science for a changing world

Prepared in cooperation with the North Platte Natural Resources District

Simulation of Groundwater Flow and Analysis of the Effects of Water-Management Options in the North Platte Natural Resources District, Nebraska

Scientific Investigations Report 2015–5093

U.S. Department of the Interior
U.S. Geological Survey

Front cover. Sheep Creek, 2007. Photograph by Steven M. Peterson, U.S. Geological Survey.

Back cover. Canals in western Nebraska, 2012. Photographs provided by North Platte Natural Resources District.

Simulation of Groundwater Flow and Analysis of the Effects of Water-Management Options in the North Platte Natural Resources District, Nebraska

By Steven M. Peterson, Amanda T. Flynn, Joseph Vrabel, and Derek W. Ryter

Prepared in cooperation with the North Platte Natural Resources District

Scientific Investigations Report 2015–5093

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod/.

Suggested citation:
Peterson, S.M, Flynn, A.T., Vrabel, Joseph, and Ryter, D.W., 2015, Simulation of groundwater flow and analysis of the effects of water-management options in the North Platte Natural Resources District, Nebraska: U.S. Geological Survey Scientific Investigations Report 2015–5093, 67 p., http://dx.doi.org/10.3133/sir20155093.

ISSN 2328-0328 (online)

Acknowledgments

This study was led as part of the U.S. Geological Survey (USGS) Cooperative Water Program and made possible by support provided by the Nebraska Natural Resources Commission Interrelated Water Management funds administered by the Nebraska Department of Natural Resources. The authors thank the North Platte Natural Resources District Board of Directors, Water Resources Committee, J. Berge, General Manager, and R. Cacek, former general manager, for providing thoughtful and insightful commentary on this work.

The authors thank James Cannia (formerly USGS) and Dennis Strauch (Pathfinder Irrigation District) for assistance with identifying potential intentional recharge sites. The authors thank M. Fienen (USGS) for assistance with parameter estimation and R. Niswonger (USGS) for assistance with the Newton-Rhapson solver. The authors also thank P. Jones and P. Barlow (USGS) for constructive reviews of earlier versions of this report and P. Barlow for assistance with application of the Groundwater-Management Process.

Contents

Figures

Tables

Conversion Factors

Inch/Pound to International System of Units

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	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
inch per year (in/yr)	2.54	centimeter per year (cm/yr)
inch per day (in/d)	2.54	centimeter per day (cm/d)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

°C=(°F-32)/1.8

Supplemental Information

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness ($[ft^3/d]/ft^2$) ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Datums

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

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

Altitude, as used in this report, refers to distance above the vertical datum, sea level.

Simulation of Groundwater Flow and Analysis of the Effects of Water-Management Options in the North Platte Natural Resources District, Nebraska

By Steven M. Peterson, Amanda T. Flynn, Joseph Vrabel, and Derek W. Ryter

Abstract

The North Platte Natural Resources District (NPNRD) has been actively collecting data and studying groundwater resources because of concerns about the future availability of the highly inter-connected surface-water and groundwater resources. This report, prepared by the U.S. Geological Survey in cooperation with the North Platte Natural Resources District, describes a groundwater-flow model of the North Platte River valley from Bridgeport, Nebraska, extending west to 6 miles into Wyoming. The model was built to improve the understanding of the interaction of surface-water and groundwater resources, and as an optimization tool, the model is able to analyze the effects of water-management options on the simulated stream base flow of the North Platte River. The groundwater system and related sources and sinks of water were simulated using a newton formulation of the U.S. Geological Survey modular three-dimensional groundwater model, referred to as MODFLOW–NWT, which provided an improved ability to solve nonlinear unconfined aquifer simulations with wetting and drying of cells. Using previously published aquifer-base-altitude contours in conjunction with newer test-hole and geophysical data, a new base-of-aquifer altitude map was generated because of the strong effect of the aquifer-base topography on groundwater-flow direction and magnitude. The largest inflow to groundwater is recharge originating from water leaking from canals, which is much larger than recharge originating from infiltration of precipitation. The largest component of groundwater discharge from the study area is to the North Platte River and its tributaries, with smaller amounts of discharge to evapotranspiration and groundwater withdrawals for irrigation. Recharge from infiltration of precipitation was estimated with a daily soil-water-balance model. Annual recharge from canal seepage was estimated using available records from the Bureau of Reclamation and then modified with canal-seepage potentials estimated using geophysical data. Groundwater withdrawals were estimated using land-cover data, precipitation data, and published crop water-use data. For fields irrigated with surface water and groundwater, surface-water deliveries were subtracted from the estimated net irrigation requirement, and groundwater withdrawal was assumed to be equal to any demand unmet by surface water.

The groundwater-flow model was calibrated to measured groundwater levels and stream base flows estimated using the base-flow index method. The model was calibrated through automated adjustments using statistical techniques through parameter estimation using the parameter estimation suite of software (PEST). PEST was used to adjust 273 parameters, grouped as hydraulic conductivity of the aquifer, spatial multipliers to recharge, temporal multipliers to recharge, and two specific recharge parameters. Base flow of the North Platte River at Bridgeport, Nebraska, streamgage near the eastern, downstream end of the model was one of the primary calibration targets. Simulated base flow reasonably matched estimated base flow for this streamgage during 1950–2008, with an average difference of 15 percent. Overall, 1950–2008 simulated base flow followed the trend of the estimated base flow reasonably well, in cases with generally increasing or decreasing base flow from the start of the simulation to the end. Simulated base flow also matched estimated base flow reasonably well for most of the North Platte River tributaries with estimated base flow. Average simulated groundwater budgets during 1989–2008 were nearly three times larger for irrigation seasons than for non-irrigation seasons.

The calibrated groundwater-flow model was used with the Groundwater-Management Process for the 2005 version of the U.S. Geological Survey modular three-dimensional groundwater model, MODFLOW–2005, to provide a tool for the NPNRD to better understand how water-management decisions could affect stream base flows of the North Platte River at Bridgeport, Nebr., streamgage in a future period from 2008 to 2019 under varying climatic conditions. The simulation-optimization model was constructed to analyze the maximum increase in simulated stream base flow that could be obtained with the minimum amount of reductions in groundwater withdrawals for irrigation. A second analysis extended the first to analyze the simulated base-flow benefit of groundwater withdrawals along with application of intentional recharge, that is, water from canals being released into rangeland areas with sandy soils. With optimized groundwater withdrawals

and intentional recharge, the maximum simulated stream base flow was 15–23 cubic feet per second (ft^3/s) greater than with no management at all, or 10–15 ft^3/s larger than with managed groundwater withdrawals only. These results indicate not only the amount that simulated stream base flow can be increased by these management options, but also the locations where the management options provide the most or least benefit to the simulated stream base flow. For the analyses in this report, simulated base flow was best optimized by reductions in groundwater withdrawals north of the North Platte River and in the western half of the area. Intentional recharge sites selected by the optimization had a complex distribution but were more likely to be closer to the North Platte River or its tributaries. Future users of the simulation-optimization model will be able to modify the input files as to type, location, and timing of constraints, decision variables of groundwater withdrawals by zone, and other variables to explore other feasible management scenarios that may yield different increases in simulated future base flow of the North Platte River.

Introduction

The North Platte Natural Resources District (NPNRD, fig. 1) has been actively collecting data and studying groundwater resources because of concerns about the future availability of the highly interconnected surface-water and groundwater resources. Development of surface water for irrigation by using canal systems primarily took place before 1900 (State Board of Irrigation, 1899), and much of the modern groundwater reservoir exists because seepage of water through the unlined bottoms of canals caused increases in groundwater levels (Verstraeten and others, 2001).

The area experiences low precipitation and was predominantly rangeland through the 19th century. Early in the 20th century, the Bureau of Reclamation began the North Platte River project to facilitate surface-water irrigation in the North Platte River valley. The project supplies surface water for irrigation of approximately 335,000 acres (Autobee, 1996). Seepage of canal water into the subsurface provided substantial recharge to the groundwater system, far more than that from precipitation alone. By the mid-20th century, groundwater withdrawals for irrigation became feasible in the area, and developed land area steadily increased to about 470,000 acres irrigated with surface water, with groundwater, or with both (R. Kern, Nebraska Department of Natural Resources, written commun., 2000; J. Sprock, North Platte Natural Resources District, written commun., 2010; J. Lawson, Bureau of Reclamation, written commun., 2010). Around 2002, the NPNRD enacted a moratorium on development of new wells (North Platte Natural Resources District, 2009). During 2001–2007, droughts in the area affected streamflows and the amount of water available for canal deliveries. Additionally, water supplies in the North Platte River Basin have been declared overappropriated (Nebraska Legislature, 2004), which means that under certain conditions, the amount of surface water needed for irrigation may exceed what is available. Within Nebraska, the NPNRD is at the upstream end of the Platte River system, and many downstream water users depend on river discharge exiting the NPNRD. A groundwater-flow model will help water resource managers better understand the interrelated groundwater and surface-water systems and the effects of various management strategies on the stream base flow (the groundwater-discharge component of streamflow) of the North Platte River. To address this need, the U.S. Geological Survey (USGS) in cooperation with the North Platte Natural Resources District, constructed a groundwater-flow model and analyzed simulation results to specifically help the NPNRD determine what management activities will provide the largest increases to the base flow at the North Platte River at Bridgeport, Nebr., streamgage.

Purpose and Scope

This report describes a groundwater-flow model of the North Platte River valley from Bridgeport, Nebr., extending west to 6 miles (mi) into Wyoming (fig. 1). This report describes the construction and calibration of the groundwater-flow simulation and the analysis of the effects of water-management options on stream base flow for the North Platte River valley in western Nebraska. The report also describes the inputs for the simulation, calibration approach, and calibration results. Lastly, the report describes the results of simulation-optimization models used to evaluate the effects of reductions in groundwater withdrawals and the addition of water diverted from the canals to adjacent sandy rangeland areas (referred to as ‘intentional recharge’) on simulated base flow at the North Platte River at Bridgeport, Nebr., streamgage.

Previous Work

Previous studies in the area include regional groundwater-flow models, geophysical investigations of aquifer and canal properties, and studies of groundwater age and quality. The Cooperative Hydrologic Study (COHYST) Western Model Unit (Luckey and Cannia, 2006) published a groundwater-flow model that spanned about 11,300 square miles (mi^2) of western Nebraska, from Lake McConaughy (fig. 1) to 6 mi into Wyoming in the west. The regional model included estimated seepage of the canal systems in the North Platte River valley. An earlier report for the same study area documented estimated rates of groundwater discharge to streams (Luckey and others, 2001).

Canal systems in western Nebraska, including canal systems in the study area, have been the focus of multiple surface-geophysical resistivity studies (Ball and others, 2006; Burton and others, 2009; and Vrabel and others, 2009). Sediment grain-size variations cause variations in seepage (leakage) rates along the canal systems. The resistivity studies were aimed at gathering more information on the sediments along

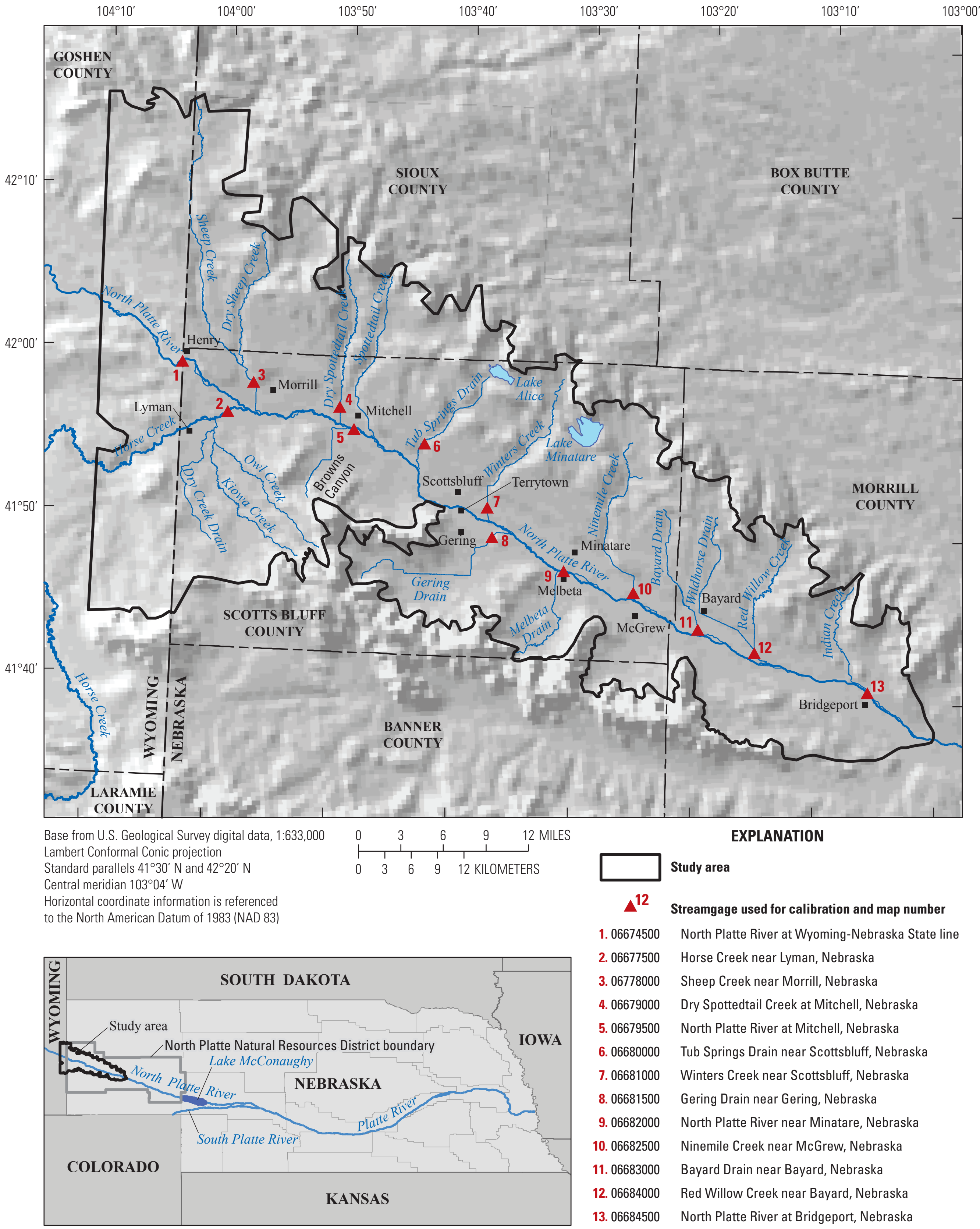

Figure 1. North Platte Natural Resources District (NPNRD) groundwater-flow-model study area in western Nebraska.

the canal systems to better understand the seepage rates. The resistivity studies used geostatistics on the highly detailed spatial resistivity data along with lithologic data to determine the seepage potential for the surveyed areas. Additionally, geophysical studies in the study area also include multiple heliborne electromagnetic surveys (Smith and others, 2010).

Additional groundwater studies focused on hydrologic characteristics, and groundwater age and quality have been researched in the study area (Steele and Cannia, 2003; Steele and others, 1998; Steele and others, 2001; Steele and others, 2002; Verstraeten and others, 1995). Groundwater and surface-water interaction also was investigated for parts of the study area by Verstraeten and others (2001).

Description of Study Area

The study area covers 1,200 mi^2 of the North Platte River valley in western Nebraska. The western boundary is 6 mi west of the Wyoming-Nebraska border, and the eastern boundary is 5 mi southeast of Bridgeport, Nebr. The northern and southern boundaries of the study area follow the edges of the river valley floor (fig. 1).

The North Platte River runs generally from west to east through the study area (fig. 1). Streams flow from the upland areas north and south of the river toward the river valley. Flow of the North Platte River is affected by releases from reservoirs in Wyoming, by local precipitation, and by gains from base-flow streams within the area. Headwaters of the North Platte River and Horse Creek are west of the study area, and these streams have sustained year-round flow across the western boundary into the study area. The rest of the streams originate inside the study area and discharge as tributaries to the North Platte River. Streamgages are shown in figure 1; four of the streamgages are on the North Platte River and nine are on tributary streams. The tributary streams are Horse Creek, Sheep Creek, Dry Spottedtail Creek, Tub Springs Drain, Winters Creek, Gering Drain, Ninemile Creek, Bayard Drain, and Red Willow Creek. During 1950–2007, average daily mean flow for the North Platte River at the Nebraska-Wyoming State line streamgage was about 750 cubic feet per second (ft^3/s), ranging from 0 to 9,700 ft^3/s, and average daily mean flow for the North Platte River at Bridgeport, Nebr., streamgage, near the eastern edge of the study area, was about 1,200 ft^3/s, ranging from 60 to 14,500 ft^3/s. The largest tributaries to the North Platte River are Ninemile Creek, Red Willow Creek, and Horse Creek. Average 1950–2007 daily mean flow was 110 ft^3/s for Ninemile Creek (streamgage number 06682500), 91 ft^3/s for Red Willow Creek (streamgage number 06684000), and 80 ft^3/s for Horse Creek (streamgage number 06677500). During 1950–2007, average daily mean flow for the remainder of the tributaries of the North Platte River was about 47 ft^3/s; the lowest flow was 24 ft^3/s for Bayard Drain (streamgage number 06683000; U.S. Geological Survey, 2012).

The study area receives about 15 inches (in.) of precipitation per year (1895–2008 average; National Climatic Data Center, 2009), creating a semiarid environment (Peel and others, 2007). Generally, annual precipitation consists of rainstorms early in the summer, with scattered storms throughout the summer (National Climatic Data Center, 2009). A smaller fraction of the annual precipitation arrives as snow throughout the winter. The summer highs can reach more than 100 degrees Fahrenheit (°F), and winter lows can reach less than 10 °F (National Climatic Data Center, 2009). The average precipitation does not generally sustain crops in the area (University of Nebraska, 2002). Irrigation was developed to sustain agricultural development as population expanded westward (State Board of Irrigation, 1899).

Increased agricultural development in the 19th century led to the construction of extensive canal systems in the area, many as early as 1895 (State Board of Irrigation, 1899). Most canals are parallel to the North Platte River and are located on the north side of the valley (fig. 2). About three-quarters of the study area is irrigated with surface water. The largest canals were operational by the beginning of the 20th century, and all the canals operating in 2012 were operating before 1950. Canals on the north side of the valley are dug into permeable silty sand, and a large part of the water diverted into the canals is lost through seepage and becomes recharge to groundwater. Many canals on the southern side of the valley have been dug into silty clay and do not lose as much water to the groundwater system as canals on the north side, based on analysis of data collected and presented in Burton and others (2009). This difference in seepage is reflected in the assigned seepage potential values for this simulation, as discussed in the "Estimation of Canal Seepage Potential using Available Geophysical Data" section of this report.

Groundwater withdrawals for irrigation have increased since the first irrigation well was registered in 1934 (Nebraska Department of Natural Resources, 2008). Most registered irrigation wells in the study area were installed after 1950 (fig. 3). The number of irrigation wells increased gradually between 1950 and 1989, as did the amount of agricultural land irrigated with only groundwater (R. Kern, Nebraska Department of Natural Resources, written commun., 2000). After 1989, the number of irrigation wells increased rapidly, but many of these wells were installed to provide supplemental water to fields already receiving surface water for irrigation (comingled acres). Supplemental irrigation wells allow land managers to apply groundwater for irrigation at times when surface water might not be available because of shortage or rotational scheduling, though currently (2012) little data exist to indicate how frequently the supplemental wells are used.

Well installation was curtailed by the passage of new integrated-management water laws in 2004, commonly referred to as Nebraska Legislative Bill 962 (Nebr. Rev. Stat 46.2, 46.6, and 46.7). Under the new law, large areas of the NPNRD were declared over-appropriated (Nebraska Department of Natural Resources, 2004), which means that the usage of surface water in the area exceeds the amount of water available under certain conditions. The declaration further precluded construction of new irrigation wells or other

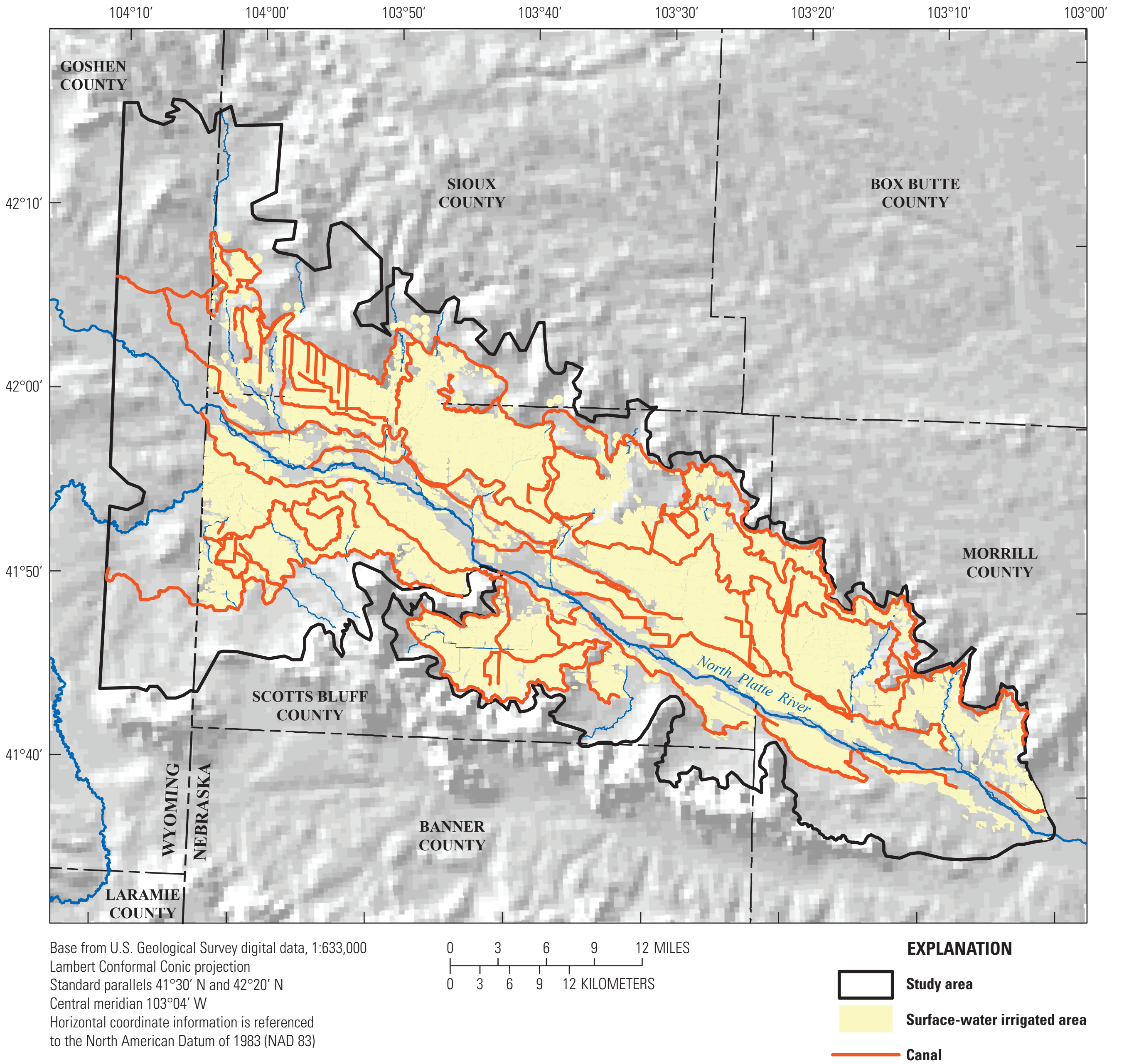

Figure 2. Canals and surface-water-irrigated land in the study area, North Platte River valley, Nebraska.

development of new irrigated acres and required development of an Integrated Management Plan by 2010 to address ground-water and surface-water resources in the NPNRD (Nebraska Legislature, 2004).

Hydrogeology

Principal surficial geologic units within the study area include alluvium and colluvium mixed with alluvium (fig. 4), primarily of Quaternary age. These geologic units compose the alluvial aquifer, which is the principal hydrogeologic unit in the study area. Several older geologic units do not exist within the study area but form flow boundaries. The oldest deposits in or near the area are fine-grained sediments of the Tertiary-age White River Group, that underlie the alluvial aquifer throughout the study area. Just outside the study area, the alluvial aquifer that exists in the valley has a limited saturated thickness and is laterally adjacent to fine-grained deposits of the Brule Formation of the Tertiary White River Group or fine-grained deposits of the Tertiary-age Arikaree Group, that overlies the Brule Formation where present (Swinehart and others, 1985). Tertiary-age Ogallala Group sediments also do not exist within the study area, having been completely removed through erosion (Lugn, 1935).

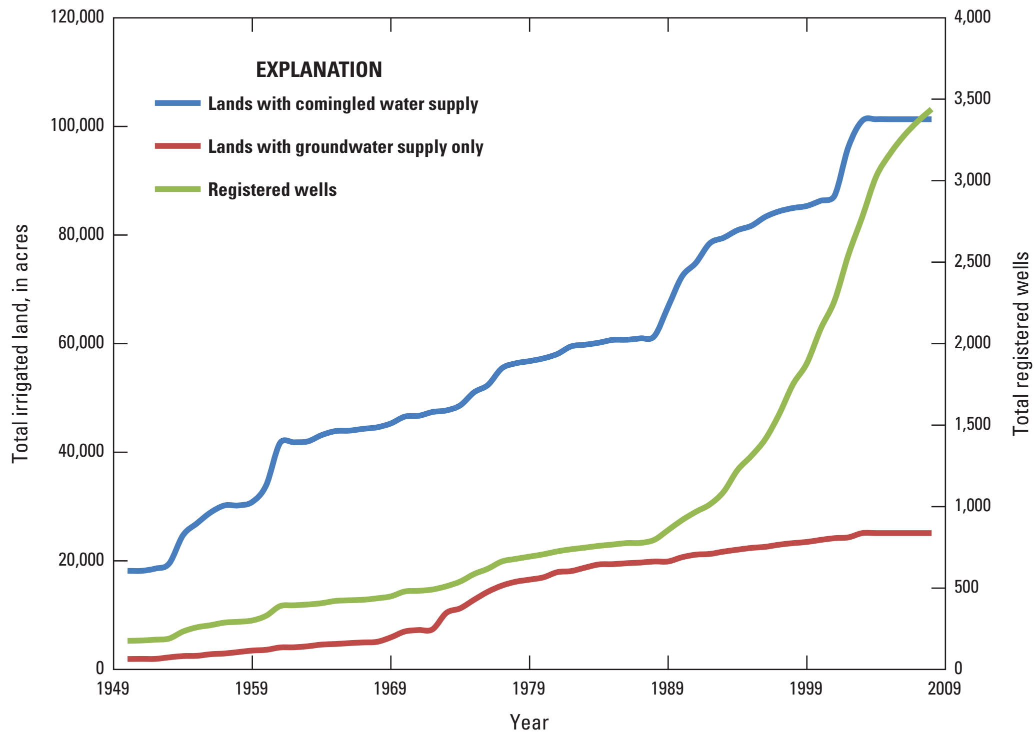

Figure 3. Irrigated agricultural acres by irrigation water source and registered wells within the study area, 1950–2008. (Acres served by comingled supplies primarily use surface water for irrigation but also have groundwater available).

Upper-Tertiary sediments present in the alluvial aquifer are mainly buried (and hence are not shown in fig. 4) and consist of coarse sand and gravel of the Broadwater Formation. The Broadwater Formation does not exist uniformly throughout the study area, but was deposited as channel-fill north of the North Platte River (Swinehart and others, 1985). The Broadwater Formation can be as much as 150 feet (ft) thick, but the upper part is usually unsaturated.

The alluvium that comprises most of the alluvial aquifer in the study area is Quaternary or Upper Tertiary (Pliocene) in age, mostly sand and gravel, and chiefly were deposited in a fluvial setting (Gutentag and others, 1984; Cannia and others, 2006; Luckey and Cannia, 2006). Colluvium mixed with alluvium include Quaternary sand, silt, and minor gravel located principally on the valley slopes (Swinehart and Diffendal, 1997). Quaternary alluvium and colluvium inside the study area (fig. 4) are hydrologically contiguous and are hereinafter referred to as the alluvial aquifer. The alluvial aquifer contains small amounts of eolian dune sand and loess deposits, as well as isolated silt and clay deposits along the North Platte River valley (Verstraeten and others, 2001; Swinehart and others, 1985). However, the silt and clay units are not continuous throughout the area and are only known to exist locally. The alluvial aquifer thins and pinches out against the valley walls outside the northern and southern boundaries of the study area (fig. 4).

The base of the aquifer, which is the surface where the oldest sediments composing the alluvial aquifer were deposited, is highly irregular and contains paleovalleys and ridges parallel or subparallel to the modern-day North Platte River. The regional direction of groundwater flow is from west-northwest to east-southeast. Locally, groundwater generally flows toward the North Platte River and toward the tributaries to the North Platte River (fig. 5). However, local bedrock topography strongly affects the direction and magnitude of groundwater flow at the local scale (Abraham and others, 2012). Paleoridges act as barriers to groundwater flow, and groundwater must rise to the altitude of the ridge top to resume downgradient flow. Many of the paleo-ridge tops are near or at land surface; thus, little aquifer thickness is present to transmit the over-topping groundwater (as depicted in Abraham and others, 2012). The paleoridges are not continuous and groundwater behind a paleoridge can also move laterally to resume downgradient flow to a gap in the paleoridge or to discharge to a tributary of the North Platte River that has eroded a channel through the ridge.

A new base-of-aquifer altitude map was generated to more accurately simulate the strong effect of the aquifer-base topography on groundwater-flow direction and magnitude. Aquifer-base-altitude contours from Cannia and others (2006) were revised using 925 test-hole logs from the Cooperative Hydrology Study (2003a), 33 test-hole logs from the Wyoming State Engineers Office (unpub. data, 2009), and selected data from Abraham and others (2012; fig. 6*A*). The data from Abraham and others (2012) are continuous resistivity profiles processed into altitude sections derived from airborne electromagnetic (AEM) data. These altitude sections were aggregated to a 10-acre spacing aligned with the 40-acre grid used for the groundwater-flow model documented in this report, resulting in 2,292 point averages of the aquifer-base altitude. Contours also were added at 50-ft intervals to depict the surface characteristics in greater detail. The revised contours and

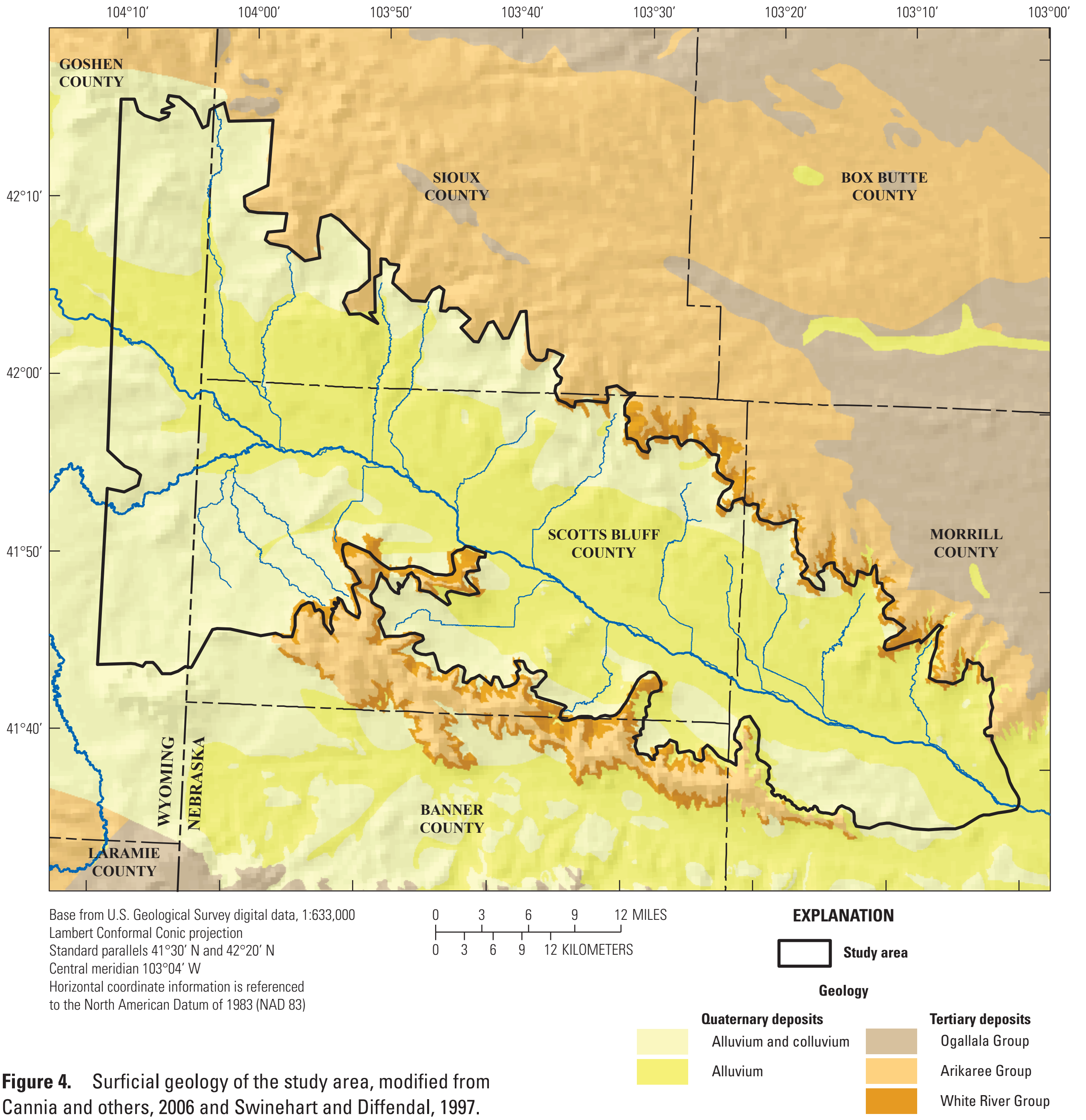

Figure 4. Surficial geology of the study area, modified from Cannia and others, 2006 and Swinehart and Diffendal, 1997.

aquifer-base-altitude data were used to interpolate a continuous alluvial aquifer-base-altitude map (fig. 6*B*). The 1995 water-table altitude contours (fig. 5) and groundwater levels measured during 1990–1999 (described in the “Calibration Targets” section of this report) were together interpolated to construct a continuous surface and compared quantitatively to the revised aquifer-base-altitude map (fig. 6*B*) to generate a map of saturated thickness (fig. 6*C*). The thickest part of the aquifer lies along the center of the study area near the modern course of the North Platte River, and a discontinuous ridge separates the deposits from a second group of thicker deposits to the north. Saturated thickness is less than 25 ft in most of the rest of the area. Near the edges of the study area, some patches with saturated thicknesses exceeding 25 ft are in areas with little or no groundwater-level measurements; therefore, actual saturated thicknesses in those areas may differ substantially from that depicted in figure 6*C*.

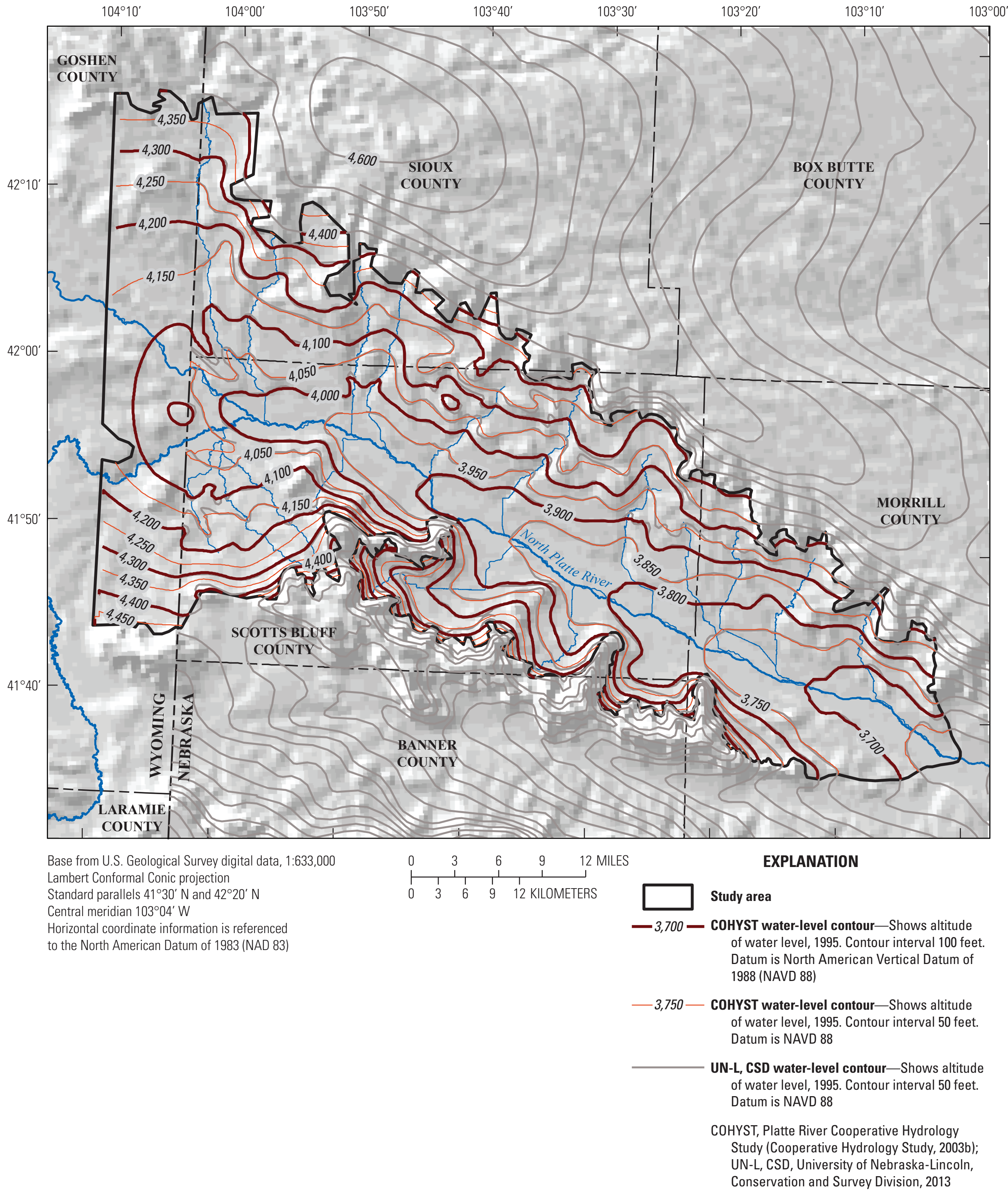

Figure 5. Water-table altitude contours, 1995, North Platte River valley, Nebraska.

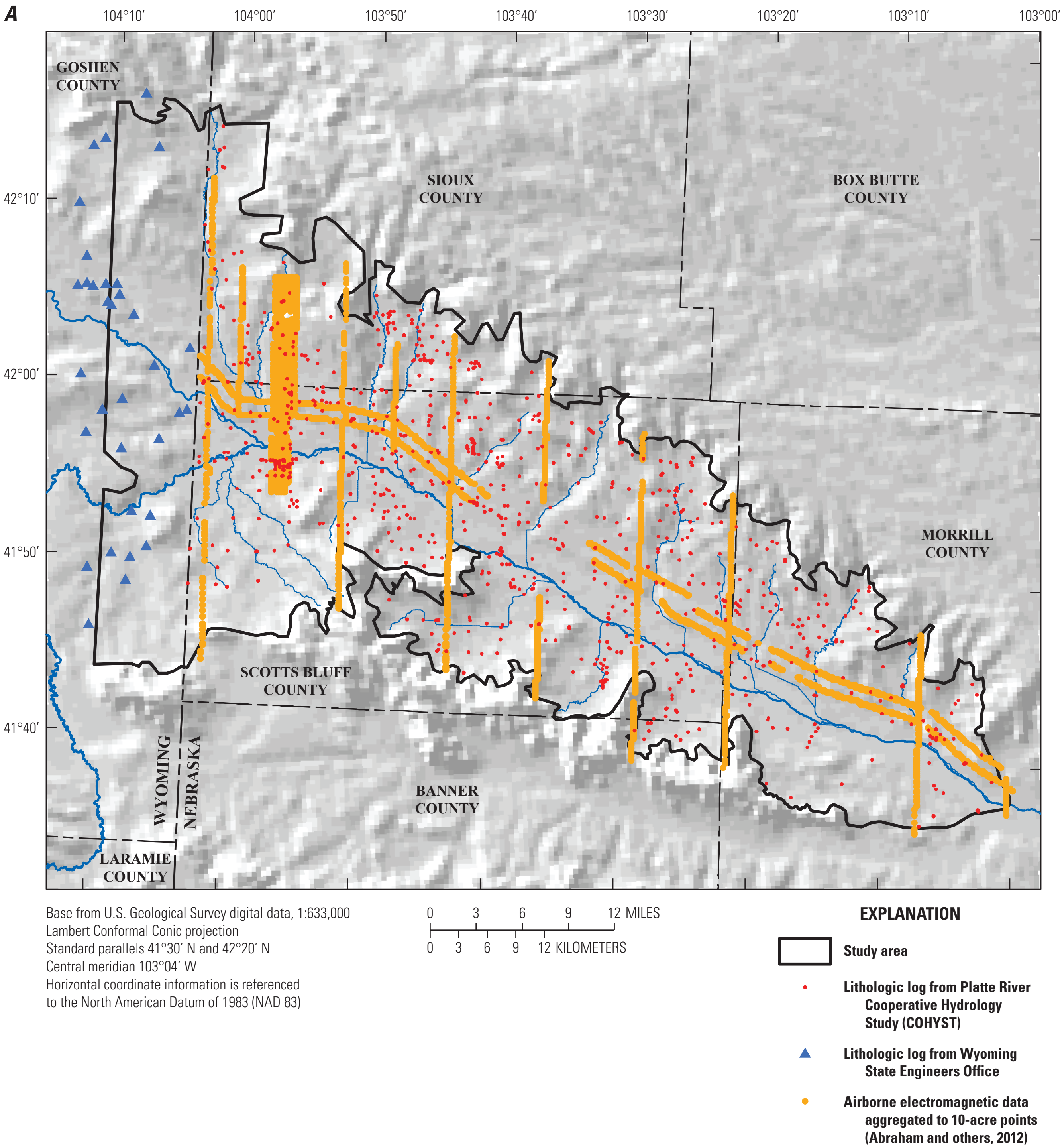

Figure 6. Alluvial aquifer base altitude and saturated thickness, North Platte River valley, Nebraska. *A*) Locations of test holes and flight lines for lithologic and airborne electromagnetic (AEM) data used to refine the altitude contour map of the base of the alluvial aquifer; revised maps of (*B*) base of the alluvial aquifer, modified from Cannia and others, 2006; and (*C*) saturated thickness of the aquifer, calculated from an interpolated version of the 1995 water-table altitude contours and the revised map of base of the alluvial aquifer.

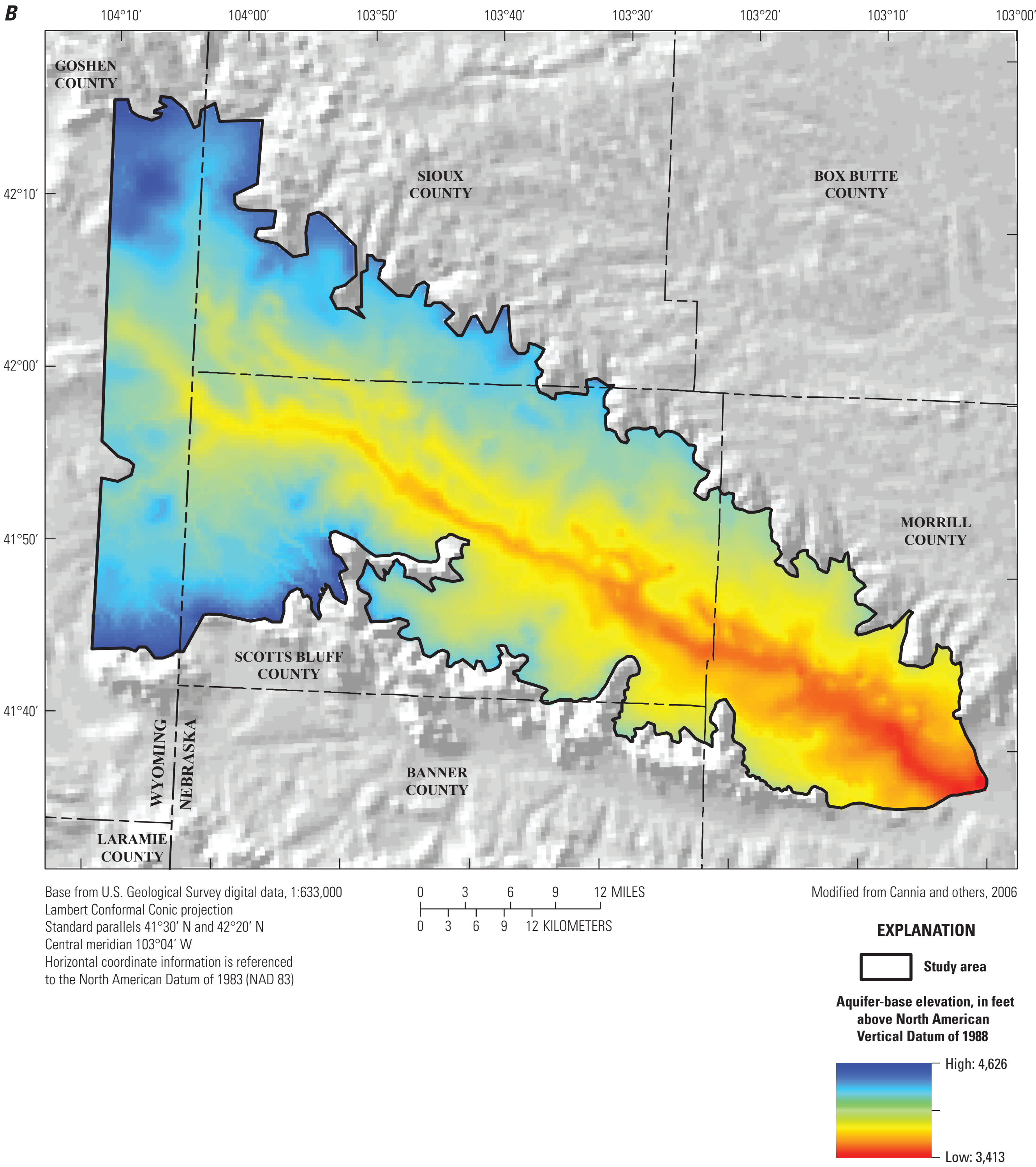

Figure 6. Alluvial aquifer base altitude and saturated thickness, North Platte River valley, Nebraska. *A*) Locations of test holes and flight lines for lithologic and airborne electromagnetic (AEM) data used to refine the altitude contour map of the base of the alluvial aquifer; revised maps of (*B*) base of the alluvial aquifer, modified from Cannia and others, 2006; and (*C*) saturated thickness of the aquifer, calculated from an interpolated version of the 1995 water-table altitude contours and the revised map of base of the alluvial aquifer.—Continued

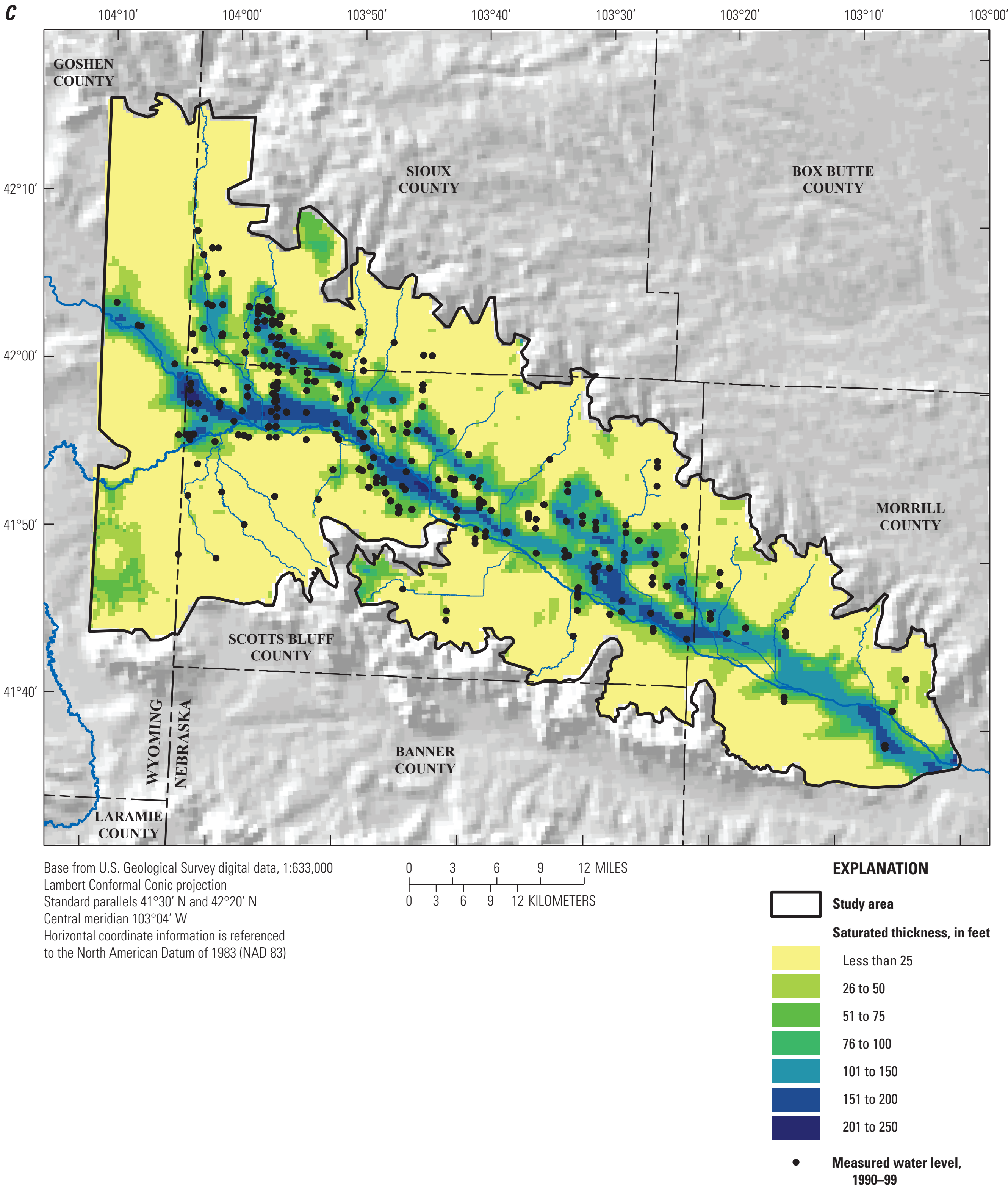

Figure 6. Alluvial aquifer base altitude and saturated thickness, North Platte River valley, Nebraska. *A*) Locations of test holes and flight lines for lithologic and airborne electromagnetic (AEM) data used to refine the altitude contour map of the base of the alluvial aquifer; revised maps of (*B*) base of the alluvial aquifer, modified from Cannia and others, 2006; and (*C*) saturated thickness of the aquifer, calculated from an interpolated version of the 1995 water-table altitude contours and the revised map of base of the alluvial aquifer.—Continued

Simulation of Groundwater Flow

This section of the report describes the simulation of groundwater flow for this study area, including the model design, model calibration, simulated groundwater budgets, model sensitivity to changes in calibration parameters, model assumptions and limitations, and a post-audit of estimated groundwater withdrawals.

Groundwater-Flow Model Design

This section of the report describes the conceptual model of groundwater flow for this study, how the conceptual model of flow was represented in the USGS modular three-dimensional groundwater model (MODFLOW) simulation, and spatial and temporal discretization of the simulation. This section also describes how selected inputs of the simulation were generated, including recharge estimated with a soil-water-balance model, recharge from canal seepage, and groundwater withdrawals.

Conceptual Model of Groundwater Flow

A conceptual model is a narrative and graphical description of the groundwater-flow system being studied and is used to design the numerical model (Anderson and Woessner, 1992). The conceptual model describes the hydrogeologic units, important sources and sinks of water, and the lateral and vertical extent of the flow system. A conceptual model further describes how the system is simplified, although retaining enough complexity so that the numerical model reproduces the behavior of the natural system. Stated another way, a conceptual model describes how the authors understand groundwater-flow processes in the area, where the water comes from and goes to, and what sources and sinks are most or least important to groundwater in the study area. A conceptual model is the theory of how a particular groundwater-flow system behaves, and the resulting numerical model is a test of how those theories, implemented in a simulation, reproduce measured or estimated hydrologic data representing actual behavior of the groundwater-flow system (Hill and Tiedeman, 2007).

Initial numerical models generally do not satisfactorily reproduce measured or estimated hydrologic data representing the natural behavior of the system (targets) but are improved through calibration and through refinement of the conceptual model (Hill and Tiedeman, 2007). Calibration means that the model inputs are adjusted to improve the match between simulated hydrology and targets. Generally, if an acceptable match between simulated flows and targets cannot be achieved with model inputs remaining in defensible ranges, an error or omission exists in the conceptual model (Anderson and Woessner, 1992). If an error or omission exists, the conceptual model must be refined and additional data or components added. The refined theory is then similarly tested through implementation in the numerical model. Evaluation of the numerical model and the efficacy of that model in reproduction of measured or estimated hydrologic data representing the natural behavior of the hydrologic system provides feedback as to the accuracy of the theories contained in the conceptual model. As various theories are tested, a conceptual model will evolve during the course of a modeling study. For this study, the theorized conceptual model is described in this section of the report, and the data or estimates supporting these theories are described in the "MODFLOW Simulation" section of this report.

With regard to the physical configuration of the flow system, as described in the "Hydrogeology" section of this report, the alluvial aquifer in the study area is composed of Quaternary alluvium and a mixture of Quaternary alluvium and colluvium. The alluvial aquifer overlies fine-grained sediments of the Tertiary White River Group, most commonly the Brule Formation in this area. Research indicates that little groundwater flows between the alluvial aquifer and underlying fine-grained sediments of the Tertiary White River Group (J. Cannia, oral commun., 2008). The areas where the Brule Formation is massive and fractured and can yield water to the alluvial aquifer are discontinuous but have been previously mapped as part of the COHYST study (Cannia and others, 2006). Fractured Brule Formation was not included as part of the modeled aquifer in this study because of the lack of continuity across the study area; therefore, the base of the alluvial aquifer is considered to be the base of the conceptual flow model.

The alluvial aquifer, shown by active model cells in figure 7 (active model cells also underlie the area of simulated evapotranspiration in figure 7), is thickest in the paleovalley in the center of the study area, and thins to 10 ft near the northern and southern boundaries, where the aquifer adjoins fine-grained sediments of the Tertiary White River Group or siltstone and volcanic ash of the Tertiary Arikaree Group (fig. 4). Because of the thinness of the alluvial aquifer near the north and south boundaries and the poor permeability of the Arikaree and White River Group sediments, little groundwater flow is assumed to cross these boundaries; therefore, the boundaries are considered no-flow boundaries as indicated by the edges of the active model cells shown in figure 7. Near the southeast part of the study area, the boundary is drawn parallel to the primary direction of groundwater flow, as shown in figure 5; thus, a no-flow boundary is appropriate in this area as well. Also, for most of the western boundary of the area, groundwater flow converges from the north and south toward the North Platte River, parallel to the boundary; thus, no-flow conditions are also appropriate. Near the North Platte River along the western boundary of the study area, groundwater flow is from west to east, and was represented using a specified water-level boundary (fig. 7). Groundwater inflows across the western boundary are limited to a small area and are thought to be a small component of the groundwater budget, consistent with simulated water budgets of a previous larger groundwater-flow model that included the study area (Luckey and Cannia, 2006).

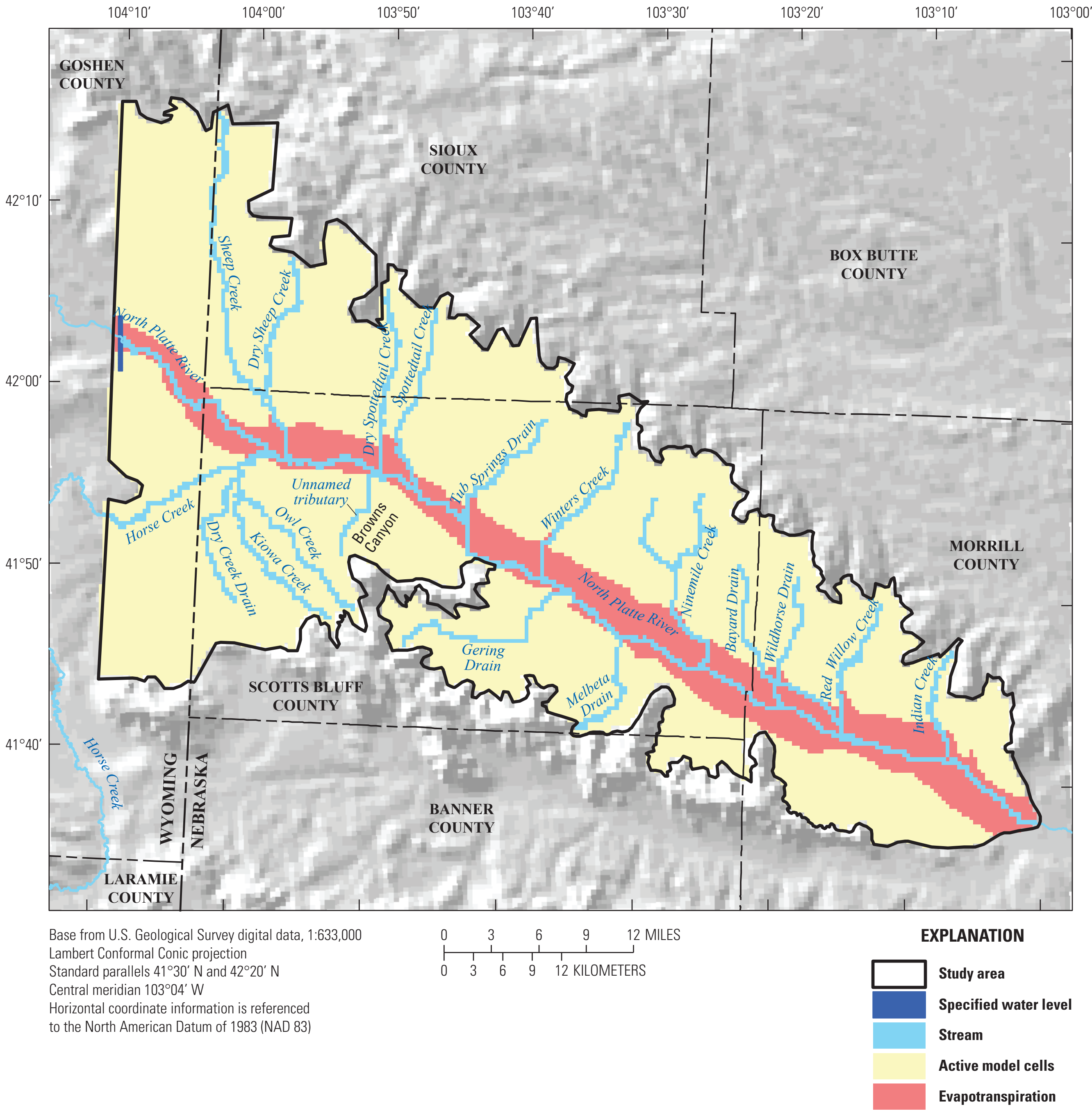

Figure 7. Boundary conditions used for the groundwater-flow model as indicated by model-cell types.

The simulation period of this model extends from pre-surface-water development (pre-1890) through 2008. Few hydrologic data exist for the early time periods of the model but it was assumed that before surface-water development for irrigation, groundwater was in a state of long-term equilibrium. Before 1890, inflows came from a small amount of recharge originating from infiltration of precipitation through the soil zone and reaching the water table. The assumption is that during this time (before development) groundwater discharge was primarily to the North Platte River and by evapotranspiration of shallow groundwater near the river. Most tributaries to the North Platte River were ephemeral and received no groundwater discharge before irrigation development (State Board of Irrigation, 1899).

During the 1890s, surface water was developed for irrigation and canals were constructed to deliver the water to agricultural lands. Leakage from the canal systems led to a large increase in the amount of recharge to the aquifer (State Board of Irrigation, 1899). The increased recharge likely caused large groundwater-level rises and an increase of groundwater discharge to the North Platte River. Once the water table rose enough to intersect the tributaries, they also likely became focal points of groundwater discharge, and many became perennial within a few decades of extensive surface-water development (Luckey and Cannia, 2006). In more recent times, such as 2008, the largest inflow to groundwater was recharge originating from water leaking from canals and at a rate that is thought to be much larger than that from recharge originating from infiltration of precipitation, consistent with data presented by Verstraeten and others (2001). The increased rate of recharge following canal emplacement caused perennial base flow in the streams that did not take place before emplacement of the canals (State Board of Irrigation, 1899).

Based on interpretations from a 1995 water-table altitude map (fig. 5), little groundwater flows across study area boundaries, and only in one area. Groundwater flows across the boundary primarily from west to east, a short distance north and south of the North Platte River (the area of specified water levels in fig. 7). This cross-boundary flow is a far smaller source of inflows to the model area than is recharge.

The largest component of groundwater discharge from the study area is to the North Platte River and its tributaries, with smaller amounts of discharge by evapotranspiration and groundwater withdrawals for irrigation. The earliest groundwater wells for irrigation in the study area were drilled before 1940; however, there were fewer than 200 wells by 1950 (Nebraska Department of Natural Resources, 2008). Therefore, groundwater withdrawals for irrigation likely were not a large component of groundwater discharge by 1950. Groundwater withdrawals for irrigation remained a small component of total groundwater outflows in 2008, though they increased during 1950–2008 and especially during the 2001–07 drought (fig. 3). The hypothesis that groundwater withdrawals for irrigation remained a small component of total groundwater discharge was subjected to further investigation during this study; see the “Groundwater Withdrawals” and “Simulated Groundwater Budget” sections of this report for additional explanation. Recharge from canal seepage and groundwater withdrawals for irrigation takes place primarily during the irrigation season, from approximately May 1 through September 30 each year.

MODFLOW Simulation

A newton formulation of the 2005 version of the USGS modular three-dimensional groundwater model, MODFLOW–NWT version 1.0.7 (Niswonger and others, 2011), was selected as the groundwater-flow modeling code for this study. MODFLOW–NWT is a version of MODFLOW with an improved ability to solve nonlinear unconfined aquifer simulations with wetting and drying of cells by applying the Newton-Rhapson linearization approach to solving the flow equations (Niswonger and others, 2011). Given the thinness of the aquifer near the sides of the valley, the possibility exists that the water table would drop to the cell bottom occasionally during the simulation, that in prior versions of MODFLOW would result in the cell being converted to inactive and being removed from the simulation (Harbaugh, 2005). MODFLOW–NWT avoids this problem and improves convergence and computational efficiency for unconfined groundwater-flow models with nonlinear features.

A model grid was built to cover the study area. Each grid cell was 1,320 by 1,320 ft (40 acres). The grid comprised 227 rows and 308 columns. Active cells were bounded by the edges of the valley and alluvial aquifer to the north and south, by a line 6 mi west of the State line to the west, and for a small section of the eastern boundary, by a no-flow boundary parallel to the primary groundwater-flow direction. The model consisted of one layer, simulated as unconfined, with 19,170 active cells. Generally, the top altitude of the model does not matter in an unconfined simulation; however, the top altitude of this model was set to an altitude (500 ft above the aquifer base) much higher than the expected water-table altitudes to prevent cells from inadvertently being simulated as confined flow conditions, particularly during early stages of model development.

The two primary development periods in the area were each represented by a model; the period before substantial groundwater withdrawals (the pre-1950 model) and the period of increasing groundwater withdrawals from May 1950 through April 2008 (the 1950–2008 model). The pre-1950 model was built with a steady-state stress period and a transient stress period. The steady-state stress period was used to simulate long-term equilibrium ending at 1900, slightly after surface-water development became widespread in the area. The transient stress period, representing 1900–50, was used to simulate the period of surface-water irrigation development in the area, using 500 time steps, or 10 per year. The 1950–2008 model was built with 77 stress periods starting in 1950, the approximate date when groundwater withdrawals for irrigation began. The 1950–2008 model used annual stress periods through 1988 and seasonal (irrigation and non-irrigation) stress periods for 1989 into 2008. The seasonal stress periods used to simulate 1989 into 2008 allowed for simulation of the seasonal differences in recharge that result from canal seepage and groundwater withdrawals for irrigation. Generally, canal seepage and groundwater withdrawals take place during the irrigation season (May 1 through September 30). Seasonal differences in canal seepage and groundwater withdrawals have existed throughout the history of irrigation development, but the differences were represented using average annual rates for stress periods used for 1988 and earlier simulations, also when the fewest data were available to calibrate the models. The increased temporal detail (seasonal stress periods) were used from 1989–2008 to calibrate effects of seasonal differences in the model outputs in the simulated period when the most calibration-target data were available.

All stress periods simulated during the 1950–2008 model used 30 time steps, which were about 12.2 days each for the annual stress periods, 5.1 days per time step for the irrigation season stress periods, and 7.1 days per time step for the non-irrigation-season stress periods.

MODFLOW Processes Used to Implement the Conceptual Model

Standard MODFLOW components of the Groundwater-Flow Process that were used in the model included the Basic Package, Output Control Option, Discretization File, and the List file (Harbaugh and others, 2000). Recharge from precipitation and recharge from canal seepage were summed and simulated with the Recharge Package. Methods used to estimate recharge for the model are described in the “Recharge Estimated with the Soil-Water-Balance Model” and “Recharge from Canal Seepage” sections of this report. The Upstream Weighting Package was used because it is required when using the Newton Solver (NWT). The Upstream Weighting Package specifies properties controlling flow between cells, such as hydraulic conductivity, anisotropy, specific storage, and specific yield. Initial values for hydraulic conductivity were from Cannia and others (2006) and ranged from 10 to 350 foot per day (ft/d) with a mean of 162 ft/d. Initial hydraulic conductivity was adjusted during calibration as described in the “Horizontal Hydraulic Conductivity Estimated at Pilot Points” section of this report. Horizontal anisotropy was set to 1.0 (no anisotropy). Specific storage was set to 10e-5 ft-1 similar to Luckey and Cannia (2006) and was not adjusted during calibration. Specific yield (dimensionless) was from Cannia and others (2006), ranged from 0.1 to 0.3 with a mean of 0.18, and was not adjusted during calibration.

The Evapotranspiration Package was used to simulate evapotranspiration in areas of active model cells where the water table is shallow (fig. 7). The evapotranspiration (ET) extinction depth was set to 7 ft (as used by Luckey and Cannia, 2006), and the maximum ET rate was set to 0.004 ft/d, or about 17.5 inches per year (in/yr), similar to but slightly larger than that used by Luckey and Cannia (2006). The Flow and Head Boundary Package was used to simulate specified water levels in the small area of cross-boundary groundwater flow at the western boundary of the model (fig. 7). Specified water levels were derived from the 1995 water-table altitude map (fig. 5).

The Streamflow-Routing Package was used to simulate streams, including the North Platte River, Sheep Creek, Dry Sheep Creek, Dry Spottedtail Creek, Spottedtail Creek, Tub Springs Drain, Winters Creek, Ninemile Creek, Bayard Drain, Wildhorse Drain, Red Willow Creek, Indian Creek, Horse Creek, Dry Creek Drain, Kiowa Creek, Owl Creek, an unnamed tributary in Browns Canyon, Gering Drain, and Melbeta Drain (fig. 7). The simulated streams were selected to represent the stream reaches coded as long-term average perennial reaches in the National Hydrography Dataset (U.S. Geological Survey, 2008). Additional simulated streams were selected based on field observations of persons familiar with the area (J. Cannia, oral commun., 2007) and based on observations of the authors during October 2007 and March 2009. Horse Creek and the North Platte River are the only streams that originate outside the study area; streamflows in these two streams at the model boundary were specified on the basis of their monthly average streamflows for April (for irrigation seasons) and October (for non-irrigation seasons; U.S. Geological Survey, 2012). Simulated stream widths were estimated using aerial photographs (Dollison, 2010) and ranged from 10 to 45 ft for tributaries and from 117 to 346 ft for the North Platte River. Streambed hydraulic conductivity was evaluated during initial testing and set to 10 ft/d for tributaries and 15 ft/d for the North Platte River. Moderate changes in streambed hydraulic conductivity only caused small changes in simulated stream base flows, so streambed hydraulic conductivity was not adjusted during calibration. The Gage Package was used to output simulated stream base flows at target locations into separate formatted files.

The Well Package was used to simulate groundwater withdrawals for irrigation. Calculation of groundwater withdrawal rates is described in the “Groundwater Withdrawals” section of this report.

Recharge Estimated with Soil-Water-Balance Model

The Soil-Water-Balance (SWB) model (Dripps and Bradbury, 2007; Westenbroek and others, 2010) was used to calculate recharge from precipitation for this study for pre-1950 and 1950–2008. The SWB model uses spatially distributed soil and landscape properties with daily weather data to calculate spatial and temporal variations in potential recharge. The SWB model (Westenbroek and others, 2010) uses a grid, in this case the same as that used for the groundwater-flow model. Soil properties and daily climate data were assigned to each model cell. The SWB model calculates the fractions of precipitation and snowmelt that become surface runoff, ET, 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 the SWB model by deep percolation, is surplus water in the soil column, which extends from land surface to the bottom of the root zone. Surplus water is calculated by subtracting the sum of the outputs (plant interception, surface runoff out of the cell to adjacent cells, and ET) from the inputs (precipitation, snowmelt, and surface runoff into the cell from adjacent cells) and accounting for change in soil moisture:

$$R = (P + SNO + RO^{in}) - (Pint + RO^{out} + ET) - \Delta S^{soil} \qquad (1)$$

where

R is daily potential recharge,
P is precipitation,
SNO is snowmelt,
RO^{in} is surface runoff into the cell,
$Pint$ is plant interception,
RO^{out} is surface runoff out of the cell,
ET is evapotranspiration, and
ΔS^{soil} is the change in soil moisture.

Inputs to the Soil-Water-Balance Model

Physical factors that control flow and loss of water on the ground surface and within the soil include the available water capacity of the soil, soil type (hydrologic group), land use and land cover, 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 and land-cover classes assigned to each cell included agricultural, urban, forest, and grassland (University of Nebraska-Lincoln, 2007). Land cover of the study area is heavily dominated by grassland (66 percent) and agricultural row crops (30 percent). Characteristics assigned to each cell on the basis of land-use and land-cover information included the Natural Resources Conservation Service (NRCS) runoff-curve number for estimating the potential for surface runoff, precipitation-interception coefficient, and root-zone depth; assigned values were obtained from the U.S. Department of Agriculture National Engineering Handbook (U.S. Department of Agriculture, 2004), Cronshey and others (1986), and Thornthwaite and Mather (1957).

To calculate the daily soil-water content from precipitation, ET, surface runoff into and from adjacent cells, snowmelt, and potential recharge that passes below the root zone, the SWB model (Westenbroek and others, 2010) requires daily precipitation and temperature. Data from a single weather station can be applied to the entire model grid, or daily grids of weather data can be interpolated from multiple stations across and just outside the study area. Because of the small extent of the study area, precipitation and temperature data from a single weather station near Scottsbluff, Nebr., (fig. 1) were used (National Climatic Data Center, 2009).

Digital elevation models (DEMs; U.S. Geological Survey and Nebraska Department of Natural Resources, 1998) were used to determine the surface-water-flow direction for each cell as described in Westenbroek and others (2010). The DEMs were first resampled to the model grid resolution (1,320 ft) using the mean altitude for each model cell. Surface-water runoff in the SWB model was calculated using the NRCS curve number method of Cronshey and others (1986) and is affected by soil properties and moisture content. If runoff water is routed to a closed surface depression, available water can exceed ET and soil-moisture demands. In these cases, unrealistic recharge values are possible. To limit excessive recharge, the maximum recharge rate was set to 2, 0.6, 0.24, and 0.12 inches per day for hydrologic soil group A, B, C, and D, respectively. The extra water that is not allowed to infiltrate was tracked as rejected recharge, and was selectively reviewed for quality assurance. Infiltration and runoff also are affected by frozen ground, which was tracked using a continuous frozen-ground index (Molnau and Bissell, 1983). In the SWB model, precipitation that falls as snow was stored on the land surface until daily air temperature indicates that the snow would melt (Westenbroek and others, 2010). The rate of snowmelt is determined from a temperature-index method where 0.0328 in. of snow melts per day per degree Fahrenheit that the daily maximum temperature is above the freezing point (Westenbroek and others, 2010). Runoff that is transferred among cells is tracked as inflow and outflow.

Several methods are available in the SWB model to estimate ET; the Hargreaves and Samani (1985) method was used for this study. The Hargreaves and Samani method uses daily maximum and minimum temperatures to calculate potential ET (PET), and the method was used for this study because it does not require additional input of solar radiation, relative-humidity, or wind-speed data that other methods require; some of these data were not collected for the Scottsbluff weather station until after 1980. The SWB model then calculates actual ET from PET, and the available soil moisture in storage is determined from the nonlinear relation between soil moisture and the accumulated potential water loss based on soil properties and root-zone depths for vegetation categories (Westenbroek and others, 2010). If precipitation exceeds PET, actual ET is equal to PET; if PET exceeds precipitation, actual ET is equal to the amount of water that can be extracted from the soil.

The potential recharge estimated using the SWB model is sensitive to root-zone depth (Stanton and others, 2011). Root-zone depths were assigned based on hydrologic soil group and land-cover classification because the same vegetation class will send roots to different depths in different soil types.

Initial soil-moisture and snow-cover values for the model were estimated by running the model for the year before the period of interest. The year 1949 was included in the model run to generate the initial soil-moisture and snow-cover values for 1950. Examples of potential recharge estimated using the SWB model for irrigation seasons of 1958, 1964, and 1982 are shown in figure 8. Based on the long-term precipitation record (1895–2008; National Climatic Data Center, 2009), 1958 was about average, 1964 was drier than average, and 1982 was wetter than average. For the irrigation season of 1958, most of the potential recharge was near the North Platte River from soil water that had first been routed across the land surface from uphill (upgradient) areas (fig. 8*A*). For the drier than average 1964 irrigation season (fig. 8*B*), the meager potential recharge was also near the North Platte River. For the wetter-than-average irrigation season of 1982 (fig. 8*C*), potential recharge was at greater rates and across a much wider area than for the other example years.

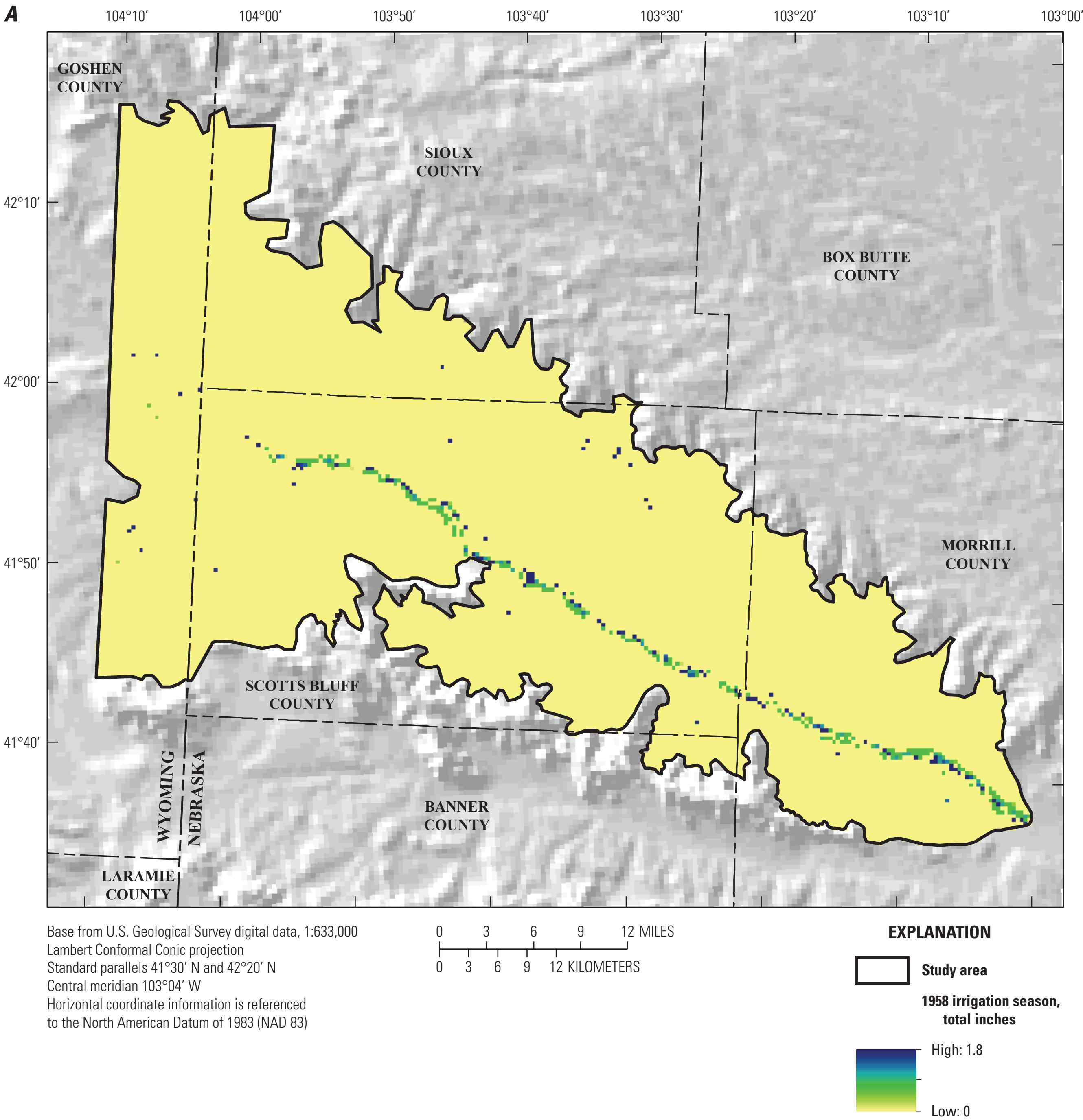

Figure 8. Potential recharge estimated with the Soil-Water-Balance (SWB) model for irrigation seasons of (*A*) 1958, (*B*) 1964, and (*C*) 1982.

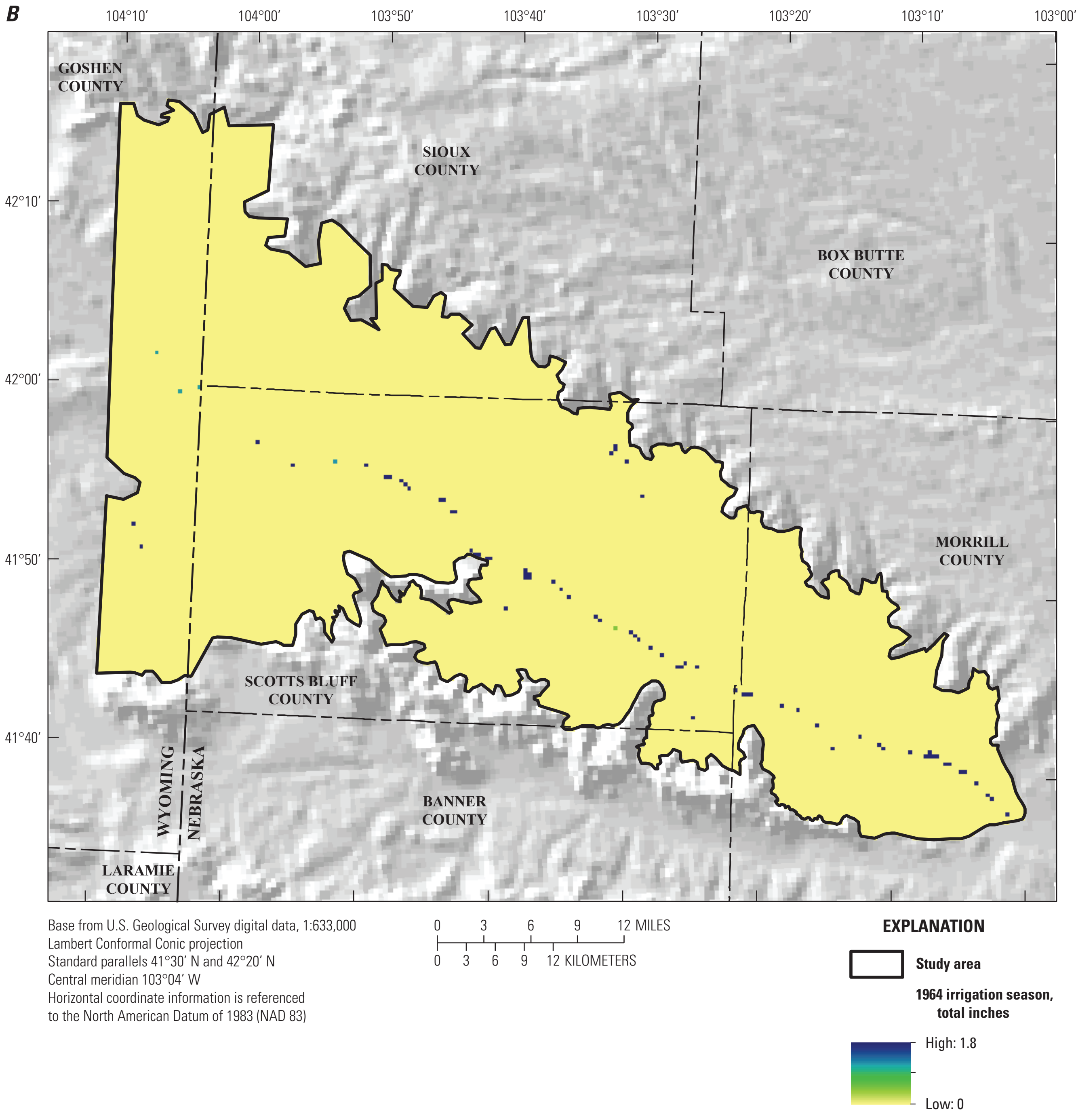

Figure 8. Potential recharge estimated with the Soil-Water-Balance (SWB) model for irrigation seasons of (*A*) 1958, (*B*) 1964, and (*C*) 1982.—Continued

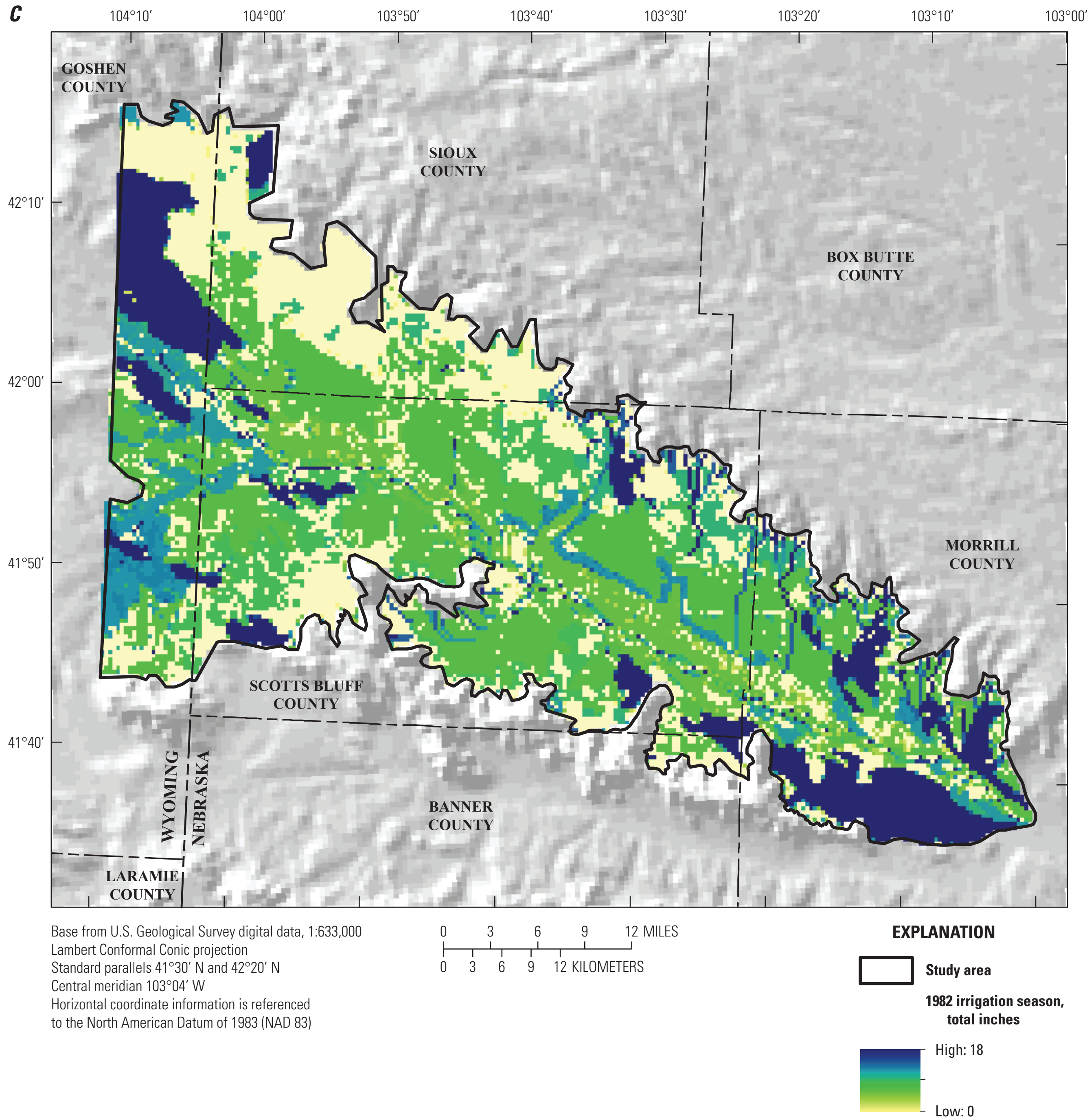

Figure 8. Potential recharge estimated with the Soil-Water-Balance (SWB) model for irrigation seasons of (*A*) 1958, (*B*) 1964, and (*C*) 1982.—Continued

Limitations of the Soil-Water-Balance 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. The following is a list of the limitations:

1. The version of the SWB model used for this analysis only accounts for precipitation and was not formulated to account for other water entering the root zone, such as irrigation or shallow groundwater.

2. In the SWB model used for this study, daily precipitation and temperature data are taken from a single weather station but assumed to represent the entire model grid.

3. 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).

Recharge from Canal Seepage

Recharge from canal seepage is the largest source of recharge; therefore, estimating the distribution of this recharge on a canal-by-canal and cell-by-cell basis is important. The three main steps used in the estimation are as follows: (1) computation of canal seepage from a mass balance analysis of flow in each canal, estimated from records of canal operation; (2) estimation of seepage potential using available surface-geophysical data; and (3) combination of canal mass balance and seepage potential to compute spatially distributed canal seepage recharge.

Canal Mass Balance

The Bureau of Reclamation manages diversions to irrigation canals in the study area. Monthly water-distribution reports for 1950–2007 were obtained from the Bureau of Reclamation for 13 canals (table 1) including acres serviced, diversion, waste, loss, and delivery data in acre-feet per year (acre-ft/yr). Evaporation from canal water surfaces was assumed to be small, no more than a few percent. Although direct measurements of evaporation from canals do not exist, a few percent evaporation loss was considered a conservative assumption; a canal 50 mi long and 60 ft wide that evaporates 50 in. of water from May through September with 1,000 ft^3/s of flow, would lose only 0.2 percent of flow to evaporation.

Canal seepage recharge annual rates were determined by using the amount of loss (calculated as the amount diverted from the North Platte River minus deliveries for irrigation and waste) multiplied by 97.5 percent (to account for additional losses from evaporation along the canal system and transpiration of recently infiltrated recharge) and dividing the value by the area of the bottom of the canal in the areas serviced in that year, resulting in a seepage rate per canal per unit area per year. Three canals (Minatare, Ninemile, and Winters Creek) had insufficient data to estimate annual recharge values and were assigned specified recharge rates for 1950–2007, based on Luckey and Cannia (2006).

Table 1. Thirteen canals for which annual recharge rates were estimated.

Canal name
1. Enterprise Canal
2. Farmers Canal
3. Gering Canal
4. Gering-Fort Laramie Canal
5. Gering-Fort Laramie Laterals
6. Gering Laterals
7. Minatare[1]
8. Ninemile[1]
9. Northport Canal
10. Pathfinder Canal
11. Pathfinder Laterals
12. Tri-state Laterals
13. Winters Creek[1]

[1]Fixed recharge rate assigned for 1950–2007 because of lack of data.

The amount of water available in the canals for seepage varied based on climatic conditions. Canals are most heavily used during years with low precipitation (fig. 9). However, because snowmelt runoff has decreased, the amount of surface water available to the irrigation districts has been less during most recent years (2000–2008) than before 2000, and has led to lower seepage rates (fig. 9).

Estimation of Canal Seepage Potential using Available Geophysical Data

In 2004 and during 2007–2009, the USGS led a land surface resistivity survey of selected irrigation canals within the North Platte River valley in western Nebraska and eastern Wyoming (Burton and others, 2009). Approximately 392 mi (630 kilometers) of 13 canals and 2 laterals of continuous resistivity profiles were collected using the Geometrics OhmMapper capacitively coupled electromagnetic instrument (Geometrics, 2009). Typically, an instrument configuration using five receivers was used to measure resistivity at five depths for an overall penetration of about 26 ft (8 m). The measured resistivity data were inverted, meaning that alternative configurations of subsurface physical properties that could have produced the geophysical survey measurements were evaluated and the most likely was selected. The inversions resulted in a set of georeferenced resistivity profiles totaling approximately 328,400 point values of simulated electrical resistivity.

Electrical resistivity of the earth is strongly related to sediment grain size and, hence, soil permeability (Ball and others, 2006). For example, fine-grained sediments tend to

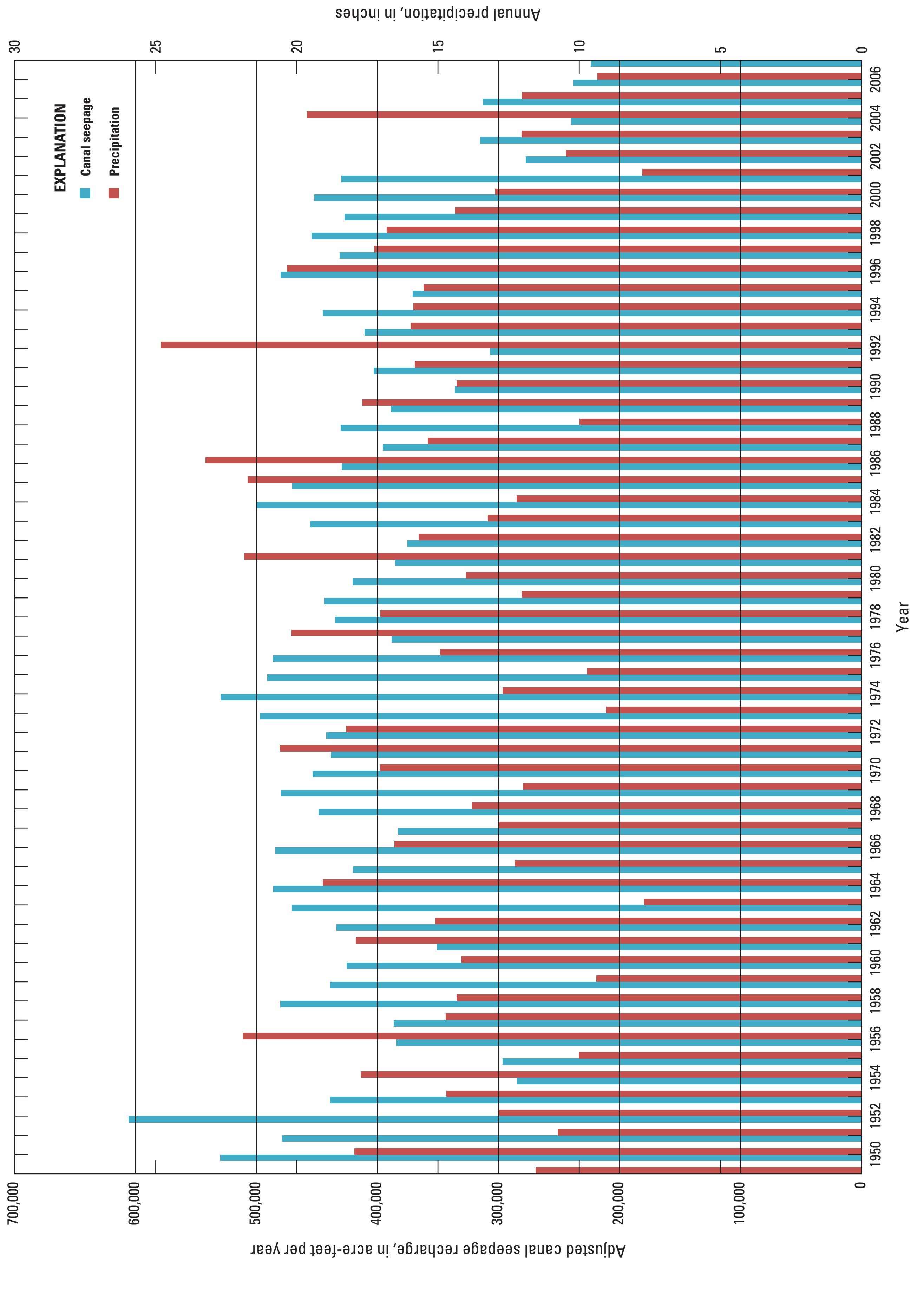

Figure 9. Annual total precipitation at Scottsbluff, Nebraska, and estimated canal seepage, 1950–2008.

be less resistive than coarser-grained sediments. The relative (dimensionless) permeability of the surveyed canal beds can be estimated by geostatistical analysis of the resistivity profiles, resulting in a seepage potential. Estimating canal seepage potential using capacitively coupled resistivity profiles is described in more detail by Vrabel and others (2009). Applying those methods to the inverted resistivity profiles resulted in a seepage potential map for the surveyed canals (fig. 10).

The length of each cell side for the groundwater-flow model was 1,320 ft, but the mapped estimates of seepage potential were on a much smaller scale (as small as one measurement point every several feet). In some cases there were hundreds of seepage potential estimates for each model cell that had to be generalized to a single estimate. A total of 2,970 model cells were associated with canals, and of these, 1,862 cells had surveyed resistivity data. In general, a surveyed path did not intersect a model cell uniformly. Factors affecting the density and distribution of the survey points within a cell included survey-line overlap, data-collection gaps, varying collection speed, and asymmetric intersection between cell boundary and surveyed line. In consideration of this spatial non-uniformity, an area-weighted mean was computed from the seepage potentials in each cell to arrive at a seepage potential for each cell intersecting a canal. Area weighting reduces spatial bias by weighting each point within a model cell by its contributing (or percentage) length. In contrast, equal weighting (computed using the simple mean) tends to give preference to areas of the cell with denser survey-point coverage. To ensure a model cell had a sufficient number of data points to estimate a reliable seepage potential, a minimum of 10 data points was required to compute an area-weighted estimate for the cell. If a cell contained less than 10 point values because of survey gaps, the cell's seepage value was computed using the mean aggregate value of the two closest cells with adequate survey coverage, defined as 10 or more points; this applied to 63 canal cells (3.4 percent of the total).

Resistivity-survey data were not available for 1,108 model cells associated with canals, precluding direct estimation of seepage potential. For these 1,108 cells, seepage potential was estimated indirectly using an inverse distance-weighted method. The inverse distance-weighted method was used on a canal-by-canal basis (Shepard, 1968). Seepage potentials were assigned to each unsurveyed cell in each canal by computing the mean of the estimated seepage potential of the surveyed cells weighted by the reciprocal of their distances to the unsurveyed cell. Estimates for unsurveyed cells are more affected by surveyed cells in closer proximity than by more distant surveyed cells, so this method tends to preserve the areal seepage potential trend better than some other methods, such as an unweighted mean. Because the geology of different canal systems can differ greatly, the indirect estimation of seepage potential was done on each canal in isolation (that is, estimated seepage potentials of unsurveyed cells were computed using only surveyed cells from the same canal system rather than including data from other canals).

Combination of Canal Mass Balance Estimates and Estimated Seepage Potentials

The estimated seepage potentials were used to distribute the recharge rates within each canal on a cell-by-cell basis. All cells in a canal were assigned the canal's annual (or seasonal, for simulation periods after 1988) recharge rate scaled in proportion to the estimated seepage potential. Cells with larger estimated seepage potentials were assigned a higher recharge rate, and cells with lower estimated seepage potentials were assigned a proportionally lower recharge rate. The resulting recharge rate was multiplied by a constant factor to preserve mass balance for the canal. Therefore, the sum of all of the cells final recharge rates in a canal equaled the original total recharge rate for the canal. Following this procedure, all canal cells (except those associated with three canals that the recharge rate was specified) were assigned an individual recharge rate for each year (or season, depending on the simulated period). These per-cell annual or seasonal recharge rates were added to recharge from precipitation to produce total estimated recharge for each stress period of the groundwater-flow simulation. All canals within the study area are shown in figure 11*A*, and figure 11*B* depicts long-term mean canal seepage recharge estimates per irrigation season, distributed by seepage potential. In figures 11*A* and 11*B*, surveyed cells are outlined. Canals in the study area only carry water during the irrigation season, so canal seepage recharge in groundwater-flow simulations was only applied to irrigation seasons during 1989–2007; however, canal seepage recharge was applied throughout the year during 1950–89.

Groundwater Withdrawals

Groundwater withdrawals were simulated in the 1950–2008 model. In this simulation, groundwater withdrawals were limited to withdrawals for irrigation purposes only, and municipal and all other uses were assumed to be negligible. In 2008, NPNRD certified irrigated acres to inventory the amount of irrigated land in the area. This information was obtained in a database containing digital spatial data describing well location, certification number, number of acres irrigated by the well, dates the well came online, and digital geospatial data for the location and extent of 2008 lands certified by NPNRD as irrigated (J. Sprock, North Platte Natural Resources District, unpub. data, 2010; fig. 12). The information in this database was used to determine the amount of groundwater needed to irrigate a defined parcel of land. Land parcels are tied to a particular canal or a particular irrigation well, or both. Not all wells in the database were used in the simulation. Criteria for well use were (1) wells had to be certified irrigation wells, servicing greater than 1 acre, (2) the screened interval of the well had to be above the revised base of the aquifer (fig. 6B), (3) the well had to have at least 5 ft of saturated thickness if located outside an area known to be underlain by Brule Formation, and (4) the well had to have at least 50 ft of saturated thickness if located within an area known to be underlain by the Brule Formation. As explained

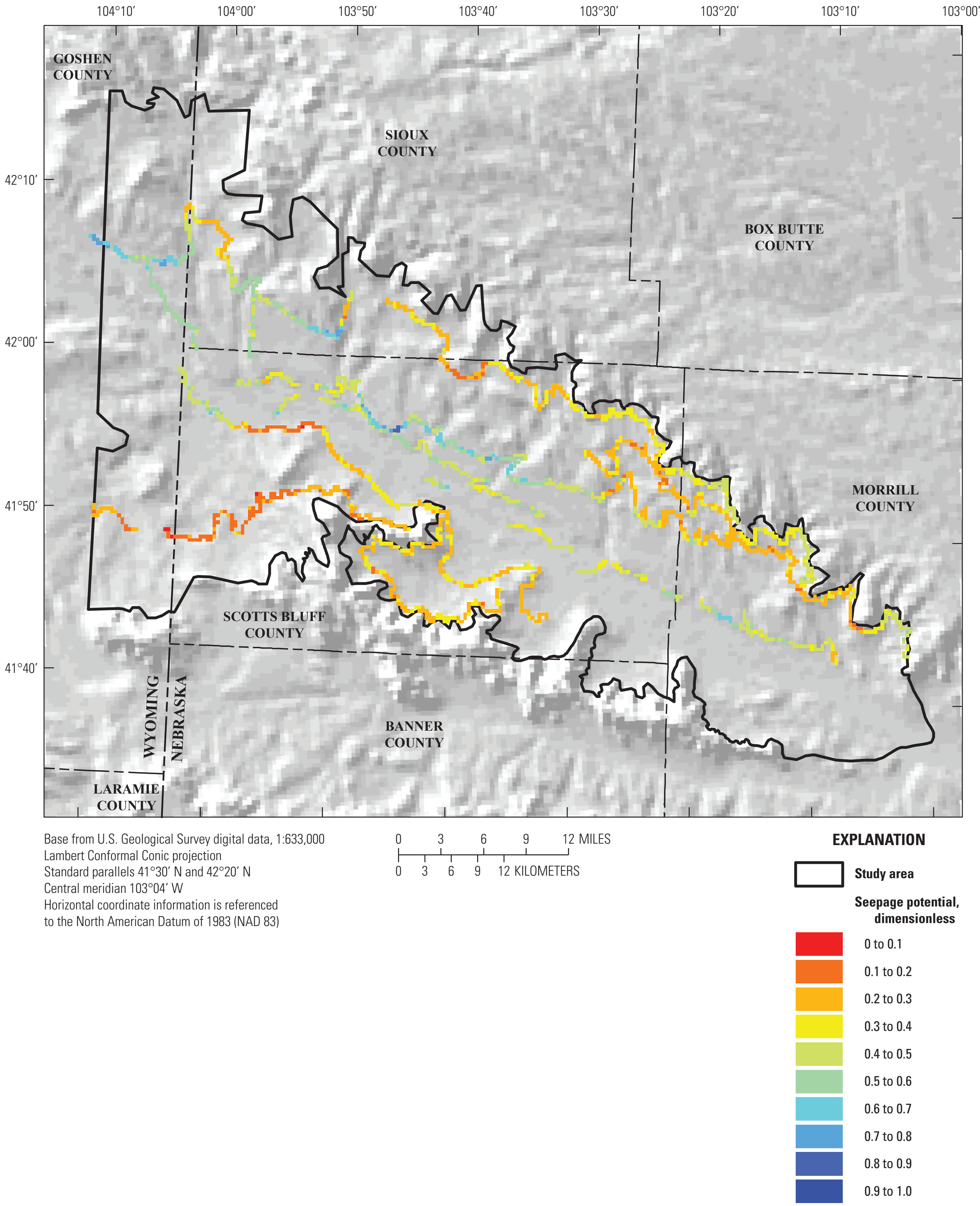

Figure 10. Relative canal seepage-potential estimates computed from inversely modeled OhmMapper resistivity profiles, North Platte River valley, Nebraska and Wyoming, 2004 and 2007–09. Dimensionless units represent fractions of the full range of canal seepage potential within the study area.

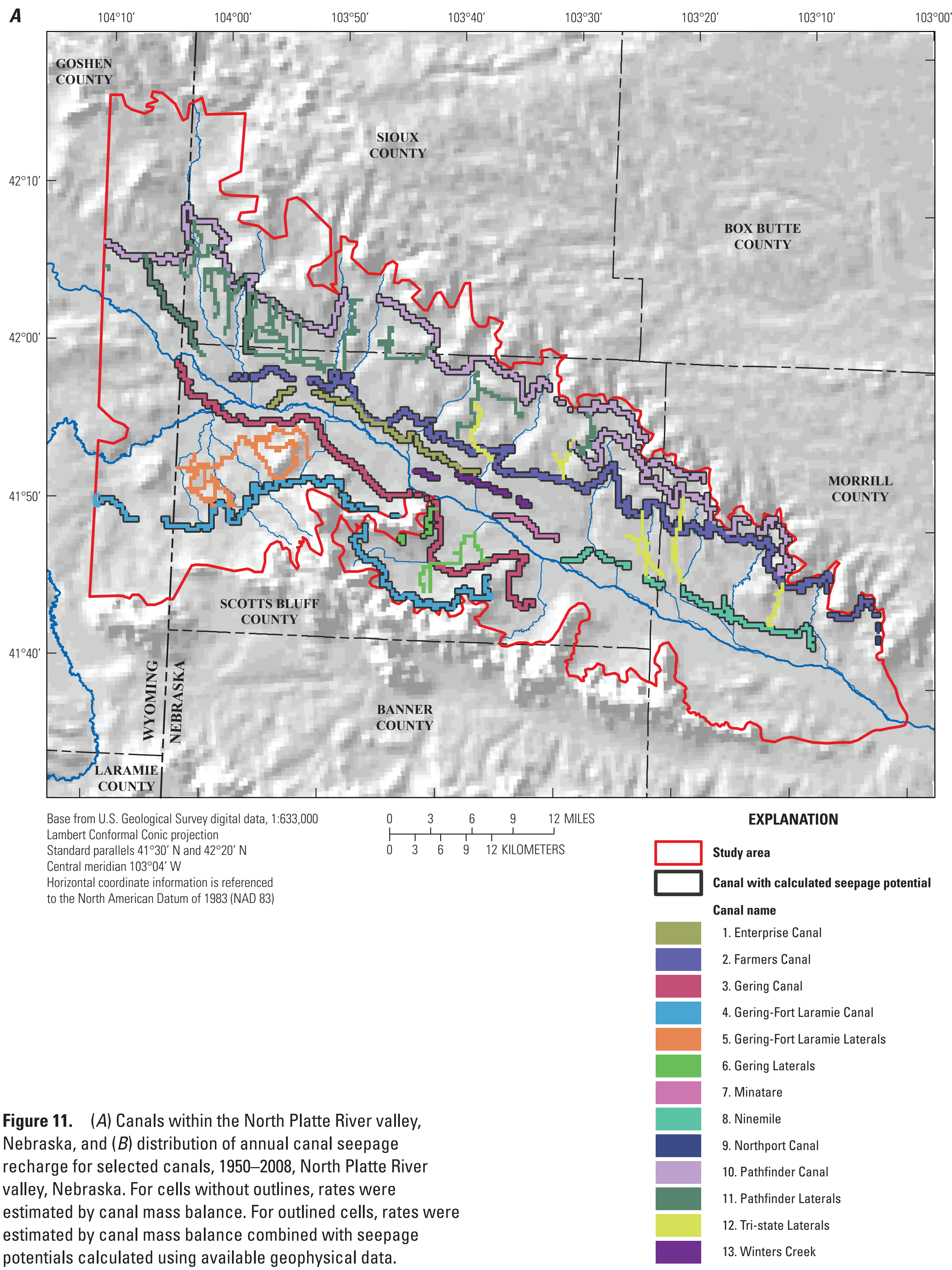

Figure 11. (*A*) Canals within the North Platte River valley, Nebraska, and (*B*) distribution of annual canal seepage recharge for selected canals, 1950–2008, North Platte River valley, Nebraska. For cells without outlines, rates were estimated by canal mass balance. For outlined cells, rates were estimated by canal mass balance combined with seepage potentials calculated using available geophysical data.

B

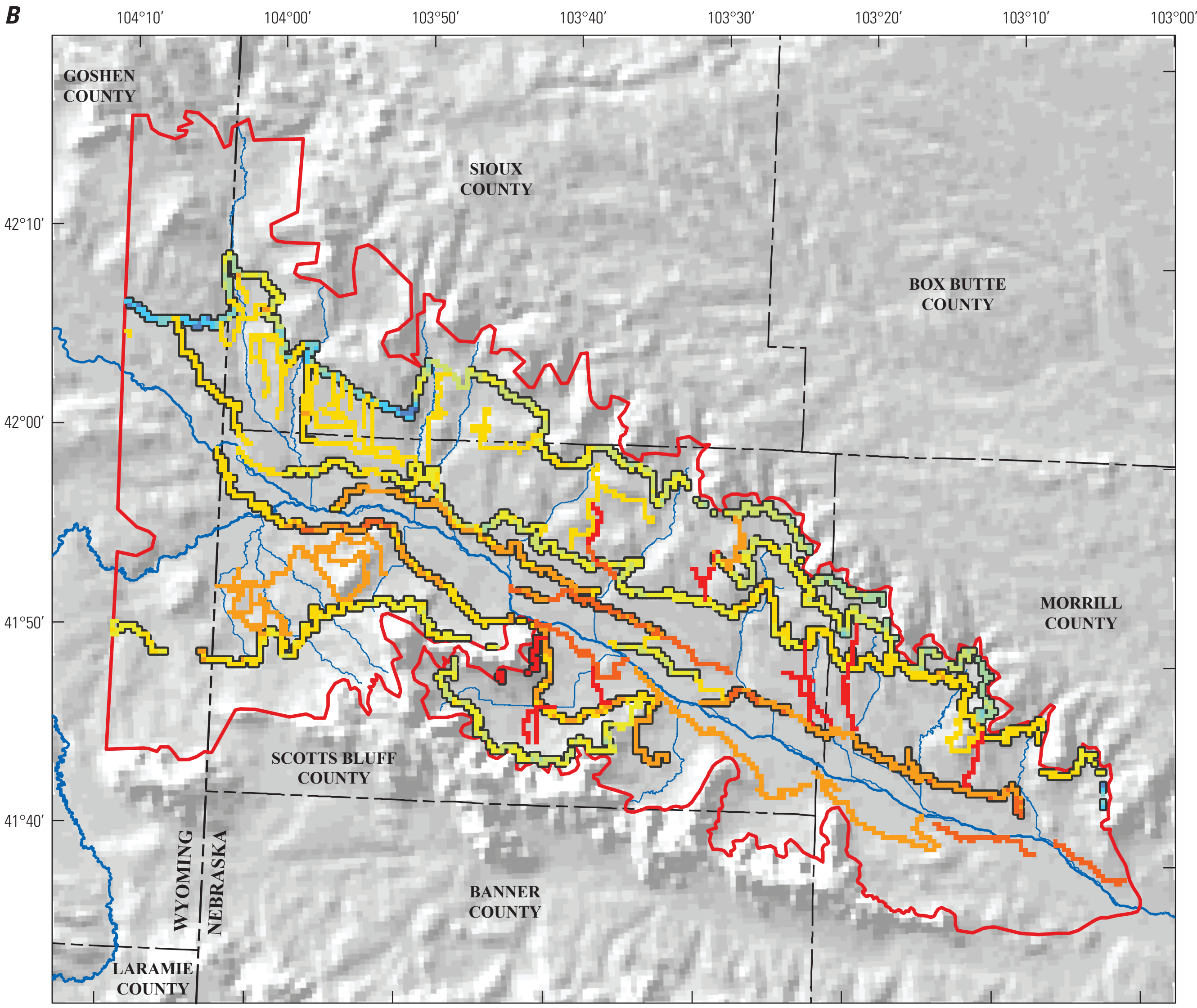

Figure 11. (*A*) Canals within the North Platte River valley, Nebraska, and (*B*) distribution of annual canal seepage recharge for selected canals, 1950–2008, North Platte River valley, Nebraska. For cells without outlines, rates were estimated by canal mass balance. For outlined cells, rates were estimated by canal mass balance combined with seepage potentials calculated using available geophysical data.

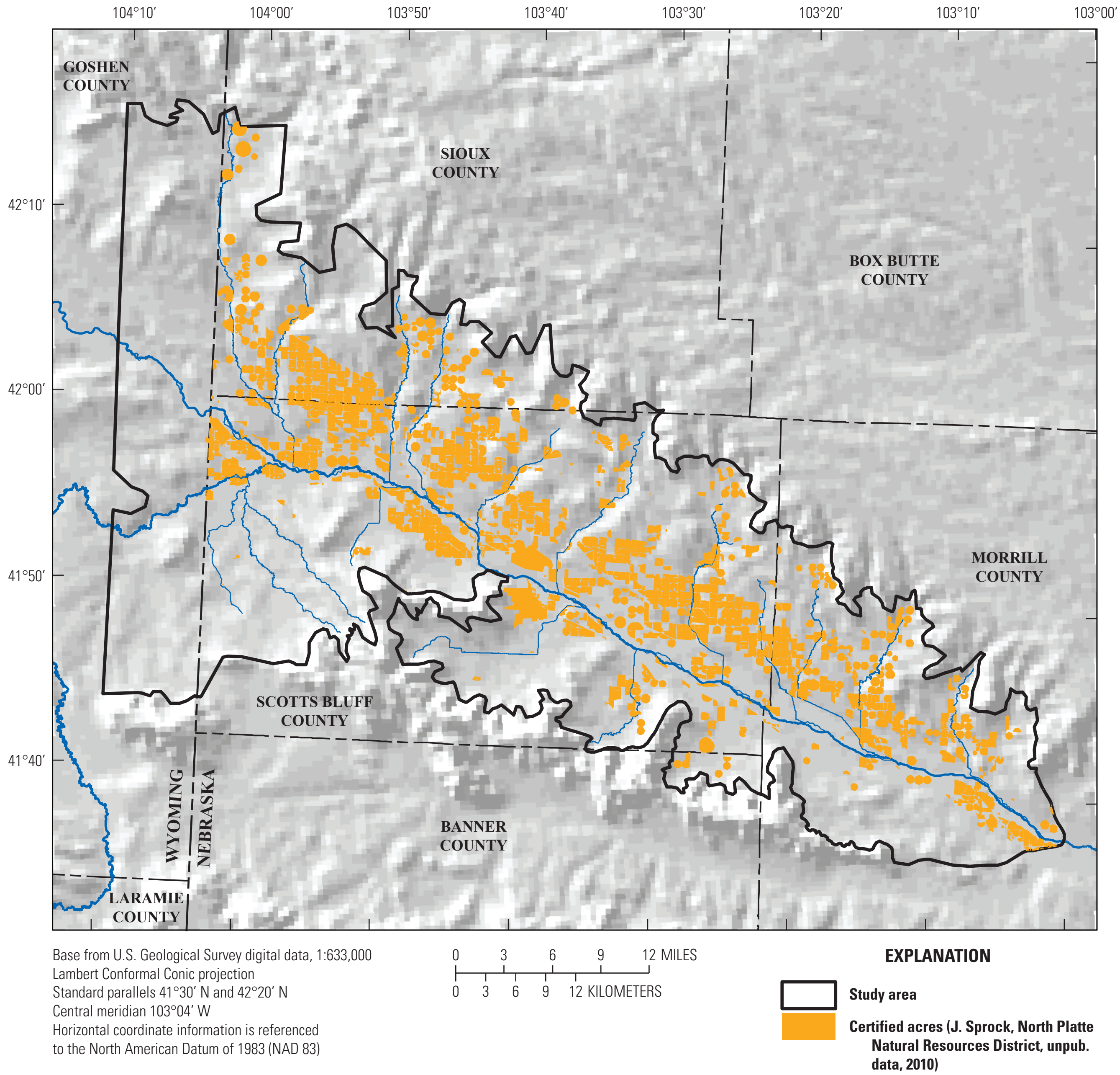

Figure 12. Land certified by North Platte Natural Resources District as irrigated acres, 2008, North Platte River valley, Nebraska.

in the “Conceptual Model of Groundwater Flow“ section of this report, the base of the aquifer was defined by fine-grained sediments of the White River Group. In most areas, the Brule Formation is the topmost unit in the White River Group. The Brule Formation is massive and fractured in areas and, therefore, can yield water to the alluvial aquifer. These areas have been previously mapped for the COHYST study (Cannia and others, 2006). The areas of fractured Brule Formation are not continuous; therefore, the areas were not included as part of the alluvial aquifer in this study. Wells that had screens that started in the alluvial aquifer and penetrated into an area with greater than 50 ft of fractured Brule Formation were included as production wells in the simulation, based on the assumption that withdrawals from these wells amounts to drainage of groundwater stored in fractures in the Brule Formation. The water in the fractures in the Brule Formation is in turn replenished by drainage from the overlying alluvial aquifer; hence, to simulate Brule Formation withdrawals as withdrawals from the alluvial aquifer was assumed reasonable in the simulation. The assumption was made that irrigation wells entirely screened at a depth deeper than the base of the aquifer were irrigating with water from a deeper aquifer not in hydrologic connection with the alluvial aquifer.

The number of irrigation wells increased from 164 registered irrigation wells in 1950 to 1,206 registered irrigation wells in 2008 (Nebraska Department of Natural Resources, 2008). This number is much larger than the 492 wells in the NPNRD certified acres database, but the disparity is likely because some registered wells were not in use during the 2008 acreage certification.

Actual groundwater withdrawals were not recorded at each Actual groundwater withdrawals were not recorded at each well during 1950–2008; therefore, groundwater withdrawals were calculated per well using effective precipitation, crop-irrigation requirement (University of Nebraska, 2002), the amount of water delivered by canal systems, land-cover class, and the total number of acres irrigated by groundwater and by comingled (groundwater and surface-water irrigated) supplies.

Precipitation data were used to determine the effective precipitation, which is the amount of precipitation available for vegetative consumption within each soil type. Soil types within the study area were determined using the hydrologic group information from the Soils Survey Geographic database (Soil Survey Staff, 2004). Each grid cell in the study area was assigned a soil type. Daily precipitation for the area was compiled from the National Climatic Data Center webpages (National Climatic Data Center, 2009). Average precipitation was extracted from the weather-station data for each MODFLOW stress period. Effective precipitation for each stress period was calculated using the curve number method (Cronshey and others, 1986), which used the average precipitation per stress period and soil type.

Groundwater-irrigated land was defined using a dataset supplied by NPNRD in the aforementioned certified-acre database. Specific crop types were assigned using the University of Nebraska-Lincoln (2007) publication of the Center for Advanced Land Management Information Technology’s 2005 land-use dataset. Land cover was classified by spatially joining the certified-acre geospatial dataset to the land-use geospatial dataset. In the event an irrigation parcel was covered by two crop types, the majority crop type was used. If the parcel contained multiple crop types that appeared equal, the parcel was assigned a unique land-cover class for that combination of crops. Each land-cover class was assigned the corresponding crop-irrigation requirement as defined by University of Nebraska (2002). The certified-acre database defined the initial date of groundwater irrigation for each parcel. The assumption was made that the parcel was irrigated annually from that initial date through 2007 and that land-cover class did not change through time. The net irrigation requirement is defined as the amount of water transpired by a given crop, above the amount supplied through natural precipitation; therefore, precipitation must be supplied by irrigation to prevent crop water stress. Net irrigation requirement for each parcel was determined by subtracting the effective precipitation from the crop-irrigation requirement. Any parcel with a positive difference required additional water to satisfy the crop requirement.

The database provided by the NPNRD also defined some parcels as irrigated by comingled supplies, meaning that the parcel received an amount of surface water to satisfy irrigation needs and also was accessible by an irrigation well. Surface-water application rates needed to be determined for comingled-irrigation acres. Surface-water application rates were determined by compiling surface-water records from irrigation districts and the Bureau of Reclamation. The Bureau of Reclamation keeps detailed service records for each irrigation district, including the number of acres in each district, amount of surface-water diverted, and amount of surface-water delivered to lands serviced by the district (J. Lawson, Bureau of Reclamation, written commun., 2011). The total amount of surface-water delivered was divided by the total acres in the district to produce an estimate of the amount of surface-water delivered to each acre. The outline of each irrigation district was determined from geospatial data (R. Kern, Nebraska Department of Natural Resources, unpub. data, 2002). A geospatial overlay analysis of the certified-irrigated-acres map supplied by the NPNRD, included the outlines of the irrigation districts that helped determine the irrigation district associated with each comingled parcel. The amount of surface water delivered to each parcel of the specific irrigation district was then assigned to the corresponding comingled parcel. The groundwater withdrawals for a comingled parcel were calculated by subtracting the surface-water application from the estimated net irrigation requirement. Resulting positive differences are the amounts of groundwater needed to satisfy the net irrigation demand. Comingled-irrigation acreages ranged from 18,200 certified acres in 1950 to 101,300 certified acres in 2008. The average annual 1950–2008 comingled groundwater withdrawal was 3,900 acre-ft/yr; the minimum annual comingled groundwater withdrawal was 130 acre-ft in 1954, and the maximum comingled groundwater withdrawal was 35,100 acre-ft in 2002.

Land parcels that were not defined as comingled-irrigation acres used only groundwater pumped from wells to satisfy the crop demand. The amount of water pumped from each well to provide a parcel of irrigated land was determined by subtracting the effective precipitation from the crop requirement. Groundwater-only irrigated acres ranged from 1,900 certified acres in 1950 to 25,100 certified acres in 2008. The 1950–2008 average annual estimated groundwater withdrawal for groundwater-only irrigated parcels was 9,700 acre-ft/yr. The minimum groundwater-withdrawal was 988 acre-ft in 1951, and the maximum groundwater withdrawal was 27,200 acre-ft in 2007. Average annual groundwater-withdrawals were lower for comingled-irrigation acres than for groundwater-only acres because comingled-irrigation also used water from canal diversions. Total estimated groundwater withdrawals for irrigation and growing season precipitation are shown in figure 13. Groundwater withdrawals for irrigation compensated for infrequent surface-water shortages on comingled-irrigation parcels, and groundwater withdrawals were largest when surface-water supply (as evidenced by seepage) was smallest (fig. 14).

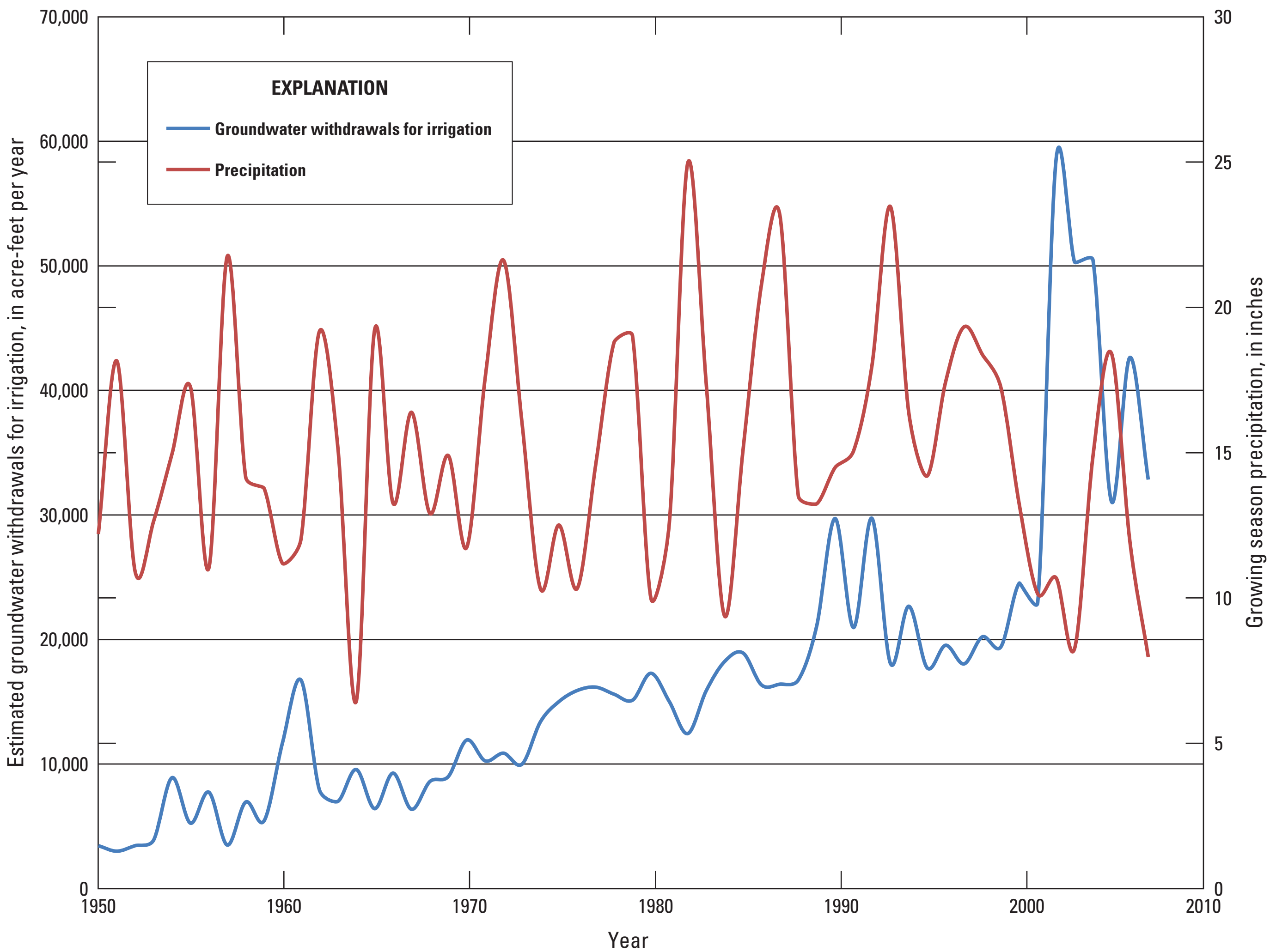

Figure 13. Growing season precipitation and estimated groundwater withdrawals for irrigation, 1950–2008.

Calibration

When a groundwater-flow model is initially constructed, some model inputs, such as the locations of streams or the altitude of the land surface, are reasonably well known; however, some model inputs, such as hydraulic conductivity or recharge, are difficult or impossible to measure directly at the scale of the aquifer or study area and, therefore, must be estimated. As a consequence of imperfect and incomplete information available to characterize aquifers and related hydrology, commonly the initial model outputs do not closely reproduce observed (measured) hydrologic conditions. Calibration is the process whereby model inputs are adjusted to make model outputs more closely match observed hydrologic data. For this study, the parameter estimation suite of software (PEST) was used for model calibration (Doherty, 2010a).

Calibration Approach and Parameters

This section of the report briefly describes the approach to model calibration through use of PEST (Doherty, 2010a) and the parameters that were adjusted to improve model calibration. In general, when groundwater-flow models are constructed, model inputs such as hydraulic conductivity, recharge, and aquifer-base altitudes are either unknown and must be estimated or are partially known and must be interpreted spatially and temporally across the simulation area and through time. Outputs of the model, such as simulated groundwater levels and groundwater discharge to streams (base flow), are then compared against calibration targets—in this case, measured groundwater levels and estimated stream base flows. These data are described in more detail in the “Calibration Targets” section of this report. Usually the initial model

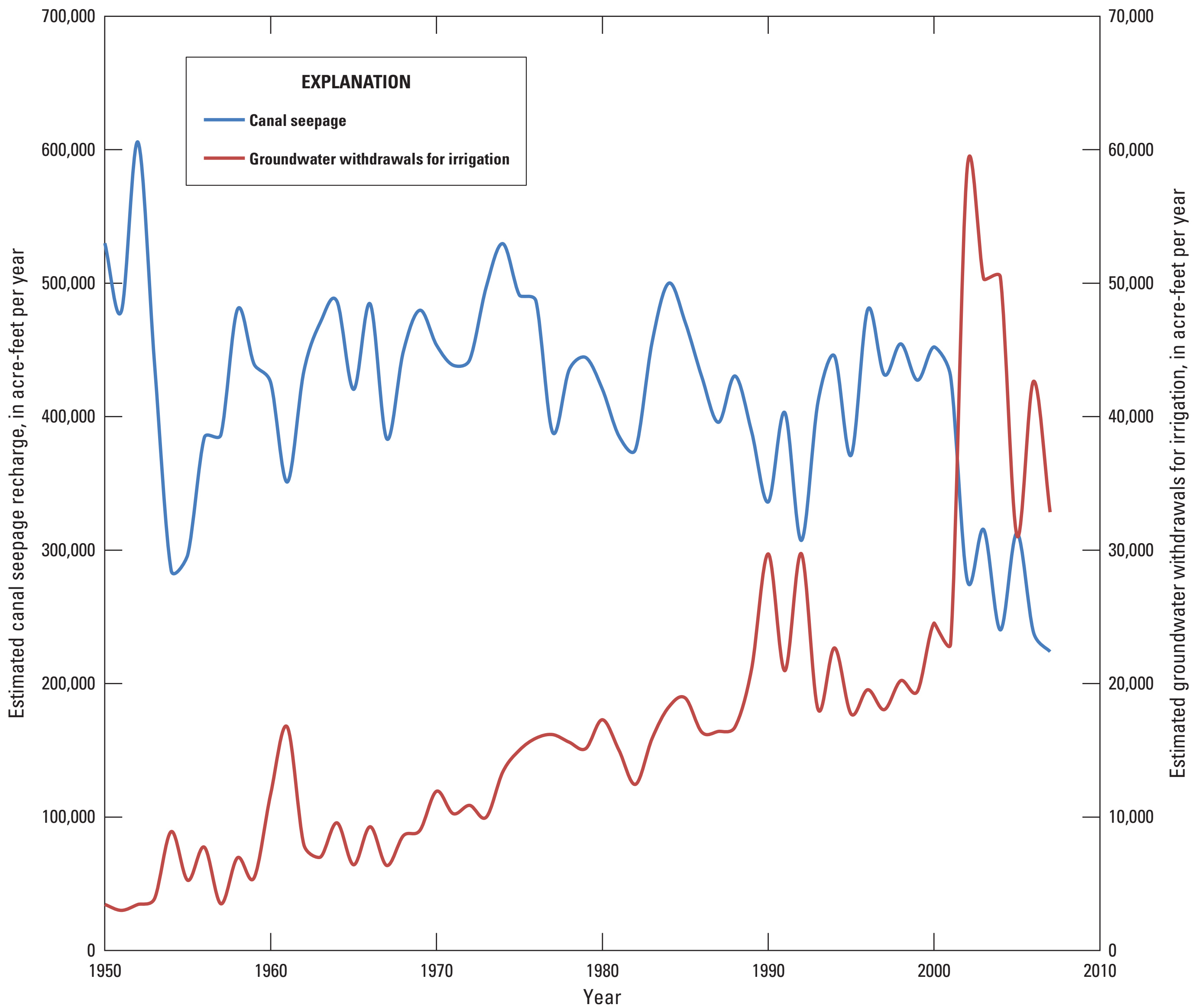

Figure 14. Estimated canal seepage and groundwater withdrawals for irrigation, 1950–2008, North Platte River valley model area, Nebraska.

outputs do not closely reproduce all of the calibration targets and, therefore, the model inputs must be adjusted so that the outputs more closely match the calibration targets. This process is known as “calibration.” Commonly, the model inputs adjusted are inputs that the least is known about or that are the most poorly constrained. Conversely, model inputs that the most is known about are usually fixed after model construction and are not adjusted during calibration.

Prior to calibration using PEST, randomly-selected model inputs from each group described in this section of the report were first individually adjusted to evaluate whether selected PEST files had been prepared correctly. If changes in a model input (written by PEST through template files) caused changes in model outputs (read by PEST through instruction files), that meant that the PEST files had been prepared correctly. Over one-half of the model inputs were tested in this way. All inputs were reset to initial values at the conclusion of this testing. Subsequently, model calibration was approached using statistical techniques through parameter estimation using PEST (Doherty, 2010a). This process generally followed Stanton and others (2010, Appendix 2), with parameters discussed in this section of the report and targets discussed in the “Calibration Targets” section of this report.

The term “parameters” has a special connotation in this report and is defined as model inputs that were potentially adjusted by PEST. Many dozens of model inputs exist, but only a small number (273) were selected as “parameters” for PEST. In general, these parameters consist of the following four groups: horizontal hydraulic conductivity (*K*) estimated at pilot points, spatial multipliers to recharge, temporal multipliers to recharge, and specific recharge parameters for areas where recharge estimated with the SWB model was either particularly low or particularly high.

Spatial Multipliers to Recharge

The canals were split into four different groups, and canal seepage rates were adjusted separately to calibrate the model, with a maximum increase or decrease of 25 percent. The four groups were (1) canals with variable calculated seepage potential rates located on the north side of the river, (2) canals with variable calculated seepage potential rates located on the south side of the river, (3) canals with uniform seepage potential rates on the north side of the river, and (4) canals with uniform seepage potential rates on the south side of the river. Canals on the north side of the river were separated from those on the south side because canals on the south side are generally dug into bedrock; whereas, canals on the north side of the river are generally dug into alluvial sediment (see the "Hydrogeology" section of this report). The canals with calculated seepage potential rates were assigned a variable recharge by cell; whereas, cells that had not been analyzed had little cell-by-cell information, so calculated seepage rates were uniform for those canals (see the "Canal Mass Balance" section of this report). The multiplier used to adjust the canal seepage rates was applied to all time periods of the simulations. Estimation of seepage potential is explained in more detail in the "Estimation of Canal Seepage Potential Using Available Geophysical Data" section of this report.

Horizontal Hydraulic Conductivity Estimated at Pilot Points

Horizontal hydraulic conductivity estimated at pilot points comprised the bulk of the parameters (190 of the 273). Pilot points are defined as locations where *K* is estimated, rather than either estimating individual *K* values for every cell of the groundwater-flow model or using zones of uniform *K*. Pilot point *K* estimates are then spatially interpolated to the model grid, resulting in a smoothly varying *K* field (Doherty, 2003) for every active cell of the groundwater-flow model. The 190 pilot points for this study were generally spaced in a regular grid across the active model area independent of test-hole locations, which are irregularly spaced.

Initial *K* was used from a previous study (Cannia and others, 2006). Cannia and others (2006) estimated hydraulic conductivity at test-hole locations based on lithologic descriptions, and produced estimates at every test hole that should be correct in magnitude relative to each other, though it was not known if the absolute values of the estimates are correct. The point hydraulic conductivity estimates of Cannia and others (2006) were interpolated from the test-hole locations across the entire active model area using inverse-distance weighting. The spacing of these test holes is irregular and nearly always larger than the 1,320-ft spacing used for the model cells. Generally, geologic deposits—including alluvial aquifers such as the one in the study area—can change rapidly across short distances, certainly within the distances between test holes in this study area. Hence the pilot-point network for this parameter estimation was designed using a regular-grid approach.

Individual pilot-point locations were adjusted slightly for a few cases where the pilot point was placed too near the edge of the active model. Pilot points too near the edge of the model could have resulted in incorrect model responses to changes in the *K* estimates and instability during automated calibration. The initial values of *K* at the pilot points were set to the values interpolated from the test-hole estimates. Tikhonov regularization was used to provide prior information (Doherty, 2010b) and impose a penalty if the *K* estimated at the pilot points deviated from the preferred condition of the initial *K* estimate. Imposing this penalty prevented model over-fitting and, further, honored the initial values that were expected to be relatively correct but are known to be incomplete. More detailed explanations of this approach are described by Hunt and others (2007), Doherty (2003), and Fienen and others (2009).

Temporal Multipliers to Recharge

Temporal multipliers to recharge were used to adjust recharge estimated with the Soil-Water-Balance Model for the 77 stress periods of the 1950–2008 model (77 of the 273 parameters). Recharge and multipliers for 1950–54 were also used to generate the recharge applied to the pre-1950 model and thereby the multipliers for 1950–54 affected the pre-1950 and 1950–2008 models.

Specific Recharge Parameters

The remaining two parameters were recharge values input to the simulation for areas where the recharge estimated with the SWB model was either particularly low (less than 0.25 in/yr) or particularly high (greater than 5 in/yr).

Calibration Targets

The measured or estimated hydrologic data used in model calibration are frequently referred to as "calibration targets," as will be used in this report. The two types of calibration targets used for this study were estimated base-flow targets and groundwater-level targets. Each calibration target was weighted to affect the calibration process. All target weights were calculated using error-based weighting (Hill and Tiedeman, 2007) that used a 95-percent confidence interval and expected errors of as much as 5 ft for groundwater levels and 10 percent for estimated base flows, except where otherwise noted.

Groundwater-Level Targets

The data for groundwater-level targets were retrieved either from the NWIS database (U.S. Geological Survey, 2012) or from water-level records collected and provided by the NPNRD (Jackie Bishop, North Platte Natural Resources District, written commun., 2008). Not many water-level records coincided closely with April 1950 (the end of the pre-1950 model), so additional targets through 1955 were included, assuming that those water levels would still adequately represent the period before major groundwater development. All measured water levels within the study area were considered to be used as a calibration target if sufficient information indicated that the well was screened in the alluvial aquifer. Wells were eliminated from consideration based on proximity to each other and based on their period of record. If a well was located within 3,280 ft of another well, the records of the two wells were compared, and the well that had the longer period of record was retained to be used as a water-level target. The water-level altitudes used as calibration targets were determined by subtracting the recorded water-level depth from the DEM-derived altitude (U.S. Geological Survey and Nebraska Department of Natural Resources, 1998) at the location. The well altitude recorded in each database was compared to the DEM altitude to help determine if any well locations were recorded incorrectly, by comparing the reported well altitude to the sampled DEM altitude at the well location. The well altitude was subtracted from the DEM altitude. If the difference was greater than 5 ft, the authors further reviewed the records to determine if the well was not located correctly, or if locally steep slopes could have caused an inaccurate DEM altitude estimate. Wells were discarded if the altitude could not be verified. Other water levels were considered suspect (that is, the targets were based on a possibly erroneous altitude) and were given a weight of zero. Wells within half a mile of the model boundary were not used to prevent interpolation artifacts from causing misleading results. This process resulted in 126 water-level targets used for calibration of the pre-1950 model and 5,101 water-level targets used for calibration for the 1950–2008 model. The total number of water-level targets per stress period for the 1950–2008 model ranged from 1 in stress periods 5 and 8 to 225 in stress period 76; during 1950–2008, the number of water-level targets generally increased. Water-level targets for the pre-1950 model were associated with a 10-ft expected error range because of the wider temporal range of measurements used as water-level targets (actual groundwater level is within plus or minus 5 ft of recorded groundwater level), resulting in a lower weight than water-level targets for the 1950–2008 model.

Base-Flow Targets

Streamflow at a given point consists of base flow and runoff. Base flow is the amount of water that is discharged to a stream from groundwater, and runoff is the water contributed to the stream from precipitation and return flows from irrigation. Base flow for the pre-1950 model was estimated using the base-flow index (BFI) method (Wahl and Wahl, 2007). Daily streamflow data were compiled from the USGS National Water Information System (NWIS; U.S. Geological Survey, 2012) and the Nebraska Department of Natural Resources (2013). Average estimated base flow for April 1950 was selected as the pre-1950 base-flow target. April 1950 was considered a time of equilibrium after surface-water irrigation had been in place for several decades but before widespread groundwater withdrawals for irrigation began. In addition, most canals do not divert water during April, so the base-flow separation should be relatively free from the effects of canal diversions. The flow targets are those reported for selected streamgage locations within the study area. This process resulted in 13 pre-1950 base-flow targets, of which 4 were for the North Platte River and 9 were for tributaries.

Base-flow targets for the 1950–2008 model also were determined using the BFI method. The target locations are the same as the pre-1950 model target locations. The average April estimated base flow for the respective year was used as the base-flow target. Average April estimated base flows were used because those base-flow values generally were free of the effects of early spring lowland snowmelt runoff, the effects of vegetative transpiration of stream water, and the effects of canal diversions. The 1950–2008 model base-flow targets and the calibrated simulated base-flow results are summarized in table 2 and discussed in the “Calibration Results” section of this report. Because of the importance of the calibration of estimated base-flow for analysis with the simulation-optimization model, the base-flow target weights were doubled for streamgages along the North Platte River.

Some streams did not have streamgages during 1950–2008, so a base flow target could not be estimated (table 3). Simulated stream base flow was also tracked for some streams that do not have streamgages to gain a better understanding of the flow system. Additionally, not all streamgages in the study area had a continuous record. Calibration targets corresponding to streams without a streamgage in the study area and to time periods without streamflow records were assigned a calibration weight of zero. Base-flow targets with a weight of zero did not affect the calibration process, but the simulated discharges from those streams were reviewed to ensure consistency with the conceptual model.

Calibration Results

The closeness of fit of simulated base flow and groundwater levels to estimated base-flow and measured groundwater-level targets indicates how closely the simulation reproduced historical conditions. Differences between simulated results and calibration targets are referred to as residuals and were calculated as the target (measured or estimated) value minus the simulated value. Therefore, when the target value is larger than the simulated value (underestimation), the residual has a positive sign, and when the simulated value is larger than the target value (overestimation), the residual has a negative sign. The mean residual, the mean absolute residual, and the root-mean-squared (RMS) residual were calculated for all water-level targets and also for subsets representing specific time periods of the pre-1950 model and the 1950–2008 model. The mean residual was calculated as the sum of residuals of each group. The mean absolute residual was calculated as the sum of the absolute value of the residuals of each group. The RMS residual was calculated as:

Table 2. Summary of estimated base flows used as calibration targets for the 1950–2008 model.

Streamgage	Streamgage number	Estimated base flow (cubic feet per second)			Number of estimated values averaged	Simulated base flow (cubic feet per second)			Average residual (cubic feet per second)	Average percent difference
		Minimum	Maximum	Average		Minimum	Maximum	Average		
North Platte River at Nebraska-Wyoming State line	06674500	3	3,885	557	58	46	3,069	355	202	77
Horse Creek near Lyman, Nebraska	06677500	4	186	27	58	21	44	35	-8	-58
Sheep Creek near Morrill, Nebraska	06678000	2	81	58	58	45	114	78	-20	-32
Dry Spottedtail Creek at Mitchell, Nebraska	06679000	11	58	22	43	13	42	28	-6	-26
North Platte River at Mitchell, Nebraska	06679500	164	4,893	751	58	164	3,268	556	195	27
Tub Springs Drain near Scottsbluff, Nebraska	06680000	0	33	23	57	12	34	25	-4	-8
Winters Creek near Scottsbluff, Nebraska	06681000	21	47	37	58	10	35	26	11	34
Gering Drain near Gering, Nebraska	06681500	11	33	22	58	15	47	37	-15	-52
North Platte River near Minatare, Nebraska	06682000	277	4,893	865	58	249	3,431	730	136	13
Ninemile Creek near McGrew, Nebraska	06682500	11	84	59	58	29	69	51	8	8
Bayard Drain near Bayard, Nebraska	06683000	0	22	9	58	10	17	13	-3	-58
Red Willow Creek near Bayard, Nebraska	06684000	17	63	47	58	29	74	53	-6	-15
North Platte River at Bridgeport, Nebraska	06684500	340	4,900	1,100	58	338	3,546	868	215	15

$$RMS = \left[\frac{1}{n} \sum_{i=1}^{n} \left(h_m - h_s \right)_i^2 \right]^{0.5} \quad (2)$$

where

n is the number of measurements,

h_m is the measured groundwater level, and

h_s is the simulated groundwater level (Anderson and Woessner, 1992).

The mean residual was calculated for the base-flow targets; however, mean residuals across targets of different sizes is not meaningful, and base-flow targets range in size from less than 10 to 1,100 ft^3/s from the smallest streams to the largest in the study area. An average of the percentage difference between simulated base-flow and base-flow targets for each streamgage location was calculated as:

$$Average\ percent\ difference = \sum_{1}^{n} \left(\frac{BFE - BFS}{\left(BFE + BFS \right) / 2} *100 \right) / n \quad (3)$$

where

n is the number of targets,

BFE is the estimated base flow, and

BFS is the simulated base flow.

Groundwater Levels

Comparisons of plotted measured groundwater-level targets and simulated groundwater levels for the end of the pre-1950 model are shown in figure 15. Also, figure 15 shows a 1:1 line; if all simulated groundwater levels perfectly matched groundwater-level targets, all points would have lain on the 1:1 line. Generally, the points in figure 15 are spaced equally small distances above and below the 1:1 line, demonstrating that although the levels did not perfectly match, simulated groundwater levels were equally balanced above and below groundwater-level targets. Only for groundwater level targets below about 3,850 ft altitude, simulated water levels tended to be near the line but slightly above the groundwater-level targets, as evidenced by their position slightly above the 1:1 line. The mean residual for the pre-1950 model water levels was -2.3 ft, with a range from -66 ft to 92 ft. The negative value for the mean residual indicates that on average the simulated groundwater levels are slightly higher than measured groundwater levels. The mean absolute April 1950 groundwater-level residual was 13.9 ft, and the RMS residual was 21.1 ft. The April 1950 simulated groundwater levels were within 25 ft of the measured groundwater levels for 108 of the 126 measured groundwater levels (86 percent). The simulated groundwater level for April 1950 (end of the pre-1950 model) was within 50 ft of the measured groundwater level for 120 of the targets (95 percent). The wells with extremely high or extremely low residuals were not spatially concentrated (fig. 16), that is, simulated water levels were not biased particularly high or low in any region of the study area. Fewer groundwater-level targets are south of the North Platte River than north of the river, but evaluation of chi-squared statistics used to test for independence (Helsel and Hirsch, 2002) indicated that there is likely no correlation between residuals being negative or positive north of the river compared to south of the river. Similarly, correlation is unlikely between residuals either north or south of the river being the largest or smallest 10 percent of the residuals.

Measured groundwater levels (targets) and simulated groundwater levels for the 1950–2008 model are compared in figure 17. Also, figure 17 shows a 1:1 line; if all simulated groundwater levels perfectly matched groundwater-level targets, all points would have lain on the 1:1 line. Generally, the points in figure 17 are spaced equally small distances above and below the 1:1 line, demonstrating that although the points did not perfectly match, simulated groundwater levels were equally balanced above and below groundwater-level targets. Only for groundwater level targets below about 3,850 ft altitude, simulated water levels tended to be near the line but slightly above the groundwater-level targets, as evidenced by their position slightly above the 1:1 line. The simulated groundwater level was within 25 ft of the measured groundwater level for 4,788 of the 5,101 targets (94 percent). The simulated groundwater level was within 50 ft of the target at 5,039 targets (99 percent). For the 1950–2008 model, the mean residual for the water levels was -5.7 ft with a range from -108 to 140 ft. The mean absolute groundwater-level residual was 10.5 ft, and the RMS residual was 15.1 ft. The wells with extremely high or extremely low residuals were not spatially concentrated (fig. 18), that is, for the 1950–2008 model simulated water levels were not particularly biased beyond the local scale.

Table 3. Summary of simulated base flows for streams without streamgages within the study area, for the 1950–2008 model.

Stream name	Simulated base flow (cubic feet per second)		
	Minimum	Maximum	Average
Dry Creek	5	10	8
Dry Sheep Creek	1	18	9
Indian Creek	2	11	6
Kiowa Creek	4	9	7
Melbeta Drain	0	3	1
Owl Creek	20	38	31
Spottedtail Creek	42	65	56
Wildhorse Drain	13	31	23
Unnamed tributary in Browns Canyon	0	6	2

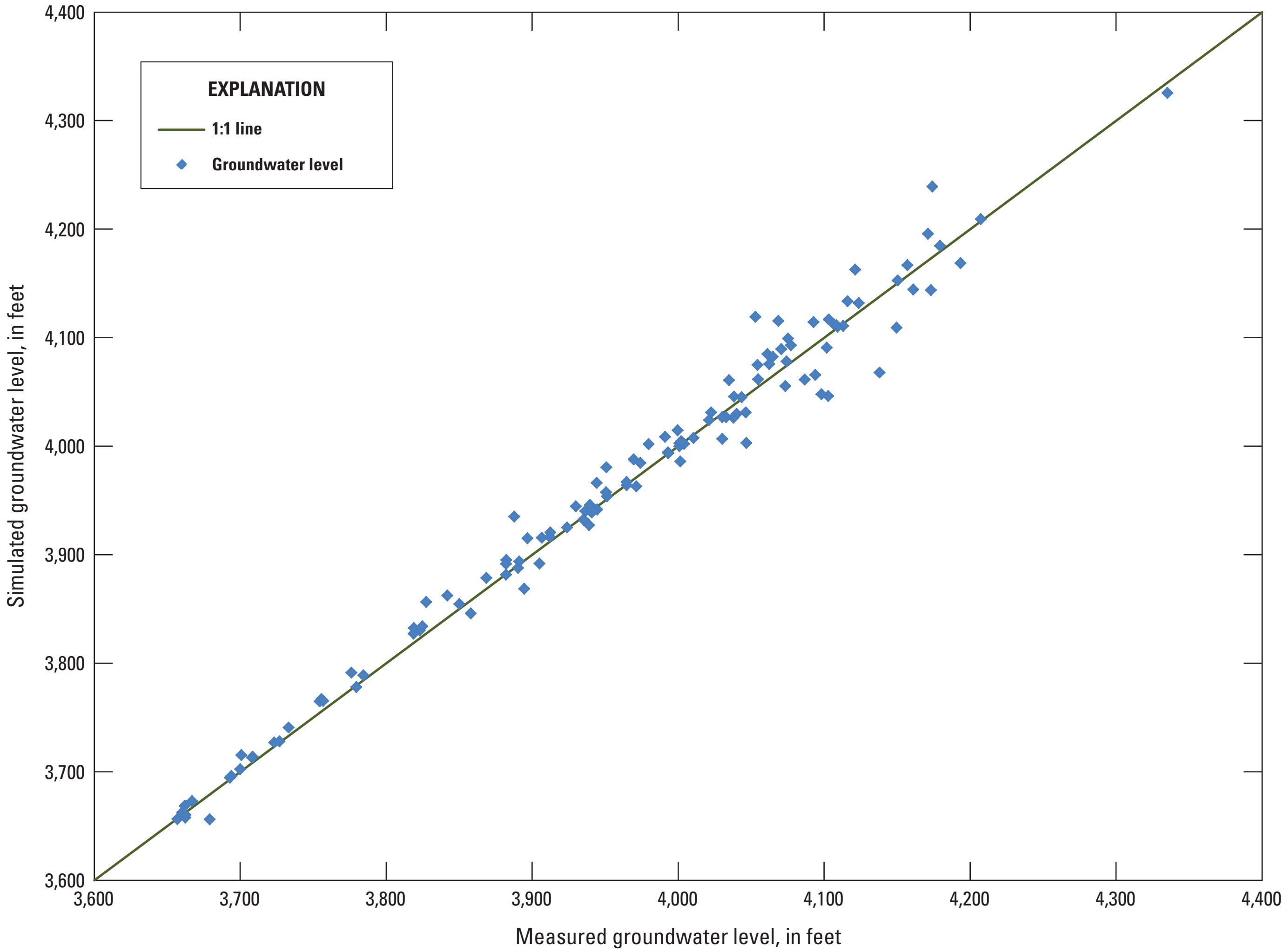

Figure 15. Relation of pre-1950 model simulated groundwater levels, April 1950, to measured groundwater levels used as calibration targets, 1945–55.

Base Flows

For the pre-1950 model, simulated base flows were about the same as estimated base flows. For the four North Platte River streamgages, the mean residual base flow was 41 ft^3/s with a range from -32 ft^3/s to 94 ft^3/s. For the nine tributary streamgages, the mean residual baseflow was 7 ft^3/s with a range from -25 ft^3/s to 11 ft^3/s.

The 1950–2008 model simulated base flows followed the overall trend of the estimated base flows reasonably well (increasing or decreasing base flow from the start of the simulation to the end), though simulations indicate some deviations for individual years. The spikes in the streamgage hydrographs along the North Platte River were caused by large reservoir release events in Wyoming, upstream from the study area (figs. 19A and 19B). Although these reservoir releases usually were not during April and, thus, did not affect the base-flow separation used for calibration target data, for a few years the reservoir releases were earlier than normal, and base-flow separation approaches are generally not able to distinguish those reservoir releases from steady groundwater discharge into the stream.

Overall, average 1950–2008 simulated base flow was about 185 ft^3/s lower than estimated base flow for the four North Platte River streamgages in the study area (table 2). However, because the estimated base flow of the North Platte River approximately doubles from the upstream end of the study area to the downstream end, the percentage difference between estimated and simulated base flow is much smaller at the downstream end (15 percent) as opposed to the upper end (77 percent). Measurement error at streamgages commonly ranges from 5 to 8 percent or greater (Rantz and others, 1982) and base-flow separation probably has at least that much uncertainty; therefore, the authors considered the difference between estimated and simulated base flow at the downstream end of the study area to be approaching the aggregate uncertainty of streamflow measurement and base-flow estimation. Simulated base flow was less than the estimated base flow for the North Platte River at the Nebraska-Wyoming

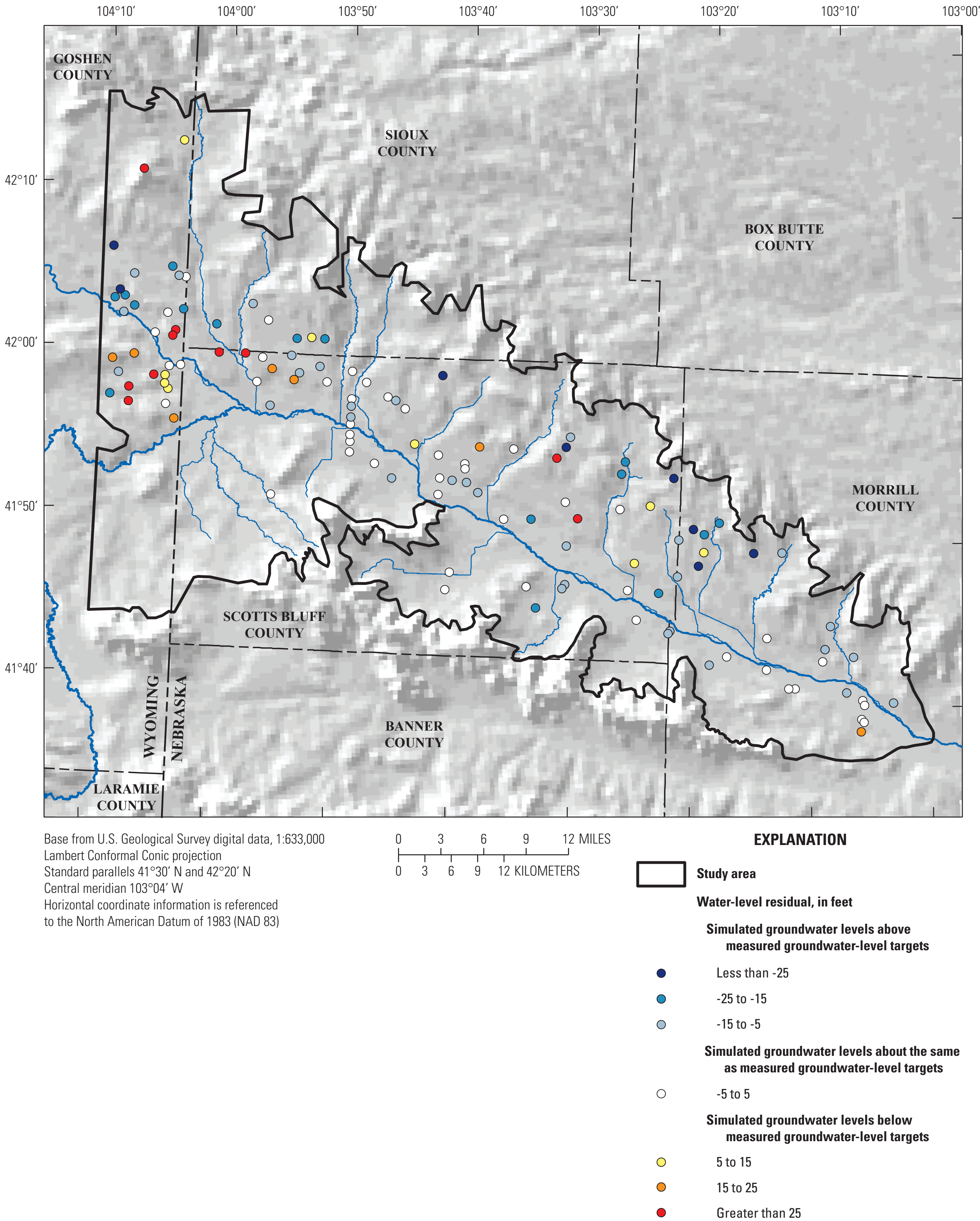

Figure 16. Spatial distribution of calibration residuals for simulated groundwater level, April 1950, end of the pre-1950 model.

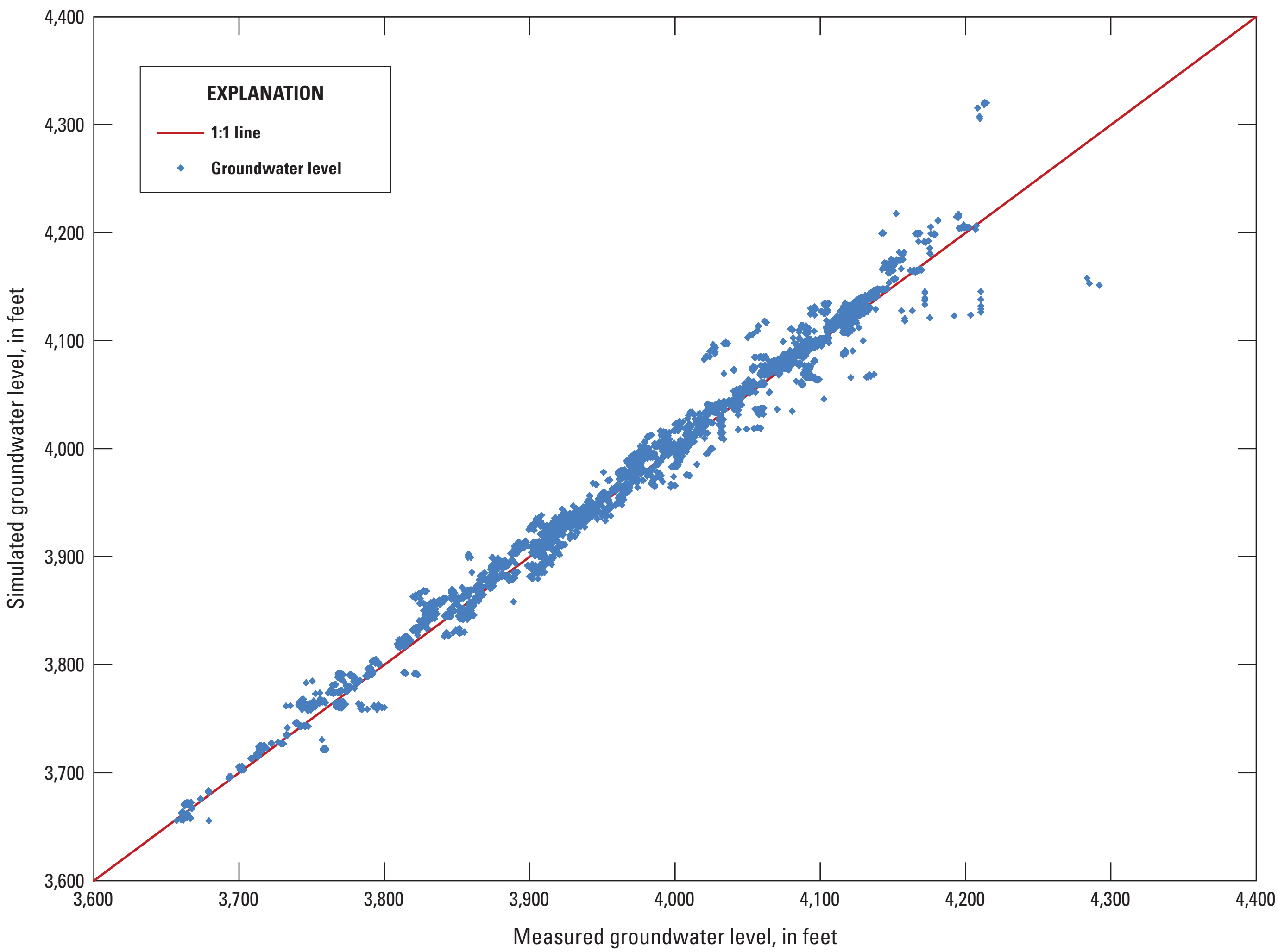

Figure 17. Relation of simulated groundwater levels to measured groundwater levels used as calibration targets for the 1950–2008 model.

State-line streamgage (77 percent difference, table 2) but indicated generally the same trend (fig. 19*A*). Simulated base flow matched estimated base flow more closely (15 percent difference, table 2) for the North Platte River at Bridgeport, Nebr., streamgage, the focus of the optimization scenarios (fig. 19*B*, table 2). Simulated base flow for most tributaries closely matched estimated base flow for many time periods, as demonstrated by Tub Springs Drain (-8 percent difference, table 2; fig. 19*C*) and Red Willow Creek (-15 percent difference, table 2; fig. 19*D*). The two streams that simulated base flow matched estimated base flow less closely are Winters Creek (34 percent difference, table 2; fig. 19*E*) and Gering Drain (-52 percent difference, table 2; fig. 19*F*). Winters Creek simulated base flow was about 11 ft^3/s less than estimated base flow at the beginning of the simulation period, and though the simulated base flow had the correct temporal trends, simulated base flow remained about 11 ft^3/s lower than estimated base flow for the duration of the simulation. Gering Drain simulated base flow was about 15 ft^3/s more than the calibration target at the beginning of the simulation and roughly approximated the correct temporal trend of estimated base flow, though the simulated base flow remained too high until the last stress period of the simulation. The simulated base flows for streams in the study area that did not have streamgages are listed in table 3. Though no measured data were available to compare to the simulated flows, the simulated flows were generally smaller than the gaged streamflows in the area and are considered reasonable until data are available or collected to indicate otherwise.

Calibrated Parameters

As described in the "Calibration Approach and Parameters" section of this report, initial parameter values are adjusted manually and through automated parameter estimation using PEST (Doherty, 2010a) so that the outputs more

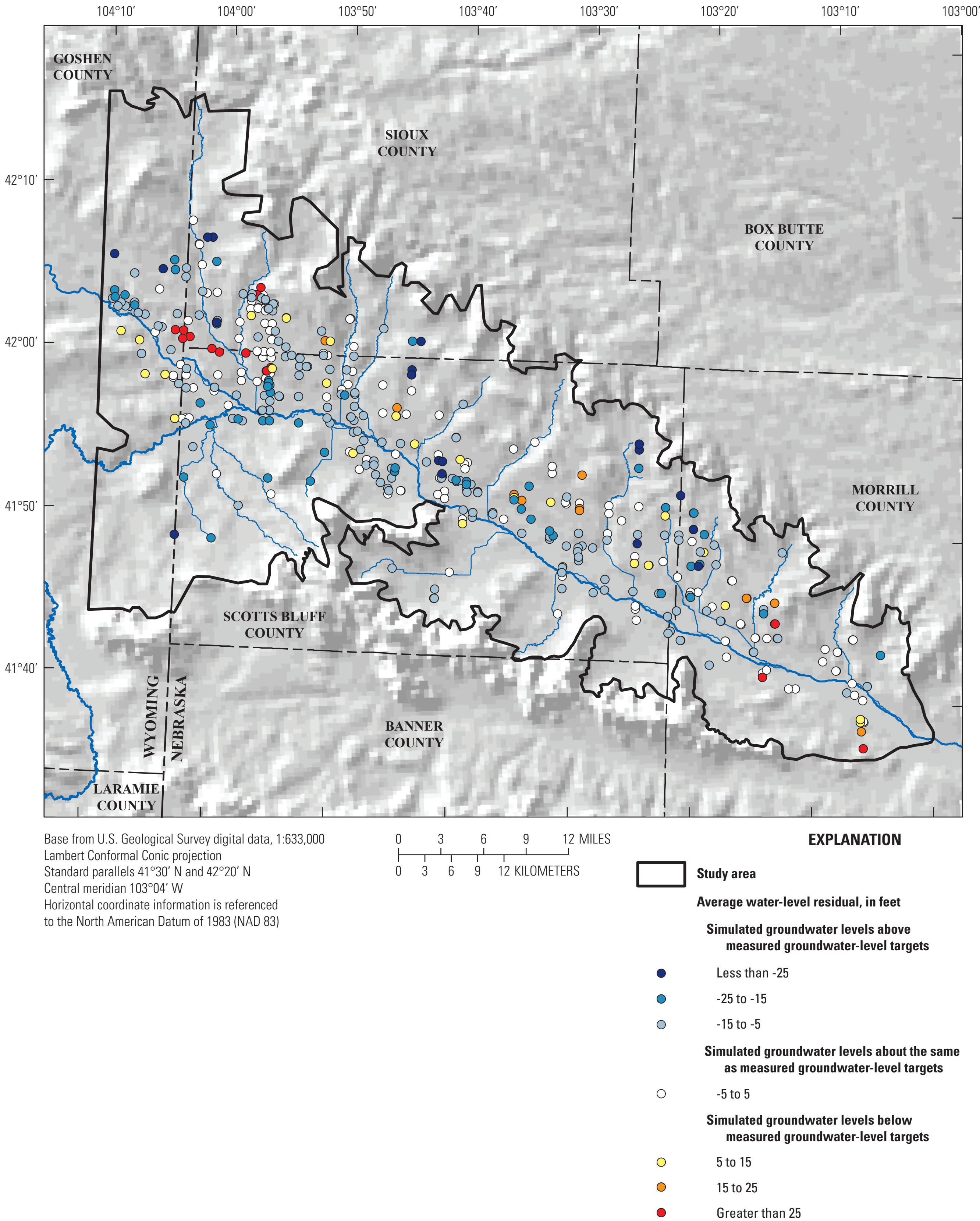

Figure 18. Spatial distribution of average calibration residuals for simulated water level for the 1950–2008 model.

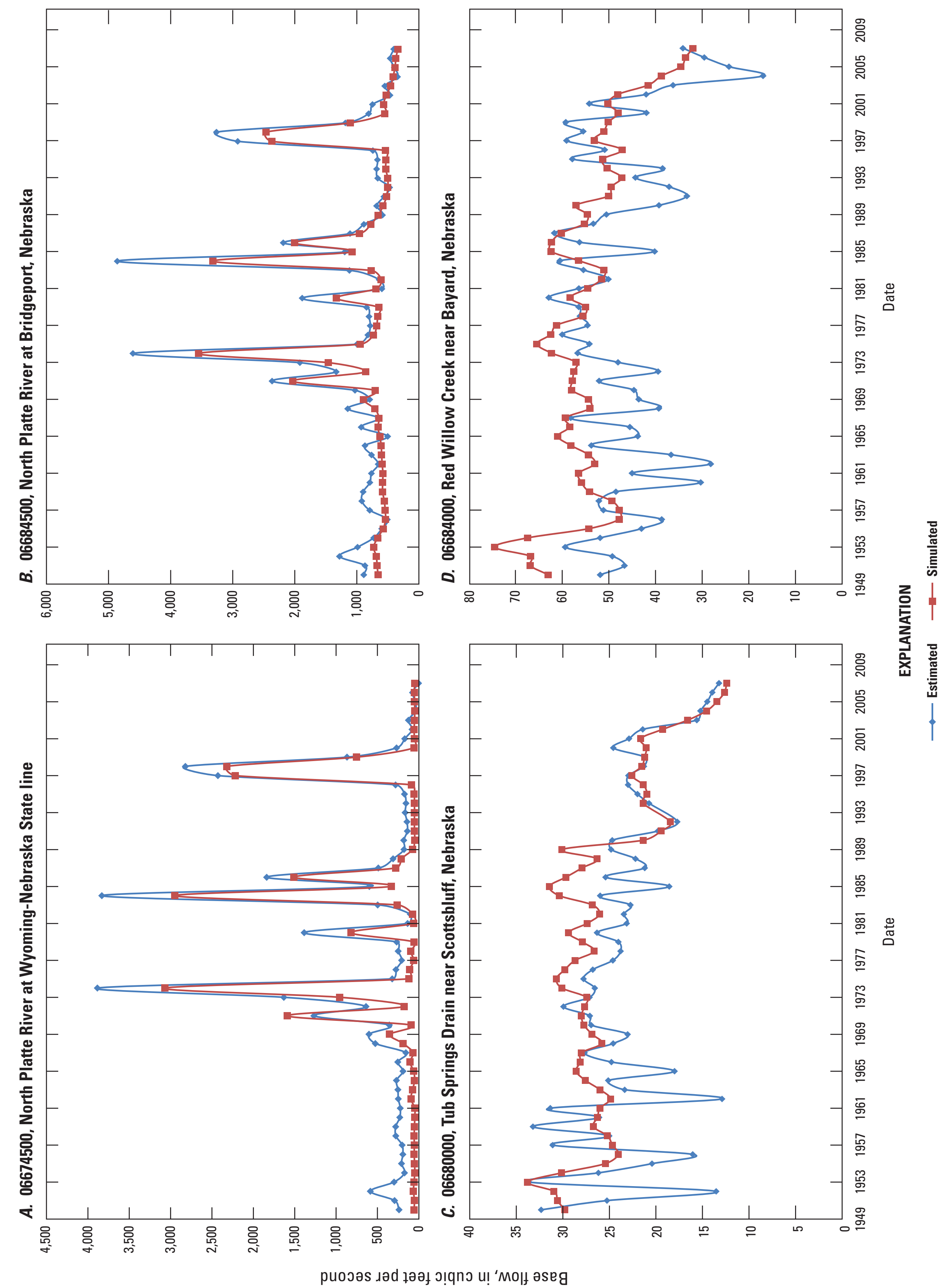

Figure 19. Simulated and estimated base flow for (*A*) North Platte River at Wyoming-Nebraska State line; (*B*) North Platte River at Bridgeport, Nebraska; (*C*) Tub Springs Drain near Scottsbluff, Nebraska; (*D*) Red Willow Creek near Bayard, Nebraska; (*E*) Winters Creek near Scottsbluff, Nebraska; and (*F*) Gering Drain near Gering, Nebraska.

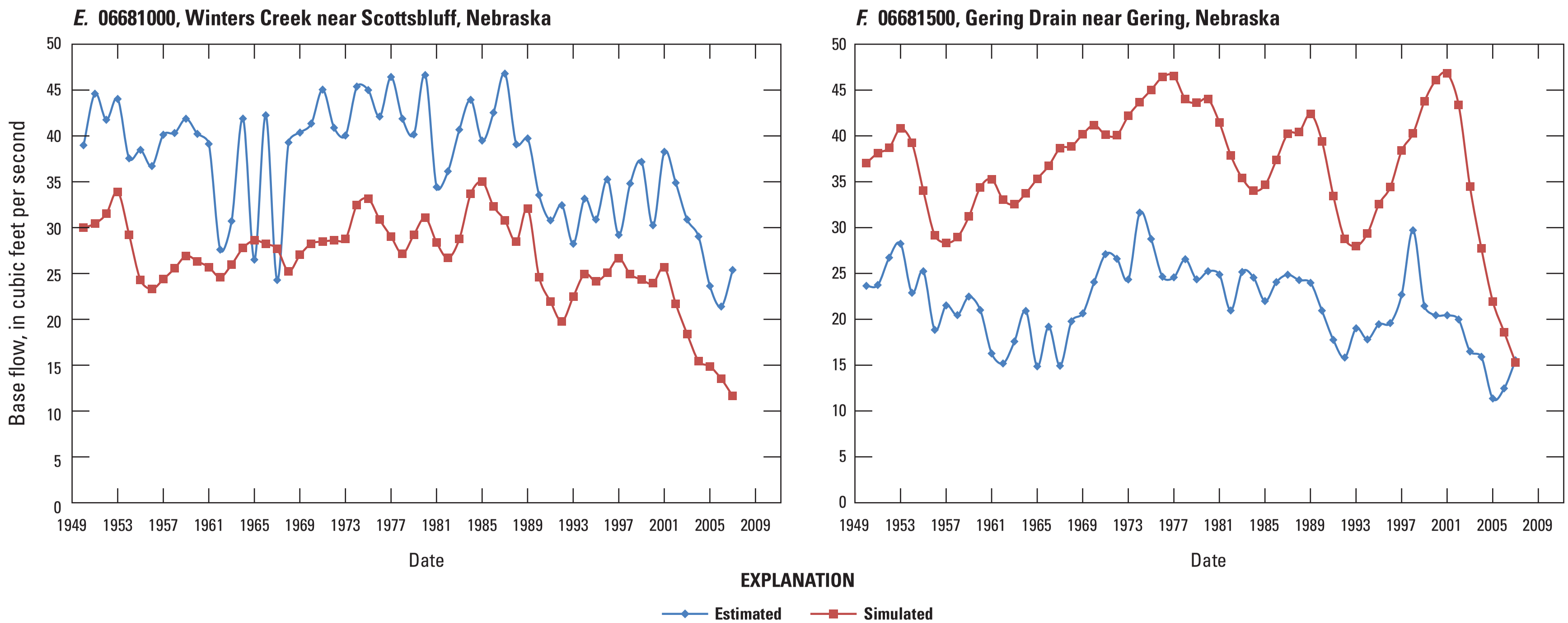

Figure 19. Simulated and estimated base flow for (*A*) North Platte River at Wyoming-Nebraska State line; (*B*) North Platte River at Bridgeport, Nebraska; (*C*) Tub Springs Drain near Scottsbluff, Nebraska; (*D*) Red Willow Creek near Bayard, Nebraska; (*E*) Winters Creek near Scottsbluff, Nebraska; and (*F*) Gering Drain near Gering, Nebraska.—Continued

closely match the calibration targets. Calibrated parameter values were inspected for gross errors or anomalous values that would indicate that the conceptual model had been violated or that some part of the automated parameter estimation process using PEST had produced erroneous results.

Spatial Multipliers to Recharge

Multiplier parameters applied to canal seepage recharge rates to improve model calibration were intended to account for imprecision or inaccuracy in canal seepage estimates and to correct for this imperfect knowledge of the system. The calibrated multiplier parameter for the canals with calculated seepage potential on the north side of the river was 0.96, or a decrease of 4 percent; and the calibrated multiplier for the canals with calculated seepage potential on the south side of the river was 0.80, or a decrease of 20 percent. The calibrated multiplier for the canals without calculated seepage potential on the north side of the river was 0.98, or a decrease of 2 percent; and the calibrated multiplier for the canals without calculated seepage potential on the south side of the river was 0.96, or a decrease of 4 percent. The calibrated multipliers, mainly at small deviations from unity, are considered reasonable, and even the largest adjustment of a decrease of 20 percent was within the uncertainty range of the canal flow data. The average calibrated canal seepage recharge rate is shown in figure 20.

Horizontal Hydraulic Conductivity Estimated at Pilot Points

PEST was allowed to decrease or increase hydraulic conductivity at the pilot points for calibration of the simulation. In three locations (purple rectangles on fig. 21), calibrated hydraulic conductivity reached more than 450 ft/d; however, the high values were detected primarily in a few areas where few data were available to describe the aquifer-base altitude, being beyond the depth of investigation of the AEM (Abraham and others, 2012). MODFLOW does primary flow calculations based on transmissivity, the product of saturated thickness and hydraulic conductivity; therefore, equivalent transmissivities can be obtained by having a larger saturated thickness and smaller hydraulic conductivity or by having a smaller saturated thickness and larger hydraulic conductivity. A large horizontal hydraulic conductivity estimated during the parameter estimation could be a result of locally poorly constrained aquifer-base altitude. In addition, unpublished aquifer tests in the area resulted in estimated horizontal hydraulic conductivity of 463 ft/d near Mitchell in the northwest part of this area (fig. 1; as reported by Verstraeten and others, 2001), and this estimated K is comparable to calibrated K values of more than 450 ft/d. The authors considered it more appropriate, however, to review the patterns and values of calibrated transmissivity across the entire area, calculated as the calibrated hydraulic conductivity multiplied by the simulated saturated thickness of the aquifer (fig. 21). Transmissivity is strongly controlled by the aquifer thickness (fig. 6*C*) and is largest in the center of the valley where the aquifer is not only the thickest but consists of the coarsest deposits.

Temporal Multipliers to Recharge

Temporal multipliers to recharge were used to adjust recharge estimated with the Soil-Water-Balance Model for the 77 stress periods of the 1950–2008 model, and to adjust recharge estimated the Soil-Water-Balance Model for the pre-1950 model. The mean calibrated temporal multiplier was 0.96, and the range was from 0.78 to 1. The mean multiplier near unity indicates that in combination with other parameters, recharge estimated with the Soil-Water-Balance Model did not need to be adjusted very much for model calibration.

Specific Recharge Parameters

The remaining two parameters were recharge values input to the simulation for areas where the recharge estimated with the SWB model was either particularly low (less than 0.25 in/yr) or particularly high (greater than 5 in/yr). For areas where recharge was particularly low, the calibrated recharge was 0.19 in/yr, or just slightly lower than the initial value of 0.25 in/yr. For areas where recharge estimated with the SWB model was particularly high, the calibrated recharge was 3.0 in/yr. This indicates that in combination with other parameters, decreases in areas where the SWB-estimated recharge was high, improved model calibration. This parameter was limited to a lower value of 3.0 in/yr, so it is possible that further reductions in this parameter might have further improved model calibration, though to what extent was uncertain. However, as described in the ”Sensitivity” section of this report, model outputs were less sensitive to changes in specific recharge parameters than to changes in other inputs, so model outputs may not have changed greatly with additional reductions in areas where recharge estimated with SWB was high.

Simulated Groundwater Budget

Average groundwater budgets for various simulated periods are shown in table 4. The mass balance of inflows and outflows was appropriately maintained because inflows approximately equal outflows (to within 1 ft^3/s) for all simulated periods except the irrigation seasons during 1989–2007. For the irrigation seasons during 1989–2007, total average simulated outflows were slightly larger than total average simulated inflows, but this difference was only about 1 percent of the total water budget, and, therefore, not considered as a concern.

During pre-1900, 66 percent of simulated inflow was recharge from precipitation and 34 percent was groundwater inflows from the west (simulated as specified water levels; table 4). Simulated outflow was to ET (90 percent) and 10 percent was outflow to streams (table 4).

During 1900–50, 90 percent of simulated inflow was from recharge from canal seepage and 7 percent was recharge

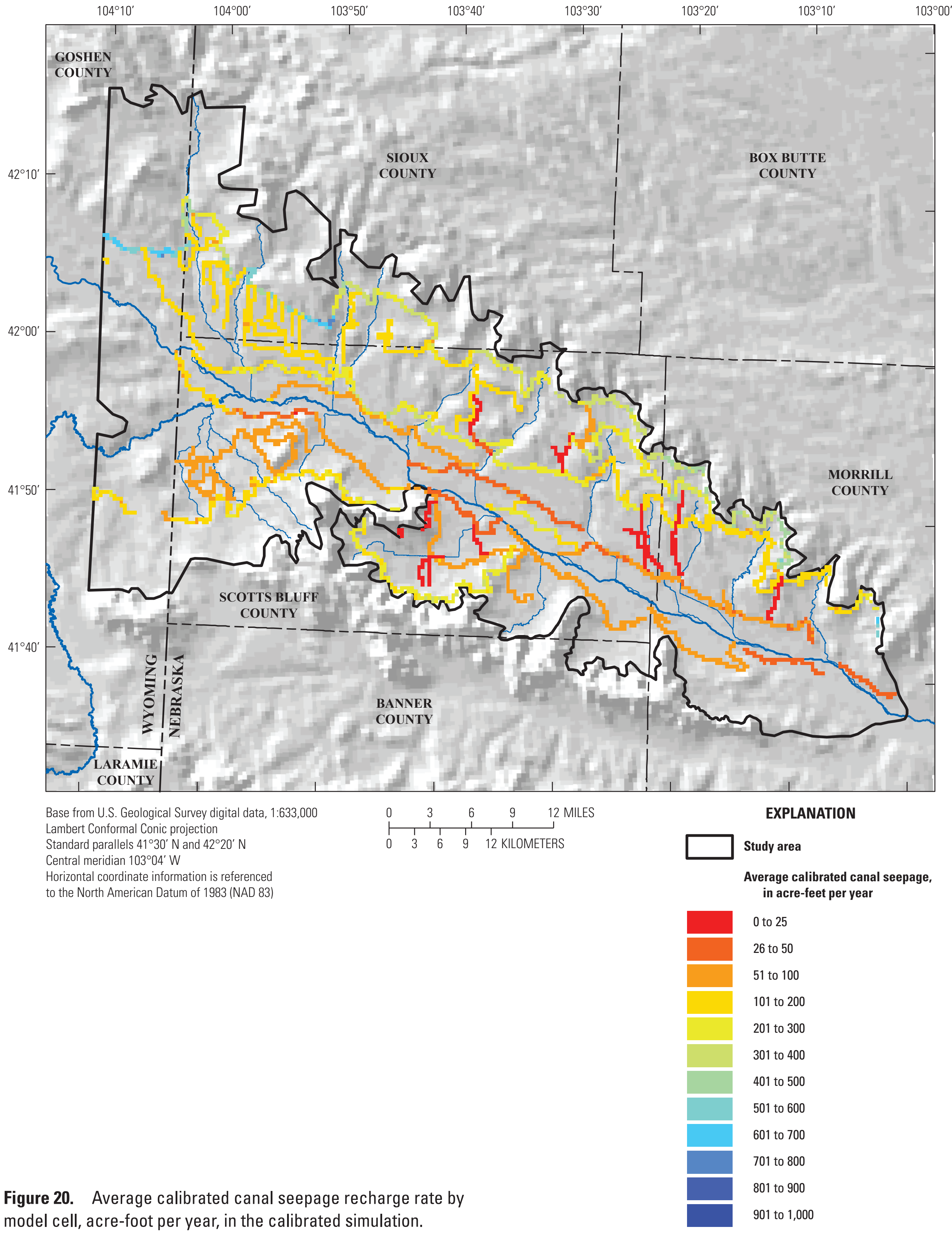

Figure 20. Average calibrated canal seepage recharge rate by model cell, acre-foot per year, in the calibrated simulation.

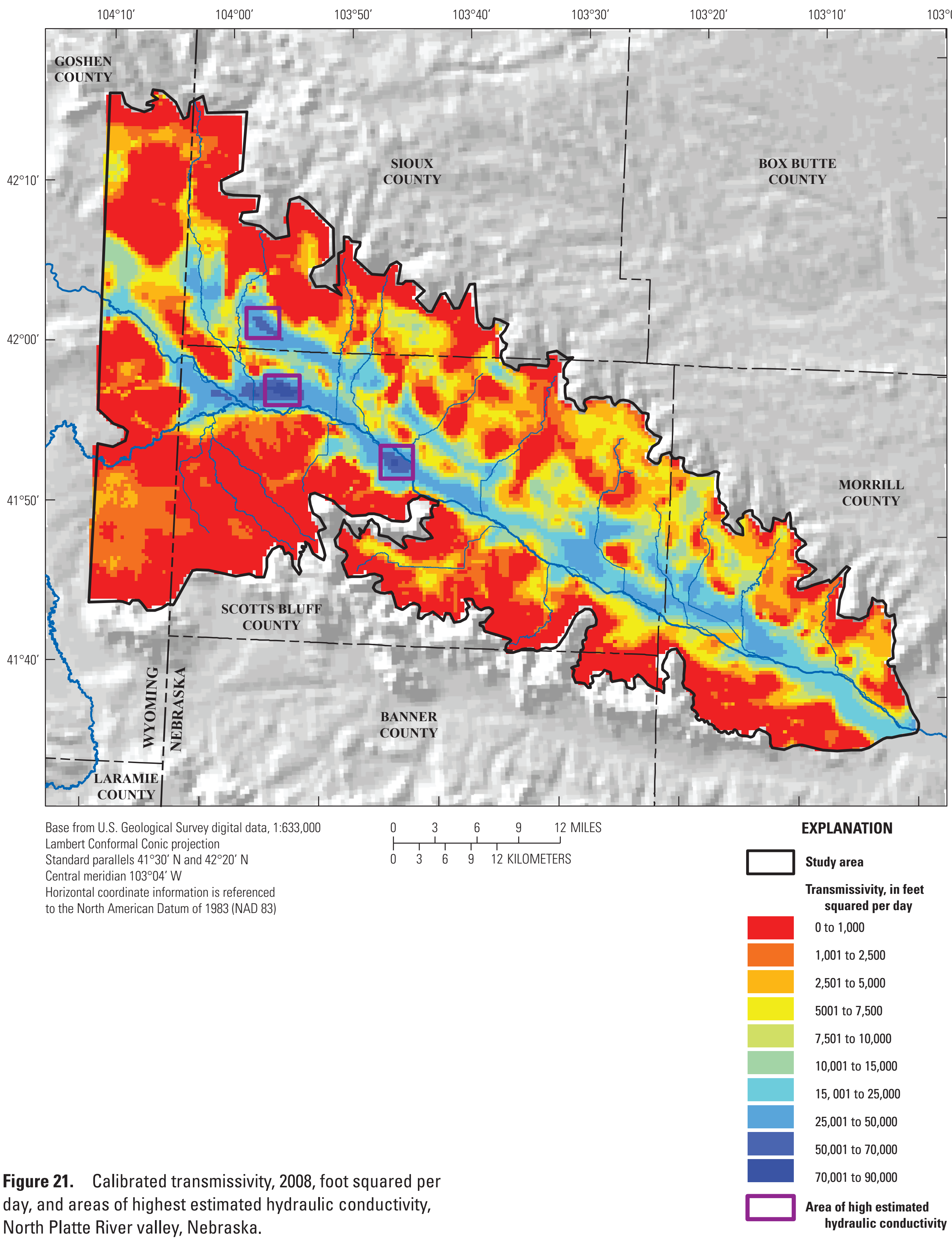

Figure 21. Calibrated transmissivity, 2008, foot squared per day, and areas of highest estimated hydraulic conductivity, North Platte River valley, Nebraska.

Table 4. Summary of average simulated annual groundwater budgets for pre-1900, 1900–50, and 1950–89 and average simulated seasonal budgets for irrigation seasons during 1989–2007 and non-irrigation seasons during 1989–2008.

[--, no data or not available; <, less than. Modflow outflows were subtracted from inflows and only net flows of each budget term are displayed. Values in parentheses (negative) indicate simulated outflows of the groundwater system, and positive numbers indicate simulated inflows to the groundwater system.]

Water budget component	Pre-1900 period		1900–50 period		1950–89 period		1989–2007		1989–2008	
	Quantity, average (cubic feet per second)	Relative quantity, as percentage of total budget	Quantity, average (cubic feet per second)	Relative quantity, as percentage of total budget	Quantity, average (cubic feet per second)	Relative quantity, as percentage of total budget	Irrigation season quantity, average (cubic feet per second)	Relative quantity, as percentage of total budget	Non-irrigation season quantity, average (cubic feet per second)	Relative quantity, as percentage of total budget
Inflows										
Recharge	--	--	--	--	--	--	--	--	--	--
—from canal seepage	0	0	720	90	686	88	1,385	92	0	0
—from precipitation	60	66	60	7	77	10	93	6	74	13
Groundwater inflows simulated as specified water levels	31	34	21	3	21	3	23	2	22	4
Storage	--	--	--	--	--	--	--	--	462	83
Outflows										
Storage	0	0	--	<1	-1	<1	-555	37	--	--
Evapotranspiration	-82	90	-162	20	-164	21	-336	22	-28	5
Wells	0	0	0	0	-15	2	-95	6	0	0
Stream base flow	-9	10	-638	80	-603	77	-531	35	-531	95
Total inflows	91	100	801	100	784	100	1,501	100	558	100
Total outflows	(91)	100	(801)	100	(784)	100	(1,517)	101*	(559)	100

*The sum of all inflow components equals the sum of all outflow components for each time period, though small differences may exist primarily because of rounding.

from precipitation (table 4). Simulated outflow was to streams (80 percent) and 20 percent was outflow to ET (table 4).

During 1950–89, 88 percent of simulated inflow was recharge from canal seepage, and 10 percent was recharge from precipitation (table 4). Simulated outflow was to streams (77 percent) and 21 percent was outflow to ET (table 4).

Later stress periods of the simulation were divided into irrigation season and non-irrigation season. During 1989–2007 irrigation seasons, 92 percent of simulated inflow was from recharge from canal seepage and 6 percent was recharge from precipitation (table 4). Simulated outflow was to water entering storage (37 percent), discharges to streams (35 percent), and to ET (22 percent; table 4).

During 1989–2008 non-irrigation seasons, 83 percent of simulated inflow was from water leaving storage and 13 percent was from recharge from precipitation (table 4). Simulated outflow during 1989–2008 non-irrigations seasons was mostly discharges to streams (95 percent; table 4).

Several observations can be made from table 4. First, simulated groundwater budget components from pre-1900 match the conceptual model of groundwater flow, but appreciable pre-1900 data do not exist to compare with simulated groundwater budget components. Therefore, it cannot be determined how well the simulated values match the actual values during that time period, for example, how well simulated stream base flow matches actual values. Second, recharge from canal seepage was the largest average inflow for most simulation periods, except during the pre-1900 period and the 1989–2008 non-irrigation seasons when recharge from canal seepage was zero (table 4).

Another aspect indicated in table 4 is that discharge to streams was nearly always the largest simulated groundwater outflow, except during pre-1900 when discharge to ET constituted most of the outflow and during the 1989–2008 irrigation seasons when outflow to water entering storage was slightly greater than outflow to streams. As discussed in the “Conceptual Model” section of this report, before the development of surface-water irrigation, most tributary streams to the North Platte River were not perennial, and most groundwater discharge (outflow) to streams during this time would have been to the North Platte River. Historical measurements that could be used to calibrate this aspect of the groundwater-flow simulation or even to indicate what groundwater budget components were dominant do not exist —for example, if outflow to ET was larger than outflow to streams such as the North Platte River. Indications are, however, that simulated outflow to streams increased greatly during 1900–50, 1950–89, and 1989–2008 as a response to the increased recharge from canal seepage. The recharge from canal seepage appears to be largest during irrigation seasons from 1989 to 2007, but the simulation used annual stress periods to represent 1950–1989; thus, the canal seepage was applied throughout the entire simulation year. From 1989 to 2008, the stress periods more closely represent the contrasting hydrology between irrigation and non-irrigation seasons. Thus, even if the seepage volume were the same before and after 1989, applying the same volume of water during a 5-month irrigation season instead of during an annual stress period (12 months) results in a higher rate of recharge during the shorter period.

Similarly, when comparing simulated seasonal groundwater budgets during the 1989–2008 non-irrigation seasons, the summary of total inflows and outflows indicates that during the irrigation seasons, the average simulated groundwater budget is nearly three times the size of the budget than during the non-irrigation seasons (table 4). This increase is largely an effect of recharge from canal seepage that occurred at an average simulated rate of 1,385 ft^3/s during the irrigation season. Other inflows, such as recharge from precipitation and from groundwater inflow, are relatively similar for irrigation and non-irrigation seasons (table 4). Recharge from canal seepage also causes a change in sign in the simulated flows to and from storage for irrigation and non-irrigation seasons. During the irrigation season, groundwater flows into storage (also referred to as water entering storage) are model outflows, as indicated by the negative sign, and can be related to groundwater-level rises that take place during the summer when the canals are full of water. During the non-irrigation season, groundwater flows from storage (water leaving storage) are inflows to the groundwater model, as indicated by the positive sign. This change in storage can be related to water-level declines that take place throughout the non-irrigation season, when the canals are empty. The changes in storage and water levels further correspond with hydrographs for many streams that also indicate periods of increasing base flow, primarily during the irrigation season (May through September), and declining base flows from the time the canals are drained of water in the fall until the time the canals are refilled before the next irrigation season (U.S. Geological Survey, 2012).

Sensitivity

The sensitivity of a model is generally characterized by the effect that a change in a parameter has on the residuals, calculated herein as the calibration targets minus the simulated equivalents, whether for either base flows or groundwater levels. The sensitivity metric was extracted from the Jacobian matrix generated by using the PEST automated calibration process (Doherty, 2010a) and then multiplying each residual by weight of the corresponding observation. Sensitivities were summed by same parameter groups used for calibration, including horizontal hydraulic conductivity estimated at pilot points; spatial multipliers to recharge; temporal multipliers to recharge; and specific recharge parameters. Larger sensitivities indicate that changes in those parameter groups had a larger effect on the size of residuals. Sensitivities were extracted from the Jacobian matrix after each calibration run to determine the parameters that had the largest effect on the calibration target residuals. Calibration targets that sensitivities were analyzed for included the following four groups: water-level targets for the pre-1950 model (126 weighted observations), estimated base-flow targets for the pre-1950 model (13 weighted observations), water-level targets for the 1950–2008 model (5,101 weighted observations), and estimated base-flow targets for the 1950–2008 model (738 weighted observations).

There were many more weighted targets for the 1950–2008 model than for the pre-1950 model; therefore, target observations for the 1950–2008 model had a larger effect on the calibration process than did the pre-1950 model. Changes in parameters that had a large effect on the calibration to 1950–2008 targets, therefore, also had the largest sensitivities. The two parameter groups that the 1950–2008 model calibration (hence, weighted-residuals) was most sensitive to were the canal-seepage spatial multipliers and hydraulic conductivity (fig. 22). Canal seepage recharge was the largest source of recharge (inflow) to the groundwater-flow model and directly affected water levels and groundwater discharge to stream base flow. Multipliers adjusting that large inflow of water, therefore, had a large effect on simulated groundwater levels and simulated stream base flows. Hydraulic conductivity controls the rate of groundwater flow through the aquifer; consequently, hydraulic conductivity also directly affected water levels and aquifer discharge.

Assumptions and Limitations

Important assumptions that affected construction of the simulation model and, therefore, the results of the simulations are included in the following list:

1. Groundwater flow in the study area is dominantly horizontal, and the water table is unconfined. As of 2012, little evidence is available to suggest that long-term vertical gradients, persisting at longer than seasonal time scales, were an important component of flow at the spatial scale of the study area. Therefore, it is appropriate to simulate horizontal flow in the aquifer, using one vertical layer, and to disregard vertical flow.

2. Groundwater flow is minimal between the alluvial aquifer represented in the model and other aquifers underlying or laterally adjacent to the alluvial aquifer. The alluvial aquifer overlies fine-grained silts and clays of the Brule Formation of the White River Group (Cannia and others, 2006). Hydraulic conductivity of the alluvial aquifer is much greater than that of the Brule Formation and little flow is thought to take place between the two aquifers; therefore, to assume this flow to be negligible is appropriate. Laterally, the alluvial aquifer is adjacent to the Brule Formation across most of the study area (fig. 4), so this assumption is appropriate horizontally, as well. In limited areas along the southern boundary, the

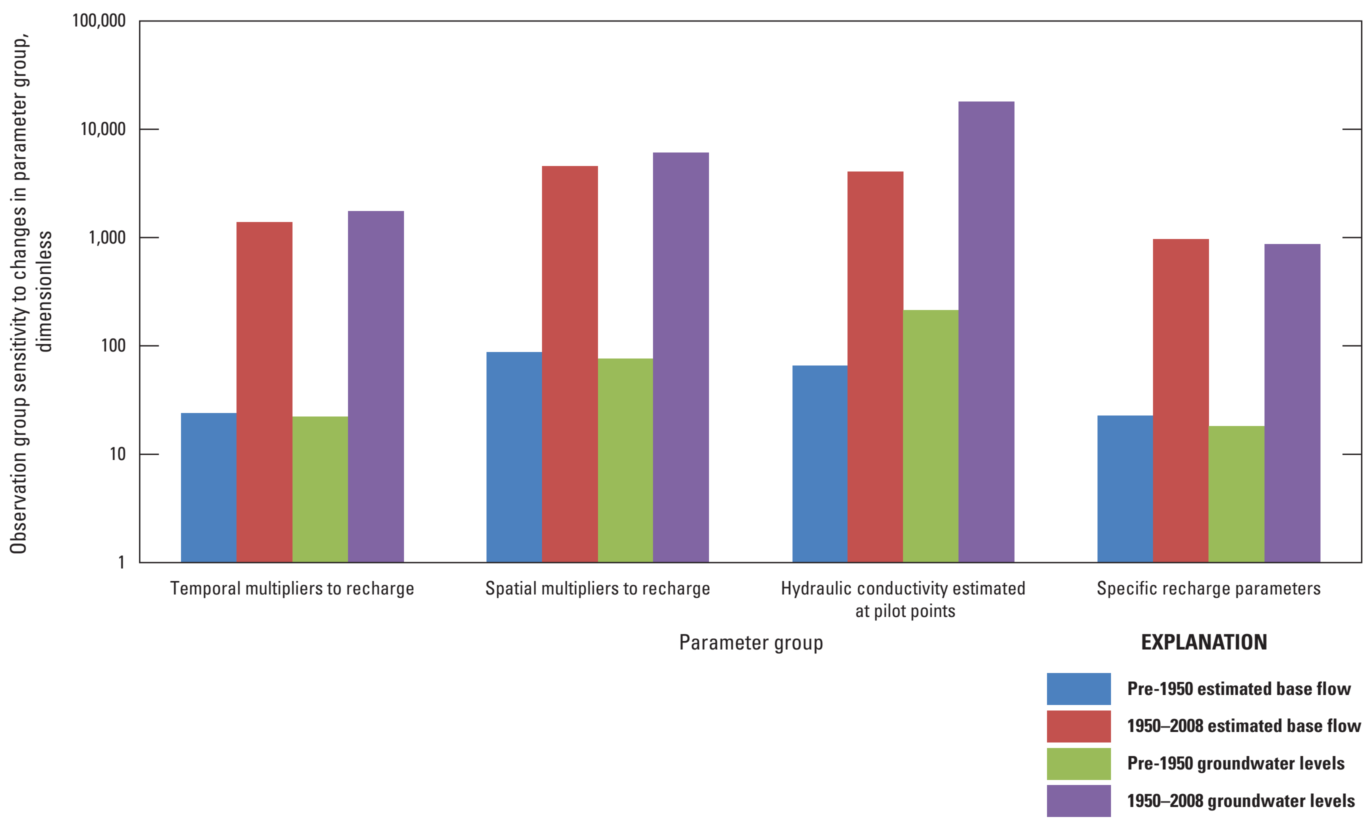

Figure 22. Sensitivity of parameter groups used for calibration.

alluvial aquifer may pinch out (thin southward) adjacent to very fine to fine-grained sandstones of the Arikaree Group; however, little flow is thought to take place between the two aquifers.

3. Sources and sinks that are important to represent in the model, such as streams, irrigation wells, and recharge, can be appropriately simulated using cells that are 1,320-ft by 1,320-ft. An inherent assumption when using MODFLOW is that aquifer properties and other model inputs must be uniformly assigned to each model cell (Harbaugh, 2005). Similarly, when a stream is represented in a MODFLOW cell, the stream effectively occupies the entire model cell, even if the actual dimensions of the stream are much smaller (or larger). Interaction of that stream with groundwater flow is simulated through calculations that represent the center of the model cell, regardless of the actual position of the stream within the cell or of how much of the cell the stream overlies. Stream channel dimensions affect the interaction of simulated streamflow with groundwater but are not related to cell dimensions.

4. Water that leaks from canals and eventually reaches the water table can appropriately be simulated as recharge. This assumption may not be true for short time periods or for small areas; however, the assumption is appropriate for the stress-period lengths and spatial resolution used in this model.

5. The largest and most important hydrologic processes affecting the groundwater system within the study area are represented appropriately in the simulation. As the calibration results indicate that the simulation approximately represents the calibration targets, an assumption can be made that all the important processes have been identified, estimated appropriately, and represented in the simulation; or that unrecognized or unrepresented processes are too small to have an important hydrologic effect; or that average effects of these unrecognized processes are included indirectly through adjustments to calibration parameters.

6. Net irrigation-requirement calculations for registered irrigation wells using published crop water requirements accurately represent actual groundwater withdrawals for irrigation. Groundwater withdrawals were only calculated for cells having irrigation wells registered with the Nebraska Department of Natural Resources, and the assumption was that no other additional wells exist. Further, another assumption was that the amount of groundwater withdrawn from the aquifer was only the amount needed to meet the crop-growth requirement as defined in University of Nebraska (2002), less the effective precipitation that fell during the growing season. Additionally, in the areas where surface water was applied in addition to groundwater, the assumption was that surface water would be applied first, and groundwater withdrawals would supplement supplies during time periods when surface water and precipitation did not satisfy the defined crop requirements.

7. Stream base flows estimated for April of each simulated year, using base-flow separation methods with streamgage data, represent the actual amount of groundwater discharge in the stream. Base-flow separation is largely a signal-processing technique, but the base-flow separation results are commonly used as though indicative of base flow (Santhi and others, 2007). Upstream regulation, such as reservoir releases or diversions that are between streamgages, can obscure the actual stream base flow. Beaver activity, ice effects, or freezing conditions can produce inaccurate or estimated streamflow records, and ET could directly or indirectly remove base flow from the stream before the base flow is measured by a streamgage. The month of April, however, is usually free from reservoir releases or diversions and ice or substantial ET.

The simulation documented in this report was primarily calibrated to 1950–2008 estimated stream base flows and groundwater levels. If the simulation would properly reproduce hydrologic responses for conditions beyond what took place during the calibration period is unknown; therefore, the hydrologic responses could not be measured or tested within the timeframe of this study. Users should be cognizant of the risk of using this model for analyses relating to different conceptual models of groundwater flow than for what this model was designed and calibrated. As an example, the entire model-calibration period included recharge from canal seepage as the largest component of inflow to groundwater, and few or no groundwater levels or streamflow measurements exist before the development of canals and the start of canal seepage. The simulation, therefore, could not have been calibrated to those conditions, and if the model would accurately simulate scenarios where the canals are no longer in operation is unknown. As a second example, during 1950–2008, if precipitation was much lower than the lowest precipitation or much higher than the highest precipitation, groundwater withdrawals for irrigation, recharge from precipitation, and recharge from canal seepage could all change and could likely be well beyond the range of the calibrated simulation. Because measured water levels and stream base flows under those conditions do not exist in the historical record, the model could not have been calibrated to those conditions, and performance of simulations for scenarios including these conditions cannot be assessed.

As an additional limitation, results are affected by simulated As an additional limitation, results are affected by simulated stream inflows and use of base-flow targets for the North Platte River. The North Platte River in western Nebraska is a complex system featuring upstream reservoir releases and diversions into many canal systems that take place inside and outside of the study area but, nonetheless, affect the estimated base flow and simulated inflows used in this study. Estimated base flows for April were used for base-flow targets for the North Platte River and for simulated routed streamflows at the western edge of the model area in Wyoming (fig. 7), which also included estimated base flows for October. April and October base flows were assumed to be free of the effects of early spring snowmelt runoff, the effects of vegetative transpiration of stream water, and the effects of canal diversions that usually take place during May through September each year. Average base flows spanning each season were not used because they would have been affected by all of these processes, which are not represented in the simulation. Current (2015) techniques such as GSFLOW (Markstrom and others, 2008), FMP2 for MODFLOW (Schmid and Hanson, 2009) or MODFLOW–OWHM (Hanson and others, 2014) would allow for a more detailed and comprehensive simulation of precipitation, runoff, base flow, and canal operations (among other related processes), but these approaches were beyond the scope of this study.

Post-Audit of Estimated Groundwater Withdrawals

After the groundwater-flow simulation calibration was complete, the NPNRD supplied the USGS with metered groundwater-withdrawal data (collected using flowmeters attached to wells) for 2009 and 2010 that were beyond the time period simulated in the model (1950–2008). Other known data do not exist for well withdrawals in the study area for use in a quality-assurance check of either simulated withdrawals or against the NPNRD flowmeter data. The authors, however, developed estimates of 2009 groundwater withdrawals based on the groundwater-flow model, using methods described next in this report, to enable comparison with the recorded withdrawals (flowmeter data) as a post-audit check on the accuracy of the groundwater withdrawal estimation method.

For the 2009 estimate, the amount of groundwater applied to each field was determined using the process described in the “Groundwater Withdrawals” section of this report, but using 2009 precipitation. The surface-water delivery data were compiled for 2009, used to satisfy crop-irrigation requirements on these fields as the first source of irrigation, and the remaining crop-irrigation requirement was considered, as before, to be the groundwater withdrawals for irrigation. The resulting total 2009 groundwater withdrawal was compared to the flowmeter values that were provided for metered locations within the simulation study area. The 2009 estimated groundwater withdrawal for cells irrigated with groundwater in the simulation area was 17,000 acre-ft, and the 2009 flowmeter reading was 13,000 acre-ft for the same wells. Not all of these wells used in the estimation had flowmeter readings for 2009, either because the well was not equipped with a flowmeter or the amount of water used was not recorded in the NPNRD database.

A similar comparison was made for fields irrigated with surface water and groundwater, also referred to as comingled irrigation. Comingled-irrigation groundwater withdrawals for 2009 were estimated using the same process as described in the “Groundwater Withdrawal” section of this report, that is, the reported surface-water irrigation deliveries were subtracted from the total irrigation demand to estimate the remainder that would have been supplied through groundwater withdrawals. The 2009 flowmeter readings for wells supplying fields with comingled irrigation totaled 22,000 acre-ft. The estimated 2009 total groundwater withdrawal in comingled areas was 2,000 acre-ft. Several possible reasons exist for this difference, which amounts to less than 2 percent of the post-1950 average groundwater budget (table 4). Groundwater withdrawals for irrigation have been increasing since the 1950s and were likely high because of drought in the early to mid-2000s. Though 2009 growing-season precipitation was only an inch less than the 1950–2008 average for the area, the 1999–2008 average growing season precipitation was 5 in. less than the 1950–2008 average (National Climatic Data Center, 2009); thus, irrigators probably had been routinely pumping much more groundwater for the entire decade preceding 2009. Also, irrigation practices in the study area could have changed during the 2001–2007 drought, wherein more irrigators were using groundwater withdrawals to supplement surface-water usage to satisfy crop demand. This change could be caused by more acres being irrigated than was previously thought, by irrigator preference to reduce surface-water consumptive use, or by different crops being planted. More detailed analysis, beyond the scope of this study, would be required to ascertain the exact cause or causes of the difference between estimated and metered groundwater withdrawals for comingled irrigation and to determine how to adjust the 1950–2008 simulated withdrawals for comingled irrigation.

Effects of Water-Management Options

The calibrated groundwater-flow model was used to build a simulation-optimization model to help the NPNRD to better understand how certain management decisions could affect stream base flows after the calibration period, during 2008–19. The simulation-optimization model was built using the Ground-Water Management Process (GWM) for the USGS modular groundwater model, (MODFLOW–2000; Ahlfeld and others, 2005). The simulation-optimization model was constructed to analyze if selected management activities would increase the simulated flow of the North Platte River at Bridgeport under varying climatic conditions. Management activities analyzed include (1) reductions in groundwater withdrawals for irrigation and (2) reductions in groundwater withdrawals for irrigation combined with application of intentional recharge. Included in this analysis were three different future climate conditions.

Conceptual Approach

The simulation-optimization models simulate 11 years beginning at the end of the calibration period groundwater-flow simulation (April 30, 2008, to April 30, 2019). The model used two stress periods per year: one for the irrigation season and one for the non-irrigation season. The simulation-optimization model inputs were constructed to simulate the following three different future climatic conditions: (1) a period of average precipitation conditions, (2) a period of above-average precipitation conditions, and (3) a period of below-average precipitation conditions. From the historical record, 10-year periods were identified that fit these criteria. During the historical record (1895–2008; National Climatic Data Center, 2009), the study area received an average of 14.8 in. of precipitation per year. The 10-year moving average of precipitation was computed and compared to the historical record average. The 10-year period with the highest average precipitation was from 1986 to 1995, with an average annual precipitation during that period of 18.0 in. The 10-year period with the average precipitation closest to the historical average was from 1961 to 1970, with an average annual precipitation during that time period of 14.7 in. The 10-year period with the lowest average precipitation was from 1999 to 2008, with the average annual precipitation during that period of 13.6 in. (fig. 23).

Construction of Future Period Model

The simulation-optimization model in this study was constructed as an 11-year future period model (2008–19) based on the calibrated historical groundwater-flow model. The files used to build the future period groundwater-flow model were modified from the calibrated groundwater-flow model files and from data used to construct the calibrated groundwater-flow model from the identified climatic conditions. That is, the mean annual data for the decades with the identified climatic conditions were applied to every year of the future period simulation. The same MODFLOW packages were used with GWM as were used for the calibration model, except that GWM did not support the NWT solver, which was replaced with the Geometric Multigrid (GMG) solver (Wilson and Naff, 2004). The change to the GMG solver also necessitated replacement of the Upstream Weighting Package with the similar Layer-Property Flow Package. Most GWM packages stayed the same for each climatic condition. The Streamflow-Routing, Recharge, and Well Packages varied by climatic

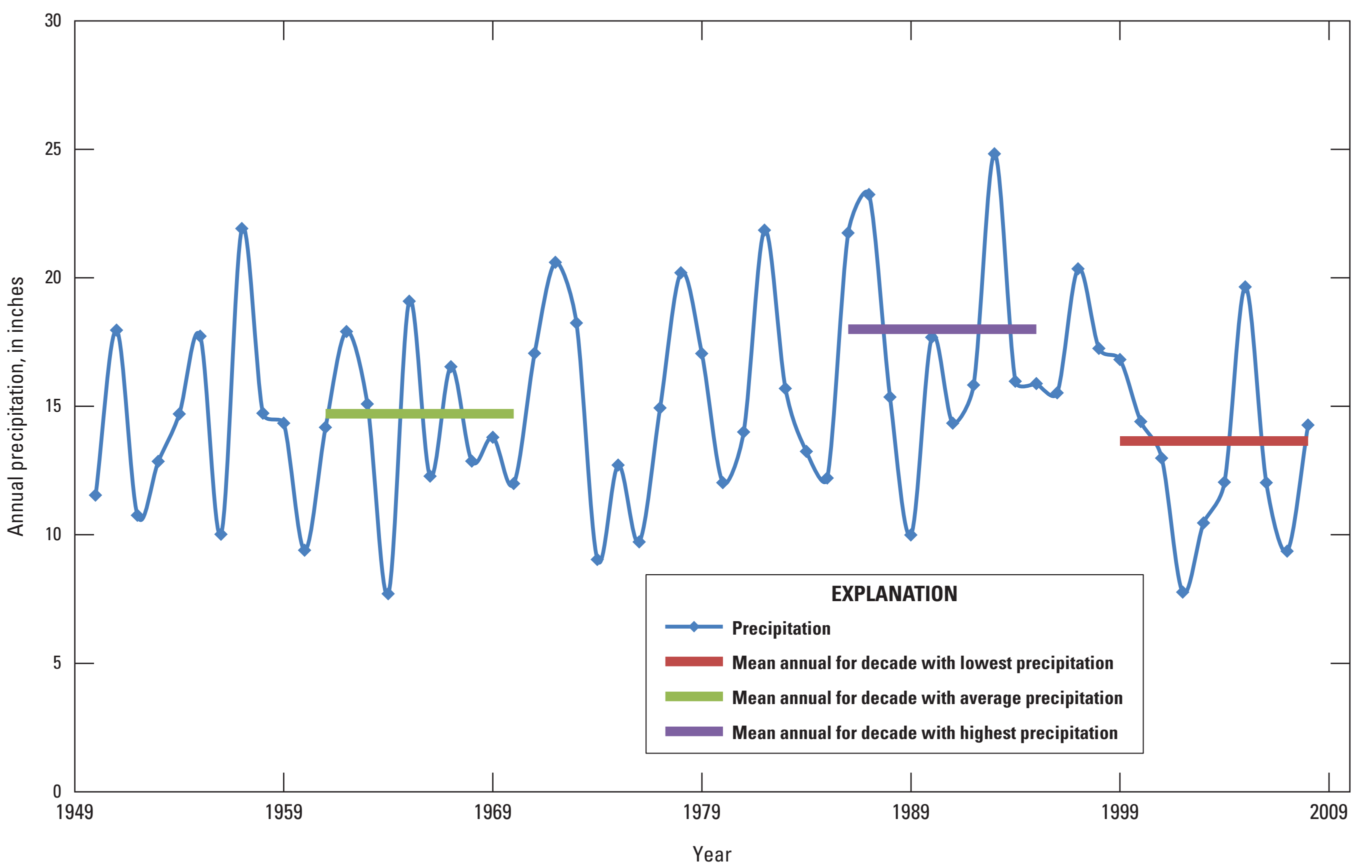

Figure 23. Annual total precipitation and decadal-mean annual precipitation for date ranges used to represent specified precipitation conditions, Scottsbluff, Nebraska, 1950–2008.

condition. The aquifer characteristics (for example, aquifer-base altitude, hydraulic conductivity, and specific yield) were the same as the calibrated inputs to the calibration period model, though only hydraulic conductivity was adjusted during calibration.

The Streamflow-Routing Package was used to simulate stream base flow. The North Platte River and Horse Creek are the only streams in the model that originate outside the study area (fig. 7); inflow from these streams was estimated based on the time periods corresponding to the identified climatic conditions, and other inputs to the Streamflow-Routing Package were identical to those streams from the calibrated model inputs for those time periods. Horse Creek inflows remained the same throughout all stress periods in the simulation-optimization model and were specified as the same input used in the calibrated model. North Platte River inflows were determined by averaging the April inflows for the corresponding historical 10-year period for the irrigation season inputs and by averaging the October inflows for the non-irrigation season inputs. In other words, mean annual April and October inflows from the corresponding 10-year period were used for all seasons of the same type; irrigation seasons or non-irrigation seasons.

Groundwater recharge for the optimization-flow model was created by calculating the average (calibrated) SWB recharge during the 10-year period corresponding to each selected climatic condition and adding the calibrated canal recharge for the same period. The average of the calibrated SWB recharge for non-irrigated conditions was used for non-irrigation seasons in the simulation-optimization model. Recharge, therefore, was the same for all seasons of the same type; irrigation seasons or non-irrigation seasons.

Groundwater withdrawals necessary to meet the full net irrigation requirement for the analysis period were estimated in a similar way as for the calibration period withdrawals. The procedure is described in the “Groundwater Withdrawals” section of this report, and assumes no future changes in the land-cover mosaic. The amount of water needed to satisfy crops in each cell was estimated from the same land-cover classification used for 2008 in the calibration model and the University of Nebraska’s crop water-use publication (University of Nebraska, 2002). The mean irrigation-season effective precipitation was calculated for the years that correspond to each climatic condition. All 492 active wells in the certified-acres database described in the “Groundwater Withdrawals” section of this report were used in the calculations, whether they supplied crops irrigated with groundwater only or if they supplied crops irrigated with surface water and groundwater. Withdrawals, however, were only optimized for wells supplying crops irrigated with groundwater only, as described in the “Optimization of the Future Period Model” section of this report. Canal delivery to comingled-irrigation acres was estimated as the mean delivery for each decadal period specified for selected climatic conditions. The total groundwater withdrawal from a well was estimated by subtracting the mean effective precipitation and mean surface-water delivery (where applicable) from the crop demand. The calculated groundwater-withdrawal values were applied to all irrigation seasons of the simulation-optimization model and varied only between climatic conditions because of the change in average precipitation during the specified climatic condition (fig. 23).

Optimization of the Future Period Model

The Groundwater-Management Process for the 2005 version of the USGS modular three-dimensional groundwater model (GWM-2005) is designed to minimize or maximize a sum of decision variables representing groundwater-management approaches, simultaneously attempting to maintain a series of constraints (Ahlfeld and others, 2005). For the first analysis, GWM-2005 was used to maximize groundwater withdrawals to as much as the full net irrigation requirement, and also to maintain the simulated streamflow constraints of the North Platte River at the Bridgeport, Nebr., streamgage. Groundwater withdrawals were maximized (to the maximum of the full net irrigation requirement) because they represent the beneficial use of irrigation water needed to successfully grow crops. The GWM-2005 decision variables were well pumping rates grouped by zone for groundwater-irrigated crops. The specified streamflow constraint was successively increased until GWM-2005 could not determine a feasible solution—that is, no groundwater-withdrawal reduction strategy could be determined to meet that specified constraint value. The maximum allowed reduction in groundwater withdrawals was 50 percent, or one-half the net irrigation requirement.

Groundwater withdrawals for groundwater-only irrigated crops were grouped using eight well-management zones named W1 through W8 (fig. 24). Groundwater-withdrawal management zones were delineated by NPNRD and based on land-use zones generated for a surface-water model used within the NPNRD (T. Kuntz, written commun., July 2010). The proportion of discharge assigned to each well in each zone was relative to the amount of withdrawal necessary to meet full irrigation demand for cropland supplied by that well relative to other wells in the zone, and the proportion of discharge assigned to each well remained the same relative to other wells in the zone as maximum withdrawals were adjusted by GWM-2005. For example, if a well-management zone contained two wells and the total withdrawals for the zone were 100 acre-ft for an irrigation season, and each well withdrew 50 percent of the total, that percentage would be maintained, even if in subsequent iterations the total pumpage was decreased by one-half to 50 acre-ft; withdrawals for each well would then be only 25 acre-ft (or one-half of the original 50 acre-ft). The same well-management zones were used for all future climatic conditions selected, though the amounts of withdrawals were different for each climatic condition.

For the second analysis, GWM-2005 was used to maximize groundwater withdrawals and also to minimize the use of intentional recharge at as many as 18 sites, and also to

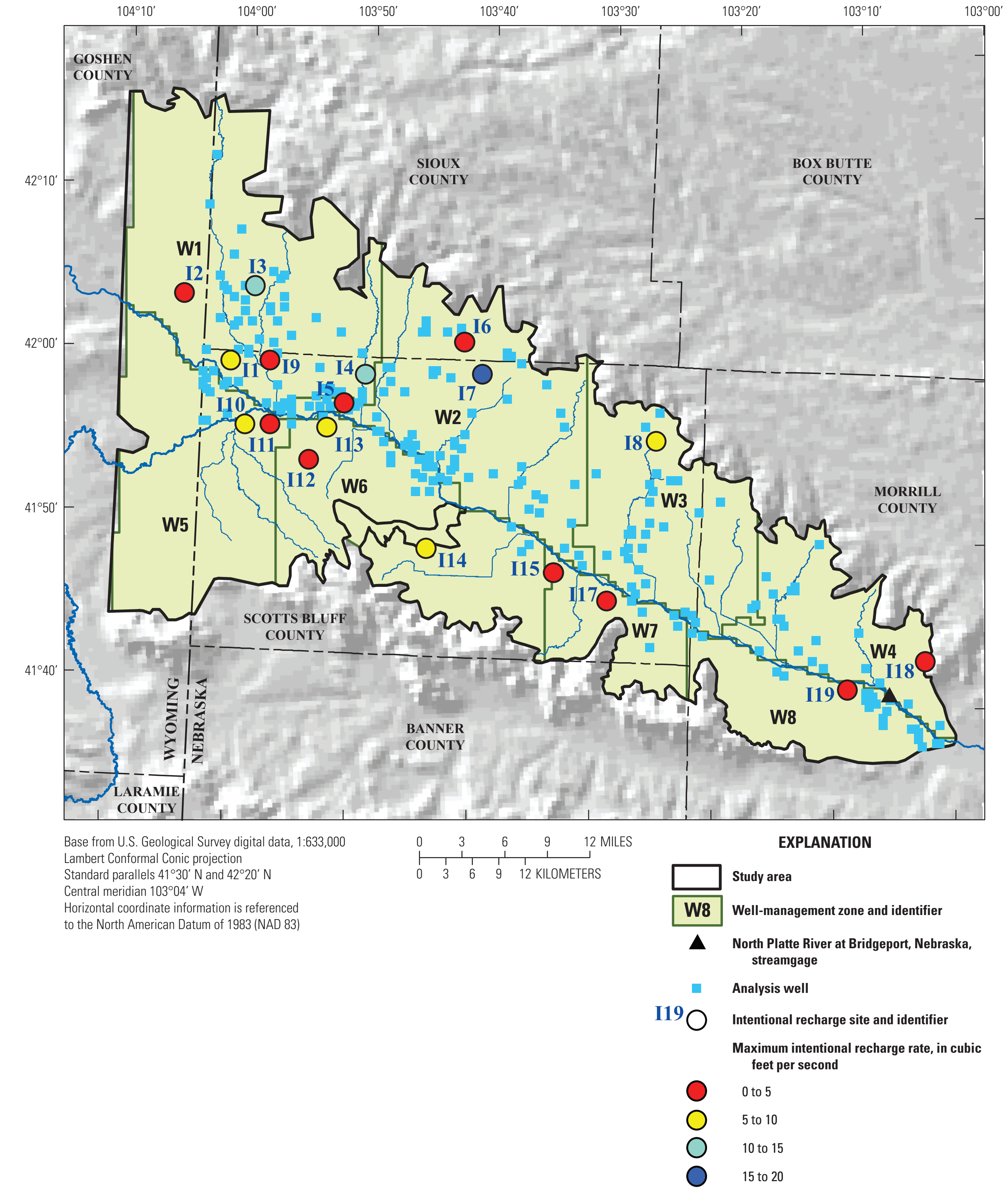

Figure 24. North Platte Natural Resources District well-management zones, analysis wells, intentional recharge sites, and maximum intentional recharge rates, and streamgage used for optimization of the future period model.

maintain the varied constraint of a specified simulated streamflow of the North Platte River at the Bridgeport streamgage. The GWM-2005 decision variables were well pumping rates for groundwater-irrigated crops by well-management zone (8 decision variables) and injection rates of hypothetical wells representing intentional recharge sites (18 decision variables). Similar to the first analysis, the streamflow constraint was successively increased until GWM-2005 could not determine a feasible solution. Intentional recharge was minimized so that only sites that helped meet the streamflow constraint would be used in the solution.

Sites suitable for intentional recharge were defined in GWM-2005 to be managed on an individual basis (instead of by zone). Conceptually, intentional recharge was envisioned as the delivery of canal water into a specified unused field with the intention of letting the water seep into the ground to recharge the aquifer. Intentional recharge sites were selected using aerial photographs (Dollison, 2010). Sites selected were sandy rangeland fields that were close in proximity to canals. Intentional recharge sites were represented as injection wells in the simulation-optimization model, which had the same effect on simulated hydrology as water being applied at land surface that instantaneously reached the water table. The maximum rate of intentional recharge was specified as 0.5 ft^3/s per cell, multiplied by the number of cells per site, and multiplied by 0.45 to account for losses to ET and other environmental losses; this loss ratio was similar to canal losses in the calibration model. Selected sites ranged from 400 to 2,800 acres, and maximum simulated intentional recharge rates ranged from 680 to 4,800 acre-ft per season (2–16 ft^3/s per site, fig. 24); with a maximum potential recharge of 113 ft^3/s for all sites combined. Simulated intentional recharge was only applied during the irrigation season. As of 2012, the canals do not carry water during the non-irrigation season; thus, no water would be available for intentional recharge during the non-irrigation season. For these simulations, the managed pumping and intentional recharge variables were active for all irrigation stress periods.

In addition to the files needed to simulate groundwater flow, control files are needed to define the GWM configuration and solution approaches for the stated problem. The GWM files used for these optimization scenarios are objective function, variable constraint, decision variable, streamflow constraint, and solution. The objective-function file was the same for each management scenario (well management or well management plus intentional recharge) and specified the objective function to be maximized as well as coefficients for each decision variable.

The decision-variable and variable-constraint files were used together to define the characteristics of the well decision variables for each optimization scenario. The decision-variable file specified what portion of the total groundwater withdrawals came from each well in a zone, the location of each well, and the stress periods that these variables were active. For the scenarios that also used intentional recharge, the decision-variable file also contained information about the location of intentional-recharge sites. The variable-constraint file specified the minimum and maximum rate of groundwater withdrawals allowed for each zone, which ranged from 50 to 100 percent of the calculated irrigation requirement for each climatic condition. For the scenarios that also used intentional recharge, the variable-constraint file also specified the allowed minimum and maximum rate of application of intentional recharge that ranged from 0 to 113 ft^3/s for all sites and from 2 to 16 ft^3/s for the 18 potential sites.

The streamflow-constraint file specified the minimum base flow at a given stream segment, corresponding to the North Platte River at Bridgeport streamgage. The streamflow-constraint value was increased by 5 ft^3/s during each iteration. Simulations iteratively determined the maximum base-flow discharge at the Bridgeport streamgage under the specified scenario's constraining decision variables, until GWM-2005 could not determine a feasible solution that satisfied all constraints applied. For below-average precipitation conditions, the streamflow constraint was applied to every irrigation season during 2009–18; however, preliminary testing for below-average precipitation conditions indicated that irrigation season streamflows declined during 2009–18. The last irrigation season for 2018 had the lowest simulated stream base flow; therefore, when the constraint for the irrigation season of 2018 was met, so were the streamflow constraints for irrigation seasons during 2009–17. For average and above-average precipitation conditions, the streamflow constraint was applied to the last five irrigation seasons of the future period, corresponding to 2014–18. Preliminary testing for average and above-average precipitation conditions indicated increases in simulated stream base flow for irrigation seasons during 2009–18. Under these conditions, when the earliest stream base-flow constraint was met, so were the constraints for following irrigation seasons.

The solution file was the same for each optimization scenario applying the future model. The solution file determines the solver and specified settings to be used in determining the best possible solution for the problem. Many different solution settings exist that can be applied to the model. For the specific problems of the studied scenarios, the linear-programing solution of GWM-2005 was used. The sequential linear-programing solution was also tested but produced nearly the same result and increased the computation time for each analysis; therefore, the linear-programing solution was used for all analyses.

Base-Case Simulations without Management

The baseline simulations, or base case, involved no managed decreases in groundwater withdrawals (no management through optimization). With average precipitation, the base-case future model simulated a maximum discharge of 425 ft^3/s at the Bridgeport streamgage at the end of the 2018 irrigation season (table 5). Groundwater withdrawals for each management zone ranged from 1 ft^3/s in zone 7 to 16 ft^3/s in zone 2 (table 6). With below-average precipitation in the future model and no management through optimization, the future model simulated a maximum discharge of 302 ft^3/s at the Bridgeport streamgage at the end of the 2018 irrigation season (table 5). Groundwater withdrawals for each zone ranged from 1 ft^3/s in zone 7 to 17 ft^3/s in zone 2 (table 6). With above-average precipitation in the future model and no management through optimization, the future model simulated a maximum discharge of 556 ft^3/s at the Bridgeport streamgage at the end of the 2018 irrigation season (table 5). Groundwater withdrawals for each zone ranged from 1 ft^3/s in zone 7 to 16 ft^3/s in zone 2 (table 6).

Table 5. Summary of optimization model results for simulated stream base flow under below-average, average, and above-average precipitation, with and without optimized groundwater withdrawals and intentional recharge, September 30, 2018, from simulation of 2008–19.

[Streamflows correspond to simulated results for the North Platte River at Bridgeport, Nebraska, in cubic feet per second]

Precipitation condition	Maximum streamflow with full pumpage (base case)	Maximum streamflow with reduced pumpage	Maximum streamflow with reduced pumpage and intentional recharge	Maximum rate for all intentional recharge sites (cubic feet per second)	Optimized rate for all intentional recharge sites (cubic feet per second)
Below average	302	310	325	113	69
Average	425	430	440	113	22
Above average	556	560	575	113	37

Table 6. Summary of optimization model results for simulated management scenarios—groundwater withdrawals by management zone and optimized intentional-recharge rates, September 30, 2018, from simulation of 2008–19.

[Results are given in cubic feet per second. na, not applicable]

Well-management zone (fig. 24)	Above-average precipitation conditions			Average precipitation conditions			Below-average precipitation conditions		
	No optimization (base case)	Optimized pumpage	Optimized pumpage and intentional recharge	No optimization (base case)	Optimized pumpage	Optimized pumpage and intentional recharge	No optimization (base case)	Optimized pumpage	Optimized pumpage and intentional recharge
W1	12	7	6	12	6	6	13	7	7
W2	16	16	8	16	16	10	17	11	9
W3	6	3	3	6	3	3	6	3	3
W4	5	5	2	5	4	3	5	3	3
W5	3	3	2	3	2	2	3	2	2
W6	2	1	1	2	1	1	3	2	2
W7*	1	0	0	1	0	0	1	0	0
W8	6	6	3	7	7	7	7	7	3
Sum	51	41	25	52	39	32	56	34	28
Intentional recharge	na	na	37	na	na	22	na	na	69

*Reduction for W7 was 50 percent but appears to be 100 percent because of rounding.

Simulations with Management of Groundwater Withdrawals

The first approach used for optimization of the future model was to determine the maximum stream base flow that could be sustained at the North Platte River at Bridgeport streamgage in the 2018 irrigation season by reducing groundwater withdrawals within each of eight management zones. The following paragraphs describe the results for each climatic condition.

For average precipitation conditions, the maximum base flow attainable at the Bridgeport streamgage by optimizing managed groundwater withdrawals was 430 ft^3/s, which is 5 ft^3/s larger than for the base case (table 5). Managed groundwater withdrawals were about 13 ft^3/s smaller than for the base case (table 6), and decreases relative to the base case varied among management zones as shown in figure 25. At a specified base-flow constraint of 435 ft^3/s, no solution to the problem was feasible; the streamflow constraint could not be met with the maximum (50-percent) reduction in groundwater withdrawals in all eight management zones.

For below-average precipitation conditions, the maximum flow at the Bridgeport streamgage with managed groundwater withdrawals was 310 ft^3/s, which is 8 ft^3/s larger than for the base case (table 5). Managed groundwater withdrawals were about 22 ft^3/s smaller than for the base case (table 6). At 315 ft^3/s, no solution to the problem was feasible; the streamflow constraint could not be met with the maximum (50-percent) reduction in groundwater withdrawals in all eight management zones.

For above-average precipitation conditions, the maximum flow at the Bridgeport streamgage with managed groundwater withdrawals was 560 ft^3/s, which is 4 ft^3/s larger than for the base case (table 5). Managed groundwater withdrawals were about 10 ft^3/s smaller than for the base case (table 6). At 565 ft^3/s, no solution to the problem was feasible; the streamflow constraint could not be met with the maximum (50-percent) reduction in groundwater withdrawals in all eight management zones.

The optimized solution determined by GWM-2005 also indicates how management of the withdrawals in each zone benefits, or does not benefit, simulated stream base flow of the North Platte River at the Bridgeport streamgage. For instance, with average precipitation, to meet a 430 ft^3/s simulated stream base flow constraint, withdrawals were reduced by the maximum amount of 50 percent of the net irrigation requirement for zones W1, W3, W6, and W7 (table 6). This means that reductions in withdrawals in these zones produced increased simulated base flow of the North Platte River at the Bridgeport streamgage. Meanwhile, withdrawals were reduced by less than 50 percent (W4 and W5) or were not reduced in the remaining zones (W2 and W8), indicating that within the simulation period analyzed, withdrawal reductions in those zones were not as beneficial to increasing the simulated stream base flow within the analysis period. Reductions in withdrawals for future simulations with below-average precipitation (fig. 26) and above-average precipitation (fig. 27) can be interpreted similarly. Also, in these three scenarios, withdrawals were never reduced in area W8, indicating that reducing withdrawals in that area did not increase stream base flow within the future model period. Generally, simulated base flow was best optimized by reductions in groundwater withdrawals north of the North Platte River and in the western half of the area.

Further insight into the benefit of managed withdrawals by zone can be gained by inspection of response coefficients (table 7). Response coefficients output by GWM-2005 represent the ratio in the value of stream base flow (or water level) at each constraint location to a change in the decision variable flow rate (Ahlfeld and others, 2009). Response coefficients for management zones W1–W8 (table 7) represent the amount of stream base flow decline at the constraint location (the North Platte River at Bridgeport), for increases in withdrawals above the 50 percent minimum withdrawal baseline (with no managed withdrawals). GWM-2005 outputs response coefficients for all constraint locations and times. Constraints for this study were always located at the North Platte River at Bridgeport but distributed in time through at least the last five irrigation seasons of the future period. For this study, simulated stream base flow increased relative to streamflow at the end of the calibration period (338 ft^3/s; fig. 19) during the future period for average and above-average precipitation conditions and decreased during the future period for below-average precipitation conditions. In this case, therefore, when the earliest stream base flow constraint was met, all the other constraints later in time would also be met. Under below-average precipitation conditions, the latest (last) streamflow constraint was binding, and when that last constraint was met, the earlier constraints were also met. Binding constraints can be thought of as the constraints that were hardest to meet in this optimization analysis, and that had the largest effect on the optimal pumping rates; therefore binding constraint response coefficients (table 7) are the most valuable to understand.

For example, if withdrawals were increased by 1 ft^3/s for management zone W1 under average precipitation conditions, table 7 indicates that that response coefficient is 0.38 at the time of the binding streamflow constraint (stress period 13), and simulated stream base flow at the constraint location would decline by 0.38 ft^3/s (1 ft^3/s multiplied by 0.38). Response coefficients are largest for management zones W6 and W7 (table 7), indicating that increases in managed withdrawals within those zones caused the largest declines in simulated streamflow at the constraint location. Alternately, response coefficients are smallest for management zones W2 and W8, indicating that increases in managed withdrawals in those zones had a much smaller effect on simulated stream base flow at the constraint location. In fact, as noted in the "Simulations with Management of Groundwater Withdrawals" section of this report, to meet the maximum of 430 ft^3/s streamflow at the constraint location under average precipitation conditions (table 5), withdrawals were reduced by the maximum amount in management zones W1, W3, W6, and

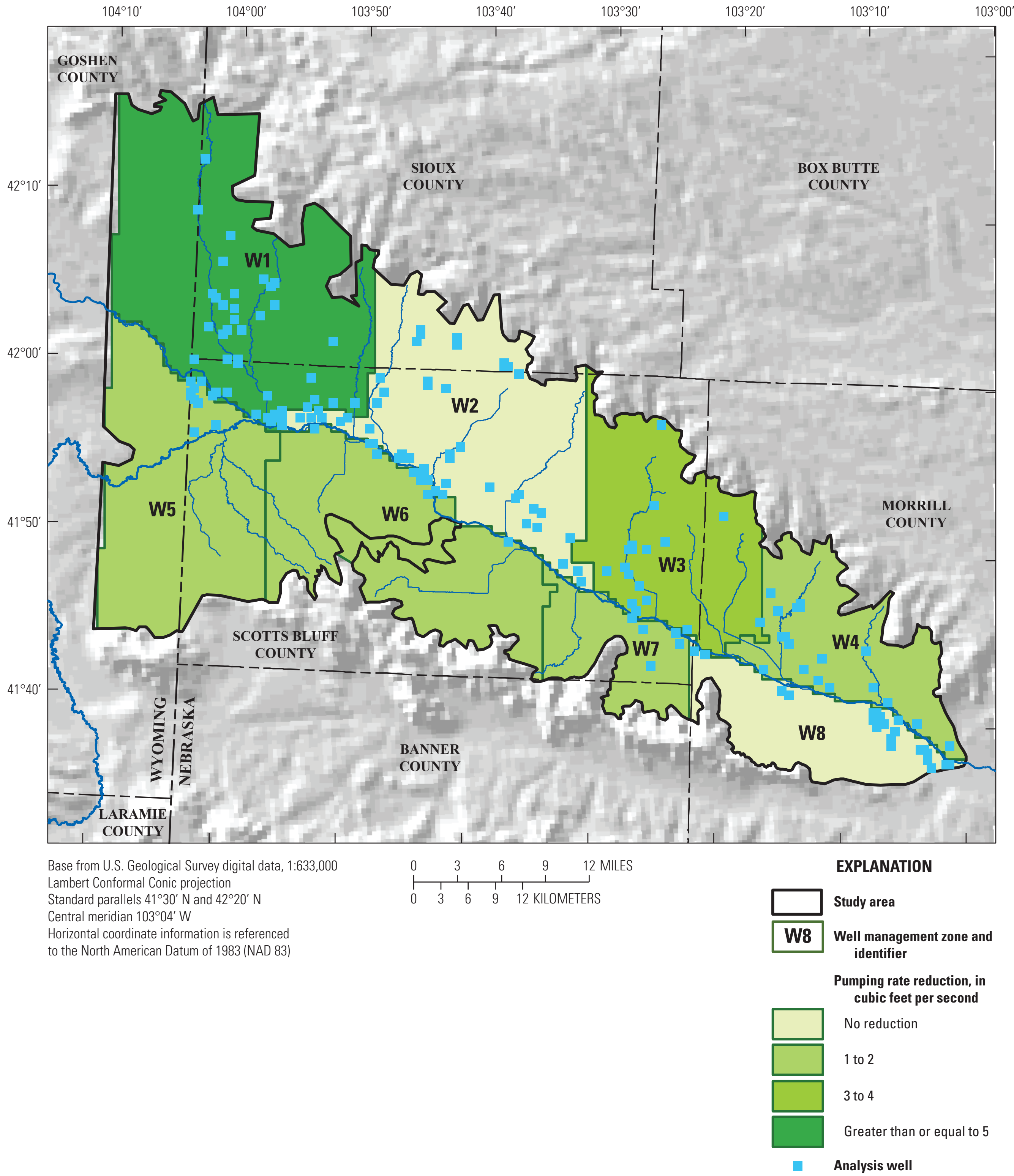

Figure 25. Optimized groundwater withdrawals by zone for the future model with average precipitation; groundwater withdrawal rate reductions are relative to the base-case scenario.

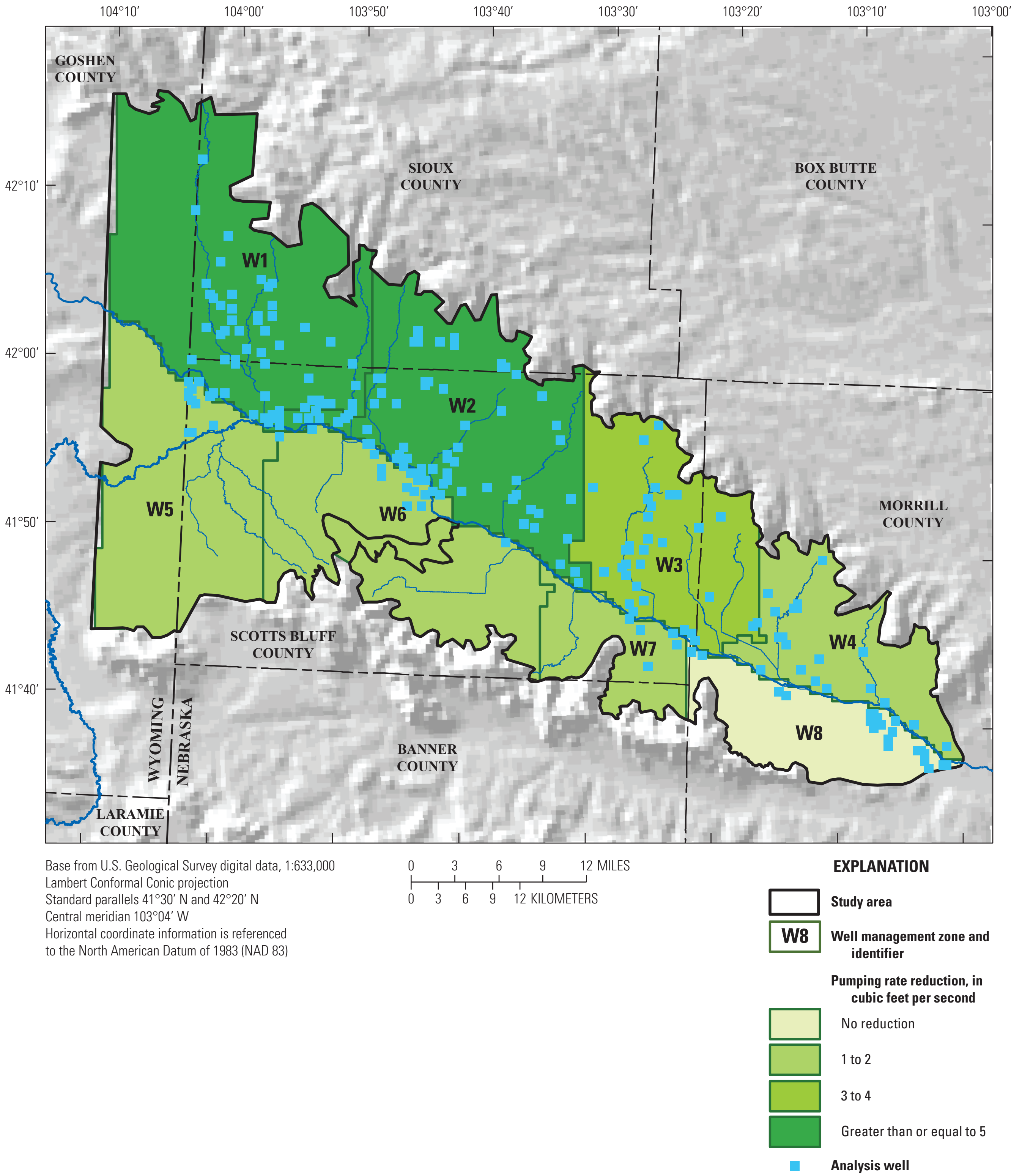

Figure 26. Optimized groundwater withdrawals by zone for the future model with below-average precipitation; groundwater withdrawal rate reductions are relative to the base-case scenario.

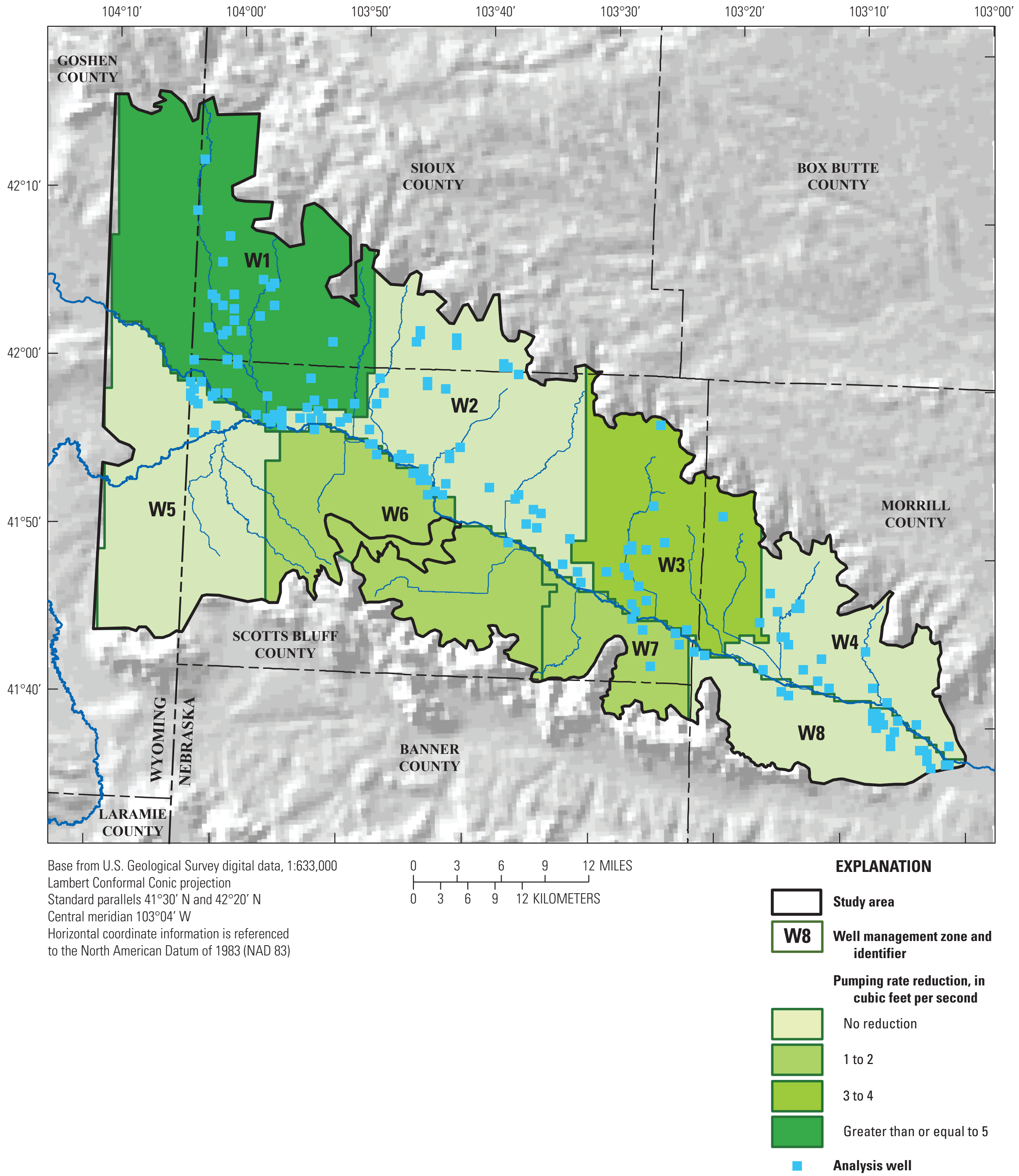

Figure 27. Optimized groundwater withdrawals by zone for the future model with above-average precipitation; groundwater withdrawal rate reductions are relative to the base-case scenario.

W7 (table 6). Zones W1, W3, W6, and W7 also have the largest response coefficients (table 7); therefore, reductions in withdrawals in those zones caused more increases in simulated stream base flow at the constraint location than did reductions in withdrawals in other zones.

Through the optimization of managed groundwater withdrawals, the simulated future base flow of the North Platte River at the Bridgeport streamgage increased by 4–8 ft^3/s in the irrigation season of 2018 across various precipitation conditions. Though this may only be a small part of base flow passing the North Platte River at Bridgeport, Nebr., streamgage, different results, such as larger base-flow increases, are possible. Results presented in this report are one set of answers given the particular timing and location of constraints and decision variables used to construct the simulation-optimization model as a tool for analysis. Future users of the simulation-optimization model will be able to modify the input files to alter constraints, to alter time periods that the constraints are applied to, to alter decision variables constraining groundwater withdrawals by zone, and to alter other variables to explore other feasible management scenarios that may yield larger increases in simulated future base flow of the North Platte River.

Table 7. Response coefficients of decision variables at time step when the binding streamflow constraint in the optimization model was evaluated, from simulation of 2008–19.

[<, less than. Shading indicates intentional recharge sites that were used in the optimized solution at the maximum possible simulated stream base flow.]

Well-management zone (fig. 24)	Above-average precipitation conditions (response coefficient)	Average precipitation conditions (response coefficient)	Below-average precipitation conditions (response coefficient)
W1	0.37	0.38	0.38
W2	0.25	0.26	0.28
W3	0.40	0.41	0.42
W4	0.32	0.33	0.33
W5	0.37	0.37	0.41
W6	0.59	0.58	0.55
W7	0.59	0.52	0.62
W8	0.16	0.15	0.16
	Intentional recharge site		
I1	0.01	0.01	0.02
I2	<0.01	<0.01	0.01
I3	<0.01	<0.01	<0.01
I4	<0.01	<0.01	0.02
I5	0.28	0.28	0.30
I6	0.70	0.70	0.67
I7	0.02	0.02	0.06
I8	0.33	0.32	0.34
I9	0.04	0.03	0.04
I10	0.30	0.32	0.35
I11	0.22	0.22	0.29
I12	0.20	0.19	0.28
I13	0.19	0.19	0.22
I14	<0.01	<0.01	<0.01
I15	<0.01	<0.01	<0.01
I17	0.07	0.07	0.13
I18	<0.01	<0.01	<0.01
I19	0.28	0.28	0.26

Simulations with Management of Groundwater Withdrawal and Intentional Recharge

The second analysis used for optimization of the future model was to determine the maximum simulated stream base flow at the Bridgeport streamgage by managing groundwater withdrawals and intentional recharge rates. Groundwater withdrawals were again grouped by the eight management zones shown in figure 24, and the proportion of discharge assigned to each well in the zone remained the same whereas the groundwater withdrawals were maximized within the range from 50 to 100 percent of the net irrigation requirement. Intentional recharge was minimized at 18 sites, managed individually; therefore, individual intentional recharge sites were only used if the sites helped satisfy the streamflow constraints.

For average precipitation conditions, the maximum flow at the Bridgeport streamgage with managed groundwater withdrawals and intentional recharge was 440 ft^3/s, which is 15 ft^3/s larger than for the base case (table 5). Managed groundwater withdrawals were reduced in seven of the management zones to about 20 ft^3/s smaller than for the base case (table 6), and 5 of the 18 possible intentional recharge sites were used (fig. 28), with a combined recharge rate of 22 ft^3/s. The five intentional recharge sites used were located across the model area, with three of the five close to the North Platte River and two closer to the northern boundary of the area (fig. 28). The five sites used in the optimized solution also had the five largest response coefficients (table 7), and because every site was optimized to apply recharge at the maximum recharge rate, the differences in applied recharge rates were proportional to the size of the sites (larger sites had larger rates). Of the five sites used, four are relatively close to streams, which may partially explain the larger response coefficient.

In addition, several sites (I1–I4, I14, I15, and I18) had low response coefficients, less than or equal to 0.01 (table 7); therefore, if 10 ft^3/s of intentional recharge were applied at one of these sites, simulated stream base flow at the constraint location would increase by a maximum of 0.1 ft^3/s. Combined, at 10 ft^3/s of intentional recharge per site across the seven sites, simulated stream base flow at the constraint location would increase by a maximum of 0.7 ft^3/s. In some cases, sites with small response coefficients are located in poorly transmissive areas of the aquifer or are near model boundaries. Conversely, site I6 is also in an area of moderately low transmissivity (fig. 21) and was not near streams (fig. 24); however, site I6 had a larger response coefficient and was used in the optimized solution (table 7). The possibility exists that site I6 had a larger response coefficient because it is up-gradient of a gap in the ridge separating the two thickest parts of alluvial valley-fill deposits in the area. The responses of the groundwater system to changes in decision variables, such as withdrawals or intentional recharge, are complex.

These results are subject to the availability and location of intentional recharge sites as well as the timing and location of the streamflow constraints specified for these analyses. For a base-flow constraint of 445 ft^3/s, no solution to the problem was feasible; the streamflow constraint could not be met even with the addition of intentional recharge and using the maximum (50-percent) reduction in groundwater withdrawals in all eight zones.

For below-average precipitation conditions, the maximum flow at the Bridgeport streamgage with managed groundwater withdrawals and intentional recharge was 325 ft^3/s, which is 23 ft^3/s larger than for the base case (table 5). Managed groundwater withdrawals were reduced in all eight of the management zones to the maximum 50-percent reduction, about 28 ft^3/s smaller than for the base case (table 6), and 13 of the 18 possible intentional recharge sites were used (fig. 29) at a combined rate of 69 ft^3/s (table 6). Of the intentional recharge sites that were used, eight sites are located in the upstream (western) end of the area and are relatively near the North Platte River, two sites are near the North Platte River but in the downstream (eastern) end of the area, and three sites are located in the central part of the area but closer to the northern boundary (fig. 29). The 13 intentional recharge sites that were used in this solution had the 13 largest response coefficients (table 7). At 330 ft^3/s, the problem was infeasible; the streamflow constraint could not be met with the addition of intentional recharge and with the maximum (50-percent) reduction in groundwater withdrawals in all eight zones.

For above-average precipitation conditions, the maximum flow at the Bridgeport streamgage with managed groundwater withdrawals and intentional recharge was 575 ft^3/s, which is 19 ft^3/s larger than for the base case (table 5). Managed groundwater withdrawals were reduced in all eight of the management zones to the maximum 50-percent reduction, about 26 ft^3/s smaller than for the base case (table 6), and 9 of the 18 possible intentional recharge sites were used (fig. 29) at a combined rate of 37 ft^3/s (table 6). The nine sites used had the nine largest response coefficients (table 7). More than 50 percent (five of nine) of the intentional recharge sites used were near the upstream end of the area and relatively near the North Platte River, and two of the nine sites used were near the North Platte River but in the downstream half of the area (fig. 30). At 580 ft^3/s, the problem was infeasible; the streamflow constraint could not be met with the addition of intention recharge and with the maximum (50-percent) reduction in groundwater withdrawals in all eight zones.

Through the optimization of maximized groundwater withdrawals and minimized application of intentional recharge, simulated stream base flow for the North Platte River at Bridgeport increased by 15–23 ft^3/s above the base-case simulation with no optimization, or about 10–15 ft^3/s larger than the tests with optimized groundwater withdrawals only. For the scenario with managed intentional recharge also included, the authors noted that because the application of intentional recharge was minimized, only the sites where simulated intentional recharge was applied, as shown in figures 28–30, produced increased simulated base flow of the North Platte River at the Bridgeport streamgage subject to the time and location of the constraints applied. Conversely,

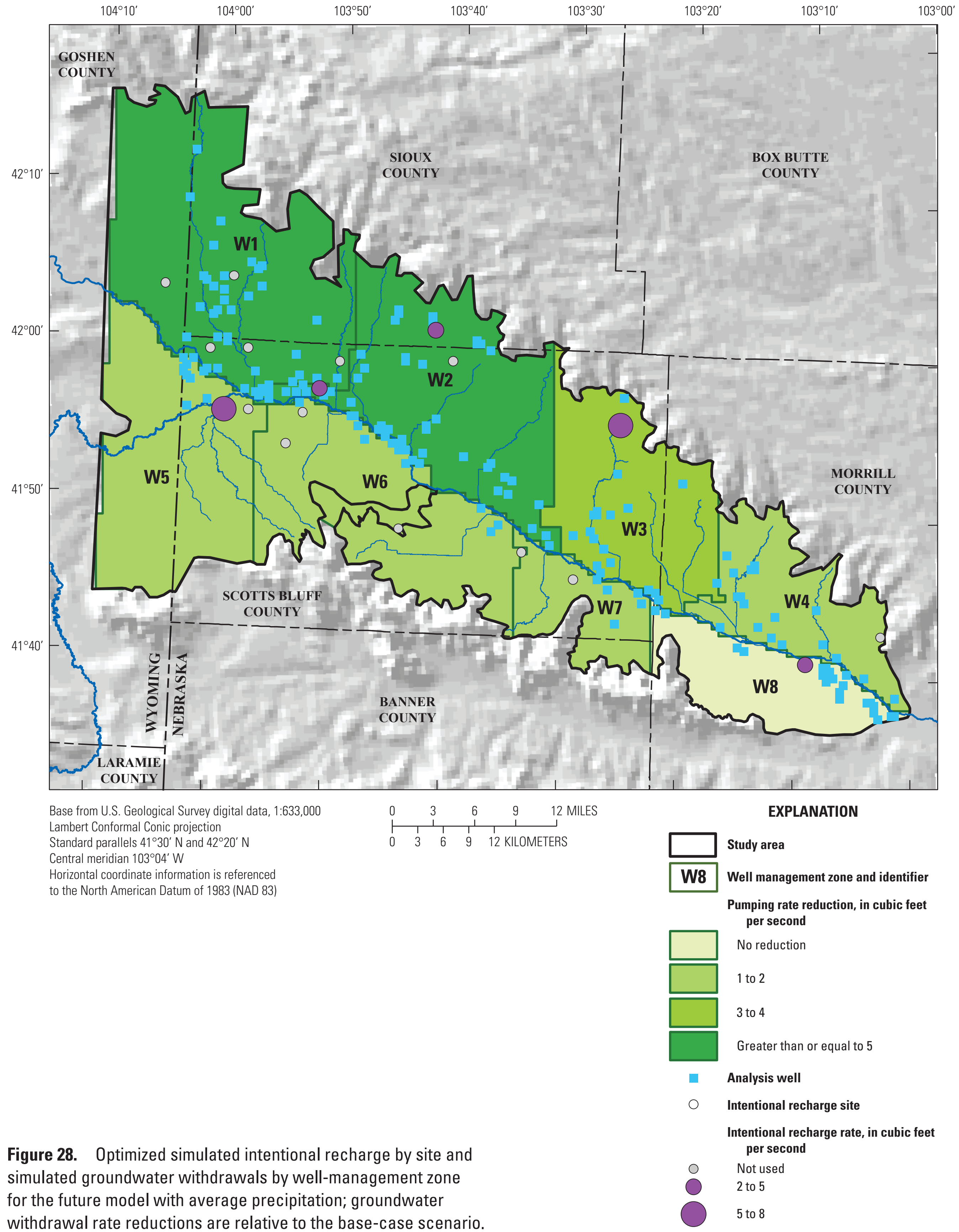

Figure 28. Optimized simulated intentional recharge by site and simulated groundwater withdrawals by well-management zone for the future model with average precipitation; groundwater withdrawal rate reductions are relative to the base-case scenario.

groundwater withdrawals were reduced the most in the management zones with the largest response coefficients. The intentional recharge sites that were used tended to be slightly biased towards being closer to the North Platte River (figs. 29–30), but not in all cases (fig. 28). Sites closer to the river likely cause a quicker increase in groundwater discharge to the North Platte River from nearby intentional recharge sites than for sites further from the North Platte River. Different intentional recharge sites might be selected for use in the optimal solution if the timing or location of the constraints were changed. Further, five of the sites were used for optimized intentional recharge regardless of the precipitation conditions in the future model (figs. 28–30). Common use of these sites indicates that application of intentional recharge at those locations increased simulated base flow of the North Platte River at the Bridgeport streamgage regardless of whether the future climate was wetter, drier, or the same as past climate. Response coefficients indicate the relative effect of each decision variable change on the binding streamflow constraint from these analyses, and for intentional recharge, the sites that had the largest coefficients were used first (table 7). In addition, five intentional recharge sites were not used in this optimization analysis regardless of future precipitation condition (I2, I3, I14, I15, and I18 [fig. 24; table 7]). Those five sites have small response coefficients and are located in poorly transmissive areas of the aquifer or near model boundaries. Less than 1 percent of the simulated intentional recharge applied at these sites would result in increases in simulated stream base flow of the North Platte River at Bridgeport.

Analysis Limitations and Potential Areas for Additional Study

The optimization analysis results presented in this report are dependent on the accuracy of the calibrated groundwater-flow model, the assumptions inherent to the groundwater-flow and simulation-optimization models, and the assumptions inherent in estimated simulation inputs for the future time periods for conditions of below-average, average, or above-average precipitation. The results are further dependent on the specifications used in the optimization setup, the timing and location of the constraints and decision variables applied, and the specified minimum and maximum rates for each decision variable. These results are not intended to catalog every possible set of circumstances but rather to provide a demonstration of how this model can be used as a tool to investigate the effects of water-management options on the base flow of the North Platte River at Bridgeport streamgage. Changes in any of the aspects mentioned before would likely generate different results and differences could be substantial. For example, in the analysis documented in this report, the streamflow constraints for the average and above-average precipitation conditions were applied for the last 5 years of the analysis period, at the end of irrigation season only. If constraints were applied to a different subset of the analysis period, perhaps only to the last year, a different amount of simulated stream base flow might be sustainable.

Additionally, an assumption was made concerning the use of injection wells to simulate intentional recharge in the optimization analysis. Intentional recharge can be adequately simulated using injection wells because the depth to the groundwater is small and the sandy areas selected as potential sites have high permeabilities. In these areas, the transit time of intentional recharge applied at land surface to reach the water table would be small, and therefore similar to that when using an injection well for artificial recharge.

In addition to the mentioned limitations, differences existed between estimated and metered groundwater withdrawals for comingled irrigation, which were beyond the scope of this study to resolve. If future studies determine the cause of these differences and an approach to adjust the simulated withdrawals is used in the calibration model to more closely match metered co-mingled withdrawals, the previous calibration may no longer be valid. The calibration could then be re-evaluated and the effects of water-management options could be re-checked. Similarly, new data and simulation approaches have become available since most of the work on this study was completed; those data and approaches could be considered for future addition to this model and may improve or further refine the results.

With respect to new data, new aquifer altitude-base data from Abraham and others (2012) could be used to further refine the base-of-aquifer surface used in this model; only part of the data from that study were complete at the time of interpretation of an aquifer base for this model; therefore, only part of those data were incorporated into the aquifer base for the simulation documented in this report. Also, approaches such as the Farm Process Version 2 for MODFLOW–2005 (MF–FMP2, Schmid and Hanson, 2009) or the One-Water Hydrologic Flow Model (MODFLOW–OWHM, Hanson and others, 2014) would (1) allow for a comprehensive, simulation of landscape (surface) hydrology fully coupled with groundwater hydrology, (2) provide for a means to simulate base flow and runoff, (3) allow for more realistic simulation of subirrigation of crops with shallow groundwater and the apportionment of water through surface-water delivery and supplemental groundwater withdrawal, (4) allow groundwater and surface-water irrigation to be driven by supply and demand concepts, (5), allow for an improved calibration to raw measured streamflow data as opposed to processed stream base-flow data, and (6) would provide an opportunity to calibrate the simulation using the metered groundwater withdrawal data. All these improvements in data and methodology could provide additional insight into the estimation of comingled groundwater withdrawal and difference from metered comingled groundwater withdrawal.

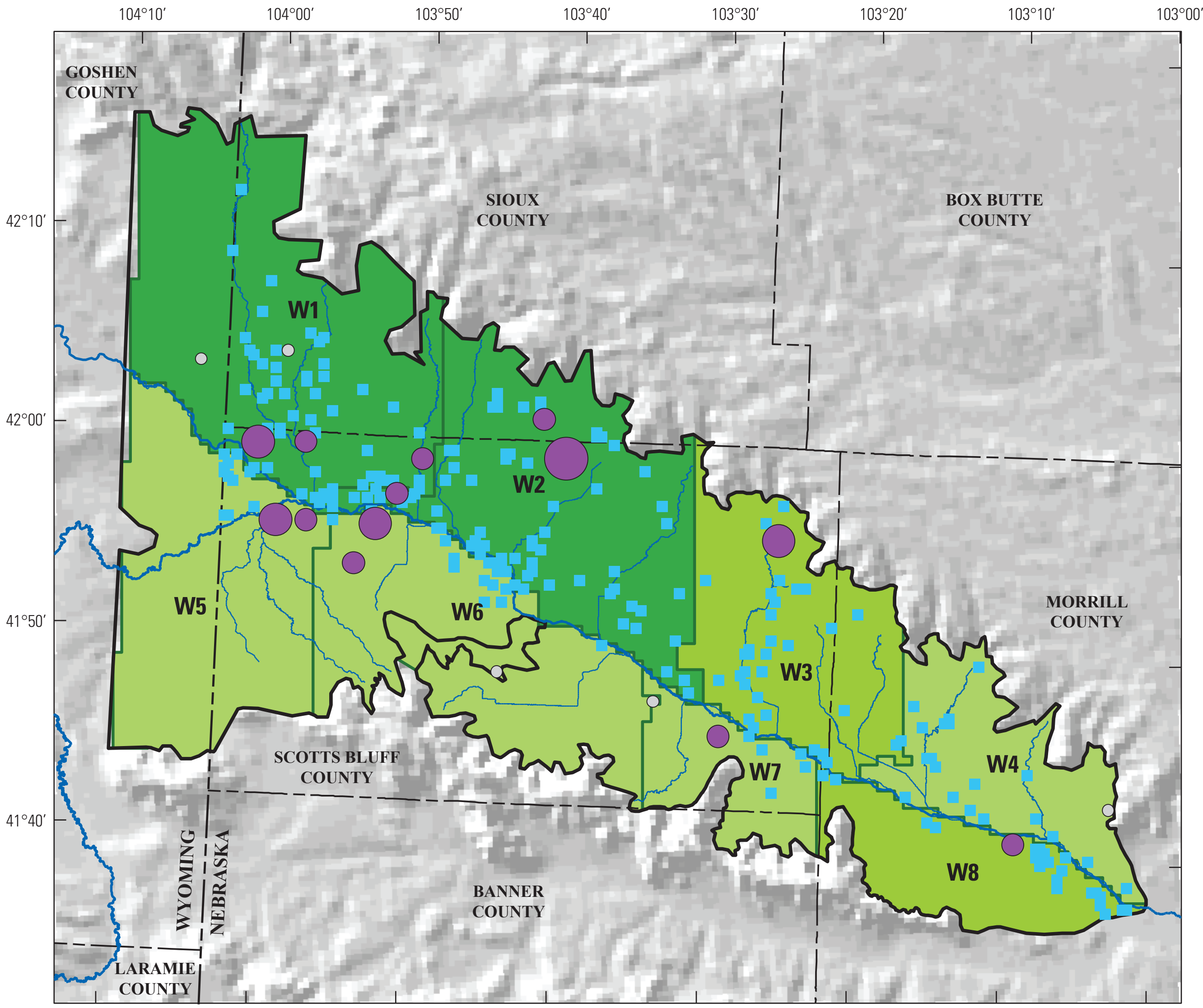

Figure 29. Optimized intentional recharge and groundwater withdrawals by zone for the future model with below-average precipitation; groundwater withdrawal rate reductions are relative to the base-case scenario.

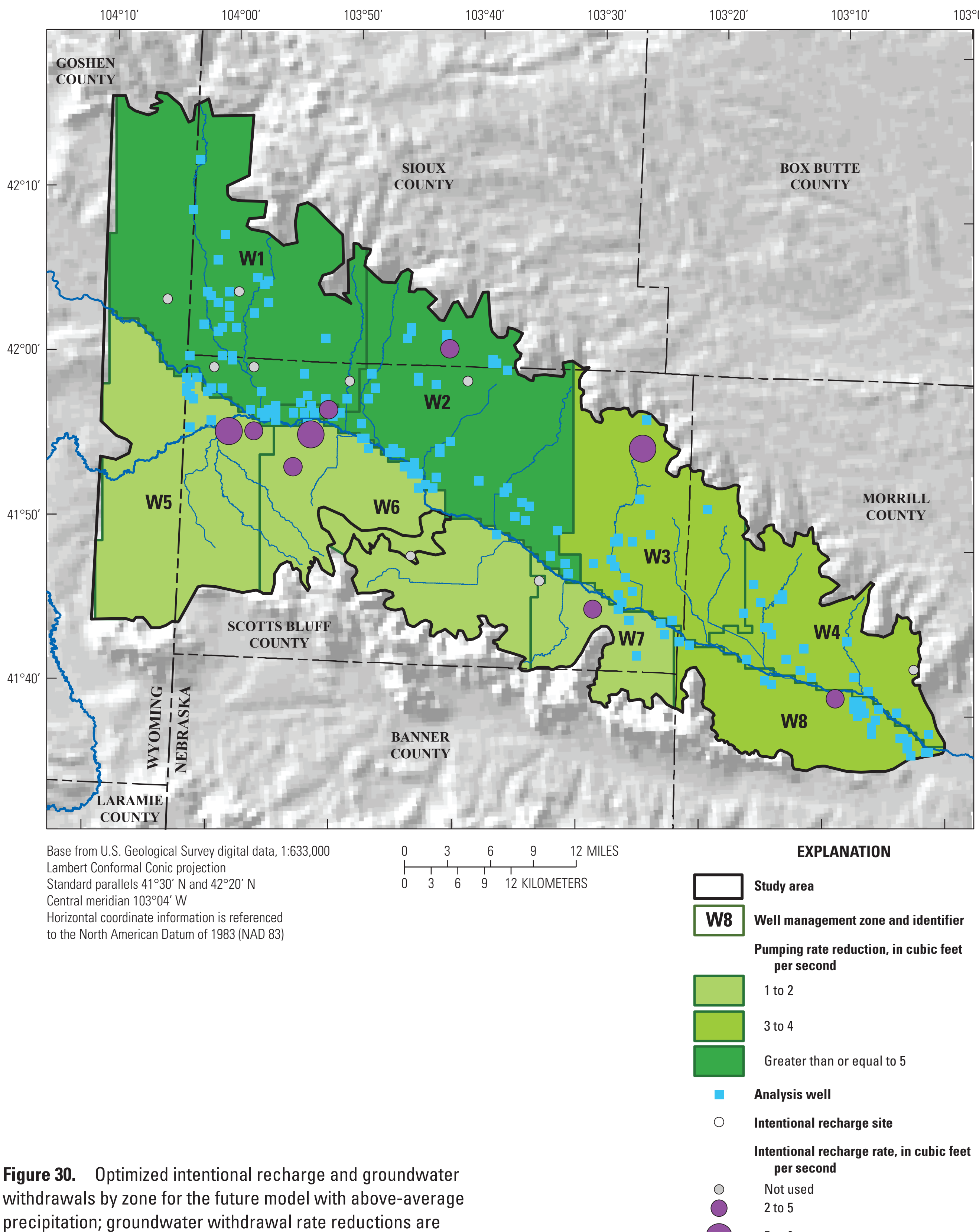

Figure 30. Optimized intentional recharge and groundwater withdrawals by zone for the future model with above-average precipitation; groundwater withdrawal rate reductions are relative to the base-case scenario.

Summary

The North Platte Natural Resources District (NPNRD) has been actively collecting data and studying groundwater resources because of concerns about the future availability of the highly interconnected surface-water and groundwater resources. This report, prepared by the U.S. Geological Survey in cooperation with the North Platte Natural Resources District, describes a groundwater-flow model of the North Platte River valley from Bridgeport, Nebraska, extending west to 6 miles into Wyoming. The model was built to improve the understanding of the interaction of surface-water and groundwater resources and as an optimization tool able to analyze the effects of water-management options on the simulated stream base flow of the North Platte River. Previous studies in this area include regional groundwater-flow models, geophysical investigations of aquifer and canal properties, and studies of groundwater age and quality. Agricultural production in the semiarid study area is sustained through irrigation that was developed primarily from surface water before 1900 and from surface water and groundwater during 1950–2008. In 2012, about three-quarters of the study area was irrigated with surface water. The principal hydrogeologic unit within the study area is Quaternary age and includes alluvial deposits and colluvial deposits mixed with alluvial deposits. The base-of-aquifer, which is the surface where the oldest sediments composing the alluvial aquifer were deposited, is highly irregular and contains paleovalleys and ridges parallel or subparallel to the modern-day North Platte River. Using previously published aquifer-base-altitude contours in conjunction with newer test-hole and geophysical data, a new base-of-aquifer altitude map was generated because of the strong effect of the aquifer-base topography on groundwater-flow direction and magnitude. Groundwater flow is generally west to east but also to the North Platte River and its tributaries. The alluvial aquifer is thickest in the paleovalley in the center of the study area and thins to 10 feet (ft) near the northern and southern boundaries where the aquifer adjoins fine-grained sediments of Tertiary age. The largest inflow to groundwater is recharge originating from water leaking from canals, and is much larger than recharge originating from infiltration of precipitation. The largest component of groundwater discharge from the study area is to the North Platte River and its tributaries, with smaller amounts of discharge to evapotranspiration and groundwater withdrawals for irrigation. Groundwater withdrawals for irrigation increased during 1950–2008, but were a relatively small component of total groundwater outflows in 2008.

The groundwater system and related sources and sinks of water were simulated using MODFLOW–NWT, a newton formulation of the 2005 version of the U.S. Geological Survey modular three-dimensional groundwater model with an improved ability to solve nonlinear unconfined aquifer simulations with wetting and drying of cells. The single-layer model of unconfined intergranular flow was built as two sequential models with stress periods ranging from months to decades to represent the system before substantial groundwater development for irrigation (pre-1950 model), and during groundwater development for irrigation through April 2008 (1950–2008 model). Potential recharge (deep percolation) from infiltration of precipitation was estimated with a daily soil-water-balance model. Annual recharge from canal seepage was estimated with available records from the Bureau of Reclamation and then modified with canal-seepage potentials estimated from geophysical data. Groundwater withdrawals were estimated using land-use and land-cover data, precipitation data, and published crop water-use data. For fields irrigated with surface water and groundwater, surface-water deliveries were subtracted from the estimated net irrigation requirement, and groundwater withdrawal was assumed to be equal to any demand unmet by surface water. Initial aquifer hydraulic conductivity was assigned to the groundwater-flow model based on published data.

Because many of the inputs were unknown and had to be estimated, the groundwater-flow model was calibrated to ensure that the simulated groundwater levels and groundwater discharge to streams reasonably reproduced measured conditions. Calibration was evaluated by comparison of simulated conditions against calibration targets comprised of base flows estimated using the base-flow index method and measured groundwater levels. The parameter estimation suite of software (PEST) was used for model calibration, to perform automated parameter adjustments using statistical techniques. PEST was used to adjust hydraulic conductivity of the aquifer, spatial multipliers to recharge, temporal multipliers to recharge, and two specific recharge parameters; for a total of 273 parameters. Tikhonov regularization was used to stabilize the parameter estimation solution process and prevent over-fitting.

Most simulated groundwater levels and stream base flows were reasonably near the calibration targets at the end of the pre-1950 model. The mean difference between pre-1950 model simulated and groundwater levels and targets was -2.3 ft. The mean residual for more than 5,100 groundwater levels spanning 1950–2008 was -5.7 ft, and simulated groundwater levels were within 25 ft from measured groundwater levels for 94 percent of those targets. The streamgage on the North Platte River at Bridgeport is near the eastern end of the model and accumulates all the base flow that is simulated everywhere else in the model; simulated base flow reasonably matched estimated base flow for this streamgage during 1950–2008, with an average difference of 15 percent. Base flow simulated by the 1950–2008 model followed the overall trend of the estimated base flow reasonably well, with generally increasing or decreasing base flows from the start of the simulation to the end. Simulated base flow also matched estimated base flow reasonably well for most of the North Platte River tributaries with estimated base flow.

Simulated groundwater budgets for the 1950–2008 model featured large inflows from recharge from canal seepage, with a small component of recharge from precipitation. About 98 percent of groundwater outflows were accounted for by

discharge to streams (77 percent) and by evapotranspiration (21 percent). Less than 2 percent of groundwater outflow was to groundwater withdrawals for irrigation. Average simulated groundwater budgets for 1989–2008 were nearly three times larger for irrigation seasons than for non-irrigation seasons.

The calibrated groundwater-flow model was used to build a simulation-optimization model to provide a tool for the NPNRD to better understand how water-management decisions could affect stream base flows in a future period from 2008 to 2019, under varying climatic conditions. The simulation-optimization model was constructed to analyze the minimum amount of reductions in groundwater withdrawals for irrigation that would be necessary to increase simulated stream base flow of the North Platte River at Bridgeport. A second analysis extended the first to analyze the simulated base-flow benefit of groundwater withdrawals along with application of intentional recharge. Using GWM-2005, the groundwater withdrawals were grouped into eight management zones, and groundwater withdrawals were maximized between 50–100 percent of the net irrigation requirement.

The analysis was iterated to solve for the maximum simulated stream base flow for the North Platte River at Bridgeport streamgage. Depending on future precipitation conditions, with no reductions in groundwater withdrawals, maximum simulated stream base flow ranged from 302 to 556 cubic feet per second (ft^3/s); whereas, with optimally managed groundwater withdrawals, simulated stream base flow was increased by 4 to 8 ft^3/s. Simulated base flow was best optimized by reductions in groundwater withdrawals north of the North Platte River and in the western half of the area. A second iterative analysis was completed to investigate the maximum simulated stream base flow attainable if intentional recharge was applied at as many as 18 sites with sandy soils. Using the Groundwater-Management Process for the 2005 version of the U.S. Geological Survey modular three-dimensional groundwater model (GWM-2005) to optimize groundwater withdrawals and intentional recharge, the maximum simulated stream base flow was 15–23 ft^3/s greater than with no management at all or 10–15 ft^3/s larger than with managed groundwater withdrawals only.

Optimization results indicate not only the amount that simulated stream base flow can be increased by applying these management options but also the locations where the management options provide the most or least benefit to the simulated stream base flow. For instance, when groundwater withdrawals were optimized, withdrawals in one of the eight management zones were not reduced under any of the precipitation conditions, indicating that those reductions would not provide a benefit to maximum simulated base flow within the future model period at the North Platte River at Bridgeport streamgage. Of the 18 intentional recharge sites, five of the sites provided benefit to simulated base flow across all future precipitation conditions considered. For above-average or below-average precipitation conditions, intentional recharge sites used in the optimized results were commonly closer to the North Platte River and slightly biased towards the western end of the area. These results are subject to the availability and location of intentional recharge sites as well as the timing and location of streamflow constraints specified in these analyses.

Optimization results presented in this report are one set of answers given the particular timing and location of constraints and decision variables used to construct the simulation-optimization model as a tool for analysis. Future users of the simulation-optimization model will be able to modify the input files as to constraints, time periods that the constraints are applied to, decision variables of groundwater withdrawals by zone, and other variables to explore other feasible management scenarios that may yield different increases in simulated future base flow of the North Platte River.

References Cited

Abraham, J.D., Cannia, J.C., Bedrosian, P.A., Johnson, M.R., Ball, L.B., and Sibray, S.S., 2012, Airborne electromagnetic mapping of the base of the aquifer in areas of western Nebraska: U.S. Geological Survey Scientific Investigations Report 2011–5219, 38 p.

Ahlfeld, D.P., Barlow, P.M., and Mulligan, A.E., 2005, GWM—A Ground-Water Management Process for the U.S. Geological Survey modular ground-water model (MODFLOW–2000): U.S. Geological Survey Open-File Report 2005–1072, 124 p.

Ahlfeld, D.P., Baker, K.M., and Barlow, P.M., 2009, GWM-2005—A Groundwater-Management Process for MODFLOW-2005 with Local Grid Refinement (LGR) capability: U.S. Geological Survey Techniques and Methods, book 6, chap. A33, 65 p.

Autobee, R., 1996, North Platte Project: Bureau of Reclamation Project report, 39 p., accessed October 23, 2014, at http://www.usbr.gov/projects//ImageServer?imgName=Doc_1305124785545.pdf.

Anderson, M.P., and Woessner, W.W., 1992, Applied groundwater modeling—Simulation of flow and advective transport: San Diego, Calif., Academic Press, 381 p.

Ball, L.B., Kress, W.H., Steele, G.V., Cannia, J.C., and Andersen, M.J., 2006, Determination of canal leakage potential using continuous resistivity profiling techniques, Interstate and Tri-State Canals, western Nebraska and eastern Wyoming, 2004: U.S. Geological Survey Scientific Investigations Report 2006–5032, 53 p.

Burton, B.L., Johnson, M.R., Vrabel, Joseph, Imig, B.H., Payne, J.D., and Tompkins, R.E., 2009, Capacitively coupled resistivity survey of selected irrigation canals within the North Platte River valley, western Nebraska and eastern Wyoming, 2004 and 2007–2009: U.S. Geological Survey Scientific Investigations Report 2009–5194, 70 p.

Cannia, J.C., Woodward, Duane, and Cast, L.D., 2006, Cooperative Hydrology Study hydrostratigraphic units and aquifer characterization report: Nebraska Department of Natural Resources, 96 p., accessed June 5, 2015, at http://cohyst.dnr.ne.gov/document/dc012hydro_aquifer_022406.pdf.

Cooperative Hydrology Study, 2003a, Test hole database: Cooperative Hydrology Study, digital data, accessed June 17, 2003, at http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html.

Cooperative Hydrology Study, 2003b, 1995 water table for the Cooperative Hydrology Study area: Cooperative Hydrology Study, digital data, accessed June 17, 2003, at http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html.

Cronshey, R.G., McCuen, R.H., Miller, Norman, Rawls, Walter, Robbins, Sam, and Woodward, Don, 1986, Urban hydrology for small watersheds—TR–55 (2nd ed.): Washington, D.C., U.S. Dept. of Agriculture, Soil Conservation Service, Engineering Division, Technical Release 55, 164 p.

Doherty, J., 2003, Ground water model calibration using pilot points and regularization: Ground Water, v. 41, no. 2, p. 170–177.

Doherty, J., 2010a, PEST, model independent parameter estimation—User manual (5th ed.): Brisbane, Australia, Watermark Numerical Computing, accessed July 26, 2011, at http://pesthomepage.org/.

Doherty, J., 2010b, PEST, model independent parameter estimation—Addendum to user manual (5th ed.): Brisbane, Australia, Watermark Numerical Computing, accessed March 5, 2012, at http://pesthomepage.org/.

Dollison, R.M., 2010, *The National Map*—New viewer, services, and data download: U.S. Geological Survey Fact Sheet 2010–3055, 2 p.

Dripps, W.R., and Bradbury, K.R., 2007, A simple daily soil-water balance model for estimating the spatial and temporal distribution of groundwater recharge in temperate humid areas: Hydrogeology Journal, v. 15, no. 3, p. 433–444.

Fienen, M.N., Muffels, C.T., and Hunt, R.J., 2009, On constraining pilot point calibration with regularization in PEST: Ground Water, v. 47, no. 6, p. 835–844.

Garen, D.C., and Moore, D.S., 2005, Curve number hydrology in water quality modeling—Uses, abuses, and future directions: Journal of the American Water Resources Association, v. 41, no. 2, p. 377–388.

Geometrics, 2009, MagMap2000, version 4.86: Geometrics, 3 p., accessed May 2009 at http://www.geometrics.com/geometrics-products/geometrics-electro-magnetic-products/ohm-mapper.

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

Hanson, R.T., Boyce, S.E., Schmid, Wolfgang, Hughes, J.D., Mehl, S.M., Leake, S.A., Maddock, Thomas, III, and Niswonger, R.G., 2014, One-water hydrologic flow model (MODFLOW–OWHM): U.S. Geological Survey Techniques and Methods, book 6, chap. A51, 120 p. [Also available at http://dx.doi.org/10.3133/tm6A51.]

Harbaugh, A.W., 2005, MODFLOW–2005, the U.S. Geological Survey modular ground-water model—The ground-water flow process: U.S. Geological Survey Techniques and Methods book 6, chap. A16, variously paged.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW–2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00–92, 121 p.

Hargreaves, G.H., and Samani, Z.A., 1985, Reference crop evapotranspiration from temperature: Applied Engineering in Agriculture, v. 1, no. 2, p. 96–99.

Helsel, D.R. and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chapter A3, 522 pages.

Hill, M.C., and Tiedeman, C.R., 2007, Effective groundwater model calibration—With analysis of data, sensitivities, predictions, and uncertainty: Hoboken, N.J., Wiley-Interscience, 455 p.

Hunt, R.J., Doherty, J., and Tonkin, M.J., 2007, Are models too simple? Arguments for increased parameterization: Ground Water, v. 45, no. 3, p. 254–262.

Luckey, R.R., and Cannia, J.C., 2006, Groundwater flow model of the western model unit of the Nebraska Cooperative Hydrology Study (COHYST) Area: Nebraska Department of Natural Resources, 63 p., accessed July 6, 2007, at http://cohyst.dnr.ne.gov/adobe/dc012WMU_GFMR_060519.pdf.

Luckey, R.R., Carney, C.C., and Peterson, S.M., 2001, Estimated groundwater discharge to streams from the High Plains aquifer in the western model unit of the Cooperative Hydrologic Study area for the period prior to major groundwater irrigation: Nebraska Department of Natural Resources, 20 p., accessed July 6, 2007, at http://cohyst.dnr.ne.gov/adobe/dc012WMU_baseflw_0901.pdf.

Lugn, A.L., 1935, The Pleistocene geology of Nebraska: Nebraska Geological Survey Bulletin 10, 223 p.

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., and Barlow, P.M., 2008, GSFLOW-Coupled ground-water and surface-water flow model based on the integration of the precipitation-runoff modeling system (PRMS) and the modular ground-water flow model (MODFLOW–2005): U.S. Geological Survey Techniques and Methods, book 6, chap. D1, 240 p.

Molnau, Myron, and Bissell, V.C., 1983, A continuous frozen ground index for flood forecasting, *in* Western Snow Conference, 51st, Vancouver, Wash., 1983, Proceedings: Brush Prairie, Wash., Western Snow Conference, p. 109–119. [Also available at http://www.westernsnowconference.org/sites/westernsnowconference.org/PDFs/1983Molnau.pdf.]

National Climatic Data Center, 2009, NCDC Online: National Climatic Data Center, digital data for Scottsbluff W. B. Heilig Field Airport, accessed September 25, 2012, at http://www7.ncdc.noaa.gov/CDO/cdo.

Nebraska Department of Natural Resources, 2004, A report of preliminary findings from a study of hydrologically connected ground and surface water and its contribution to conflicts between ground water users and surface water appropriators in the North Platte Natural Resources District: Nebraska Department of Natural Resources, 48 p., accessed December 19, 2014, at http://www.dnr.ne.gov/Media/PDF/technicalreport.pdf.

Nebraska Department of Natural Resources, 2008, Registered well database: Nebraska Department of Water Resources, digital data, accessed May 26, 2015, at http://dnr.nebraska.gov/gwr/registered-groundwater-wells-data-retrieval.

Nebraska Department of Natural Resources, 2013, Department of Natural Resources stream gaging: Nebraska Department of Natural Resources, digital data, accessed June 5, 2015, at http://data.dnr.nebraska.gov/RealTime/Gage/Index.

Nebraska Legislature, 2004, Legislative Bill 962–Order designating over-appropriated river basins, subbasins, or reaches, and describing hydrologically connected geographic area: Nebraska Department of Natural Resources, 5 p., accessed September 20, 2012, at http://dnr.nebraska.gov/iwm/overappropriated-basin-order-9-15-04-2.

Niswonger, R.G., Panday, S., and Ibaraki, M., 2011, MODFLOW–NWT, A Newton formulation for MODFLOW–2005: U.S. Geological Survey Techniques and Methods, book 6, chap. A37, 44 p.

North Platte Natural Resources District, 2009, Integrated management of ground and surface water: North Platte Natural Resources District, accessed March 31, 2009, at http://www.npnrd.org/ground-water/integrated-management-plan-imp/.

Peel, M.C., Finlayson, B.L., and McMahon, T.A., 2007, Updated world map of the KÖppen-Geiger climate classification: Hydrology and Earth System Sciences, v. 11, p. 1633–1644.

Rantz, S.E, and others, 1982, Measurement and computation of streamflow, Volume 1–Measurement of stage and discharge: U.S. Geological Survey Water Supply Paper 2175, 284 p.

Santhi, C., Allen, P.M., Muttiah, R.S., Arnold, J.G., and Tuppad, P., 2007, Regional estimation of base flow for the conterminous United States by hydrologic landscape regions: Journal of Hydrology, v. 12, p. 139–153.

Schmid, W., and Hanson, R.T., 2009, The Farm Process version 2 (FMP2) for MODFLOW–2005—modifications and upgrades to FMP1: U.S. Geological Survey Techniques and Methods, book 6, chap. A32, 102 p.

Shepard, Donald, 1968, A two-dimensional interpolation function for irregularly-spaced data *in* Association for Computing Machinery National Conference, 23rd, New York, N.Y., 1968, Proceedings: New York, N.Y., Association for Computing Machinery, p. 517–524.

Smith, B.D., Abraham, J.D., Cannia, J.C., Minsley, B.J., Deszcz-Pan, M., and Ball, L.B., 2010, Helicopter electromagnetic and magnetic geophysical survey data, portions of the North Platte and South Platte Natural Resources Districts, western Nebraska, May 2009: U.S. Geological Survey Open-File Report 2010–1259, 33 p.

Soil Survey Staff, 2004, Web Soil Survey 3.0: U.S. Department of Agriculture, Natural Resources Conservation Service, accessed September 25, 2012, at http://websoilsurvey.nrcs.usda.gov/.

Stanton, J.S., Peterson, S.M., and Fienen, M.N., 2010, Simulation of groundwater flow and effects of groundwater irrigation on stream base flow in the Elkhorn and Loup River basins, Nebraska, 1895–2055—Phase two: U.S. Geological Survey Scientific Investigations Report 2010–5149, 78 p. with app.

Stanton, J.S., Qi, S.L., Ryter, D.W., Falk, S.E., Houston, N.A., Peterson, S.M., Westenbroek, S.M., and Christenson, S.C., 2011, Selected approaches to estimate water-budget components of the High Plains, 1940 through 1949 and 2000 through 2009: U.S. Geological Survey Scientific Investigations Report 2011–5183, 79 p.

State Board of Irrigation, 1899, Second biennial report to the Governor of Nebraska: Lincoln, Nebr., State Board of Irrigation, 235 p., 1 map.

Steele, G.V., and Cannia, J.C., 2003, Occurrence of pesticides in ground water of the North Platte Natural Resources District, Nebraska, 2003: U. S. Geological Survey Fact Sheet 114–03, 4 p.

Steele, G.V., Cannia, J.C., and Scripter, K.G., 2002, Hydrologic characteristic of selected alluvial aquifers in the North Platte Natural Resources District, western Nebraska: U.S. Geological Survey Water-Resources Investigations Report 2001–4241, 24 p.

Steele, G.V., Cannia, J.C., and Stanton, J.S., 1998, Geohydrology and water quality of the North Platte River alluvial aquifer, Garden County, western Nebraska, 1993–94: U.S. Geological Survey Water-Resources Investigations Report 98–4033, 75 p.

Steele, G.V., Verstraeten, I.M., and Cannia, J.C., 2001, Surface-water/ground-water interaction and implications for ground-water sustainability in the Dutch Flats area, western Nebraska: U.S. Geological Survey Fact Sheet 074–01, 4 p.

Swinehart, J.B., and Diffendal, R.F. Jr., 1997, Geologic map of the Scottsbluff 1° X 2° quadrangle, Nebraska and Colorado: U.S. Geological Survey Geologic Investigations Map I–2545, 1 plate.

Swinehart, J.B., Souders, V.L., DeGraw, H.M, and Diffendal, R.F., 1985, Cenozoic paleogeography of western Nebraska, *in* Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of west-central United States: Denver, Colo., Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 209–230.

Thornthwaite, C.W., and Mather, J.R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Centerton, N.J., Drexel Institute of Technology, Laboratory of Climatology, v. 10, no. 3, p. 185–311.

U.S. Department of Agriculture, 2004, Hydrology, Chapter 9 of USDA–NRCS National Engineering Handbook: Washington, D.C., U.S. Department of Agriculture, 14 p.

U.S. Department of Agriculture, 2006, United States General Soil Map (STATSGO2): Natural Resources Conservation Service, digital data, accessed May 26, 2009, at http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx.

U.S. Geological Survey, 2008, National Hydrography Dataset (medium resolution): U.S. Geological Survey, digital data, accessed September 10, 2008, at http://nhd.usgs.gov/index.html/.

U.S. Geological Survey, 2012, National Water Information System: U.S. Geological Survey, digital data (Water Data for the Nation), accessed December 2, 2013, at http://waterdata.usgs.gov/nwis/.

U.S. Geological Survey and Nebraska Department of Natural Resources, 1998, 7.5 Minute digital elevation models—DEM–10 meter—Index for the State of Nebraska: Nebraska Department of Natural Resources geospatial data, accessed May 2010 at ftp://dnrftp.dnr.ne.gov/pub/data/dems/dem10/.

University of Nebraska, 2002, Crop water use in western Nebraska: University of Nebraska, Cooperative Extension, NebGuide G1465, accessed May 26, 2015, at http://www.ianrpubs.unl.edu/epublic/archive/g1465/build/g1465.pdf.

University of Nebraska-Lincoln, 2007, 2005 Land use mapping: Center for Advanced Land Management Information Technologies (CALMIT), digital data, accessed March 15, 2009, at http://www.calmit.unl.edu/2005landuse/.

University of Nebraska-Lincoln, Conservation and Survey Division, 2013, Configuration of the water table, 1995: University of Nebraska-Lincoln, Conservation and Survey Division, geospatial data, accessed December 2013 at http://snr.unl.edu/data/geographygis/water.aspx.

Verstraeten, I.M., Sibray, S.S., Cannia, J.C., and Tanner, D.Q., 1995, Reconnaissance of ground-water quality in the North Platte Natural Resources District, western Nebraska, June–July 1991: U.S. Geological Survey Water Resources Investigations Report 94–4057, 114 p.

Verstraeten, I.M., Steele, G.V., Cannia, J.C., Hitch, D.E., Scripter, K.G., Bohlke, J.K., Kraemer, T.F., and Stanton, J.S., 2001, Interaction of surface water and ground water in the Dutch Flats area, western Nebraska, 1995–99: U.S. Geological Survey Water-Resources Investigation Report 01–4070, 56 p.

Vrabel, J., Teeple, A.P., and Kress, W.H., 2009, Estimation of leakage potential of selected sites in Interstate and Tri-State Canals using geostatistical analysis of selected capacitively coupled resistivity profiles, western Nebraska, 2004: U.S. Geological Survey Scientific Investigations Report 2009–5223, 24 p. [Also available at http://pubs.usgs.gov/sir/2009/5223/.]

Wahl, K.L., and Wahl, T.L., 2007, BFI—A computer program for determining an index to base flow, version 4.15: Bureau of Reclamation software release, accessed July 23, 2008, at http://www.usbr.gov/tsc/hydlab/twahl/bfi/.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB—A modified Thornthwaite-Mather Soil-Water-Balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods, book 6, chap. A31, 60 p., accessed December 20, 2010, at http://pubs.usgs.gov/tm/tm6-a31/.

Wilson, J.D., and Naff, R.L., 2004, The U.S. Geological Survey modular ground-water model—GMG linear equation solver package documentation: U.S. Geological Survey Open-File Report 2004–1261, 47 p.

Publishing support provided by:
Rolla Publishing Service Center

For more information concerning this publication, contact:
Director, USGS Nebraska Water Science Center
5231 South 19th Street
Lincoln, NE 68512
(402) 328–4100

Or visit the Nebraska Water Science Center Web site at:
http://ne.water.usgs.gov

Peterson and others—**Simulation of Groundwater Flow and Water-Management Options in the North Platte Natural Resources District, Nebraska**—SIR 2015–5093

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20155093