–2000	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Luckey and others (1986)	Regional	NHP	High Plains	Undeveloped	P	0.076	Pre-1960	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Luckey and others (1986)	Regional	NHP	High Plains	Rangeland, irrigated cropland, nonirrigated cropland	P,I,C	0.0–4.0 (mid=2)	1960–80	Irrigation return flow ranged from 30 to 46 percent of total pumpage
Groundwater	Groundwater-flow model	Sophocleous (2004); Stullken and others (1985)	Regional	NHP	Northwestern Kansas	Unspecified	U	0.00–0.79 (mean=0.2)	Pre-1950	--
Groundwater	Groundwater-flow model	Luckey and Cannia (2006)	Regional	NHP	Western Nebraska	Irrigated cropland	C	1.39–21.93 (mean=7.21)	1900–98	Mean is average canal seepage from 26 irrigation districts
Groundwater	Groundwater-flow model	Luckey and Cannia (2006)	Regional	NHP	Western Nebraska	Irrigated cropland	I	0.68–7.09 (mean=3.19)	1900–98	Mean is average surface-water irrigation return flow from 26 irrigation districts
Groundwater	Groundwater-flow model	Luckey and Cannia (2006)	Regional	NHP	Western Nebraska	Undeveloped	P	0.15–2.3 (mean=0.75)	Pre-1950	--
Groundwater	Groundwater-flow model	Luckey and Cannia (2006)	Regional	NHP	Western Nebraska	Nonirrigated cropland	P	1.37	1950–98	Average supplemental recharge on nonirrigated cropland plus average pre-1950 recharge
Groundwater	Groundwater-flow model	Luckey and Cannia (2006)	Regional	NHP	Western Nebraska	Irrigated cropland	P	4.15	1950–98	Average supplemental recharge on irrigated cropland plus average pre-1950 recharge
Groundwater	Groundwater-flow model	Carney (2008)	Regional	NHP	Southwestern Nebraska	Undeveloped	P	0.15–2.5 (mean=1.2)	Pre-1950	--
Groundwater	Groundwater-flow model	Carney (2008)	Regional	NHP	Southwestern Nebraska	Nonirrigated cropland	P	1.6	1950–98	Average supplemental recharge on nonirrigated cropland plus average pre-1950 recharge
Groundwater	Groundwater-flow model	Carney (2008)	Regional	NHP	Southwestern Nebraska	Irrigated cropland	P	6.2	1950–98	Average supplemental recharge on irrigated cropland plus average pre-1950 recharge
Groundwater	Groundwater-flow model	Peterson (2007)	Regional	NHP	South-central Nebraska	Undeveloped	P	0.30–2.50 (mean=0.86)	Pre-1950	--
Groundwater	Groundwater-flow model	Peterson (2007)	Regional	NHP	South-central Nebraska	Nonirrigated cropland	P	1.76	1950–98	Average supplemental recharge on nonirrigated cropland plus average pre-1950 recharge

Table A2. Recharge rates in the High Plains compiled from previously published studies.—Continued

[NHP, northern High Plains; P, precipitation; --, no notes; I, irrigation return flow; S, streamflow seepage; C, canal and reservoir seepage; U, unspecified; CHP, central High Plains; SHP, southern High Plains]

Method type	Method	Reference(s)	Scale[1]	Region	Location	Land cover	Water sources	Recharge rate, inches per year	Time period	Notes
Groundwater	Groundwater-flow model	Peterson (2007)	Regional	NHP	South-central Nebraska	Irrigated cropland	P	6.06	1950–98	Average supplemental recharge on irrigated cropland plus average pre-1950 recharge
Groundwater	Groundwater-flow model	Peterson and others (2008)	Regional	NHP	North-central Nebraska, including Sand Hills	Undeveloped	P	0–3.1 (mean=2.2)	Pre-1940	--
Groundwater	Groundwater-flow model	Peterson and others (2008)	Regional	NHP	North-central Nebraska, including Sand Hills	Nonirrigated cropland	P	2.7	1940–2005	Supplemental recharge on nonirrigated cropland plus average pre-1940 recharge
Groundwater	Groundwater-flow model	Peterson and others (2008)	Regional	NHP	North-central Nebraska, including Sand Hills	Irrigated cropland	P	5.7	1940–2005	Supplemental recharge on irrigated cropland plus average pre-1940 recharge
Groundwater	Groundwater-flow model	Peterson and others (2008)	Regional	NHP	North-central Nebraska, including Sand Hills	Rangeland, nonirrigated and irrigated cropland	P,C	2.7	1940–2005	--
Groundwater	Groundwater-flow model	Stanton and others (2010)	Regional	NHP	North-central Nebraska, including Sand Hills	Undeveloped	P	0.5–5.0 (mean=2.5)	Pre-1940	--
Groundwater	Groundwater-flow model	Stanton and others (2010)	Regional	NHP	North-central Nebraska, including Sand Hills	Rangeland	P	1.0–4.5 (mean=2.9)	1940–2005	--
Groundwater	Groundwater-flow model	Stanton and others (2010)	Regional	NHP	North-central Nebraska, including Sand Hills	Nonirrigated cropland	P	3.4	1940–2005	Supplemental recharge on nonirrigated cropland plus average pre-1940 recharge
Groundwater	Groundwater-flow model	Stanton and others (2010)	Regional	NHP	North-central Nebraska, including Sand Hills	Irrigated cropland	P	3.9	1940–2005	Supplemental recharge on irrigated cropland plus average pre-1940 recharge
Groundwater	Groundwater-flow model	Stanton and others (2010)	Regional	NHP	North-central Nebraska, including Sand Hills	Rangeland, nonirrigated, irrigated cropland	P, C	3.1	1940–2005	--
Groundwater	Groundwater-flow model	Long and Putnam (2010)	Regional	NHP	South Dakota	Ogallala aquifer, mostly rangeland and hay production	P	2.91	1979–2008	--
Groundwater	Groundwater-flow model	Long and Putnam (2010)	Regional	NHP	South Dakota	Arikaree aquifer, mostly rangeland and hay production	P	1.45	1979–2008	--
Surface water	Watershed model	Strauch and Linard (2009)	Regional	NHP	North-central Nebraska	Sand hills, rangeland, nonirrigated, irrigated cropland	U	1.5–12.9 (mean=7.4)	1940–2005	Mean of 6 subbasins
Surface water	Watershed model	Strauch and Linard (2009)	Regional	NHP	North-central Nebraska	Sand dune	P	6.47	1940–2005	Mean of 3 Sand Hills subbasins
Tracer (unsaturated zone)	Tritium	McMahon and others (2006)	Local	NHP	Southwestern Nebraska	Rangeland	P	2.8	2000–02	--
Tracer (unsaturated zone)	Tritium	McMahon and others (2006)	Local	NHP	Southwestern Nebraska	Irrigated land	P,I	4.0	2000–02	--

Table A2. Recharge rates in the High Plains compiled from previously published studies.—Continued

[NHP, northern High Plains; P, precipitation; --, no notes; I, irrigation return flow; S, streamflow seepage; C, canal and reservoir seepage; U, unspecified; CHP, central High Plains; SHP, southern High Plains]

Method type	Method	Reference(s)	Scale[1]	Region	Location	Land cover	Water sources	Recharge rate, inches per year	Time period	Notes
Tracer (unsaturated zone)	Tritium	McMahon and others (2006)	Local	NHP	Northeastern Colorado	Irrigated land	P,I	4.4	2000–02	--
Water budget	Soil-water-balance model	Dugan and Zelt (2000)	Regional	NHP	Great Plains	Nonirrigated land	P	0.25–5 (mid=2.6)	1951–80	--
Water budget	Soil-water-balance model	Dugan and Zelt (2000)	Regional	NHP	Great Plains	Irrigated land	P	0.25–7 (mid=3.6)	1951–80	--
Unspecified	Unspecified	Sophocleous (2004); KGS Bulletins, Kansas Water Resources Board, and Hansen (1991)	Intermediate	NHP	Western Kansas	Unspecified	U	0.09–0.88 (mean=0.3)[2]	Unspecified	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Luckey and others (1986)	Regional	CHP	High Plains	Undeveloped	P,S	0.056–0.84 (mean=0.14)[3]	Pre-1950	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Luckey and Becker (1999)	Regional	CHP	Between Arkansas and Canadian Rivers	Undeveloped	P	0.068–0.69 (mean=0.155)[3]	Pre-1946	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Luckey and Becker (1999)	Regional	CHP	Between Arkansas and Canadian Rivers	Rangeland, nonirrigated cropland, irrigated cropland	P,I	0.41	1946–97	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Stullken and others (1985)	Regional	CHP	Southwestern Kansas	Undeveloped	P	0.0–2.0 (mean=0.24)[3]	Pre-1950	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Stullken and others (1985)	Regional	CHP	Southwestern Kansas	Undeveloped	S	0.036–0.045 (mid=0.040)	Pre-1950	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Watts (1989)	Regional	CHP	Southwestern Kansas	Unspecified	U	0.58	1982	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Havens and Christenson (1984)	Regional	CHP	Northwestern Oklahoma and southwestern Kansas	Unspecified	P	0.23–0.45 (mean=0.34)[3]	Pre-1940, 1940–80	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Cobb and others (1983)	Regional	CHP	South-central Kansas	Unspecified	P	0.75	Unspecified	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Sophocleous and others (1982)	Intermediate	CHP	Equus Beds	Sand dunes	P	6.5	Unspecified	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Sophocleous and others (1982)	Intermediate	CHP	Equus Beds	Non-sand dune	P	1.2	Unspecified	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Spinazola and others (1985)	Intermediate	CHP	Equus Beds	Unspecified	U	1.7	Pre-1940	--

Table A2. Recharge rates in the High Plains compiled from previously published studies.—Continued

[NHP, northern High Plains; P, precipitation; --, no notes; I, irrigation return flow; S, streamflow seepage; C, canal and reservoir seepage; U, unspecified; CHP, central High Plains; SHP, southern High Plains]

Method type	Method	Reference(s)	Scale[1]	Region	Location	Land cover	Water sources	Recharge rate, inches per year	Time period	Notes
Groundwater	Groundwater-flow model	Sophocleous (2004); Spinazola and others (1985)	Intermediate	CHP	Equus Beds	Unspecified	U	1.69–1.91 (mid=1.8)	1964–79	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Myers and others (1996)	Intermediate	CHP	Equus Beds	Undeveloped	P	2.58	Pre-1940	--
Groundwater	Groundwater-flow model	Sophocleous (2004); Myers and others (1996)	Intermediate	CHP	Equus Beds	Irrigated and nonirrigated land	P,I	2.32–2.59 (mid=2.46)	1964–89	Irrigation return flow considered negligible
Surface water	Streamflow-duration curve analysis	Sophocleous (2004); Fader and Stullken (1978)	Regional	CHP	South-central Kansas	Unspecified	P	0.9	Unspecified	--
Tracer (unsaturated zone)	Chloride mass balance	McMahon and others (2006)	Local	CHP	Kansas	Rangeland	P	0.2	2000–02	--
Tracer (unsaturated zone)	Tritium	McMahon and others (2006)	Local	CHP	Kansas	Irrigated cropland	P,I	1.5–2.1 (mean=1.8)	2000–02	--
Unsaturated zone	Zero-flux plane	Sophocleous (2004); Prill (1968)	Local	CHP	Southwestern Kansas	Vegetated area, sand dune	P	0.5	1964–66	--
Unsaturated zone	Darcy equation	Sophocleous (2004); Sophocleous and Perry (1985)	Local	CHP	Great Bend Prairie and Equus Beds Aquifers	Sand dune	P	0.1–6.1 (mid=3.1)	1982–83	--
Tracer (unsaturated zone)	Heat-dissipation sensors	Sophocleous (2004); Sophocleous and others (2002)	Local	CHP	Southwestern Kansas	Irrigated cropland	P,I	0.02–0.12 (mid=0.07)	Unspecified	Error estimated to be at least 102 percent
Tracer (unsaturated zone)	Heat-dissipation sensors	Sophocleous (2004); Sophocleous and others (2002)	Local	CHP	Northwestern Kansas	Native grassland	P	0.004–0.01 (mid=0.007)	1951–80	Error estimated to be at least 102 percent
Unsaturated zone	Zero-flux plane	Klemt (1981)	Local	CHP	Northern Texas	Nonirrigated cropland and rangeland	P	0.17	1978–79	--
Unsaturated zone	Zero-flux plane	Klemt (1981)	Local	CHP	Northern Texas	Irrigated cropland	P	1.9	1978–79	--
Combination	Soil-water-balance model and water-table fluctuation	Sophocleous (2004); Sophocleous (1992, 2000)	Local	CHP	Great Bend Prairie Aquifer	Unspecified		0.0–6.5 (mean=1.4)[4]	1985–92	--
Unspecified	Unspecified	Sophocleous (2004); Gutentag and others (1981)	Regional	CHP	Southwestern Kansas	Irrigated cropland	P,S	1.5	1975	--
Unspecified	Unspecified	Sophocleous (2004); Gutentag and others (1981)	Regional	CHP	Southwestern Kansas	Nonirrigated land	P,S	0.15	1975	--
Unspecified	Unspecified	Sophocleous (2004); Gutentag and others (1981)	Regional	CHP	Southwestern Kansas	Irrigated and nonirrigated land	P,S	0.6	1975	--

Table A2. Recharge rates in the High Plains compiled from previously published studies.—Continued

[NHP, northern High Plains; P, precipitation; --, no notes; I, irrigation return flow; S, streamflow seepage; C, canal and reservoir seepage; U, unspecified; CHP, central High Plains; SHP, southern High Plains]

Method type	Method	Reference(s)	Scale[1]	Region	Location	Land cover	Water sources	Recharge rate, inches per year	Time period	Notes
Unspecified	Unspecified	Sophocleous (2004); Fader and Stullken (1978)	Regional	CHP	South-central Kansas	Unspecified	P	2	Unspecified	--
Unspecified	Unspecified	Sophocleous (2004); KGS Bulletins, Kansas Water Resources Board, and Hansen (1991)	Intermediate	CHP	Southwestern Kansas	Unspecified	U	0.09–0.99 (mean=0.4)[2]	Unspecified	From county averages
Water budget	Soil-water-balance model	Dugan and Zelt (2000)	Regional	CHP	Great Plains	Nonirrigated land	P	0.25–5 (mid=2.6)	1951–80	--
Water budget	Soil-water-balance model	Dugan and Zelt (2000)	Regional	CHP	Great Plains	Irrigated cropland	P	0.25–7 (mid=3.6)	1951–80	--
Groundwater	Groundwater-flow model	Knowles and others (1984)	Regional	SHP	Texas	Sand dunes	P	0.83	1960–79	--
Groundwater	Groundwater-flow model	Knowles and others (1984)	Regional	SHP	Texas	Composite	P, I	0.2	1960–79	--
Groundwater	Groundwater-flow model	Luckey and others (1986)	Regional	SHP	Texas	Undeveloped	P	0.13	Pre-1940	--
Groundwater	Groundwater-flow model	Luckey and others (1986)	Regional	SHP	Texas	Irrigated cropland	P	2.13	1940–80	--
Groundwater	Groundwater-flow model	Luckey and others (1986)	Regional	SHP	Texas	Composite	P	0.73	1940–80	--
Groundwater	Groundwater-flow model	Stovall and others (2000)	Regional	SHP	Texas	Composite	P, I	2.75	1985–95	--
Groundwater	Groundwater-flow model	Dutton and others (2001)	Regional	SHP	Texas	Undeveloped	P	0.3	1950	--
Groundwater	Groundwater-flow model	Dutton and others (2001)	Regional	SHP	Texas	Composite	P, I	0.35	1998	--
Groundwater	Groundwater-flow model	Blandford and others (2003)	Regional	SHP	Texas	Undeveloped	P	0.04	1940	--
Groundwater	Groundwater-flow model	Blandford and others (2003)	Regional	SHP	Texas	Composite	P,I	0.67	2000	--
Tracer (unsaturated zone)	Chloride mass balance	Reedy and others (2003)	Regional	SHP	Texas	Nonirrigated cropland and rangeland	P	0.31	1985–2000	Method yields long-term average recharge
Tracer (saturated and unsaturated zone)	Tritium	Reedy and others (2003)	Regional	SHP	Texas	Irrigated cropland	P,I	0.7–5.0 (mean=1.6)	1953–2001	--
Tracer (unsaturated zone)	Chloride mass balance	Scanlon and Goldsmith (1997)	Local	SHP	Texas	Unspecified (playa)	P	2.4–3.9 (mid=3.2)	Unspecified	Method yields long-term average recharge
Tracer (unsaturated zone)	Tritium	Scanlon and Goldsmith (1997)	Local	SHP	Texas	Unspecified (playa)	P	4.7	Unspecified	Method yields long-term average recharge

Table A2. Recharge rates in the High Plains compiled from previously published studies.—Continued

[NHP, northern High Plains; P, precipitation; --, no notes; I, irrigation return flow; S, streamflow seepage; C, canal and reservoir seepage; U, unspecified; CHP, central High Plains; SHP, southern High Plains]

Method type	Method	Reference(s)	Scale[1]	Region	Location	Land cover	Water sources	Recharge rate, inches per year	Time period	Notes
Tracer (unsaturated zone)	Chloride mass balance	Scanlon and Goldsmith (1997)	Local	SHP	Texas	Undeveloped	P	0.004–0.16 (mid=0.08)	Unspecified	Method yields long-term average recharge
Tracer (unsaturated zone)	Tritium	Gurdak and Roe (2009); Wood and others (1997)	Regional	SHP	Texas	Unspecified (playa)	P	3	1962–1993	--
Tracer (unsaturated zone)	Chloride mass balance	McMahon and others (2006)	Local	SHP	Texas	Rangeland (interplaya)	P	0.008	2000–02	--
Tracer (unsaturated zone)	Tritium	McMahon and others (2006)	Local	SHP	Texas	Irrigated cropland (interplaya)	P,I	0.67–1.26 (mean=0.96)	2000–02	--
Tracer (unsaturated zone)	Tracer profile	Scanlon and others (2010)	Local	SHP	Texas	Irrigated cropland	P,I	0.87–1.4 (median=1.1)	Unspecified	Method yields long-term average recharge; Fine grain soils
Tracer (unsaturated zone)	Tracer profile and chloride mass balance	Scanlon and others (2010)	Local	SHP	Texas	Irrigated cropland	P,I	0.71–3.8 (median=1.9)	Unspecified	Method yields long-term average recharge; Coarse grain soils
Tracer (unsaturated zone)	Tracer profile and chloride mass balance	Scanlon and others (2010)	Local	SHP	Texas	Nonirrigated cropland	P	0	Unspecified	Method yields long-term average recharge; Fine grain soils
Tracer (unsaturated zone)	Chloride mass balance	Scanlon and others (2010)	Local	SHP	Texas	Nonirrigated cropland	P	0.39–0.83 (median=0.61)	Unspecified	Method yields long-term average recharge; Coarse grain soils
Tracer (unsaturated zone)	Tracer profile and chloride mass balance	Scanlon and others (2010)	Local	SHP	Texas	Rangeland	P	0	Unspecified	Method yields long-term average recharge
Tracer	Chloride mass balance	Scanlon and others (2007)	Local	SHP	Texas	Nonirrigated cropland	P	0.19–3.6 (median=0.94)	Unspecified	Method yields long-term average recharge
Unsaturated zone	Zero-flux plane	Klemt (1981)	Local	SHP	Texas	Nonirrigated cropland and rangeland	P	0.18	1978–79	--
Unsaturated zone	Zero-flux plane	Klemt (1981)	Local	SHP	Texas	Irrigated cropland	P	1.6	1978–79	--
Water budget	Soil-water-balance model	Dugan and Zelt (2000)	Regional	SHP	Great Plains	Nonirrigated land	P	0.25–1 (mid=0.62)	1951–80	--
Water budget	Soil-water-balance model	Dugan and Zelt (2000)	Regional	SHP	Great Plains	Irrigated land	P	0.10–1.5 (mid=0.8)	1951–80	--

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[1] Regional scales represent recharge rates for thousands of square miles, intermediate-scale studies represent recharge rates for hundreds of square miles, and local-scale studies represent recharge rates for areas less than 10 square miles.

[2] Mean represents average of county recharge values within the specified region.

[3] Mean represents the average over the study area.

[4] Represents area-weighted mean of 10 sites.

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Back cover: illustration showing the United States and the location of the High Plains aquifer.

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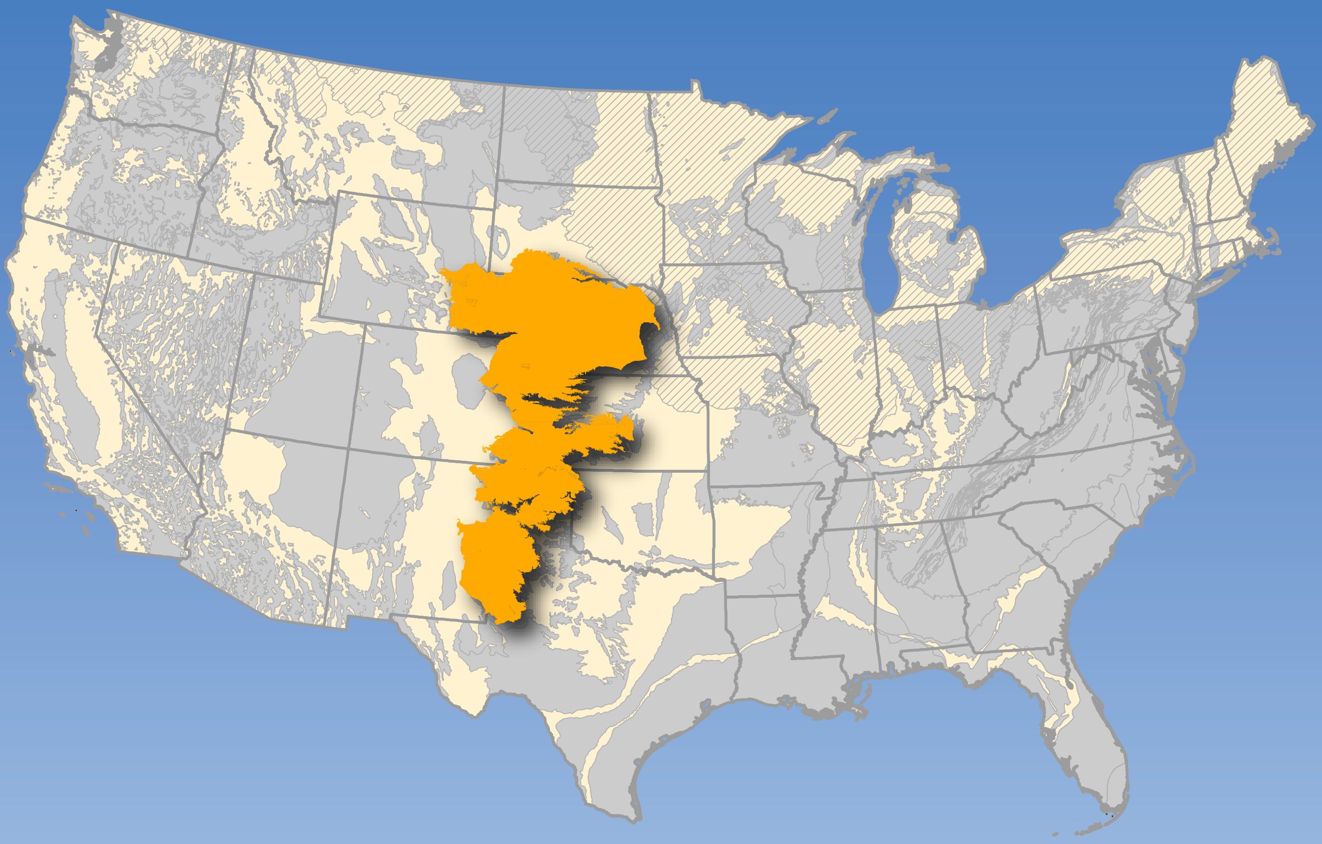
Stanton and others—**Selected Approaches to Estimate Water-Budget Components of the High Plains, 1940 through 1949 and 2000 through 2009**—Scientific Investigations Report 2011–5183



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