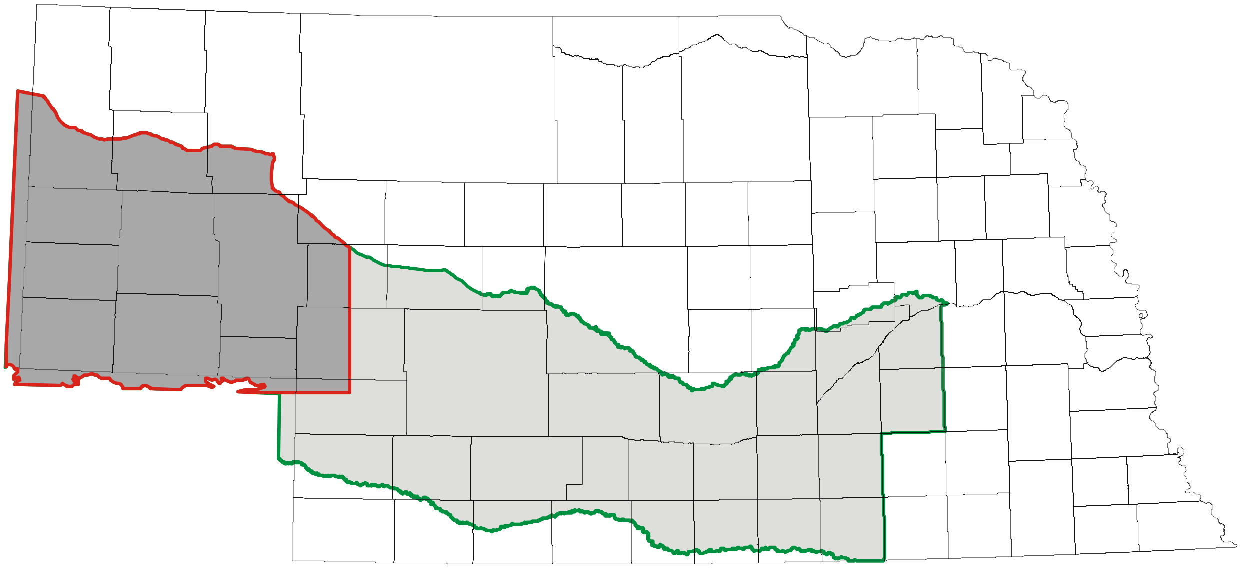
Groundwater Flow Model

of the Western Model Unit of the Nebraska

Cooperative Hydrology Study (COHYST) Area



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Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 – a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly call Sea Level Datum of 1929.

Elevation: In this report, “elevation” refers to distance above sea level.

Executive Summary

The Cooperative Hydrology Study (COHYST) is a hydrologic study the Platte River Basin of Nebraska upstream from Columbus, Nebraska. The study will assist Nebraska in meeting its obligations under the Three-State Cooperative Agreement, assist the Natural Resources Districts in the study area with regulation and management of groundwater, provide Nebraska with the basis for groundwater and surface-water policy, and help analyze the hydrologic effects of proposed activities of the Three-State Cooperative Agreement.

The COHYST study area covers 29,300 square miles and extends from the Republican River and Frenchman Creek on the south to the Loup River, South Loup River, and a mapped groundwater divide on the north. The eastern boundary follows counties lines. The western boundary and part of the southern boundary are 6 miles inside Colorado and Wyoming. The COHYST study area was divided into three overlapping units. This report describes the groundwater flow model that was constructed for the Western Model Unit.

COHYST developed a formal strategy for construction and calibration of flow models. The overall strategy was to start simple and add detail to the models as required. This report describes the final model for the Western Model Unit. This model had a grid size of 160 acres and a single layer. Models for two separate periods were constructed. The first was for the period prior to large-scale development of the aquifer for irrigation (pre-groundwater development period, prior to 1950) and the second was for the period after the beginning of large-scale development (groundwater development period, 1950-98).

The Western Model Unit is about 130 miles east-west by 90 miles north-south and cover 11,300 square miles. About 90,000 people inhabit the area. Agriculture dominates the livelihood and landscape of the region, with land in the valleys irrigated with both surface water and groundwater. Upland areas are used primarily for grazing, dryland crops, and irrigated crops using groundwater from the High Plains aquifer. The topography varies from relatively flat areas such as tablelands and floodplains to hummocky sand dunes. Climate is generally semiarid. Average 1961-90 precipitation ranges from less than 14 to more than 18 inches per year. Most of the precipitation occurs in the summer with about two-thirds of the annual total occurring in May through September. Abundant sunshine, frequent winds, and low humidity contribute to a relatively high rate of evaporation.

The North Platte River flows approximately through the center of the Western Model Unit, and the South Platte River flows across the southeastern part. Other major streams in the area include Blue Creek, Lodgepole Creek, and Pumpkin Creek. Lake McConaughy is in the eastern part of the area. Numerous natural small lakes and wetlands occur in the Sand Hills in the northeastern part of the model unit.

The water table in the High Plains aquifer ranges from more than 5,300 feet above sea level in the southwest to less than 3,200 feet in the east. Depth to water ranges from nearly zero close to streams to as much as 300 feet in the southwestern part of the Western Model Unit. The water table generally slopes to the east at 15 to 20 feet per mile.

The geologic units in the Western Model Unit important to the flow model consist of various Pliocene and Quaternary age deposits, the Ogallala Group, the Arikaree Group, and the Brule Formation. Pliocene and Quaternary age deposits typically yield large amounts of water to wells. The Ogallala also typically yields large amounts of water to wells. The Arikaree Group generally yields only minor amounts of water to wells, but where sufficient saturated thickness exists, it can yield large amounts of water to wells. The Brule Formation normally does not yield water to wells, but in some areas, it is highly fractured and yields large quantities of water.

The process of constructing a numerical flow model begins with a conceptual flow model, which is a description of the characteristics of the flow system that are important to the numerical model. The conceptual model includes the state of the flow system at the beginning of the simulation period, how the flow system interacts with external sources or sinks of water, the lateral and vertical boundaries of the model, and what happens to the elevation or flow of water at these boundaries. The external boundaries of the Western Model Unit consist of fixed-flow boundaries at the eastern, western, and part of the northern boundaries and zero-flow boundaries along much of the northern and the entire southern boundary. The North Platte and South Platte Rivers were river boundaries. All other perennial streams were stream boundaries. The areas of numerous lakes in the Sand Hills were treated as groundwater evapotranspiration areas, as were 1-2 mile wide corridors along the North Platte and South Platte Rivers. Recharge from surface-water irrigation and canal leakage was included in the model beginning in 1900. Lake McConaughy was included in the model beginning in 1940. The pre-groundwater development period model simulated the groundwater system in 1900 as being in a state of long-term dynamic equilibrium, called steady state. The groundwater development period model simulated the 1950-98 groundwater system as being in a transient state due to increasing groundwater development.

MODFLOW was selected as the groundwater flow modeling code for this study. The Groundwater Modeling System (GMS version 5.1) was selected as the pre- and post-processor for MODFLOW. A north-south grid, consisting of 228 rows and 260 columns, resulted in 45,040 active 160-acre cells.

The pre-groundwater development period model started with the period prior to 1900. This was a 2,000-year simulation to allow the groundwater system to come into dynamic equilibrium with recharge from precipitation on rangeland. The distribution of this recharge was generally based on soils and topography. The recharge ranged for 2.30 inches per year in the Sand Hills to 0.15 inches per year on the clay-loam soils in Box Butte and Sioux Counties. Recharge due to canal leakage and surface-water irrigation was added to the model beginning in 1900, and ranged from 17 to 51 percent of average historical canal diversions for 1965-94. Lake McConaughy was added to the model in 1940.

Hydraulic conductivity was assigned, in a general sense, based on geologic units. The largest hydraulic conductivity, 150 feet per day, was assigned to the North Platte Valley. The smallest hydraulic conductivity, 5 feet per day, was assigned to the area south of the North Platte River where the Brule Formation underlies colluvium. The hydraulic conductivity of areas where the Ogallala Group is the dominant water-bearing unit was subdivided into zones of high, intermediate, and low hydraulic conductivity. The high zone represents a high-energy depositional environment generally west of the Rush Creek Structure. The low zone represents a low-energy depositional environment generally east of this structure. The intermediate zone represents a mixture of depositional environments. Specific yield was set to 0.18 over much of the Western Model Unit, but was set to 0.12 where the Arikaree Group in the dominant geologic unit of the aquifer and was set to 0.20 along the North Platte and South Platte Valleys. The maximum groundwater evapotranspiration rate was 16 inches per year in the western half of the model and 15 inches per year in the eastern half. This rate was reduced to zero when the depth to water reached 7 feet in the riparian corridors along the rivers and 5 feet elsewhere.

Simulated 1950 water levels were compared to observed water levels at 144 observation points. The mean difference was 1.09 feet, the mean absolute difference was 10.63 feet, and the root-mean-square difference was 14.50 feet. Simulated groundwater discharge to the North Plate River and to its north-side tributaries were within calibration range. Simulated discharge to Pumpkin Creek and Blue Creek were below the calibration range. Simulated discharge to the South Platte River was within calibration range. Simulated discharge to Lodgepole Creek was above calibration range.

The groundwater development period model simulated the period 1950-98 and started with the simulated 1950 water level from the pre-groundwater development period. All of the inputs from the per-groundwater development period model were retained and other time-varying inputs were added for the 1950-98 period. Annual pumpage for groundwater-irrigated crops was estimated based on reported county land uses for various years from Census of Agriculture, mapped 1997 land use, and estimated net irrigation requirements. Net irrigation requirements were estimated in two ways, NebGuide and CropSim. These estimates are for net pumpage, which is total pumpage less any runoff and deep percolation.

Additional time-varying recharge, above the amount in the pre-groundwater period model, was added during the groundwater development period. This recharge was added only to cropped land, with more recharge added to irrigated land than to dryland. This recharge varied over time because the amount of dryland and irrigated crop land varied over time. The additional recharge on dryland ranged from 0.25 inches per year on soils with the largest soil water capacity to 1.10 inches per year on soils with the smallest soil water capacity. Additional recharge on irrigated land ranged from 2.10 to 3.60 inches per year when NebGuide net pumpage was used and ranged from 3.10 to 4.60 inches per year when CropSim net pumpage was used. This difference compensated for differences in the net pumpage estimates.

Simulated water-level changes were compared to measured water-level changes for five periods (1950-61, 1961-73, 1973-85, 1985-98, and 1950-98), with the number of points per period ranging from 31 to 92. The mean difference with CropSim net pumpage ranged from -0.68 to 1.31 feet, the mean absolute difference ranged from 1.46 to 4.67 feet, and the root-mean-square difference ranged from 2.42 to 7.20 feet. Similar results were obtained with NebGuide net pumpage. The simulated 1950-98 changes were also compared to estimated changes at 145 points. The mean difference with CropSim pumpage was 0.05 feet, the mean absolute difference was 5.01 feet, and the root-mean-square difference was 7.17 feet.

This model was compared to the pre-groundwater development period model of the Central Model Unit to the east. Hydraulic conductivity was arrived at in different ways for the two models, but the values were similar. Rangeland recharge was based on topographic setting in both models and similar results were obtained. The model of the Central Model Unit simulated a smaller evapotranspiration rate, but over a larger area, than the model of the Western Model Unit. The simulated 1950 water tables were generally similar in the southern half of the area of overlap. In the northern half of the area of overlap, the 100-foot contours were parallel, but were displaced from each other by about 3 to 8 miles. This difference probably was due to differences in simulated evapotranspiration. The groundwater development period model of the Central Model Unit had not been completed at the time this report was written, so no comparison of this period could be made.

An analysis was performed to determine the sensitivity of the calibrated model to changes in model inputs. A separate analysis was performed for the pre-groundwater development period model and the groundwater development period model, and different inputs were investigated for different periods. For the pre-groundwater development period, changes in evapotranspiration rate, hydraulic conductivity, rangeland recharge, and streambed conductance were investigated. The model was most sensitive to changes in rangeland recharge followed by changes in hydraulic conductivity. The model was only somewhat sensitive to evapotranspiration rate and was relatively insensitive to streambed conductance. For the groundwater development period, changes in dryland recharge, irrigated land recharge, net pumpage, and specific yield were investigated. The groundwater development model was most sensitive to changes in net pumpage and was about equally sensitive to changes in the other three inputs.

This model was designed to be a regional representation of the groundwater flow system. As such, it is useful for investigating the effects of water-management plans over townships or counties. Care should be exercised if this model is used beyond the purpose for which it was constructed. This model is better calibrated in regions with greater numbers of water-level or streamflow observations to calibrate against, and is less precise in regions without calibration information.

This model can only represent the flow system as it was understood at the time the model was constructed. As more information is collected and the understanding of the flow system improves, this model should be updated. The groundwater development period model was severely hampered by the lack of pumpage data. Recharge from precipitation on dryland fields was poorly defined in this model. This model input could be improved with additional water-level data. Evapotranspiration parameters for areas where the water table is near land surface also were poorly defined in this model. The representation of evapotranspiration in the model, as well as evapotranspiration parameters, also needs further research and refinement.

Description and Purpose of COHYST and Purpose of Report

The Cooperative Hydrology Study (COHYST) is a hydrologic study of surface water and groundwater resources in the Platte River Basin of Nebraska upstream from Columbus, Nebraska. COHYST was started in early 1998 to develop scientifically supportable hydrologic databases, analyses, models, and other information which, when completed, will:

1. Assist Nebraska in meeting its obligations under the Three-State Cooperative Agreement (Governors of Wyoming, Colorado, and Nebraska, and the Secretary of the Interior, 1997; for more information, see http://www.platteriver.org/);
2. Assist the Natural Resources Districts (NRD's) in the study area with regulation and management of groundwater;
3. Provide Nebraska with the basis for groundwater and surface-water policy; and
4. Help Nebraska analyze the hydrologic effects of proposed activities of the Three-State Cooperative Agreement.

The COHYST study area (fig. 1) covers 29,300 square miles (mi^2) and extends from the Republican River and Frenchman Creek on the south to the Loup River, South Loup River, and a mapped groundwater divide on the north. The eastern boundary is a geographic boundary that follows county lines, but was located sufficiently far east that errors in estimated groundwater flow across this boundary are likely to have minimal effect on groundwater discharge to the Platte River at Columbus. The western boundary and part of the southern boundary also are geographic boundaries, and are placed 6 miles (mi) inside Colorado and Wyoming. The remainder of the southern boundary in Colorado is the extent of the aquifer. These boundaries are sufficiently far from Nebraska that errors in estimated groundwater flow across these boundaries will have minimal effect on the study results in Nebraska. Additionally, the southern boundary along the Nebraska panhandle in Colorado nearly follows a mapped groundwater flow line, so little groundwater is likely to cross this boundary.

The COHYST study area was divided into three overlapping areas, called Model Units, for the purpose of constructing groundwater flow models (fig. 1). This report describes the groundwater flow model that was constructed for the Western Model Unit.

Acknowledgments

This study was supported by the various state and local agencies that make up the COHYST Sponsors, including two state agencies, seven NRD's, and two public power districts. The Sponsors include:

Nebraska Department of Natural Resources (previously Nebraska Natural Resources Commission
    and Nebraska Department of Water Resources)
Nebraska Game and Parks Commission
Central Platte NRD
Little Blue NRD
North Platte NRD
South Platte NRD

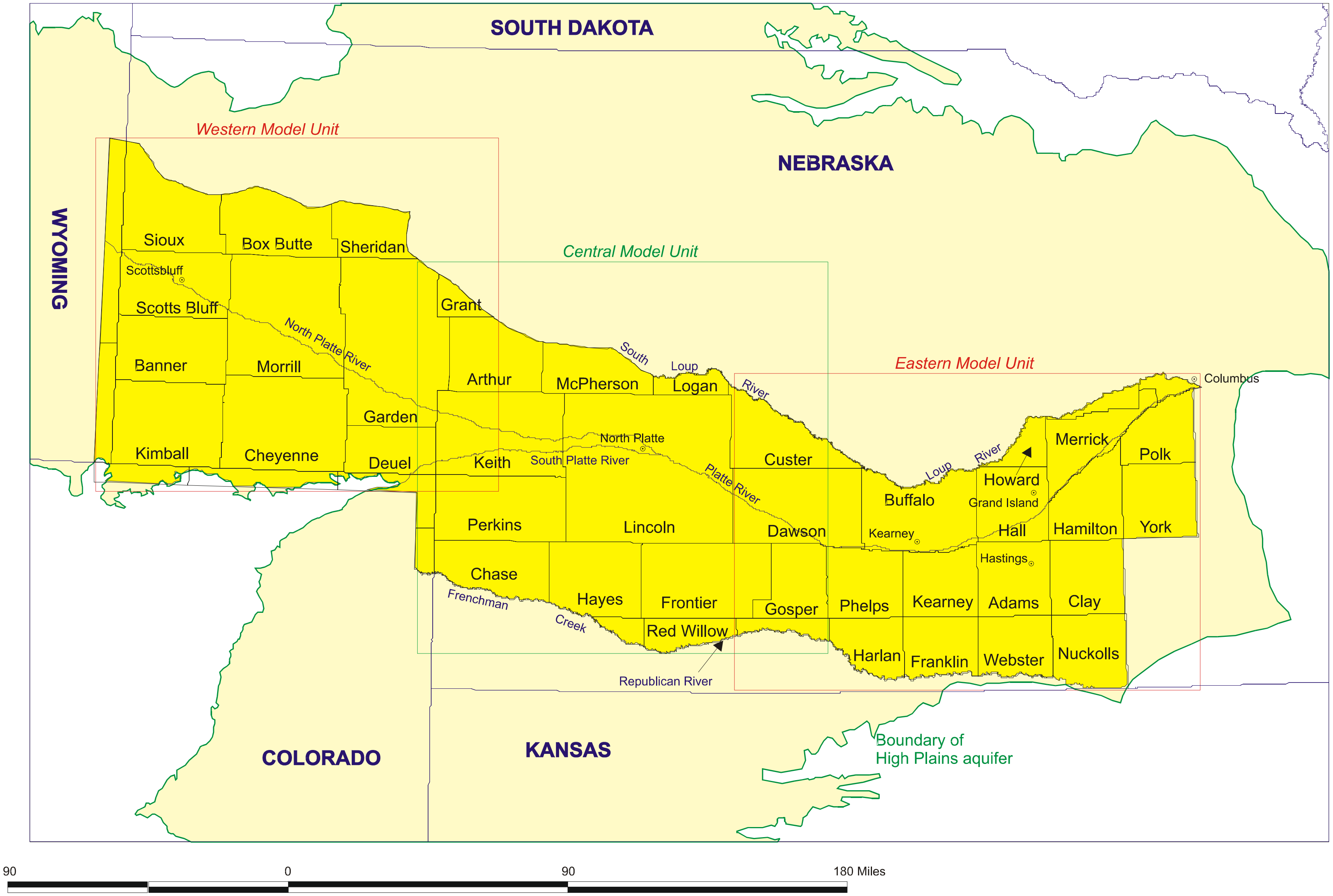

Figure 1. COHYST study area (darker yellow) and model units. Model units do not include the area outside of the COHYST study area.

Tri-Basin NRD
Twin Platte NRD
Upper Big Blue NRD
The Central Platte Public Power and Irrigation District
Nebraska Public Power District

COHYST also was supported by two grants from the Nebraska Environmental Trust, one in 1997 and one in 2001. This study was conducted in cooperation the U.S. Geological Survey.

Previous Studies

The earliest studies of groundwater in western Nebraska were done by Darton (1899, 1903, and 1905). Meinzer (1917) did a brief investigation of Lodgepole Creek Valley and Bjorklund (1957) did a more extensive study of the area. Cady and Scherer (1946) did the first of several studies of Box Butte County. Later studies of Box Butte County included those of Nace (1953), Souders and others (1980), and Pettijohn and Chen (1984). Wenzel and others (1946) studied Scotts Bluff County and Babcock and Visher (1952) studied the Pumpkin Creek Valley, which is predominately in Banner and Morrill Counties. Bjorklund and Brown (1957) studied the South Platte Valley. Smith (1969) studied Cheyenne County, Smith and Souders (1971) studied Kimball County, and Smith and Souders (1975) later studied Banner County.

Large area studies after the Darton (1905) study began with the Missouri River Basin Commission (1975). This was later followed by the Missouri Basin States Association (1982a and 1982b). A study of the entire High Plains aquifer was reported by Gutentag and others (1984) and Weeks and others (1988). Pettijohn (1983a and 1983b) did more detailed reports on the Nebraska portion of this study of the High Plains aquifer.

More recent groundwater studies in the North Platte Valley include those of Steele and others (1998), Verstraeten and others (2001), and Steele and others (2002). These studies covered only small parts of the Western Model Unit.

Studies of western Nebraska that included a groundwater flow model or other detailed numerical analysis include Missouri River Basin Commission (1975), Lappala and others (1979), Missouri Basin States Association (1982a and 1982b), Pettijohn and Chen (1984), Luckey and others (1986), and McLean and others (1997). In 2005, a groundwater modeling study of the Elkhorn and Loup River basins was begun by the U.S. Geological Survey and Nebraska Department of Natural Resources. The southwestern corner of that study coincided with the northeastern corner of this study.

Testhole descriptions have been published for most of the counties in the study area. These include Arthur County (Diffendal and Goeke, 2000), Banner County (Smith, 2000a), Box Butte County (Smith, 2000b), Cheyenne County (Diffendal, 2000), Deuel County (Diffendal, 1999), Garden County (Smith and Swinehart, 2000), Keith County (Diffendal and Goeke, 2004), Kimball County (Smith 2000c), Morrill County (Souders and Swinehart, 2000), and Scotts Bluff County (Sibray and Smith, 2000).

Modeling Strategy

Groundwater flow models are one of the primary tools being developed by COHYST to meet its objectives. Flow models can be used to better understand the resource and predict the effects of implementing groundwater management alternatives. Effects of these alternatives include changes in water levels with time and changes in streamflows due to groundwater discharge to or groundwater recharge from streams. After implementing data collection, COHYST developed a formal strategy for construction and calibration of flow models (Cooperative Hydrology Study Technical Committee, 2000). The overall strategy was to start simple and add detail to the models as required. The COHYST strategy called for constructing flow models for three overlapping areas (fig. 1). The Western Model Unit overlaps approximately 25 mi with the Central Model Unit to the east. Within the area of overlap, work was coordinated to make model inputs as consistent with each other as reasonably possible. However, because the models were developed on somewhat different schedules, some differences occurred. Differences between this model and the adjacent model to the east are described in the “Comparison to Adjacent Model” section.

The strategy called for initially developing models with a fixed grid of 4 mi^2 and a single layer, and eventually decreasing grid size to 160 acres and including one to eight layers. This report describes only the model with a grid size of 160 acres and a single layer. Construction of a multi-layer model proved unnecessary for the Western Model Unit because most of the area was underlain by only a single hydrostratigraphic unit. Models for two separate periods were constructed. The first was for the period prior to large-scale development of the aquifer for irrigation (pre-groundwater development period) and the second was for the period after the beginning of large-scale development (groundwater development period). For COHYST purposes, the start of major groundwater development for irrigation was defined to be 1950 (fig. 2). Virtually all of the surface-water development for irrigation was completed in the region covered by the Western Model Unit decades before 1950. Both the pre-groundwater development period model and the groundwater development period model are described in this report.

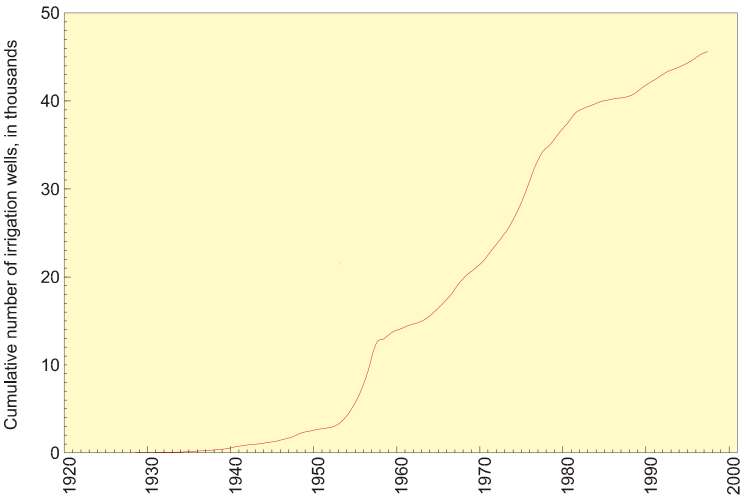

Figure 2. Irrigation well development in the COHYST area. Data from Nebraska Department of Natural Resources.

Description of Western Model Unit

The Western Model Unit (fig. 1) is about 130 mi east-west by 90 mi north-south and covers 11,300 mi^2. The western boundary of the model unit is a geographic boundary formed by a north-south line 6 mi west of the Wyoming-Nebraska state line. The northern boundary of the model unit is a curved line that generally follows a mapped groundwater divide in Sioux, Box Butte and Sheridan Counties. The northern boundary continues east through Garden and Grant Counties where it follows a flow line. The eastern boundary of the model unit is a geographic boundary formed by a north-south line through the central part of Arthur, Keith, and Perkins Counties, which extends 25 mi into the Central Model Unit. The southern boundary of the model unit is defined as a geographic boundary formed by an east-west line 6 mi south of the Colorado-Nebraska state line or the extent of the aquifer. Groundwater crosses the western and eastern boundary of the model unit, but very little groundwater crosses the southern and northern boundaries.

About 90,000 people inhabit the area of the Western Model Unit. Scottsbluff-Gering-Terrytown form the largest urban area in the model area (combined 2000 population of 23,129). Other larger towns in the area and their 2000 populations are Alliance (8,959); Sidney (6,282); Torrington, Wyoming (5,776); Ogallala (4,930); and Kimball (2,559). Counties, major perennial streams, and lakes are shown on figure 3, and Natural Resources Districts (NRD's), larger towns, and selected meteorological and stream gaging sites are shown on figure 4.

Agriculture dominates the livelihood and landscape of the region, with land in the valleys irrigated with both surface water and groundwater. Upland areas are used primarily for grazing, dryland crops, and irrigated crops using groundwater from the High Plains aquifer. As of 1950, coinciding with the time considered the start of groundwater development, approximately 23 percent (1,700,000 acres) of the total land area was harvested with wheat, hay, corn, dry beans, other small grains, and sugar beets being major crops (Cooperative Hydrology Study, 2001a).

The topography of much of the Western Model Unit varies from relatively flat areas such as tablelands and floodplains of the North and South Platte Rivers to hummocky sand dunes. Steep ridges and canyons occur in the area of the Wildcat Hills, north of the North Platte River, south of Pumpkin Creek, and along Lodgepole Creek and Sidney Draw. The tablelands slope at 20 to 25 feet per mile (ft/mi) from west to east, although local variations exist. Scotts Bluff, a prominent erosional remnant of the tableland in Scotts Bluff County, stands more than 700 feet (ft) above the adjacent North Platte River. The North Platte Valley varies in width from 2 to 10 mi and slopes to the east at about 6 to 7 ft/mi. The South Platte Valley varies in width from 2 to 5 mi and slopes to the east at about 8 ft/mi. The northeastern part of the Western Model Unit includes the southwestern extent of the Sand Hills, one of the largest grass-stabilized dune regions of the world (Bleed and Flowerday, 1989). This part of the Sand Hills contains numerous inter-dune lakes and wetlands.

Climate in the Western Model Unit is generally semiarid (Conservation and Survey Division, 1998). Average 1961-90 precipitation ranges from less than 14 inches per year (in/yr) in some northwestern parts of the model unit to more than 18 in/yr in some south-central and eastern parts (fig. 5). The average precipitation computed from 1895-1999 data for the Panhandle Climatic Division, consisting of Deuel, Garden, and Sheridan Counties and counties west, is 17.29 in/yr (National Climatic Data Center, 2001). The climatic division includes the area north of the Western Model Unit and excludes the eastern-most part of the unit. The annual precipitation average for stations in the climatic division has ranged from a low of 10.98 in/yr in 1934 to a high of 27.67 in/yr in 1915. Precipitation can vary substantially from year to year and station to station (fig. 6). Most of the precipitation occurs in the summer with about two-thirds of the annual total occurring in May through September. Abundant sunshine, frequent winds, and low humidity contribute to a relatively high rate of evaporation. Lake evaporation at Mitchell (fig. 6) in the western part of the model area averaged about 45 in/yr for 1949-94 (Nebraska Department of Natural Resources, 2001). Lake evaporation does not change substantially across the study area and reaches a maximum of about 48 in/yr in the southeast corner (fig. 5).

The North Platte River flows approximately through the center of the Western Model Unit, and the South Platte River flows across the southeastern part of the unit. Other major streams in the area include Blue Creek, Lodgepole Creek, and Pumpkin Creek (fig. 3). Blue Creek is dominated by groundwater discharge and has a fairly uniform flow (fig. 7). Pumpkin and Lodgepole Creeks are runoff dominated and have more erratic flows. Lake McConaughy, a large reservoir in the eastern part of the Western Model Unit, is used to store water for irrigation and power generation. Several smaller reservoirs north of the North Platte River in the western part of the study area also store water for irrigation. Numerous natural small lakes and wetlands occur in the Sand Hills in the northeastern part of the model unit. These range in size to about 2 mi^2.

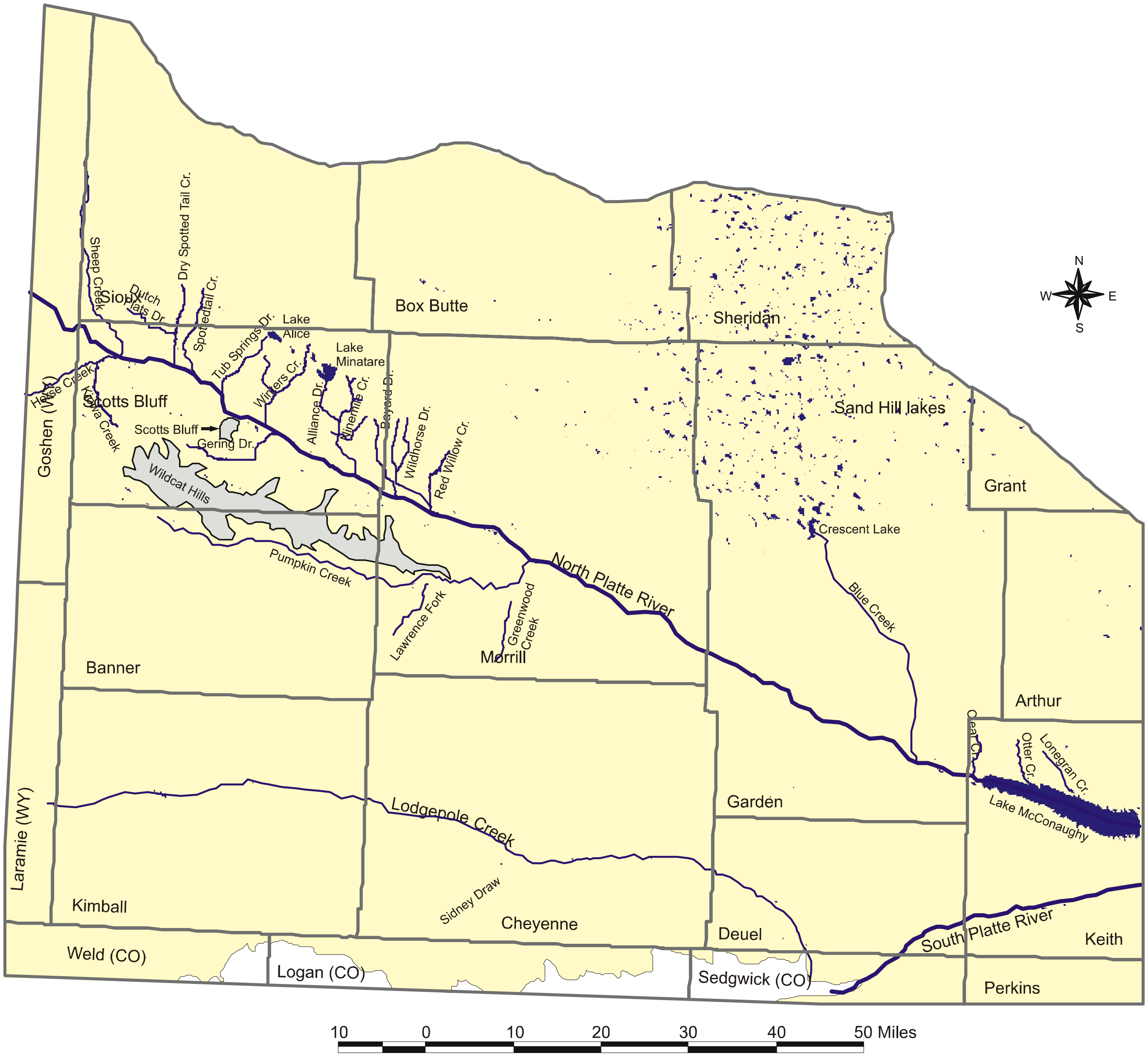

Figure 3. Western Model Unit, counties, major perennial streams and lakes, and selected features.

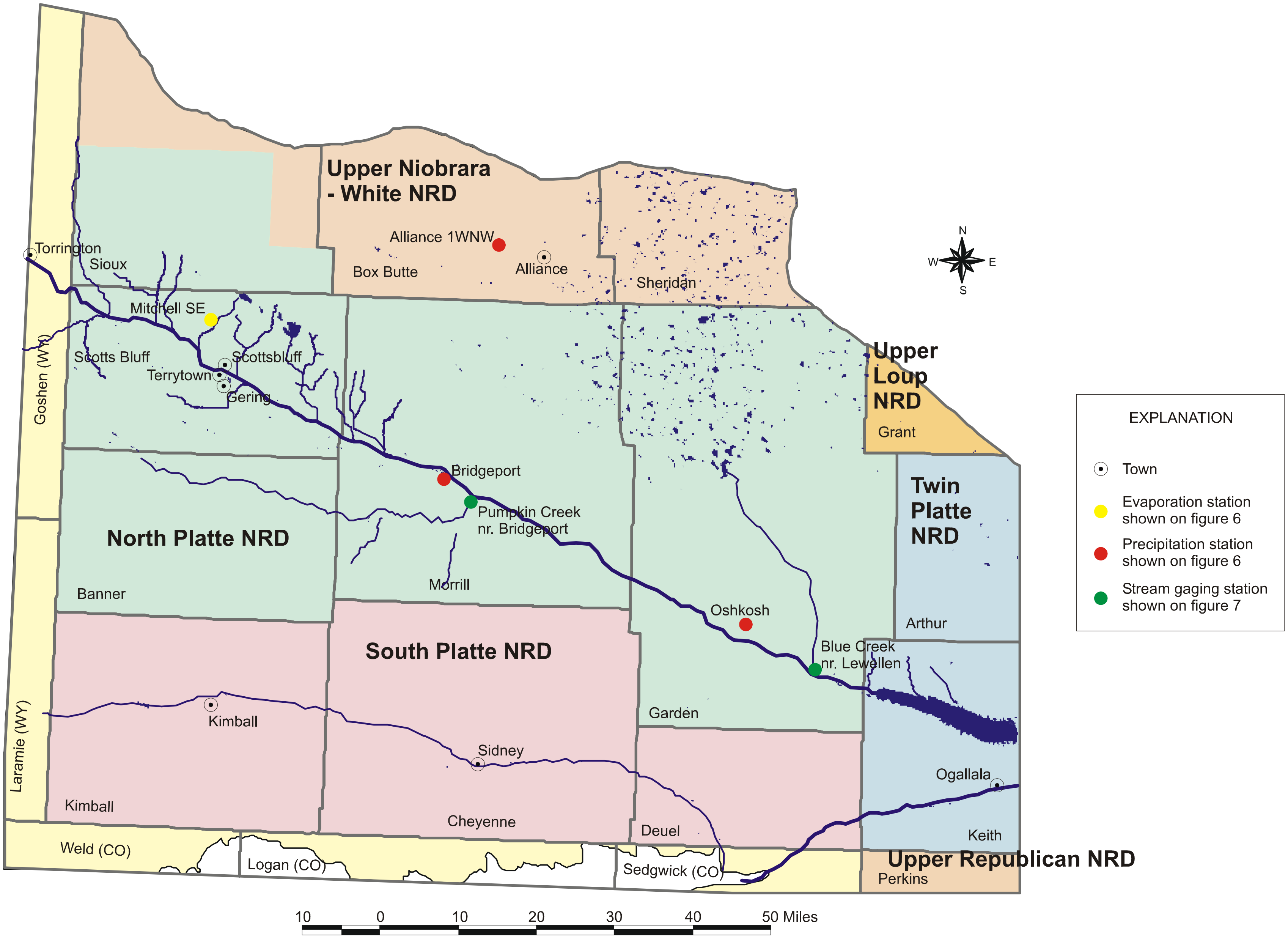

Figure 4. Natural Resources Districts (NRD), major towns, and selected meteorological and stream-gaging sites in the Western Model Unit.

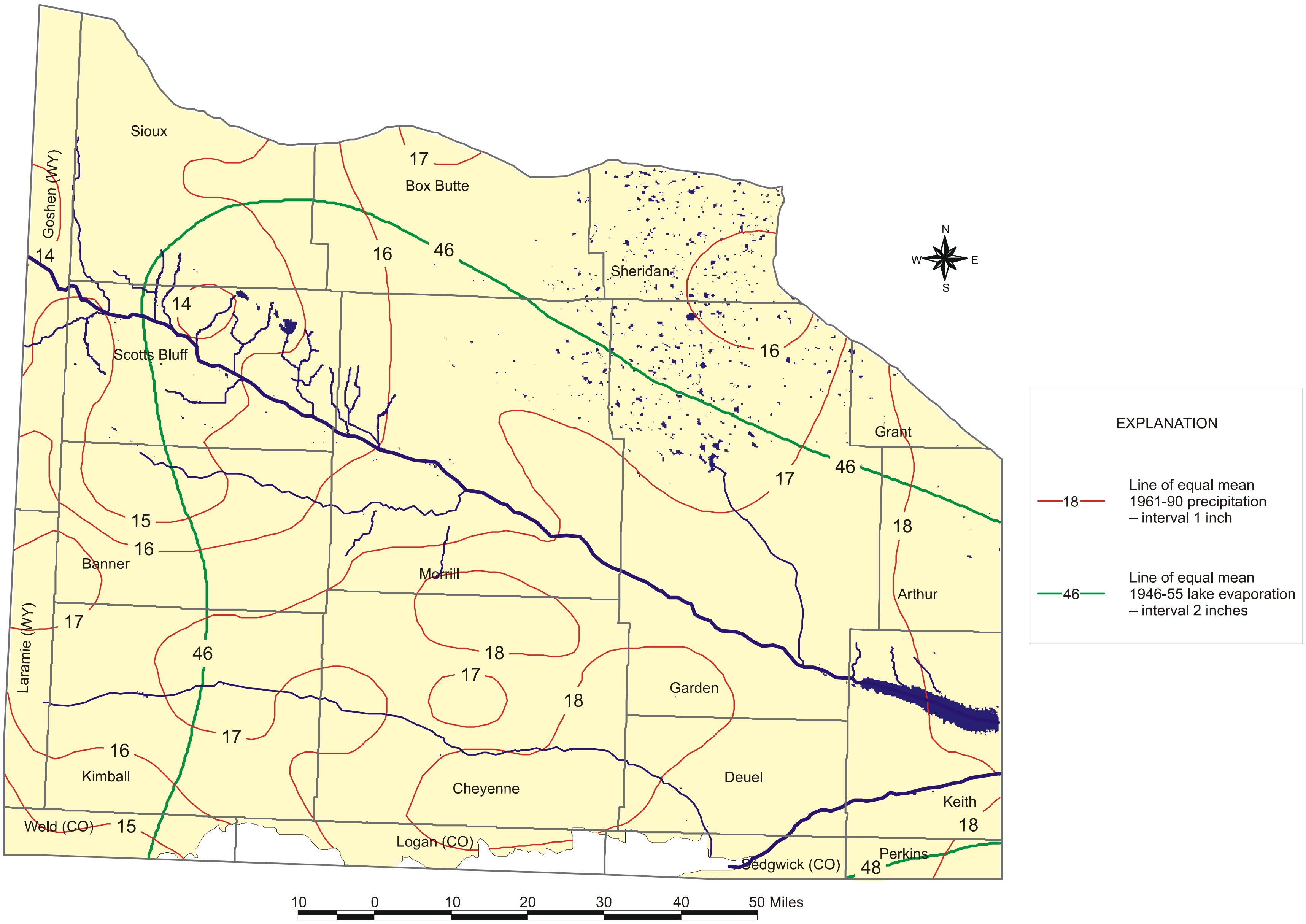

Figure 5. Average annual 1961-90 precipitation and 1946-55 lake evaporation in the Western Model Unit. Modified from Spatial Climate Analysis Service (2000) and U.S. Weather Bureau (1959).

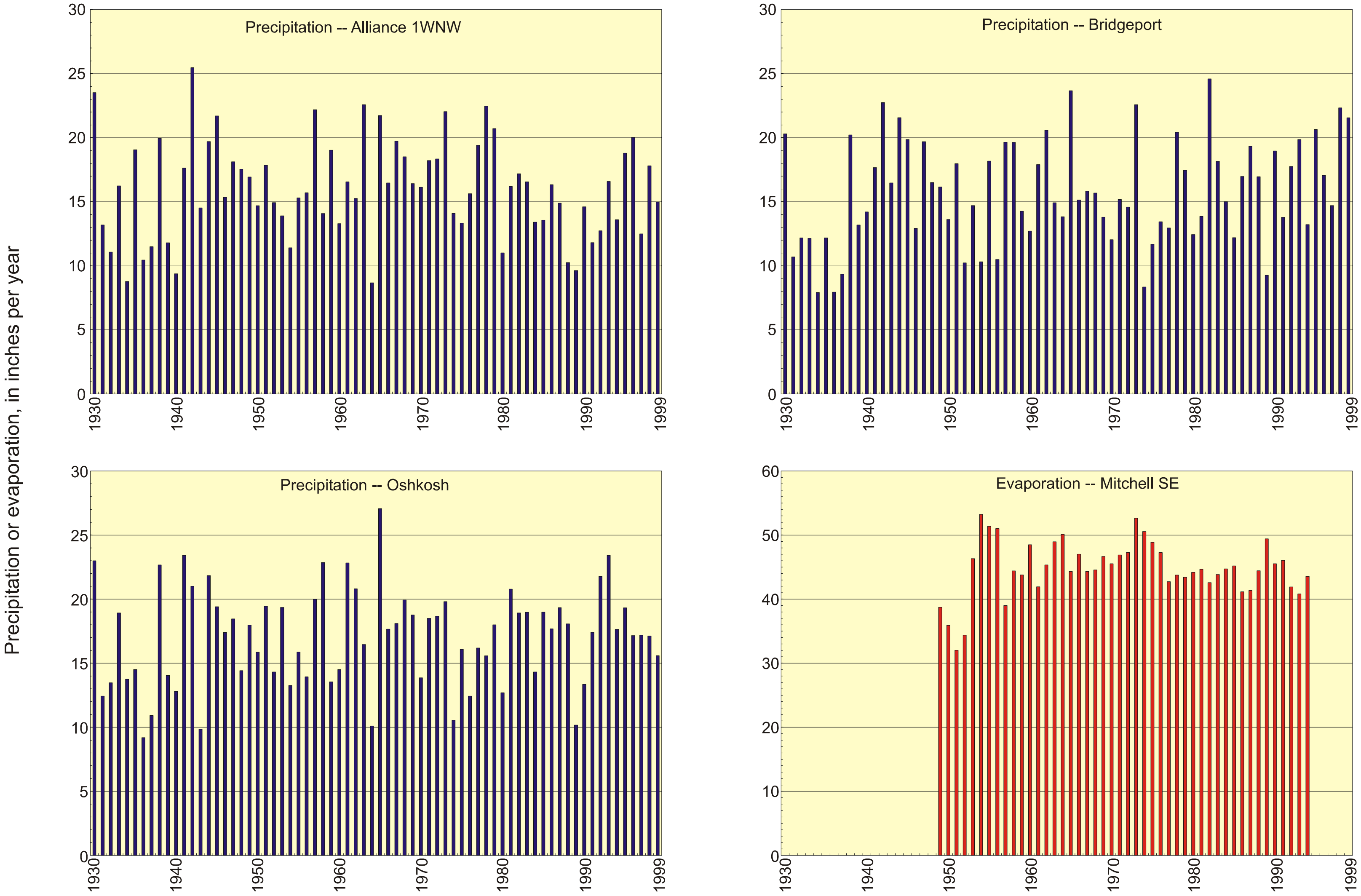

Figure 6. Annual precipitation at Alliance, Bridgeport, and Oshkosh for 1930-99 and annual lake evaporation at Mitchell for 1949-99. Data from Nebraska Department of Natural Resources (2001). Note the scale for evaporation is twice that for precipitation.

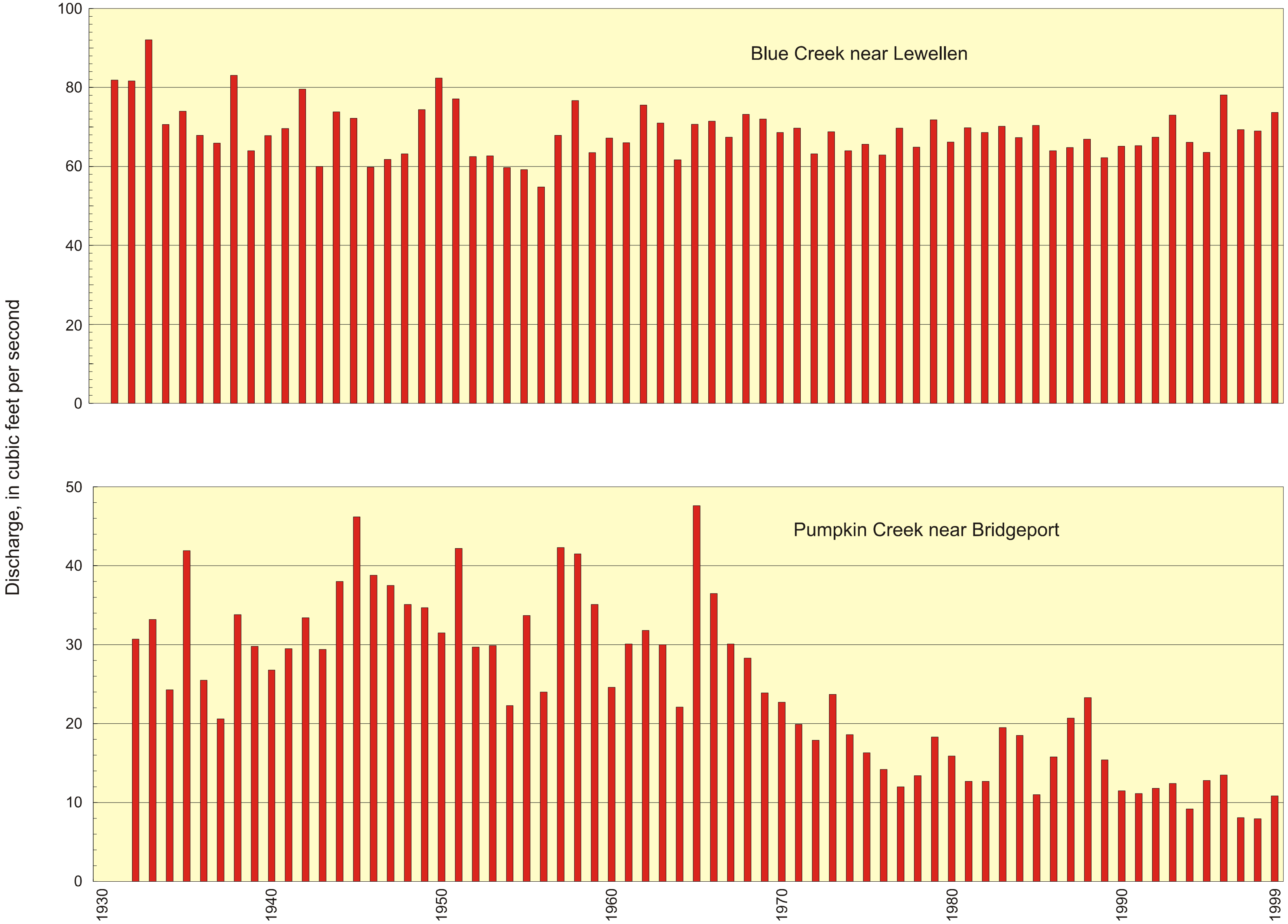

Figure 7. Annual discharge for Blue Creek for 1931-99 and Pumpkin Creek for 1932-99. Data from Nebraska Department of Natural Resources and U.S. Geological Survey.

Wetlands and other areas of high evapotranspiration are mainly limited to the floodplains of the North and South Platte Rivers, the area around the western part of Lake McConaughy, and the region that contains the Sand Hill lakes. Other small wetlands exist along some of the smaller streams and in places immediately downgradient from irrigation canals.

As shown in figure 8, the water table in the High Plains aquifer ranges from more than 5,300 ft above sea level in the southwest part of in the Western Model Unit to less than 3,200 ft in the east (Gutentag and others, 1984; Cederstrand and Becker, 1999). Depth to water ranges from nearly zero close to streams and around the Sand Hills lakes to as much as 300 ft in the southwestern part of the Western Model Unit. The water table generally slopes to the east at 15 to 20 ft/mi across much of the southern one-third of the study area. Within a few miles of the North Platte River, the water table slopes toward the river at 30 to 50 ft/mi. The water-table configuration is very complex in the western part of the area, particularly south of the North Platte River. The water table is relatively flat in the area of Sand Hill lakes where the slope is about 4 ft/mi. Upgradient from this area, flow is predominately to the east, whereas downgradient from this area, flow is predominately to the southeast.

Geologic and Hydrostratigraphic Units of the Western Model Unit

The geologic units in the Western Model Unit important to the flow model consist of various Pliocene and Quaternary age deposits, the Ogallala Group, the Arikaree Group, and the Brule Formation (table 1 and fig. 9). Pliocene and Quaternary age deposits consist of Pliocene and Pleistocene age fluvial deposits, Pleistocene and Holocene age loess, Pleistocene and Holocene age dune sand, and Holocene age alluvial and colluvial deposits. The Pliocene and Pleistocene age alluvial deposits are predominately north of the North Platte River and are generally above the water table. When they are below the water table, they typically yield large amounts of water to wells. The loess deposits are most common in the southeastern part of the Western Model Unit and north of the North Platte Valley. These deposits are generally above the water table, but when they are below the water table, they are capable of storing and slowly releasing large amounts of water. Dune sand is wide spread north of the North Platte River and also occurs south of the river and along Pumpkin Creek. Dune sand will yield minor amounts of water to wells, but the saturated thickness of dune sand generally is small and much larger amounts of water usually can be developed from underlying units. Holocene age alluvial deposits occur primarily along the North Platte and South Platte Rivers and along Lodgepole and Pumpkin Creeks. Sidney Draw, a large valley in Cheyenne County that is connected to Lodgepole Creek Valley, also contains Holocene age alluvium. These deposits are a heterogeneous mixture of gravel, sand, silt, and clay and typically yield large amounts of water to wells when they are below the water table. The Holocene age alluvial deposits typically are 2-4 mi wide in the North and South Platte Valleys and Sidney Draw and 1-2 mi wide in Lodgepole Creek and Pumpkin Creek Valleys. Holocene age colluvial deposits are common in the North Platte and Pumpkin Creek Valleys, especially below steeper slopes.

The Ogallala Group consists of a very heterogeneous mixture of unconsolidated gravel, sand, silt, and clay and consolidated limestone, siltstone, sandstone, and conglomerate. The Ogallala Group consists of the Ash Hollow, Valentine, and Runningwater Formations, but this unit was not subdivided below the group level for the purposes of this model. Outside of Nebraska, the Ogallala is treated as a formation. The part of the Ogallala Group that is below the water table typically yields large amounts of water to wells. The Ogallala Group is absent from approximately the northwestern quarter of the Western Model Unit.

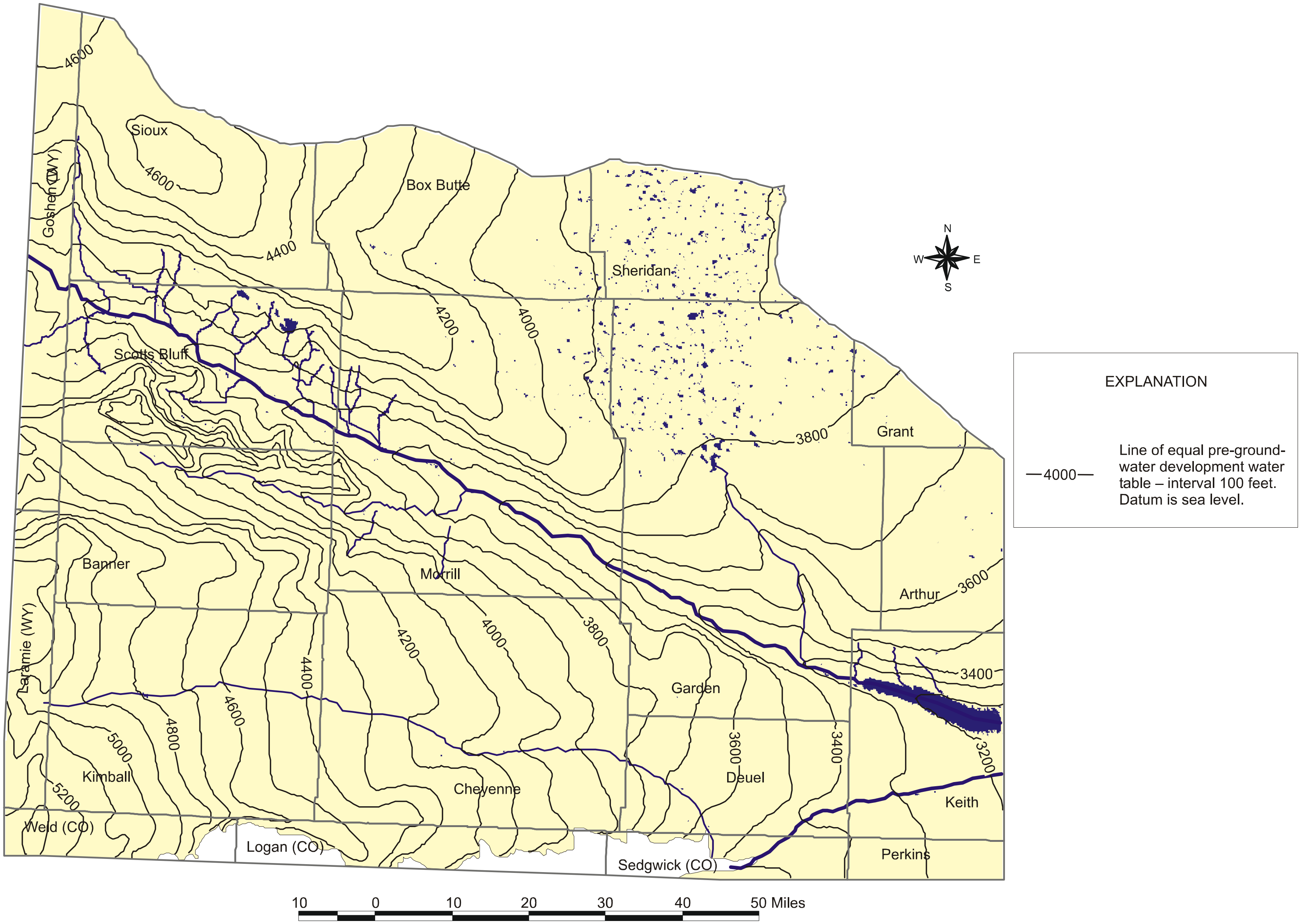

Figure 8. Pre-groundwater development water table in the Western Model Unit. Modified from generalized map by Gutentag and others (1984) and detailed digital map by Cederstrand and Becker (1999) by clipping, re-projecting, and scaling.

Table 1. Generalized section of geologic units used in the Cooperative Hydrology Study (modified from Gutentag and others, 1984).

System	Series	Geologic unit	Hydrostratigraphic unit	Description
Quaternary	Holocene	Alluvium and colluvium	Generally unit 2	Gravel, sand, silt, and clay with coarser materials more common. Generally fluvial deposits. Upper fine material, if present, is assigned to Hydrostratigraphic unit 1. Lower fine material, if present, is assigned to unit 3. Occurs in major river valleys where it can be over 150 feet thick.
	Pleistocene and Holocene	Dune sand	Generally unit 1	Generally fine sand but may contain some medium and even coarse sand. May also contain some finer material. Eolian deposits. Thickness may exceed 300 feet in northeastern part of the Western Model Unit, but much of this thickness is above the water table.
		Loess deposits	Unit 1 when above unit 2, otherwise unit 3	Generally silt, but may contain some very fine sand and clay. Deposited as eolian dust. Generally less than 20 feet thick, but may be more than 200 feet thick in southeastern part of Western Model Unit (Swinehart and Diffendal, 1997). Generally above the water table.
	Pleistocene	Alluvial deposits	Generally unit 2	Gravel, sand, silt, and clay with coarser materials more common. Generally fluvial deposits. Upper fine material, if present, is assigned to Hydrostratigraphic unit 1. Lower fine material, if present, is assigned to unit 3. Underlies alluvium and colluvium in places along North Platte River and Pumpkin Creek, where it is generally less than 100 feet thick.
Tertiary	Pliocene	Broadwater Formation	Unit 2	Coarse gravel and sand with some silt and clay. Fluvial deposits. Generally found in channel deposits north of the North Platte. Occurs in northeast part of Western Model Unit where it can be over 150 feet thick, but much of this thickness is above the water table.
	Upper and middle Miocene	Ogallala Group	Units 4-6	Heterogeneous mixture of gravel, sand, silt, and clay. Generally fluvial deposits but also contains eolian deposits. Upper fine material, if present, is assigned to Hydrostratigraphic unit 4. Center coarse material, if present, is assigned to unit 5. Lower fine material, if present, is assigned to unit 6. Typically 200-400 feet thick, but may exceed 600 feet thick.
	Lower Miocene and upper Oligocene	Arikaree Group	Unit 7	Predominately very fine to fine-grained sandstone but may also contain siltstone. Eolian volcanic ash deposits. Locally, may contain conglomerates, gravels, and sands of fluvial origin. Occurs in northwestern part of Western Model Unit. Typically 200-400 feet thick, but may exceed 600 feet thick.
	Lower Oligocene	Brule Formation of White River Group	Unit 8 if High Plains aquifer or Unit 9 if below High Plains aquifer	Predominately siltstone, but may contain sandstone and channel deposits. Sometimes highly fractured with areas of fracturing difficult to predict. Upper part of Brule Formation is included in High Plains aquifer and Hydrostratigraphic unit 8 only if fractured or contains sandstone or channel deposits, otherwise it is unit 9 and is excluded from the High Plains aquifer. Eolian volcanic ash deposits with some fluvial deposits.
	Upper Eocene	Chadron Formation of White River Group	Unit 9; below the High Plains aquifer	Silt, siltstone, clay, and claystone. Generally forms impermeable base of High Plains aquifer. Fluvial deposits and eolian volcanic deposits. Some coarser fluvial deposits exist at the base of this unit.
Cretaceous	Undifferentiated	Undifferentiated	Unit 10; below the High Plains aquifer	Shale, chalk, limestone, siltstone, and sandstone. Except for a few minor areas of Fox Hills Sandstone in the extreme western part of the COHYST area and the Dakota Group in the extreme eastern part of the area, generally forms an impermeable base of High Plains aquifer. Deep marine deposits to beach deposits.

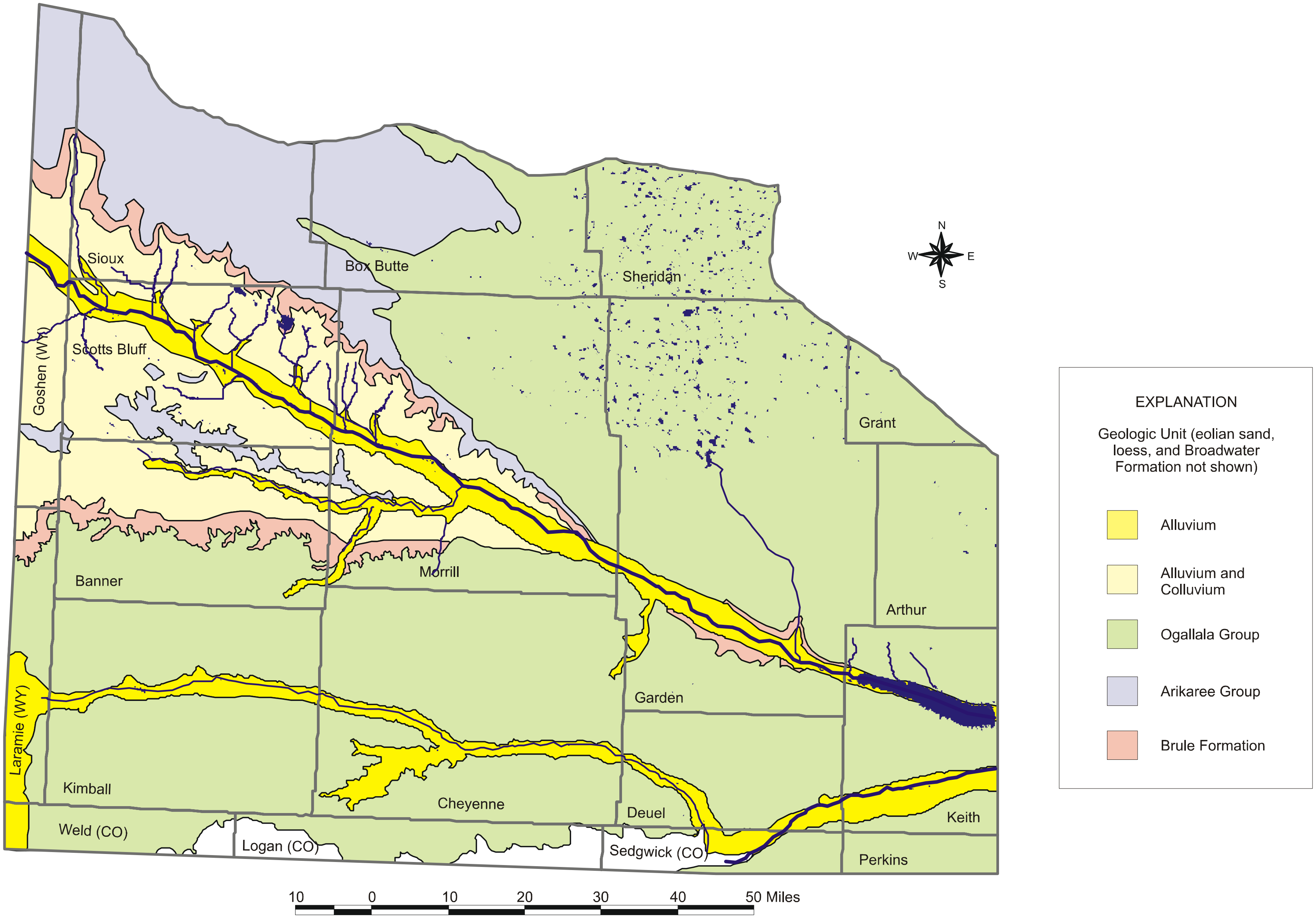

Figure 9. Generalized geology of the Western Model Unit. Modified from Conservation and Survey Division (1996) and Swinehart and Diffendal (1997).

The Arikaree Group is predominately a very fine to fine-grained sandstone that yields only minor amounts of water to wells. Where sufficient saturated thickness exists, such as in areas of Box Butte County, the Arikaree Group can yield large amounts of water to wells. It also is an important source of water on the Wildcat Hills where the Ogallala Group is absent and the Brule Formation does not transmit much water.

The Brule Formation is predominately a siltstone but in some areas it is highly fractured and transmits large quantities of water. These areas are mostly in Lodgepole Creek and Pumpkin Creek Valleys and Sidney Draw. In these areas, the fractured Brule Formation is included in the High Plains aquifer. Scattered alluvial channels filled with sand and gravel are present in the formation, and can supply large amounts of water to wells. These parts of the Brule Formation also are included in the High Plains aquifer. The upper part of the Brule Formation consists of siltstone, silt, sand, or even fine gravel that transmits small amounts of water. This part of the formation is not included in the High Plains aquifer. The remainder of the Brule Formation is excluded from the High Plains aquifer and is the base of the aquifer in the Western Model Unit.

The Fox Hills Sandstone of Cretaceous age underlies the High Plains aquifer in the western part of the Western Model Unit and this sandstone may exchange small amounts of water with the High Plains aquifer beneath the western part of the North Platte Valley. However, the amounts are negligible when compared to the amount of water moving through the overlying Holocene age alluvium.

COHYST divides the High Plains aquifer into eight Hydrostratigraphic Units (table 1) and defines two additional units beneath the aquifer (J.C. Cannia, North Platte Natural Resources District, Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report, written commun., draft dated March 22, 2005). These units are different from the geologic units discussed previously. Geologic units are frequently grouped or subdivided on the basis of hydrostratigraphic characteristics, with units that have similar water-transmitting and storage characteristics grouped together. Some of the units are discontinuous over large areas and there is not any one area with all ten Hydrostratigraphic Units. Unit 1 consists of near land surface Quaternary age fine sand, silt, or clay and exists over most of the Western Model Unit. Unit 1 is generally above the water table. Unit 2 consists of Quaternary or upper Pliocene age sand or gravel and exists in the valleys and in much of the eastern one-third of the Western Model Unit. Unit 3 consists of Quaternary age silt or clay, if it exists below Unit 2. Some sand and gravel may occur in parts of Units 1 and 3 and some silt and clay may occur in parts of Unit 2. Unit 4 consists of an upper Tertiary age silt or clay. Units 3 and 4 have the same hydrostratigraphic characteristics but different ages and cannot be distinguished from each other except where described by detailed descriptions of cutting from test holes. Units 3 and 4 exist in isolated areas of various sizes throughout the Western Model Unit. Unit 5 consists of a Tertiary age sand or gravel and exists in much of the Western Model Unit except for the northwestern quarter, along the North Platte River in much of Garden County, along the lower half of Lodgepole Creek Valley and in Sidney Draw, and near the Colorado-Wyoming state line. Unit 6 consists of a lower Tertiary age silt or clay, if it exists below Unit 5. Unit 6 exists in isolated areas of various sizes throughout the Western Model Unit. Some sand and gravel may occur in parts of Units 4 and 6 and some silt and clay may occur in parts of Unit 5. Unit 7 consists of the Arikaree Group and exists over most of the area of the Western Model Unit north of the North Platte Valley, on the Wildcat Hills, and in southern Banner County and part of northern Kimball County. Unit 8 consists of that part of the Brule Formation included in the High Plains aquifer because it is fractured or contains channel deposits. Unit 8 exists primarily in Pumpkin Creek Valley, Lodgepole Creek Valley, and Sidney Draw. Unit 9 consists of non-fractured silt and clay of the Brule Formation and the Chadron Formation of the White River Group. Unit 9 is the impermeable part of the White River Formation that forms the base of the High Plains aquifer in almost all of the Western Model Unit. Unit 10 is Cretaceous age materials that form the base of aquifer where Unit 9 is absent. Unit 10 forms the base of the High Plains aquifer in very limited areas beneath the western part of the North Platte Valley.

Conceptual Flow Model

A conceptual flow model is a narrative description of the characteristics of the flow system that are important to constructing the numerical model. The important characteristics may be somewhat dependent on the ultimate use of the model. The conceptual model includes the state of the flow system at the beginning of the simulation period, how the flow system interacts with external sources or sinks of water, the lateral and vertical boundaries of the model, and what happens to the elevation or flow of water at these boundaries. For example, a part of the conceptual model is how the hydraulic conductivity (parameter describing the ability of the aquifer to transmit water) varies over the model area.

The state of the flow system at the beginning of simulation describes whether the system is in a state of dynamic equilibrium or in a state of long-term change. Recharge from applied irrigation water is an example of an external source of water and evapotranspiration by a stand of cottonwood trees whose roots directly tap the aquifer is an example of an external sink of water. The details of the conceptual model may evolve as the numerical model evolves, but the basic framework generally is understood at the start of model construction.

The external boundaries of the Western Model Unit consist of fixed-flow boundaries (sometimes called specified flux boundaries) at the eastern and western boundaries and zero-flow boundaries along much of the northern and the entire southern boundary (fig. 10). Along a fixed-flow boundary, flow is specified prior to the simulation and held constant throughout the simulation (McDonald and Harbaugh, 1988). A fixed-flow boundary means that the simulated water level can change at the boundary, but flow across the boundary cannot change. These boundaries are geographic boundaries of the model area, and were chosen to have relatively small influence on the internal area of the model in Nebraska. Further discussion on the use of fixed-flow boundaries can be found in the COHYST Modeling Strategy (Cooperative Hydrology Study Technical Committee, 2000). Zero-flow boundaries along the northern and southern boundaries were delineated along lines where water-table maps indicated that little or no groundwater crossed these boundaries. Much of the northern boundary coincides with either a groundwater divide or a flow line, so no groundwater crosses this boundary. Part of the northern boundary in Sioux County was a fixed-flow boundary with a total outflow of 17 cubic feet per second (ft^3/s) or 0.8 ft^3/s per mi. This flow was estimated based on aquifer parameters and the gradient of the water table. This boundary was originally thought to be a zero-flow boundary, but was later determined that the boundary was not placed on the groundwater divide. The southern boundary was either the extent of the aquifer or a geographic east-west line 6 mi south of the Colorado-Nebraska state line. Because groundwater flow is generally from west to east with little north-south flow in this locale (fig. 10), this boundary also was treated as a zero-flow boundary. The lower boundary of the western model was the relatively impermeable rocks beneath the High Plains aquifer and was treated as a zero-flow boundary. The upper boundary of the model was the water table.

Rivers and streams can be modeled as either river boundaries or as stream boundaries. Stream boundaries are allowed to gain water from the aquifer or to lose water to it, up to the amount of water in the stream. River boundaries are similar to stream boundaries except that the amount of water in the river is not tracked by the flow model. River boundaries are appropriate for large features that seldom go dry whereas stream boundaries are appropriate for smaller features. The interaction between the rivers or streams and the aquifer beneath the river or stream boundaries is controlled in the flow model by relative elevations of the feature and the simulated water table and estimated parameters that control the rate of movement between the aquifer and the streams. The North Platte River and the South Platte River were simulated as river boundaries (fig. 10). All other perennial streams were simulated as stream boundaries in the model. These include Kiowa Creek, Horse Creek, Sheep Creek, Dutch Flats Drain, Dry Spottedtail Creek, Spottedtail Creek, Tub Springs Drain, Winters Creek, Gering Drain, Alliance Drain, Ninemile Creek, Bayard Drain, Wildhorse Drain, Red Willow Creek, Lawrence Fork, Greenwood Creek, Pumpkin Creek, Blue Creek, Clear Creek, Otter Creek, Lonegran Creek, and Lodgepole Creek (fig. 3 and10).

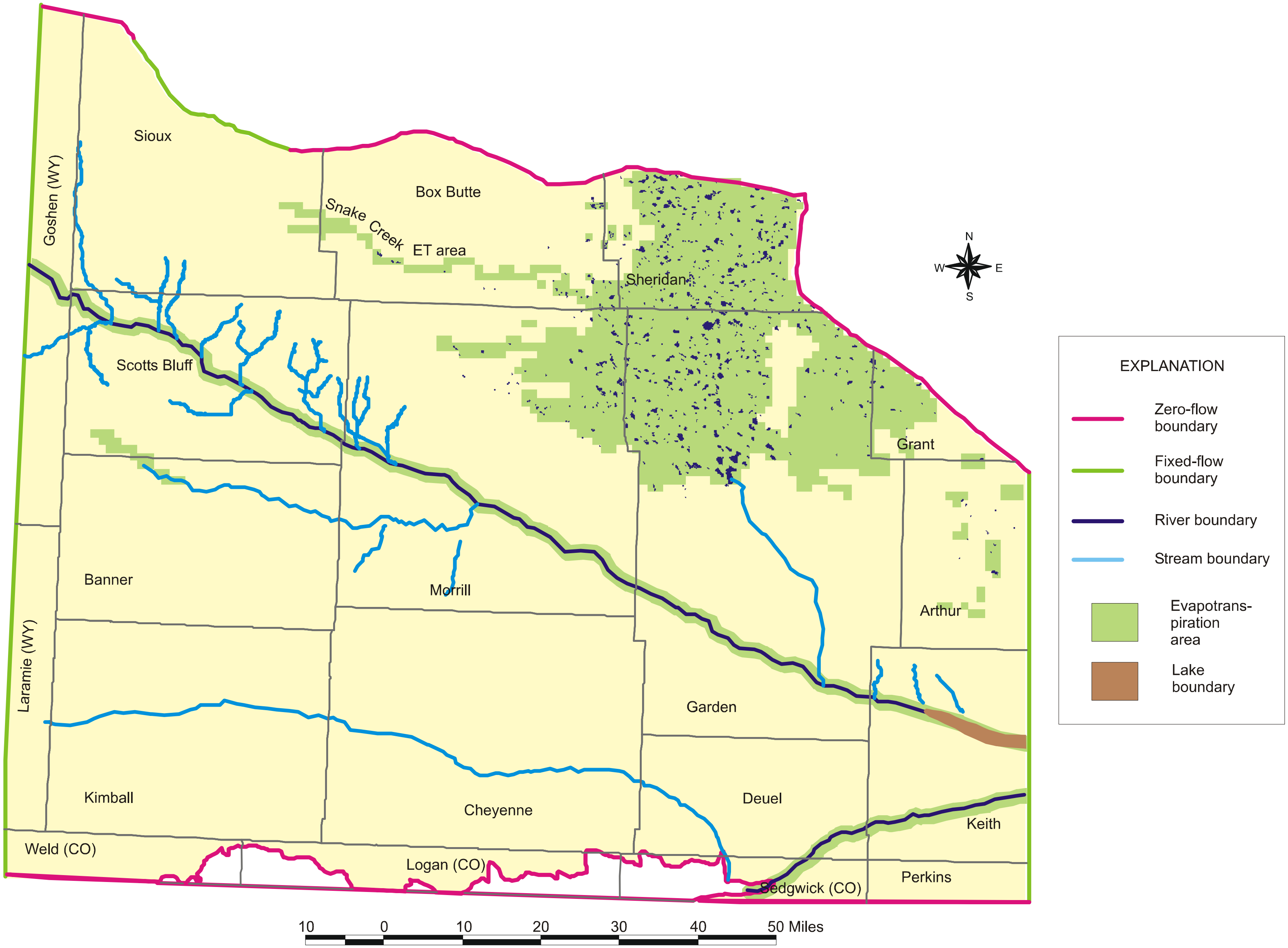

Figure 10. Conceptual model features in the Western Model Unit.

The areas of numerous natural lakes and wetlands in the Sand Hills (fig. 10) were treated as groundwater evapotranspiration areas where groundwater was removed from the model to supply transpiration by wetland plants and open-water evaporation. The areas of few Sand Hill lakes and wetlands were not simulated as evapotranspiration areas in the model because groundwater evapotranspiration in these areas was assumed to be relatively small compared to the areas of numerous lakes and wetlands. Corridors 1- to 2-mi wide along the North Platte River and South Platte River were simulated as groundwater evapotranspiration areas to supply water for the riparian woodlands transpiration and open-water and bare ground evaporation. Areas of groundwater evapotranspiration also were simulated along Snake Creek in Sioux and Box Butte Counties and along upper Pumpkin Creek in Scotts Bluff and Banner Counties to supply water for wetland plants. Although some groundwater evapotranspiration occurs along other tributaries, this evapotranspiration is relatively small compared to that in the evapotranspiration areas shown in figure 10. This other evapotranspiration was assumed to be negligible in the regional model and was not simulated.

Recharge from surface-water irrigation and canal leakage was included in the model beginning in 1900, although the canals came online at various dates ranging from 1887 to 1904. Lake McConaughy was included in the model beginning in 1940. The exact date the canals came online was not important in the model because the aquifer came into equilibrium with the recharge from surface-water irrigation and canal leakage in a matter of a few years, so the aquifer was in equilibrium with all of them by 1950. This model result is consistent with data presented by Verstraeten and others (2001).

The pre-groundwater development period model simulated the groundwater system in 1950 as being in a state of long-term dynamic equilibrium, called steady state, except for possibly the area around Lake McConaughy. Water levels in the area around Lake McConaughy were rising in 1950 due to recent construction of the lake. These water-level rises had little effect on the rest of the model. The groundwater development period model simulated the 1950-98 groundwater system as being in a transient state due to increasing groundwater development (fig. 2).

Numerical Model Construction

After fully conceptualizing the model, a numerical representation of flow within an aquifer and the exchange of water between the aquifer and the external environment can be constructed. The groundwater flow model necessarily simplifies and aggregates the true system, but includes those features important to the intended uses of the model. This numerical model was constructed to simulate and investigate the important effects of recharge to and discharge from the regional aquifer. Important regional effects include changes in water levels and changes in groundwater discharge to or groundwater recharge from streams.

The following assumptions are made for this numerical flow model:

1. Flow in the aquifer obeys Darcy’s Law of water movement through porous media, and mass and energy are conserved. These assumptions are valid over the scale at which this model is constructed.
2. The density and viscosity of water is constant over time and space. This assumption is approximately true and any small variations in water density or viscosity would be masked by the uncertainties in model parameters.
3. Model parameters are uniform within 160-acre areas. This assumption is appropriate because the model is intended as a regional representation of the groundwater flow system and because the spacing of testholes to define model parameters is large compared to 160-acre areas.
4. The interchange of water between the aquifer and streams can be adequately simulated as one-dimensional flow through a discrete streambed layer. Such a discrete layer may or may not actually exist, but this conceptualization is appropriate over the scale at which this model is

constructed. Additionally, the Model Sensitivity section shows that the model was not sensitive to conductance of this streambed layer.

5. Groundwater flow throughout the model is two-dimensional. This assumption is a consequence of treating the aquifer as a single layer in the Western Model Unit. However, vertical-flow components probably are small compared to horizontal-flow components over much of this model area, so this assumption is appropriate over the scale at which this model is constructed.
6. Hydraulic conductivity is isotropic within a model cell in both the horizontal and vertical directions. Because the aquifer is predominately composed of fluvial deposits with some eolian deposits, some small-scale anisotropy probably exists, but changes direction over small areas. The assumption about isotropy within a model cell in the horizontal directions is valid at the scale of this model. The vertical hydraulic conductivity may be anisotropic with respect to horizontal hydraulic conductivity, but this cannot be accounted for in a single layer model. However, because vertical flow components are relatively small, neglecting vertical anisotropy should have little effect on model results. Large-scale anisotropy is represented in the model as areal variation in hydraulic conductivity from cell to cell.

MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; and Harbaugh and others, 2000) was selected as the groundwater flow modeling code for this study. MODFLOW is a widely used code that uses block-centered finite-difference techniques to solve the three-dimensional partial differential equations that describe the flow of groundwater through porous media, such as in the High Plains aquifer. The finite difference techniques treat space and time as finite sets of discrete points rather than as continuums. This approach introduces a negligible error into the solution, compared to the uncertainties associated with the real system.

To use the finite-difference technique, the aquifer is subdivided into a grid with individual connected blocks called cells. Although the flow code allows variation in cell sizes within the grid, a constant cell size was used in this study. Aquifer properties are assumed to be uniform within a single cell, but can vary between cells. Water levels are calculated at the centroid, or node, of each cell. MODFLOW accounts for the flow of water between adjacent cells and the flow of water into and out of each individual cell from various external sources and sinks. The flow code generates a finite-difference equation for each active cell in the model domain and uses numerical techniques to simultaneously solve the equations. The numerical techniques make successive approximations, called iterations, to obtain the solution. When the difference between successive approximations becomes negligible, a solution is reached.

The Groundwater Modeling System (GMS version 5.1), developed for the U.S. Department of Defense by the Environmental Modeling Research Laboratory at Brigham Young University (Environmental Modeling Research Laboratory, 2006), was selected as the pre- and post-processor for MODFLOW. GMS supports a number of groundwater flow and transport codes in addition to MODFLOW. GMS allows a wide variety of data inputs and outputs, including Geographic Information System (GIS) coverages and data tables of points, lines, and polygons. In addition, GMS supports images, borehole data, Triangulated Irregular Networks (TIN’s), and data sets for modeling with two and three-dimensional grids. Such data sets can be created within the preprocessor or imported from external sources. GMS uses the GIS coverages and other data sets to prepare the input files required by MODFLOW. The output from MODFLOW can be read by GMS, and the GMS post-processor displays the results with maps, graphs, diagrams, cross sections, and tables. These capabilities allow GMS users to efficiently conceptualize and simulate flow in groundwater systems. The conceptual and numerical models can evolve as the simulations are compared to actual historic hydrologic data.

The grid for the entire Western Model Unit consisted of 228 rows and 260 columns, with 45,040 active cells. The grid lines were oriented in a north-south east-west fashion, each cell contained 160 acres, and each cell was 2,640 ft on a side. A small portion of the grid from the northeast corner of the model in

Sheridan County is shown on figure 11. The north-south orientation was maintained for all three model units to make it easier to compare results and inputs in the areas of model overlap.

MODFLOW simulates the interaction between the groundwater system and the surface-water system as flow through a hypothetical bed layer with properties potentially different from those of the aquifer. This applies to streams, rivers, and lakes. A lumped parameter termed “conductance” accounts for the hydraulic conductivity and thickness of the layer, feature width, and feature length in each stream, river, or lake cell. Conductance controls the ease of interaction between the surface-water and groundwater systems. GMS automatically calculates the length of stream and river features and the area of lake features in each model cell, so the value input to GMS actually is conductance per unit length or unit area. In this report, conductance means the lumped parameter that accounts for layer hydraulic conductivity, layer thickness, and feature width (for linear features only) to which GMS will apply feature length or area.

Both MODFLOW Stream (Prudic, 1989) and River (McDonald and Harbaugh, 1988) Packages were used to simulate stream and river boundaries. Stream and river locations followed the generalized courses of the streams but did not duplicate exact details of the stream. Stream and river water elevations were estimated at points from 1:24,000 scale topographic maps where 100-ft contours crossed the streams and GMS performed linear interpolations between points. Streambed and riverbed conductance values were determined during calibration and are discussed in the Numerical Model Calibration section.

The MODFLOW General Head Boundary Package (McDonald and Harbaugh, 1988) was used to simulate Lake McConaughy. The simulated extent approximated the area inundated by a moderately low stage and the lake elevations of the boundary were set at the long-term average for various model periods. During transient simulations, the long-term average elevation was 3,240 ft for 1940-54, 3,230 ft for 1954-60, 3,257 ft for 1960-89, 3,240 ft for 1989-94, and 3,257 ft for 1994-98. The elevation was changed at the beginning of the irrigation season for the indicated year.

Long-term average recharge due to canal leakage and surface-water irrigation (table 2) was based primarily on a study by Bishop-Brogden Associates, Inc. (2002, table 5.1a). Canal leakage estimates ranged between 17 and 51 percent of average historical canal diversions for 1965-94. Leakage was assumed to be split between groundwater recharge (95 percent) and non-beneficial evapotranspiration (5 percent). The leakage estimate for Pathfinder Irrigation District (fig. 12) was reduced 2 percentage points from values reported in the Bishop-Brogden study to account for leakage and delivery to about 1,800 acres in Wyoming (out of total of about 96,000 acres for the district). Leakage for the Western Canal was estimated to be 40 percent of historical diversions, which is approximately the average for the longer canals in the Bishop-Brogden study. Leakage from canals diverting from Blue Creek was estimated to be 25 percent of historical diversions, which is what the Bishop-Brogden study used for the shorter canals. Bishop-Brogden Associates, Inc. (2002, p. 66-67) estimated long-term recharge from surface-water irrigation to be 20 percent of historical farm deliveries for Pathfinder and Gering-Ft. Laramie Irrigation Districts and 25 percent for all other irrigation districts. Recharge from surface-water irrigation from the Western Canal and canals diverting from Blue Creek was estimated to be 25 percent to be consistent with the Bishop-Brogden study. Recharge from canal leakage and recharge from surface-water irrigation were combined and were applied uniformly over the service areas of the various canals. Recharge from Gering-Ft. Laramie, Gering, and Castle Rock Irrigation Districts was not added to the model because limited aquifer and numerous drains in these districts prevented the recharge from affecting the regional aquifer. This long-term average recharge was fixed during model construction and was not changed during model calibration. This recharge was added to the model for the period 1900 to 1998.

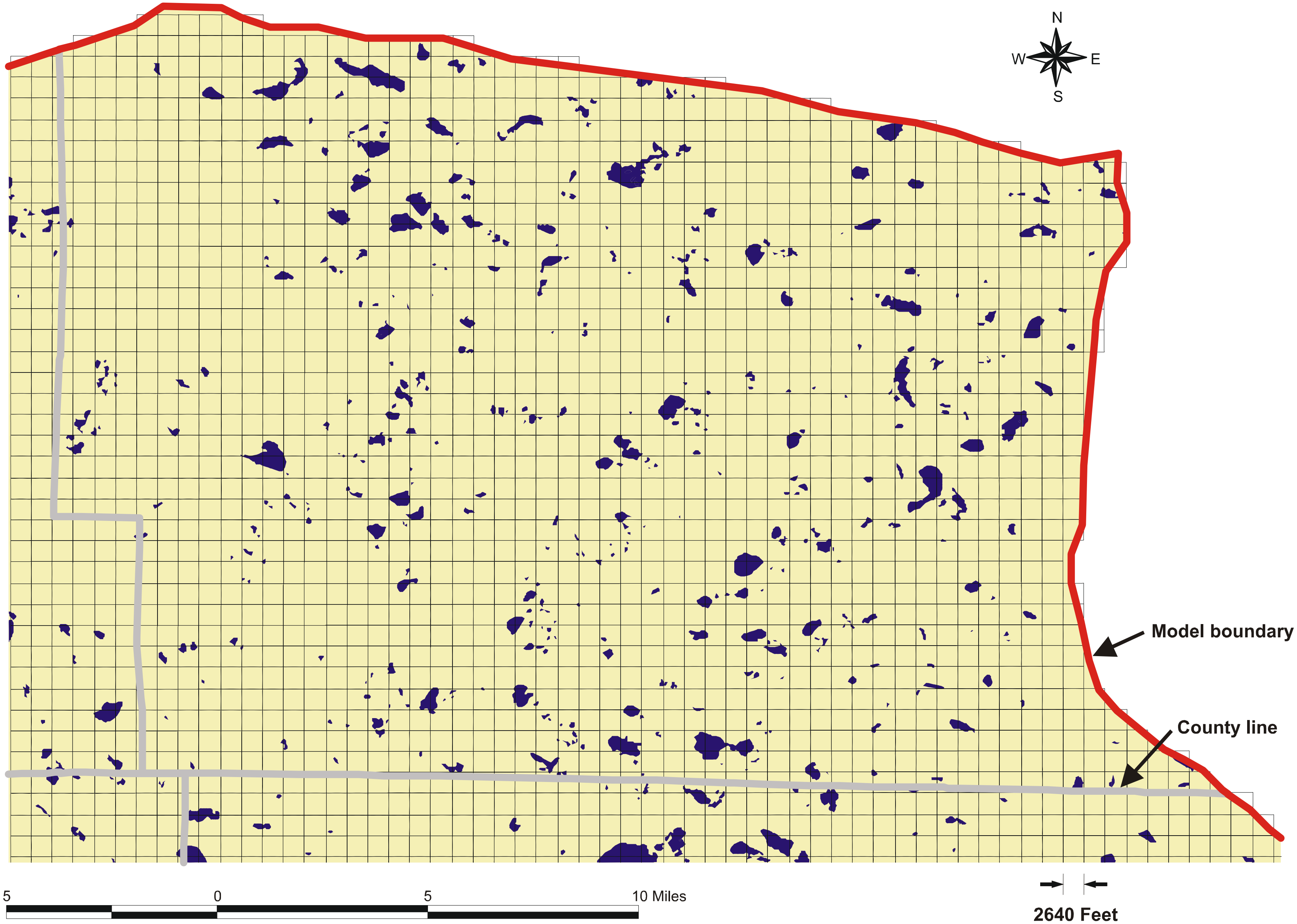

Figure 11. Active cells and Sand Hill lakes in that part of Sheridan County that is in the Western Model Unit.

Table 2. Estimated recharge from canal leakage and surface-water irrigation in the Western Model Unit. Most values are from Bishop-Brogden Associates, Inc. (2002). Irrigation districts and items in bold were not in that study and were estimated in this study. Recharge from Gering-Ft. Laramie, Gering, and Castle Rock Irrigation Districts was not added to the model because limited aquifer and numerous drains in these districts prevented the recharge from affecting the regional aquifer.

[% – percent; A – acres; AF/yr – acre-feet per year; GW – groundwater; in/yr – inches per year; Values for Pathfinder Irrigation District are for only the Nebraska part of the District. Acres and acre-feet are rounded to nearest 100; inches are rounded to nearest 0.01. Values are rounded after calculations]

Irrigation District	Historical diversions (AF/yr)	Area (A)	Canal loss (%)	Loss to GW (AF/yr)	Loss to GW (in/yr)	Delivered to farm (AF/yr)	Application recharge (%)	Application recharge (AF/yr)	Application recharge (in/yr)	All recharge (in/yr)
Alliance Irrigation District	18,200	11,100	45	7,800	8.39	10,000	25	2,500	2.70	11.09
Beerline Irrigation District	2,200	2,800	42	900	3.80	1,300	25	300	1.38	5.18
Blue Creek and Hooper Irrigation Districts	**8,100**	**5,000**	**25**	**1,900**	**4.59**	**6,100**	**25**	**1,500**	**3.63**	**8.22**
Bridgeport Irrigation District	30,100	36,200	37	10,600	3.51	19,000	25	4,700	1.57	5.08
Browns Creek Irrigation District	13,300	13,100	42	5,300	4.87	7,700	25	1,900	1.77	6.63
Castle Rock Irrigation District	20,700	9,500	40	7,900	9.89	12,400	25	3,100	3.90	13.80
Central Irrigation District	5,600	2,600	41	2,200	10.05	3,300	25	800	3.80	13.85
Chimney Rock Irrigation District	15,100	7,000	42	6,000	10.38	8,800	25	2,200	3.77	14.16
Empire Irrigation District	5,600	1,800	25	1,300	8.98	4,200	25	1,100	7.09	16.07
Enterprise Irrigation District	23,300	10,700	42	9,300	10.47	13,500	25	3,400	3.80	14.27
Farmers Irrigation District	189,900	78,200	41	74,000	11.35	112,000	25	28,000	4.30	15.64
Gering Irrigation District	41,400	16,700	38	14,900	10.72	25,700	25	6,400	4.60	15.32
Gering-Ft. Laramie Irrigation District	142,000	79,800	20	27,000	4.06	113,600	20	22,700	3.42	7.48
Graf Irrigation District	**2,100**	**3,900**	**25**	**500**	**1.53**	**1,600**	**25**	**400**	**1.21**	**2.75**
Lisco Irrigation District	9,600	5,200	37	3,400	7.82	6,000	25	1,500	3.50	11.32
Midland-Overland Irrigation District	1,900	3,900	25	500	1.39	1,400	25	400	1.10	2.49
Minatare Irrigation District	19,700	4,600	45	8,400	21.93	10,800	25	2,700	7.05	28.99
Mitchell Irrigation District	23,000	20,100	17	3,700	2.21	19,100	25	4,800	2.85	5.06
Ninemile Irrigation District	15,600	9,800	45	6,700	8.15	8,600	25	2,100	2.62	10.78
Northport Irrigation District	37,100	27,800	48	16,900	7.31	19,300	25	4,800	2.08	9.40
Paisley Irrigation District	**2,900**	**2,300**	**25**	**700**	**3.55**	**2,200**	**25**	**500**	**2.80**	**6.35**
Pathfinder Irrigation District	397,800	157,000	51	192,700	14.73	194,900	20	39,000	2.98	17.71
Short Line Irrigation District	7,400	3,300	25	1,800	6.33	5,600	25	1,400	5.00	11.33
Union Irrigation District	**2,400**	**1,500**	**25**	**600**	**4.45**	**1,800**	**25**	**500**	**3.51**	**7.96**
Western Irrigation District	**25,200**	**23,900**	**40**	**9,600**	**4.81**	**15,100**	**25**	**3,800**	**1.90**	**6.71**
Winters Creek Irrigation District	5,000	12,100	45	2,100	2.12	2,800	25	700	0.68	2.80

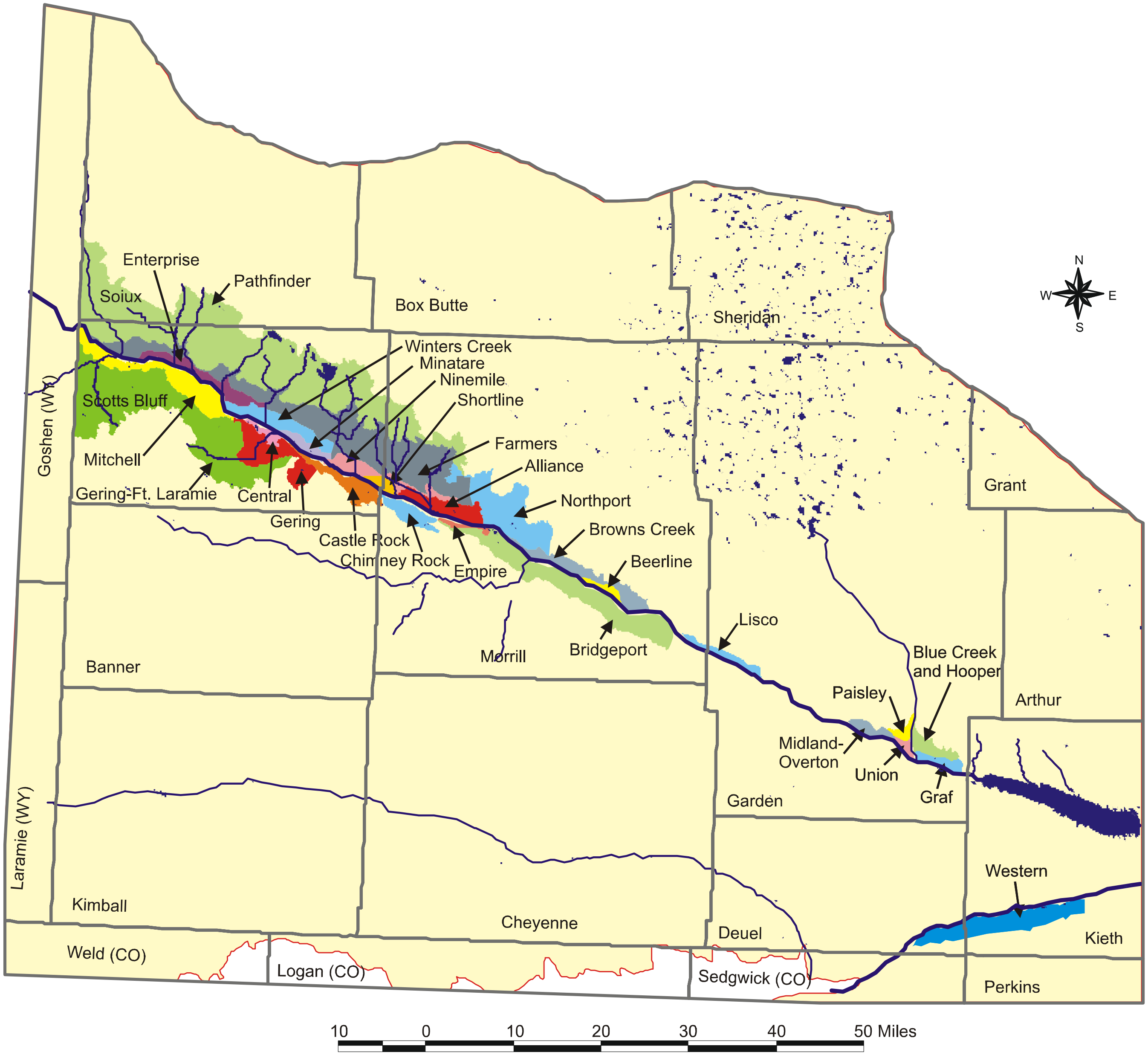

Figure 12. Irrigation districts in the Western Model Unit.

The configuration of the base of the aquifer came from Cannia and others (J.C. Cannia, North Platte Natural Resources District, Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report, written commun., draft dated March 22, 2005). The base of the aquifer was interpolated at the model nodes from 100-foot contours. In some places, particularly along Pumpkin Creek and Lodgepole Creek, the interpolated values were modified to keep the base of aquifer below stream level. The interpolated values also were modified in a small area southeast of the mouth of Pumpkin Creek to maintain known paleovalleys in the model as continuous features.

The first simulation was for the period prior to 1900. This was a 2,000-year long simulation to allow the groundwater system to come into dynamic equilibrium with recharge from precipitation. This long period was required so that equilibrium was assured throughout the model area, although much of the model reached equilibrium within a few hundred years. This equilibrium, called steady state, is commonly simulated directly by MODFLOW, but had to be achieved indirectly using the 2,000-year period because small saturated thicknesses along Brule Formation outcrops caused numerical instability that precluded direct simulation of steady-state conditions. Equilibrium was verified at the end of the 2,000-year simulation by running the model an additional 400 years. Mean water-level change during this 400-year period was about 0.004 ft and the standard deviation was about 0.050 ft.

Next, the period 1900-40 was simulated as a transient period when extra recharge from canal leakage and surface-water irrigation was added to the model, affecting much of the area around the North Platte and South Platte Rivers. Then, the period 1940-50 was simulated as a transient period when Lake McConaughy was added to the model. Finally, the period 1950-98 was simulated as a transient period when groundwater irrigation and additional recharge from precipitation on cultivated land were added to the model.

The initial water level for the 2,000-year simulation was set to a small height above the base of aquifer to control numerical stability early in the simulation period. The model was then run for several 2,000-year periods so the groundwater levels rose until they came into dynamic equilibrium with recharge from precipitation. Because equilibrium was reached, the 1900 simulated water table was independent of the initial water levels. The water level from the 2000-year simulation was the initial water level for the 1900-40 period, the simulated 1940 water level was the initial water level for the 1940-50 period, and the simulated 1950 water level was the initial water level for the 1950-98 period. Simulated water levels, rather than observed water levels, were used at the beginning of 1900, 1940, and 1950 because the simulated water levels were in equilibrium with model inputs. If observed water levels had been used and were not in equilibrium with model inputs, the model would have simulated artificial water-level changes due to this disequilibrium.

The 2,000-year period prior to 1900 was simulated with 10,000 time steps of about 29 days and 10,000 time steps of about 44 days. The small time steps used to achieve steady state prevented cells from going dry due to numerical errors. The 1900-40 transient period was simulated with 3,000 time steps of about 4 days and the 1940-50 transient period was simulated with 1,000 time steps of about 4 days.

Beginning May 1, 1950, an irrigation season stress period (May-September) and a non-irrigation season stress period (October-April) were simulated with the transient model. Within a stress period, pumpage and recharge were held constant. The irrigation season stress period was simulated with 10 time steps of about 15 days and the non-irrigation season stress period was simulated with 10 time steps of about 21 days. Although the October-April period is called the non-irrigation season, some irrigation on alfalfa and wheat was simulated during this period.

The period 1950-98 was subdivided into four shorter periods for calibration (discussed in the Numerical Model Calibration section). These shorter periods were 1950-61, 1961-73, 1973-85, and 1985-98. These periods were selected after examining numerous water-level hydrographs and noting dates of natural breaks. More water-level change data were available for calibration of the shorter periods, particularly the last two periods, than were available for the entire period 1950-98.

Annual pumpage for groundwater-irrigated crops was estimated for the calibration period spring of 1950 through spring of 1998. The estimates were based on reported land uses for various years from Census of Agriculture county crop statistics (U.S. Department of Commerce, 1949-92, and U.S. Department of Agriculture, 1997), mapped 1997 land use (Dappen and Tooze, 2001), and estimated net irrigation requirement. These estimates are for net pumpage, which is total pumpage less any runoff and deep percolation from total pumpage.

The Census of Agriculture reports contain county-level crop statistics on about a 5-year recurring basis. Beginning with the 1954 Census, irrigated acres by selected crops were reported. For the 1949 Census, only total irrigated acres were reported and irrigated acres by crop had to be estimated. Not all crops were reported for all years, so dryland and irrigated acres had to be estimated in some cases. This usually happened with minor crops. When more acres were grown, the Census included these crops.

Some counties are only partially within the COHYST area. For these counties, the Census data were reduced by a factor based on the proportion of the county that is in the study area. A linear interpolation between Census years was used to estimate irrigated and dryland acres by crop for non-Census years.

The location of irrigated cropland, dry cropland, and rangeland within a county for 1950-96 was estimated based on the 1997 land-use map (Dappen and Tooze, 2001), location of surface-water irrigated land, registered irrigation wells (Cooperative Hydrology Study, 2001b), and topographic regions (Conservation and Survey Division, 1998, fig. 2). Land use mapped for 1997 (Dappen and Tooze, 2001) was assumed to continue into the spring of 1998.

Dappen and Tooze (2001) mapped nine crops (alfalfa, corn, dry edible beans, potatoes, small grains, sorghum, soybeans, sugar beets, and sunflowers) for 1997, and also mapped whether they were irrigated or not, for a total of 18 land uses. They also mapped fallow land, rangeland and six other land uses, including urban, open water, woodlands, wetlands, other agricultural land, and roads. Of the 26 land uses mapped by Dappen and Tooze (2001), dryland potatoes and dryland sugar beets were assumed to be actually irrigated, because these crops are always irrigated in the Western Model Unit, so the number of land uses was reduced to 24. The six other land uses (urban, open water, woodlands, wetlands, other agricultural land, and roads) combined cover less than 7 percent of the study area, with wetlands and woodlands being the dominant of these six land uses. These six land uses were assumed not to change over time. The remaining 18 land uses were modified over time as described next.

The 1997 land uses (Dappen and Tooze, 2001) were aggregated to 640-acre cells that covered the entire COHYST area. The number of acres in each of the 24 land uses in 1997 was calculated for each cell. The 640-acre cell size was necessary because of the large file sizes and long processing times required to accomplish the process of estimating land use described below. The 640-acre cells were coincident with four 160-acre cells of the model described in this report. Pumpage was calculated for the 640-acre cells and then was equally distributed to the four 160-acre cells for this model. The 1997 land uses also were aggregated to 10-acre cells and were saved for potential future use.

The process of estimating 1950-96 land use by 640-acre cell for the 18 land uses that were allowed to change over time started with 1997 land use (Dappen and Tooze, 2001) and worked backwards in time. If total acres for a particular land use in a county were less in 1996 than in 1997, random fields, weighted as described below, were removed from the 1997 data set to develop the 1996 data set. The land use with the largest decrease going back in time was processed first. The fields that were removed were tracked for later re-assignment of land use. After all the land uses in a county that had decreased from 1997 to 1996 were processed, land uses that increased were processed, beginning with the land use that had the largest increase. These land uses were assigned to random fields, also weighted, that had been previously removed.

The random process of removing or adding acres by cells was weighted based on topographic regions. The 18 variable land uses were grouped into three general categories, row crops (alfalfa was placed in this category), small grains/fallow, and rangeland, and a weight was assigned to the likelihood of a category being present within a topographic region. For example, the "row crop" land use category was given large weights for cells in valleys and plains and small weights for cells in the Sand Hills, sand dunes, and bluffs/escarpments. This meant that the weighted random process was much more likely to add a row crop field to cells in a valley or plain, and was similarly much more likely to remove it from cells in the Sand Hills, sand dunes, or bluffs/escarpments.

The re-assignment process also considered the location of surface-water irrigated lands and registered irrigation wells. Irrigated cropland was preferentially kept on surface-water irrigated lands by rejecting removal of an irrigated land use or favoring addition of an irrigated land use on surface-water irrigated lands. In a similar manner, the number of irrigation wells in an area was used to weight retention or removal of irrigated land uses from 1997 to 1996.

Once the 1996 land-use data set was built from the 1997 land-use data set, the 1995 data set was built from the 1997 data set in the same manner. Then the 1994 data set was built from the 1997 data set, and so on until the 1950 land-use data set was built. The decision to always start with the 1997 land use had the advantage of keeping any bias in any particular year from affecting other years.

Net irrigation requirement in the Western Model Unit was estimated in two different ways, which resulted in two different annual pumpage data sets and two calibrations for the 1950-98 period. The differences in the data sets and calibrations are discussed in the Numerical Model Calibration section. Other methods of estimating net irrigation requirement and pumpage were considered, but none were deemed better than either of the two that were used.

The first net irrigation requirements were computed from crop consumptive use estimated by Klocke and others (1990, table 1). Crop consumptive use minus effective precipitation is the estimated net irrigation requirement for the crop. This method is called "NebGuide" net irrigation requirement or net pumpage in this report. The second net irrigation requirements were computed with an unpublished soil-water-balance model developed by Dr. Derrel Martin, University of Nebraska–Lincoln. This method is called "CropSim" net irrigation requirement or net pumpage in this report.

NebGuide is simplistic in that it deals with average climatic and soil conditions on an ideal crop and is based on years of experience of the University of Nebraska Extension Service and others in various areas. Klocke and others (1990) present this table for seasonal crop water use (ET), in inches per year, in Nebraska:

Crop	Western	Central	Eastern
Corn	23-26	24-27	25-28
Soybeans	20-22	21-23	22-25
Dry Beans	15-16		
Sorghum	18-20	19-22	20-23
Winter Wheat	16-18	16-18	16-18
Alfalfa	31-33	32-35	34-36
Sugar Beets	24-26		

For the Western Model Unit, the Western column was selected and the midpoint of the range was assumed to be the crop consumptive use for each year. Although crop consumptive use varies from year to year and place to place, average values were considered acceptable because the model was calibrated over many years. As noted earlier, crop consumptive use minus effective precipitation for a particular year was the net irrigation requirement for that year. Effective precipitation is that part of precipitation that is available to meet crop consumptive use. Effective precipitation calculated by CropSim was used in the NebGuide net pumpage estimates. Because effective precipitation varies on an annual basis, NebGuide net irrigation requirement varies on an annual basis.

The sum of the net irrigation requirement times the area of each irrigated crop in each 640-acre cell gave the net pumpage for that cell for each year. The NebGuide net pumpage was then reduced by 10 percent to account for less–than-ideal crops in the real world, because real-world crops are less healthy, do not always receive all the nutrients and water they would like, are stressed by insects and other pests, and thus consume less water.

CropSim is much more complex than NebGuide in that it attempts to deal with the areal variation in soils, land uses, and the areal and temporal variations in meteorology. CropSim is a model that uses daily time steps to account for precipitation, crop evapotranspiration, and remaining available soil moisture. When soil moisture decreases to a specified level in the CropSim model, irrigation water is added. Seasonal net irrigation requirement is equal to the total amount of water added for the season. CropSim is very data intensive because it requires daily inputs for precipitation and data to compute potential evapotranspiration (also known as reference crop evapotranspiration).

The data to compute daily potential evapotranspiration, the most critical data input to CropSim, is not available for much of the 1950-98 period, and had to be estimated indirectly from meteorological data using the Hargreaves method (Hargreaves, 1994) adjusted for each meteorological station (more than those shown of figure 4). Daily potential evapotranspiration should not change dramatically from station to station. However, the calculated potential evapotranspiration changed several inches on an annual basis from one station to the next, probably due to limitations of the calibrations of the Hargreaves method to the meteorological stations. To correct for this, potential evapotranspiration was averaged over the full COHYST area on a daily basis. This calculated value was greater than generally accepted values, so daily potential evapotranspiration determined by this method was reduced by 10 percent to bring them into the accepted range. CropSim, like NebGuide is for an ideal crop and thus CropSim net pumpage was reduced by 10 percent to account for reduced water use by real-world crops.

CropSim has been calibrated to natural conditions only to a very limited extent. It also requires data that are not continuously or universally available or are very sparse. NebGuide is based on experience of many people averaged over large areas and many years. NebGuide is simplistic whereas CropSim is complex, but neither approach offered clear advantages over the other. As a result, two pumpage data sets were produced and two calibrations were completed.

Numerical Model Calibration

A groundwater flow model should be calibrated prior to being used for analysis and prediction. Calibration is a process of systematically adjusting selected model inputs within reasonable limits while comparing simulated and observed water levels and groundwater discharge to or from streams. This model was calibrated for both the pre-groundwater development period (pre-1950) and the groundwater development period (1950-98). In the pre-groundwater development period model, rangeland recharge, streambed conductance, evapotranspiration rate, and hydraulic conductivity were adjusted. In the groundwater development period model, dryland recharge, irrigated land recharge, and specific yield were adjusted. Other model inputs, such as boundary flows, canal leakage and surface-water irrigation recharge, configuration of base of aquifer, and net pumpage were fixed during model construction and were not varied during calibration.

A groundwater flow model calibration may not be unique in that different combinations of model inputs may produce similar results. For example, simulated recharge and hydraulic conductivity are highly interrelated with respect to simulated water levels. This means the simulated values for recharge and hydraulic conductivity could be in considerable error and the model could still produce reasonable matches to measured water levels if the ratio between the two input values is correct. Fortunately, simulated recharge and hydraulic conductivity are not interrelated with respect to simulated groundwater discharge to or from streams, so a model calibration that produces good matches to both water levels and stream discharges is more likely to be unique.

This model is a refinement of several models previously constructed and calibrated as described in the COHYST modeling strategy (Cooperative Hydrology Study Technical Committee, 2000). The models started with a coarse grid and simple distributions of parameters and stresses. Over time, the grid was refined and the inputs became more complex and realistic. Documentation of calibrations of previous versions of the model were reviewed by the COHYST Technical Committee, but were not publicly released because the previous versions were not considered final products by the Technical Committee.

Observed water levels from U.S. Geological Survey and Nebraska Department of Natural Resources databases and estimates of groundwater discharge to streams (Luckey and others, 2001) based on streamflow station data were used to calibrate the 1950 pre-groundwater development period model. Observed and estimated water-level changes were used to calibrate the 1950-98 groundwater development period model. Water-level changes rather than absolute water levels were used in the development period so that any errors in the simulated 1950 water levels were not propagated into the development period. Changes in streamflow were used only in a qualitative manner in the 1950-98 model, because groundwater discharge to most streams changed only slightly between 1950 and 1998 (Luckey and others, 2001). Lodgepole Creek and Pumpkin Creek, both of which experienced dramatic declines in discharges, were the exceptions to this.

Observed water levels used in calibration of the pre-groundwater development period model were selected from water levels measured in wells during 1946-55 during a period of relative stability in water levels. Some areas contain numerous observation wells that reflect the same conditions, so a 4-mi by 4-mi grid was overlain on the COHYST area and the most reliable water level in each grid was selected for use in calibration. This selection process prevented a cluster of closely spaced observation wells from dominating the calibration process. Because the largest potential errors in the water level are errors in location or land-surface elevation, the most reliable water level was the level associated with the most accurate location and land-surface elevation. After screening values in all of the 4-mi by 4-mi cells, a few points that appeared to have large errors in location or land-surface elevation were excluded from the calibration data set. The final data set used in this calibration consisted of 144 water levels in the Western Model Unit.

Water-level changes used in calibration of the groundwater development period model were of two types, observed changes and estimated changes. Estimated changes had to be used because so few observation wells were measured in both 1950 and 1998. The estimated changes were obtained at the same points used by Stanton (1999) to construct the predevelopment to 1998 water-level change map. These points had a measured 1998 water level but had an estimated predevelopment water level supplied by the Conservation and Survey Division of the University of Nebraska. The estimates were based on unpublished maps in Conservation and Survey Division files. A total of 154 estimated change points were identified by this method in the Western Model Unit.

The second type of changes, observed water-level changes, were selected from water levels measured near the beginning and end of the periods 1950-98, 1950-61, 1961-73, 1973-85, and 1985-95. To select these points, a 4-mi by 4-mi grid was overlain on the COHYST area and the point with the most water levels in the cell, including ones near the beginning and ending date, was selected. The number of points in the Western Model Unit for each period was:

Period	Number
1950-98	32
1950-61	45
1961-73	42
1973-85	63
1985-98	103

Not all observed water-level changes were equally useful for calibration. For example, nine of the 1950-98 observed water-level changes were in areas of evapotranspiration in the Sand Hills where water levels change little over time. Many of the rest of the water levels were in stream valleys, where water levels also change little over time. Only the 1973-85 and 1985-98 data sets were deemed sufficient for meaningful calibration.

Simulated versus observed water levels in groundwater models are commonly compared by computing three calibration statistics: mean difference, mean absolute difference, and root-mean-squared difference. The mean difference (MD) is defined as:

$$MD = \frac{1}{n}\sum_{i=1}^{n}(wl_s - wl_o)$$

where wl_s is the simulated water level, wl_o is the observed water level, and n is the number of points in the calibration data set. The mean difference is not necessarily a good measure of calibration because errors of opposite sign tend to cancel out. However, the mean difference is a measure of overall bias in the calibration and as such, it should be close to zero.

The mean absolute difference (MAD) is defined as:

$$MAD = \frac{1}{n}\sum_{i=1}^{n}\left|(wl_s - wl_o)\right|$$

The mean absolute difference is a good measure of model calibration because positive and negative differences do not cancel out. It gives all points equal weights, so large differences between simulated and observed water levels do not tend to dominate this measure of error.

The root-mean-square difference (RMS) is defined as:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(wl_s - wl_o)^2}$$

and is the standard deviation of the differences between simulated and observed water levels. The root-mean-square difference emphasizes large differences between simulated and observed water levels and these points tend to dominate this measure of error.

The above statistics are frequently normalized by dividing them by the range in observed water levels. In this report, the normalized mean difference, normalized mean absolute difference, and normalized root-mean-square difference are reported in percent. Observed water-level elevations range from 3,212 ft to 5,083 ft.

Similar statistics were defined for comparison of simulated and observed changes in water-levels. MODFLOW computes water-level changes as drawdowns, which means that water-level declines are positive and water-level rises are negative. As a result, the sign convention on water-level changes is counterintuitive. Normalized statistics were not computed for water-level changes.

Groundwater discharge to streams was estimated using streamflows recorded at gaging stations during the fall (generally October and November), because this period is least affected by diversions and runoff. The techniques used to estimate groundwater discharge using gaged streamflow data are described by Luckey and others (2001). A minimum, mean, and maximum estimate of observed groundwater discharge was made for each stream or segment of stream with a gaging station for one or more time periods, depending on the period of record available. If estimates were made for multiple periods, the period closest to 1941-97 was used in the calibration (Luckey and others, 2001). If the simulated discharge was within the range of estimates (minimum to maximum), the model was considered calibrated with respect to that stream. Some streams, such as Otter Creek, have relatively narrow ranges of observed groundwater discharges, whereas other streams, such as the North Platte River, have relatively wide ranges. Qualitatively, the model calibration was deemed better if the simulated groundwater discharge was close to the mean estimate of observed discharge to that stream, but no truly quantitative measure of model fit to observed groundwater discharge to streams was made.

During external review of this model (Eagle Resources, 2005), the assumption that fall groundwater discharge to streams was representative of non-irrigation season groundwater discharge to stream was checked. The review concluded that this was an acceptable assumption.

Pre-Groundwater Development Period Calibration

Numerous hydraulic-conductivity distributions were tested in calibrating this model. The best fit between simulated and observed water levels and groundwater discharges to streams occurred when hydraulic conductivity was assigned as shown on figure 13. Hydraulic conductivity was, in a general sense, based on geologic units with some units subdivided into several hydraulic conductivity zones. The largest hydraulic conductivities (150 and 100 ft/d) were assigned to the valleys along the North Platte and South Platte Rivers because they contain coarse-grained alluvial deposits. Somewhat smaller hydraulic conductivity (shown in yellowish green on figure 13 with a value of 50 ft/d) was assigned to alluvium in Sidney Draw, adjacent Lodgepole Creek Valley, and a small valley in southern Garden County. Small hydraulic conductivities (5 and 10 ft/d) were assigned south of the North Platte River in Scotts Bluff County and adjacent counties where the Brule Formation underlies thin colluvium. Another area of small hydraulic conductivity (6 ft/d) was assigned to Sioux and Box Butte Counties where the aquifer is composed of fine-grained sediments of the Arikaree Group. Small hydraulic conductivity (10 ft/d) also was assigned north of the North Platte River in Sioux, Scotts Bluff, Box Butte, and Morrill Counties. This area represents outcrops of very fine-grained deposits of the Brule Formation and the Arikaree Group. The hydraulic conductivity of areas where the Ogallala Group (fig. 9) is the dominant water-bearing unit was subdivided into zones of high, intermediate, and low hydraulic conductivity (fig. 13). The high zone (shown in yellowish green with a value of 50 ft/d and dark sand color with a value of 35 ft/d on figure 13) represents a high-energy depositional environment generally west of the syncline of the Rush Creek Structure of Swinehart and others (1985, fig. 22). The high-energy depositional environment resulted in coarser sediments with higher hydraulic conductivities. The location of the structure was modified based on new base-of-aquifer information acquired during COHYST and was extended to the southwest and northeast because observed water levels indicated high hydraulic conductivity in this area. The area generally southeast of the northern part of the anticline of the structure and beneath and west of the southern part of the structure, the low hydraulic conductivity zone (in faded pink with a value of 15 ft/d on figure 13) is thought to correspond to a low-energy environment, fine-grained sediments, and smaller hydraulic conductivities. The low hydraulic conductivity zone was extended north of the North Platte River because the simulated water levels were more reasonable with a lower hydraulic conductivity in that area even though the structure could not be traced north of the river. Another high hydraulic conductivity zone (in dark sand color with a value of 35 ft/d in figure 13) in southern Box Butte County represents a paleochannel filled with coarser sediments with higher hydraulic conductivities. The remainder of the Ogallala Group (light sand color in figure 13) represents a mixture of depositional environments and was assigned an intermediate hydraulic conductivity of 25 ft/d.

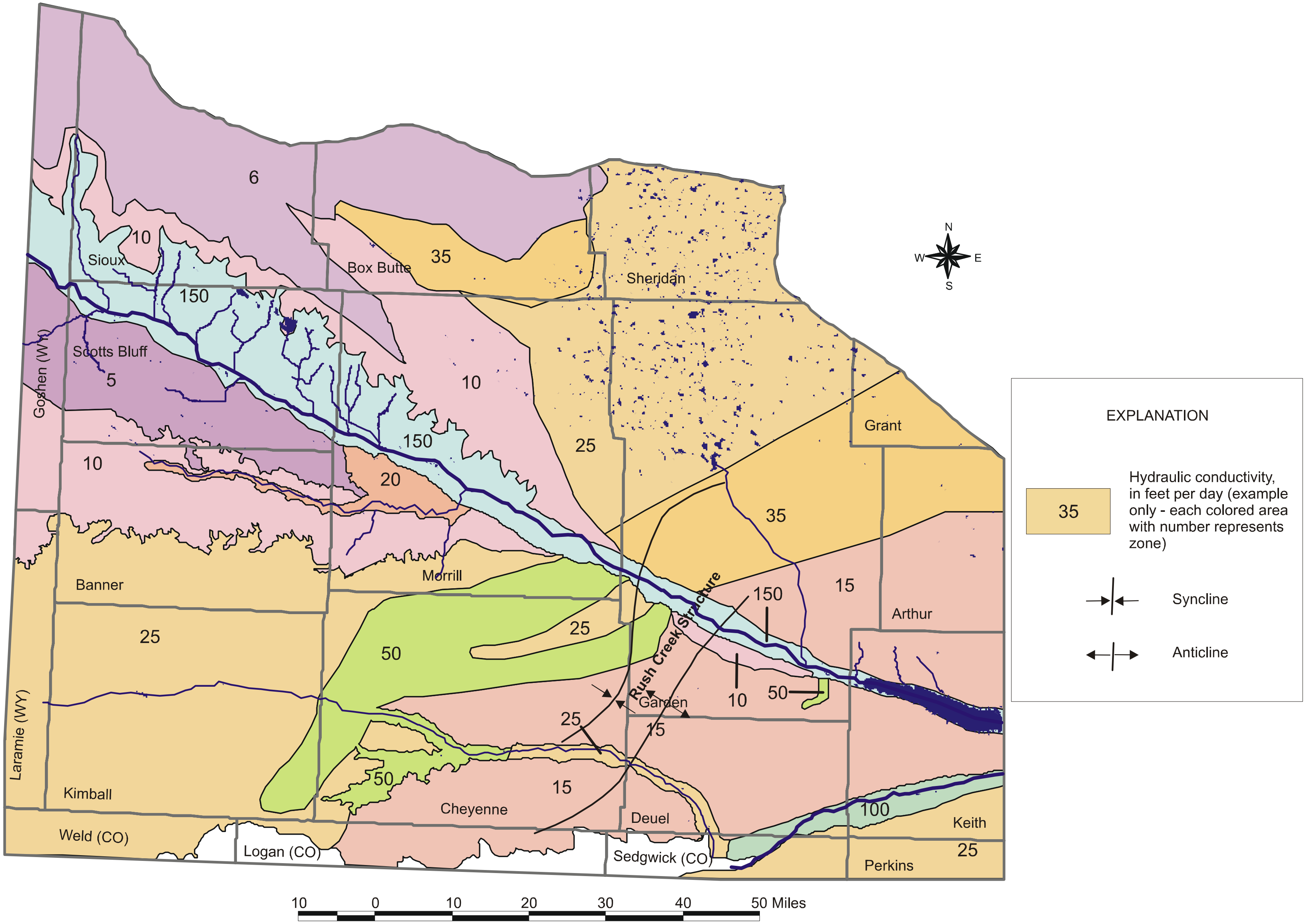

Figure 13. Hydraulic conductivity distribution used in the calibrated pre-groundwater development period model of the Western Model Unit. Rush Creek Structure modified from Swinehart and others (1985, fig. 22).

Stream conductances were initially selected based on stream groups, and the values by group were varied to obtain the best fit between simulated and observed water levels and discharges to streams. The stream groups were based on Landon and others (2001), Rus and others (2001), Cooperative Hydrology Study (2001c and 2001d), and Chen (2004). The groups were based on texture and size of streambed sediments. The groups were major rivers, streams predominately flowing over Brule Formation, and other streams. Conductances for North Platte and South Platte Rivers (major rivers) were set to 22.5 feet per day (ft/d) per unit length. Streams predominately flowing over Brule Formation were Gering Drain, Lodgepole Creek, and Pumpkin Creek. These streams were assigned a streambed conductance of 1.0 ft/d per unit length. The group "other streams" was subdivided into three subgroups during calibration. The first subgroup was the streams flowing out of the Sand Hills that had very fine-grained streambed sediments and included Blue Creek, Clear Creek, Lonegran Creek, and Otter Creek. Streambed conductance for this subgroup was set to 1.0 ft/d per unit length. The second subgroup was two small tributaries to Pumpkin Creek that flowed through narrow valleys cut into the Brule Formation and had fine-grained streambed sediments, Greenwood Creek and Lawrence Fork. Streambed conductance for this subgroup was set to 0.1 ft/d per unit length. All other streams were in the third subgroup and were assigned a streambed conductance of 10 ft/d per unit length. The conductance for Lake McConaughy was set to 1.0 per unit area per day.

The distribution of rangeland recharge due to precipitation was generally based on soils and topography (fig. 14). The rangeland recharge zones were set during model construction and the values applied to the zones were determined during calibration. The values that gave the best fit between simulated and observed water levels and groundwater discharge to streams were Sand Hills (2.30 in/yr), sand dunes in the northwest corner of the Western Model Unit (1.50 in/yr), sand dunes in upper Pumpkin Creek Valley (1.00 in/yr), fine sandy-loam soils predominantly in Sioux County (0.80 in/yr), silt- and clay-loam soils predominantly in Box Butte County (0.15 in/yr), and all remaining areas (0.18 in/yr). The simulated groundwater discharges to Blue Creek, Clear Creek, Otter Creek, and Lonegran Creek were particularly sensitive to the simulated recharge on the Sand Hills. Simulated water levels were sensitive to rangeland recharge in the other zones. Rangeland recharge was assumed to be the only recharge due to precipitation until 1950. Although this assumption may not be correct, there were insufficient data to determine if recharge changed after settlement but before 1950.

Evapotranspiration from groundwater was simulated in the area of numerous Sand Hill lakes (fig. 10). The maximum groundwater evapotranspiration rate in the Western Model Unit was initially estimated as 14 in/yr in the western half of the model and 13 in/yr in the eastern half of the model. These estimates were based on the difference between lake evaporation and precipitation, and a factor based on riparian woodland evapotranspiration studies near Gothenburg and Odessa, Nebraska (M.K. Landon, U.S. Geological Survey, oral commun., July 2004), accounting for the fact that vegetation evapotranspiration rates are less than open-water rates. The initial values were later increased 2 in/yr during calibration to result in 16 in/yr in the western half and 15 in/yr in the eastern half of the model area. This rate occurred when the simulated water table was at or above the evapotranspiration surface. The evapotranspiration surface was initially estimated as half way between the mean land surface in a 160-acre grid and the minimum land surface in the grid. This surface was assumed to approximate lower areas of a model cell where evapotranspiration would occur. This value was decreased by 10 ft in the Sand Hills, extreme eastern Box Butte County, and along lower Snake Creek during calibration to get a better fit between simulated and observed water levels. This change was reasonable because the initial surface was above inter-dune and valley-bottom areas where evapotranspiration would occur. The evapotranspiration rate was reduced linearly and reached zero when the simulated water table was at the extinction depth below the evapotranspiration surface. The extinction depth was 7 ft in the riparian corridor along the North Platte and South Platte Rivers because of the deeply rooted cottonwood trees, and 5 ft elsewhere because of less deeply rooted grasses and wetland plants.

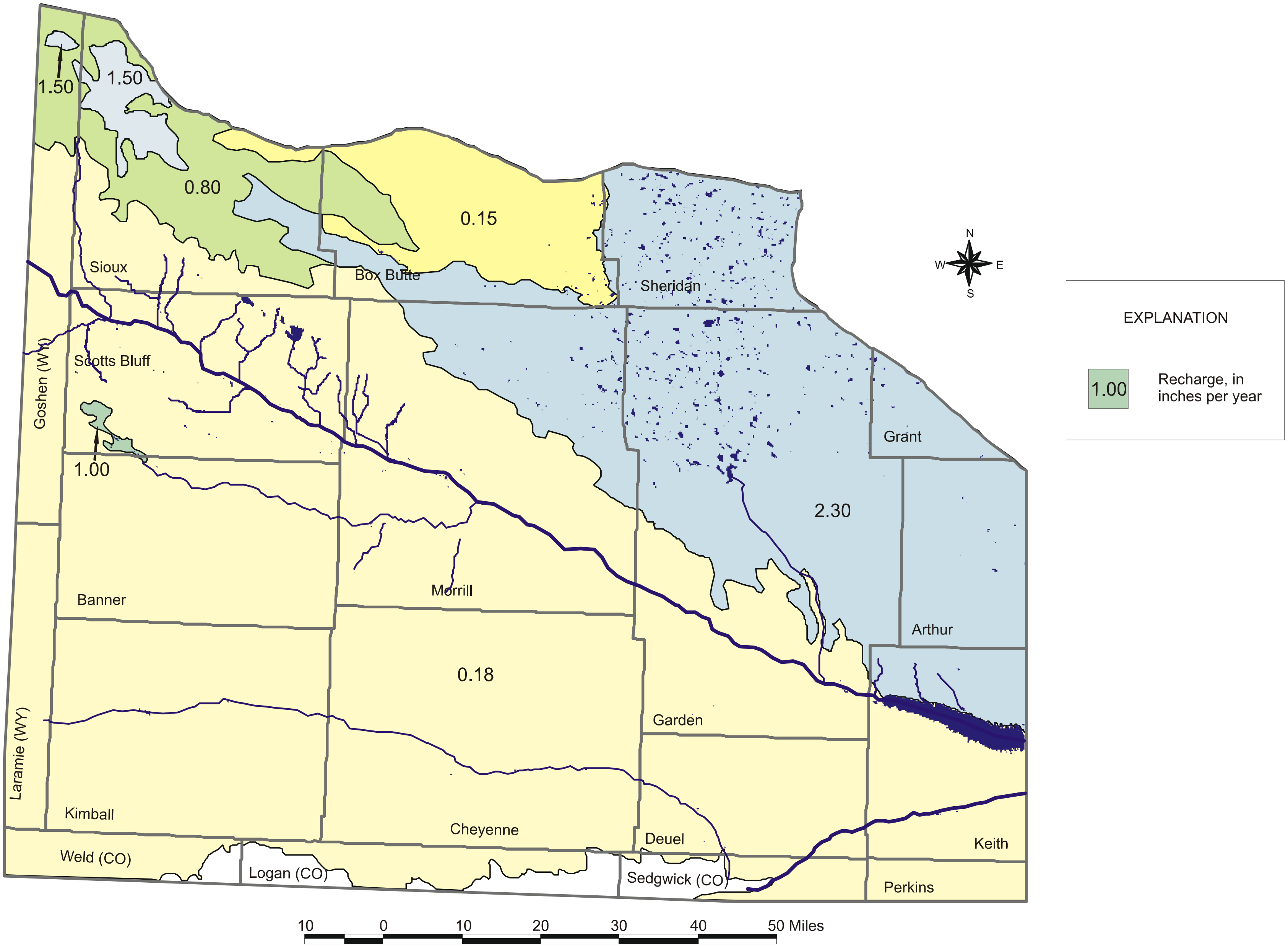

Figure 14. Rangeland recharge distribution used in the calibrated pre-groundwater development period model of the Western Model Unit. Recharge due to canal leakage and surface-water irrigation was added to rangeland recharge for the last 50 years of the simulation.

The calibration statistics for simulated versus observed 1950 water levels at the 144 observation points in the calibrated pre-groundwater development period model were:

Statistic	Value (ft)	Value (%)
Mean difference	2.20	0.12
Mean absolute difference	10.33	0.55
Root-mean-square difference	14.15	0.76

The mean difference of 2.20 ft indicated that the simulated water levels (fig. 15) were on average somewhat above observed water levels at calibration points. The mean difference was relatively small compared to many of the differences between simulated and observed water levels. The differences ranged from –51 ft to +55 ft. Simulated 1950 water levels were within 25 ft of observed water levels in 133 of 144 calibration points (92 percent of points). There was no consistent regional pattern in the differences between the simulated and observed water levels. The lack of a regional pattern to the differences was consistent with there being no major flaws in the conceptualization of the regional flow system. The small normalized differences indicated a very good fit between simulated and observed 1950 water levels.

Simulated groundwater discharge to the North Platte River (table 3) was just above the minimum of the calibration range. Without riparian ET in the model, the simulated groundwater discharge to the North Platte River would be closer to the mean. Estimated discharge was determined using October and November data and may be more indicative of discharges during the non-evapotranspiration season. The sum of simulated groundwater discharges of north-side tributaries to the North Platte River above Pumpkin Creek was at the minimum of the calibration target. Some individual streams were in considerable error, with simulated flows either too large or too small. Most notable were Bayard Drain and nearby Wildhorse Drain and Red Willow Creek. The model under-simulated discharge to Bayard Drain and over-simulated discharge to Wildhorse Drain and Red Willow Creek. This could have been corrected in the model by changing individual streambed conductances, but this was not done because there was no independent evidence that these streams do not have the same bed characteristics as other streams within the stream subgroup. The low simulated groundwater discharge to Gering Drain resulted because estimated recharge from canal leakage and surface-water irrigation was not simulated for the Gering-Ft. Laramie, Gering, and Castle Rock Irrigation Districts. These districts are covered with numerous small drains that were impractical to simulate with this model. Alliance Drain is a toe drain for the dam on Lake Minatare, and part of the estimated groundwater discharge to Alliance Drain may actually be seepage through or beneath the dam. Simulated groundwater discharge to Pumpkin Creek was below the calibration range. There was an evapotranspiration area at the head of the creek, so its estimated discharge also may be more indicative of the non-evapotranspiration season. Blue Creek was below the calibration range, as was Otter Creek. The estimated discharge for these creeks also may be more indicative of the non-evapotranspiration season.

The simulated water budget for the pre-groundwater development period model for 1950 is shown in table 4. The simulated inflows to the aquifer in 1950 (table 4) were 10 ft^3/s greater than the simulated outflows. The majority of this disequilibrium probably was because the simulated system had not yet come into complete equilibrium with the effects of Lake McConaughy by 1950.

The calibrated pre-groundwater development period model was deemed a reasonable representation of the system, given the data available and the size of the grid. This calibrated model became the starting point for the groundwater development period model.

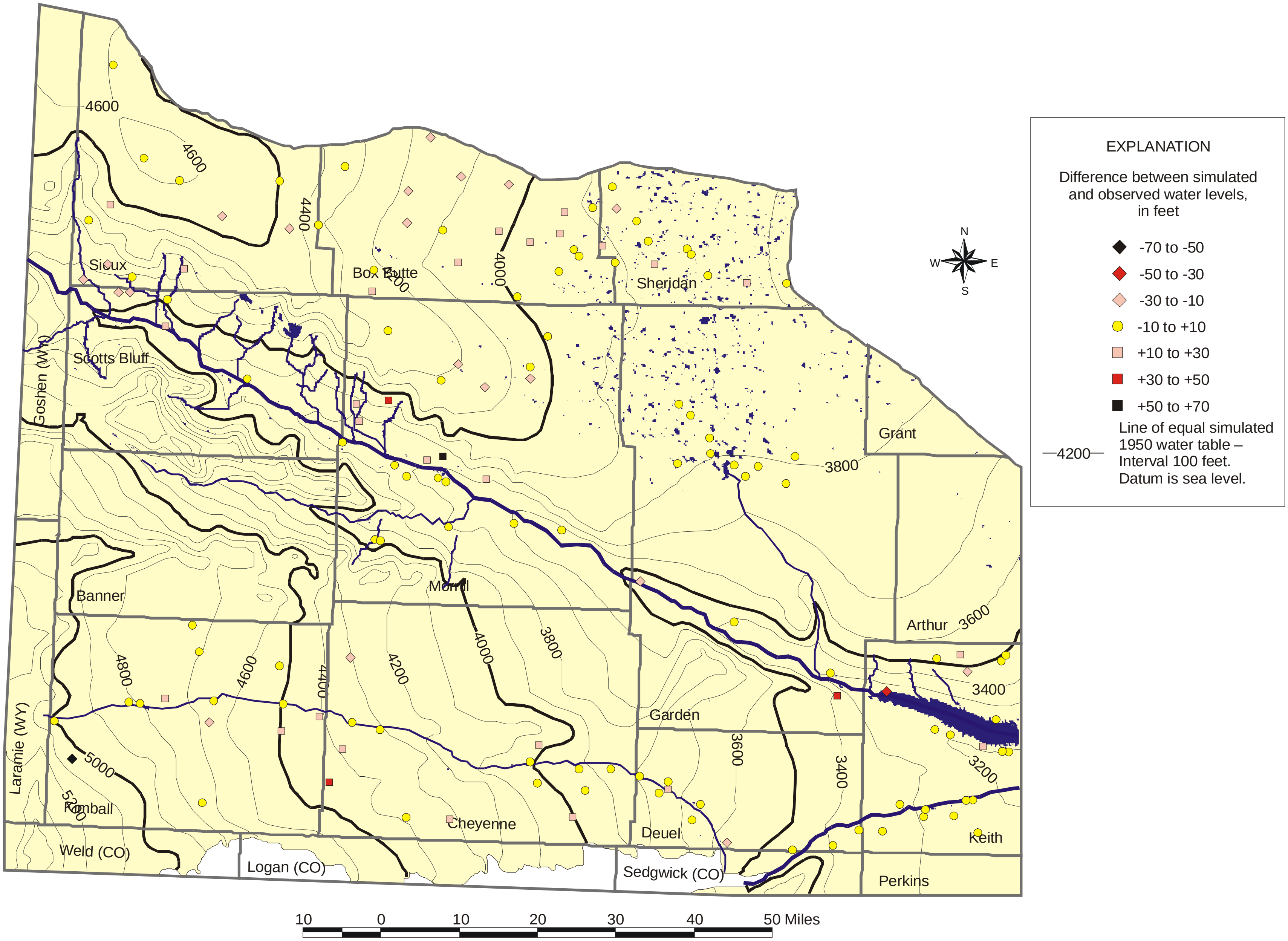

Figure 15. Simulated 1950 water table for the calibrated pre-groundwater development period model and comparison between simulated and observed water levels at observation points in the Western Model Unit.

Table 3. Simulated versus observed groundwater discharge to streams for the calibrated pre-groundwater development period model of the Western Model Unit. Simulated values represent 1950; observed values are long-term averages, generally 1941-97. All values are in cubic feet per second.

Stream	Simulated gain	Observed gain (negative is loss)			Remarks
		Minimum	Mean	Maximum	
North Platte River	289	260	590	900	Within calibration range
Kiowa and Horse Creeks	30	31	35	38	Below calibration range
Sheep Creek	69	75	83	90	Below calibration range
Dutch Flats Drain and Dry Spottedtail Creek	30	19	21	23	Above calibration range
Spottedtail Creek	36	Not gaged			
Tub Springs Drain	32	37	40	43	Below calibration range
Winters Creek	50	46	48	51	Within calibration range
Gering Drain	2	24	27	30	See note in text
Alliance and Ninemile Drains	75	87	96	110	See note in text
Bayard Drain	3	22	24	27	Below calibration range
Wildhorse Drain and Red Willow Creek	102	72	78	83	Above calibration range
North Platte north-side tributaries above Pumpkin Creek, except Spottedtail Creek, included above	361	360	390	430	Within calibration range
Lawrence Fork	1	Not gaged			
Greenwood Creek	<1	Not gaged			
Pumpkin Creek	6	7	10	14	Below calibration range
Blue Creek	74	78	83	87	Below calibration range
Clear Creek	4	Not gaged			
Otter Creek	4	16	18	19	Below calibration range
Lonegran Creek	<1	Not gaged			
South Platte River	5	-18	-4	20	Within calibration range
Lodgepole Creek	17	0	4	9	Above calibration range

Table 4. Simulated 1950 water budget for the calibrated pre-groundwater development period model of the Western Model Unit.

Item	Cubic feet per second	Acre-feet per year (thousands)	Percent of inflow or outflow
Inflow to aquifer			
Recharge (pre-settlement)	620	449	44.0
Recharge (canals/irrigation)	741	537	52.6
From streams	30	22	2.2
Fixed-flow boundaries	15	11	1.1
From Lake McConaughy	1	1	0.1
Total	1,407	1,020	100.0
Outflow from aquifer			
To streams	829	600	59.3
Evapotranspiration	436	316	31.3
Fixed water-level boundaries	100	72	7.1
To Lake McConaughy	32	23	2.3
Total	1,397	1,011	100.0

Groundwater Development Period Calibration

Simulated water levels from the pre-groundwater development period model were used as the starting water levels for the transient groundwater development period model, which simulated the period May 1, 1950, through April 30, 1998. All of the inputs to the pre-groundwater development period model were retained and other time-varying inputs were added for the 1950-98 period. Net pumpage, as described in the Numerical Model Construction section, was added to the groundwater development period model and was not changed during calibration. A spatially varying specific yield was added to the model and the values were determined during calibration. Additional time-varying recharge on cultivated land also was added to the model and the values were determined during calibration.

Numerous specific yield distributions were tested in calibrating this model. The model initially used a uniform value of 0.15, but this gave too little simulated water level change in the northern part of the model. The best fit between simulated and observed water-level changes occurred when specific yield was assigned as shown on figure 16. Specific yield of most of the Western Model Unit was set to 0.18, with 0.12 used where the Arikaree Group forms the major aquifer and 0.20 used where the alluvium along the North Platte and South Platte Rivers forms the major aquifer. Although a specific yield of 0.15 was initially used in the pre-groundwater development period calibration, the values used here were later tested and resulted in the same simulated 1950 water levels. This result was expected because the effect of specific yield becomes negligible as the flow system approaches dynamic equilibrium.

Specific storage was set to a uniform value of 0.00001. However, this value had no effect on the simulation of a single-layer unconfined aquifer. For such an aquifer, storage is simulated using specific yield.

Additional time-varying recharge, above the amount in the pre-groundwater development period model, was added during the groundwater development period. This recharge was added only to cropped land, both dry and irrigated, with more recharge added to irrigated land than to dryland. This recharge varied over time only because the amount of dryland and irrigated crop land varied over time. The justification for adding this extra recharge to dryland is that dryland, when fallow, is cultivated to capture and maintain soil moisture, and thus soil moisture on dryland regularly exceeds that on rangeland. Therefore, when precipitation falls on dryland, it has a better chance to become recharge than precipitation on uncultivated rangeland. Likewise, on irrigated crop land, soil moisture is maintained by irrigation and precipitation on irrigated land has a better chance of becoming recharge than precipitation on either dryland or rangeland. The extra recharge on irrigated crop land is not the same as deep percolation of applied irrigation water. Deep percolation of applied irrigation water is accounted for by using net pumpage. The amount of additional recharge was assumed to vary by soil (fig. 17) with more recharge added to lighter soils (less water holding capacity) than to heavier soils (more water holding capacity). The amount of additional recharge on dryland and irrigated land was determined during model calibration. Some simulations made the additional recharge a function of precipitation, but these simulations were not as good as the calibrated model. Because both soils and precipitation vary in a somewhat systematic fashion from west to east, the variation of additional recharge by soil may mask the variation due to precipitation.

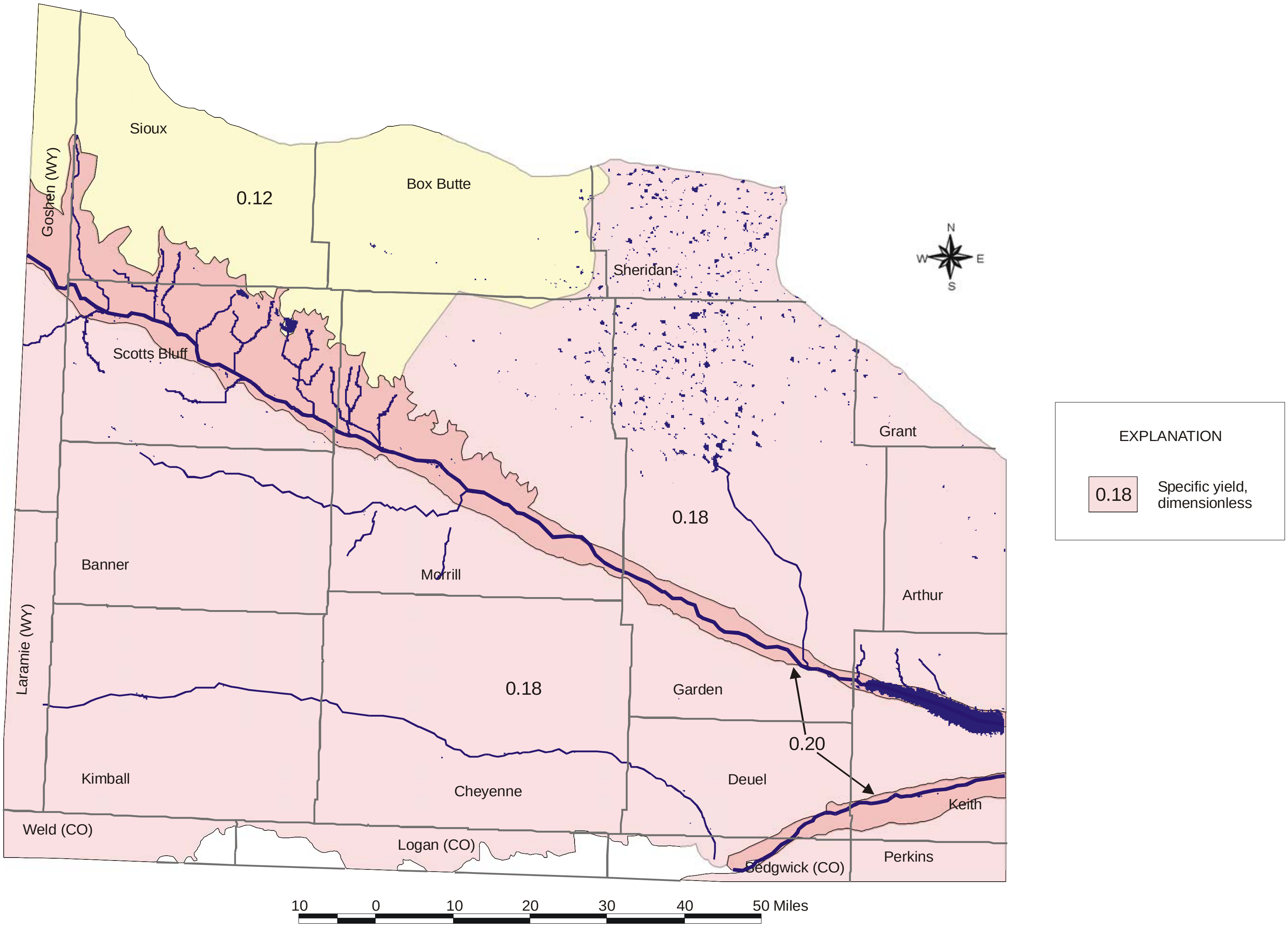

Figure 16. Specific yield distribution used in the calibrated 1950-98 groundwater development period model of the Western Model Unit.

The following recharge, in inches per year, was added to 1950 simulated recharge to calibrate the 1950-98 period:

Soil water Capacity (in/ft)	NebGuide pumpage		CropSim pumpage	
	Dryland (in/yr)	Irrigated land (in/yr)	Dryland (in/yr)	Irrigated land (in/yr)
1.00	1.10	3.60	1.05	4.60
1.25	0.90	3.30	0.85	4.30
1.50	0.70	3.00	0.65	4.00
1.75	0.50	2.70	0.45	3.70
2.00	0.40	2.40	0.35	3.40
2.25	0.30	2.10	0.25	3.10

The extra recharge added to dryland was 0.05 in/yr greater when the calibration was done with NebGuide net pumpage than when it was done with CropSim net pumpage. This small difference in dryland recharge between the two net pumpage data sets was the result of an effort made during calibration to keep the dryland recharge as close as possible for the two data sets.

The extra recharge added to irrigated crop land was 1.0 in/yr greater when using CropSim net pumpage instead of NebGuide net pumpage. This difference compensated for differences in the net pumpage estimates. Either CropSim net pumpage was too large and the larger recharge compensated for it or NebGuide net pumpage was too small and the smaller recharge compensated for that.

The calibration statistics for the simulated versus observed water-level change in the calibrated 1950 to 1998 groundwater development period models were:

[Mean – Mean difference; Mean abs. – Mean absolute difference; RMS – root-mean-square difference; No. – number of points; statistics are in feet]

Period and type	NebGuide Net Pumpage				CropSim Net Pumpage			
	Mean	Mean abs.	RMS	No.	Mean	Mean abs	RMS	No.
1950-61 measured	-0.26	2.28	4.27	46	-0.17	2.28	4.16	46
1961-73 measured	0.59	1.52	2.59	43	0.71	1.49	2.45	43
1973-85 measured	-0.12	2.60	3.74	64	0.06	2.51	3.66	64
1985-98 measured	0.44	2.99	4.18	103	0.43	2.99	4.25	102
1950-98 measured	0.16	4.21	6.14	34	0.26	4.27	6.22	34
1950-98 estimated	-1.26	4.99	7.13	150	-0.03	4.63	6.51	149

The calibrations were very similar, although CropSim net pumpage calibration was slightly better for both the mean absolute error and root-mean-square error. The number of change points was somewhat less for some periods than was shown in the Numerical Model Calibration section because some model cells went dry, particularly later in the groundwater development period. In these areas, simulated change could not be calculated and the points were not used in the statistics.

The mean differences were generally close to zero, which indicated that simulated and observed water-level changes were generally about the same (fig. 18). For the 1950-98 estimated water-level changes with CropSim pumpage, the mean for the 149 points was -0.03 ft. The differences ranged from -18.8 ft to +21.9 ft. Nine points differed by more than 15 ft, with two of them in eastern Box Butte along the northern boundary only 0.3 mi apart with differences of -16.1 ft and +14.9 ft. The estimated water-level changes for these two points were 45.9 ft and 14.8 ft. It seems unlikely that such a large difference in actual water-level change could occur over such a small distance.

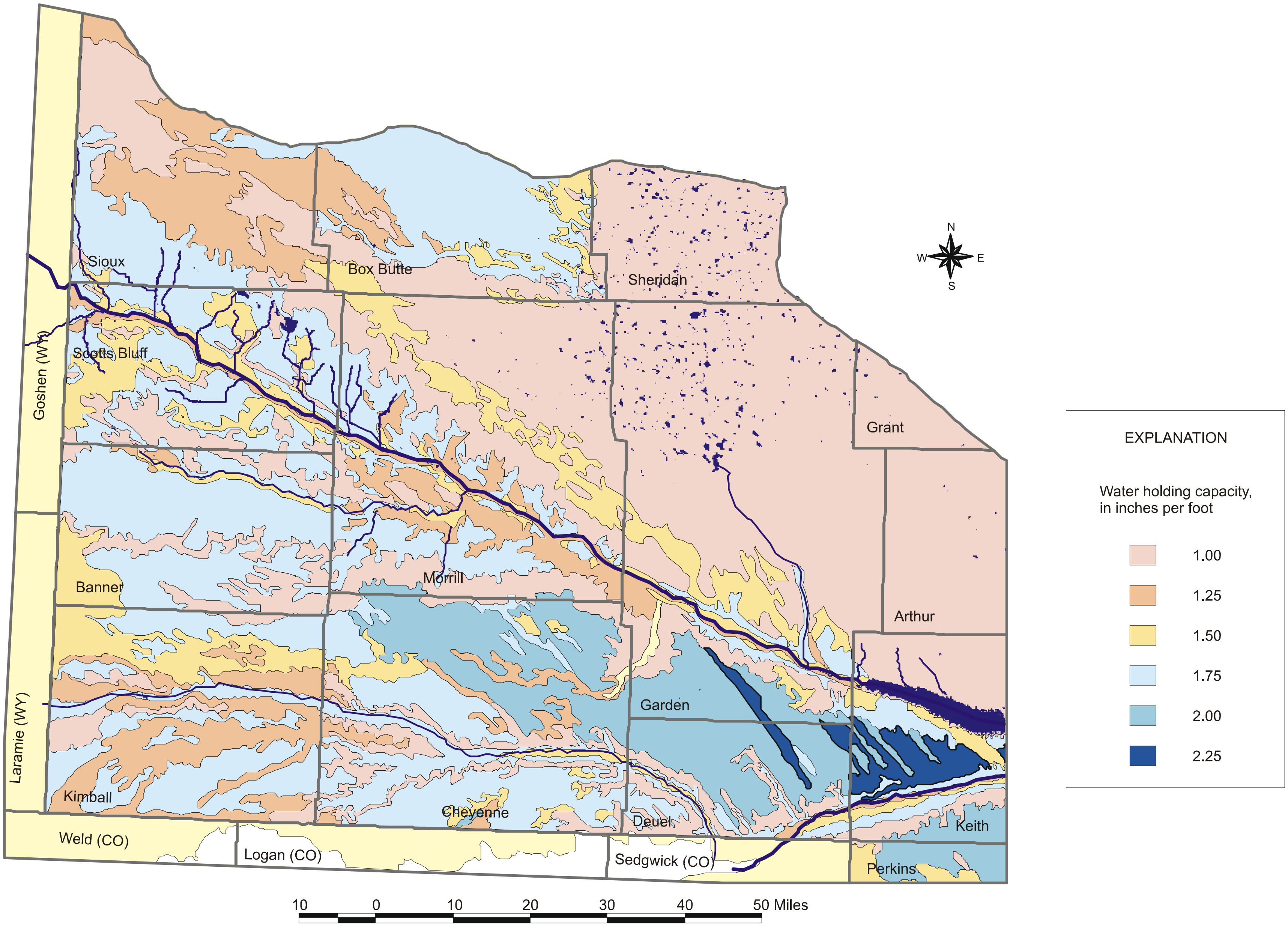

Figure 17. Generalized water-holding capacity of soils in the Western Model Unit. Soils are only shown for Nebraska part of the COHYST area. Soil groups prepared by Dr. Derel Martin, University of Nebraska–Lincoln from the STATSGO data set.

Simulated streamflow was very similar between the NebGuide net pumpage calibration and the CropSim net pumpage calibration, with the CropSim calibration having slightly larger streamflows. The largest difference for North Platte River tributaries was 4 ft^3/s for Red Willow Creek, including Wildhorse Drain. For the CropSim calibration, the total simulated flow to North Platte tributaries north of the river above Pumpkin Creek was 398 ft^3/s, whereas for the NebGuide calibration it was 386 ft^3/s, compared with a mean observed value of 390 ft^3/s (table 3). For the pre-groundwater development period, simulated flow to these tributaries was 364 ft^3/s (table 3).

Simulated flow to the North Platte River was 312 ft^3/s for the CropSim calibration, whereas it was 302 ft^3/s for the NebGuide calibration. For the pre-groundwater development period, simulated flow to the North Platte River was 288 ft^3/s (table 3). Simulated flow to the South Platte River was 2 ft^3/s for the CropSim calibration, whereas it was 4 ft^3/s for the NebGuide calibration. For the pre-groundwater development period, simulated flow to the South Platte River was 3 ft^3/s (table 3).

For both calibrations, Pumpkin Creek was simulated as nearly dry by 1998, but Lodgepole Creek was simulated as having flow by 1998. However, Lodgepole Creek was simulated as having too much flow in 1950 and if the simulated 1950 flow had been correct, it would have been simulated as nearly dry in 1998. For all other streams, simulated 1998 flows for both calibrations were similar to simulated 1950 flows (table 3).

The simulated water budget for the 1950-98 period for CropSim net pumpage is shown in table 5. The simulated outflows were nearly the same as the simulated inflows, indicating that, when averaged over the 48-year period, the groundwater flow system appears to be approximately in equilibrium. This can be misleading because of the large area of the model and the long time of the groundwater development period. For example, net pumpage in the summer of 1997 was 763 ft^3/s, whereas the 1950-98 average was 264 ft^3/s. Much of the area north of the North Platte River Valley, except Box Butte County, probably was in equilibrium in 1997, whereas much of the area south of the valley probably was not. The simulated water budget for the NebGuide net pumpage was similar to that for the CropSim pumpage.

The calibrated groundwater development period model was deemed a reasonable representation of the system, given the data available and the size of the grid. This model is adequate to simulate management scenarios on a regional scale.

Table 5. Simulated average water budget for the calibrated 1950-98 period model of the Western Model Unit using CropSim net pumpage. Values are averages for the 48-year period.

Item	Cubic feet per second	Acre-feet per year (thousands)	Percent of inflow or outflow
Inflow to aquifer			
Recharge (pre-settlement)	620	449	36.6
Recharge (canals/irrigation)	741	537	43.7
Recharge (dryland/irr. land)	273	198	16.1
From streams	34	25	2.0
Fixed-flow boundaries	15	11	0.9
From Lake McConaughy	12	9	0.7
Total	1,695	1,229	100.0
Outflow from aquifer			
To streams	873	632	51.5
Evapotranspiration	429	311	25.3
Fixed-flow boundaries	100	72	5.9
To Lake McConaughy	30	22	1.7
Net pumpage	264	191	15.6
Total	1,696	1,228	100.0

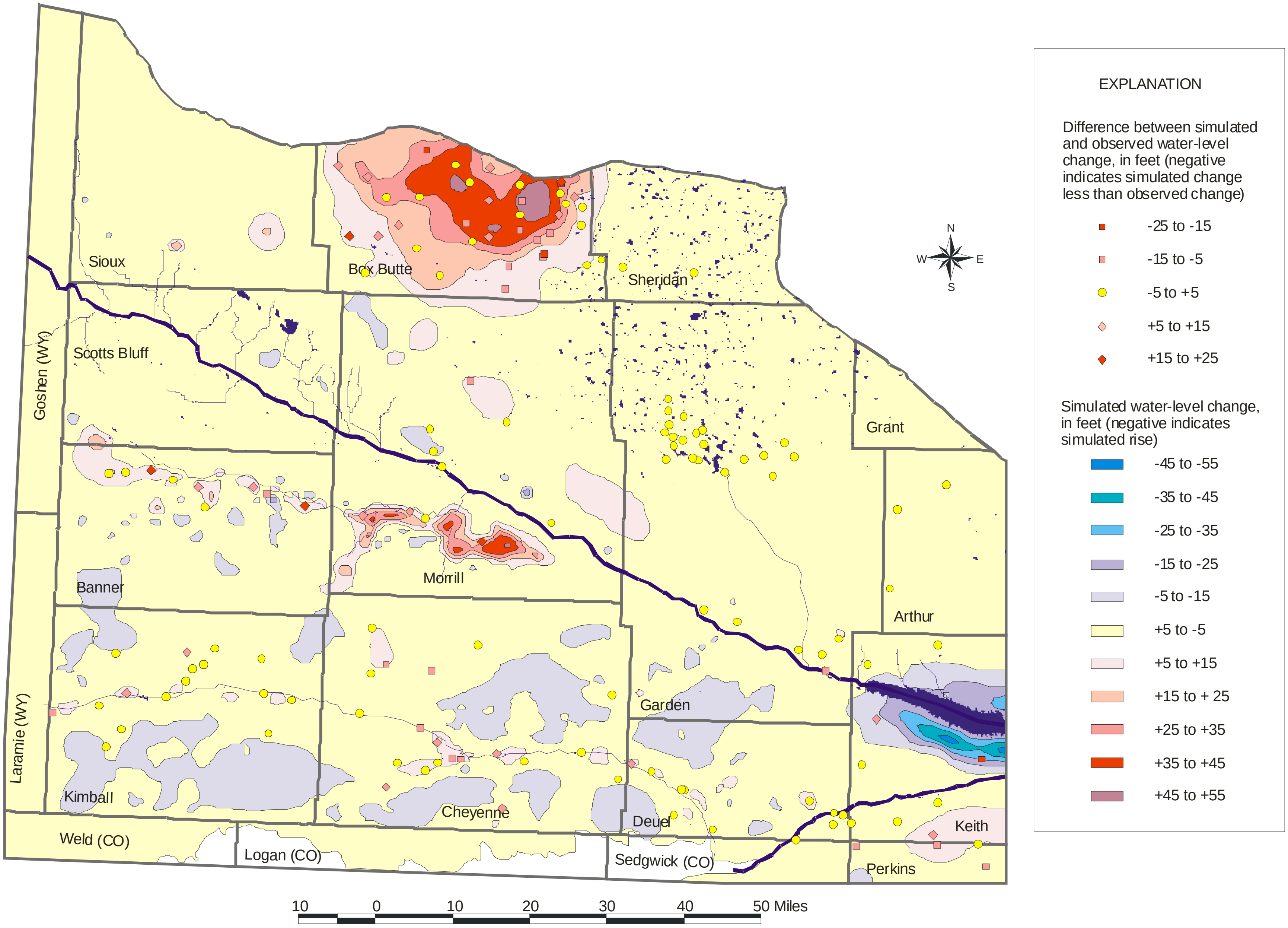

Figure 18. Simulated 1950-98 water-level change for the calibrated groundwater development period model using CropSim pumpage and comparison between simulated and estimated water-level change at observation points in the Western Model Unit. Simulated water-level rises due to recharge on irrigated land in Gering-Ft. Laramie, Gering, and Castle Rock Irrigation Districts (fig. 12) is not shown because of limited aquifer and numerous drains in these districts that could not be simulated.

Comparison to Adjacent Model

The model east of this model, in the area called the Central Model Unit, was documented by the Cooperative Hydrology Study Technical Committee (2004). That model was a six-layer model that simulated the pre-groundwater development period. Although a single-layer model of the groundwater development period was created and was being calibrated for the same area, that model had not been documented at the time this report was prepared. The comparison of simulated pre-groundwater development period water levels for the Central Model Unit and Western Model Unit is shown in figure 19.

The simulated 1950 water tables are generally similar in the southern half of the area of overlap (fig. 19), although there is some difference in the 3,200-ft contour south of Lake McConaughy, probably due to differences in calibrated hydraulic conductivity. In the northern half of the area of overlap, the 3,800-ft contours are parallel but are displaced from each other by about 3 mi. The 3,700-ft contours are displaced from each other by about 8 mi. This is in an area of small hydraulic gradient, but the displacement could represent a difference in simulated water tables of as much as 50 ft. The differences in the evapotranspiration parameters and areas probably account for much of this difference in simulated water tables. There are no observation points in this area, so it is impossible to tell which model more accurately represents the real system.

Hydraulic conductivity was arrived at in different ways for the two models, but this parameter generally had similar values in the area of overlap. In the area of overlap, hydraulic conductivity for the Western Model Unit was based on subdivisions of geologic units and a conceptual model of deposition as influenced by the Rush Creek Structure. For the Central Model Unit, hydraulic conductivity was mapped for three model layers based on test-hole lithology (model layers 2, 3, and 4 or hydrostratigraphic units 2, 3-4, and 5) and was averaged for the other three model layers, also based on test-hole lithology. In the area of overlap, the Western Model Unit had values of hydraulic conductivity of 15 or 35 ft/d north of the North Platte Valley, 15 or 25 ft/d south of the North Platte Valley, and 100 ft/d in the South Platte Valley. In the area of overlap, the Central Model Unit had values of 0-25 and 25-50 ft/d north of the North Platte Valley, 50-100 ft/d south of the North Platte Valley, and 150-200 ft/d in the South Platte Valley. The largest relative difference was between the North Platte Valley and the South Platte Valley, where the western model had 15 ft/d and the central model had 50-100 ft/d. This area was insensitive to hydraulic conductivity during calibration because the flow system in this area was dominated by the rivers.

Recharge was based on topographic settings in both the Western Model Unit and the Central Model Unit. In the area of overlap, calibrated recharge on areas of dunes was 2.30 in/yr in the Western Model Unit and was 2.50 in/yr in the Central Model Unit. In much of the remainder of the area of overlap, recharge was 0.18 in/yr in the Western Model Unit and 0.10 or 0.15 in/yr in the Central Model Unit. The largest relative difference was in the South Platte Valley where the western model had 0.18 in/yr and the central model had 0.90 in/yr. This area was insensitive to recharge during calibration because it was dominated by the river, although higher recharge in the valley is a reasonable assumption.

A small part of the groundwater evapotranspiration areas in the Western Model Unit exists in the area of overlap. The Central Model Unit simulated evapotranspiration in a somewhat similar, but much larger area. The Western Model Unit used a maximum groundwater evapotranspiration rate of 17 in/yr in the area of overlap, whereas the Central Model Unit used a maximum rate of 12 in/yr. In both models, the maximum rate occurred when the water table was at land surface. The rate decreased linearly to zero when the water table was 5 to 7 ft below land surface in the western model and 10 ft below land surface in the central model. A version of the central model still under development by COHYST will more closely correspond to the evapotranspiration parameters of the western model.

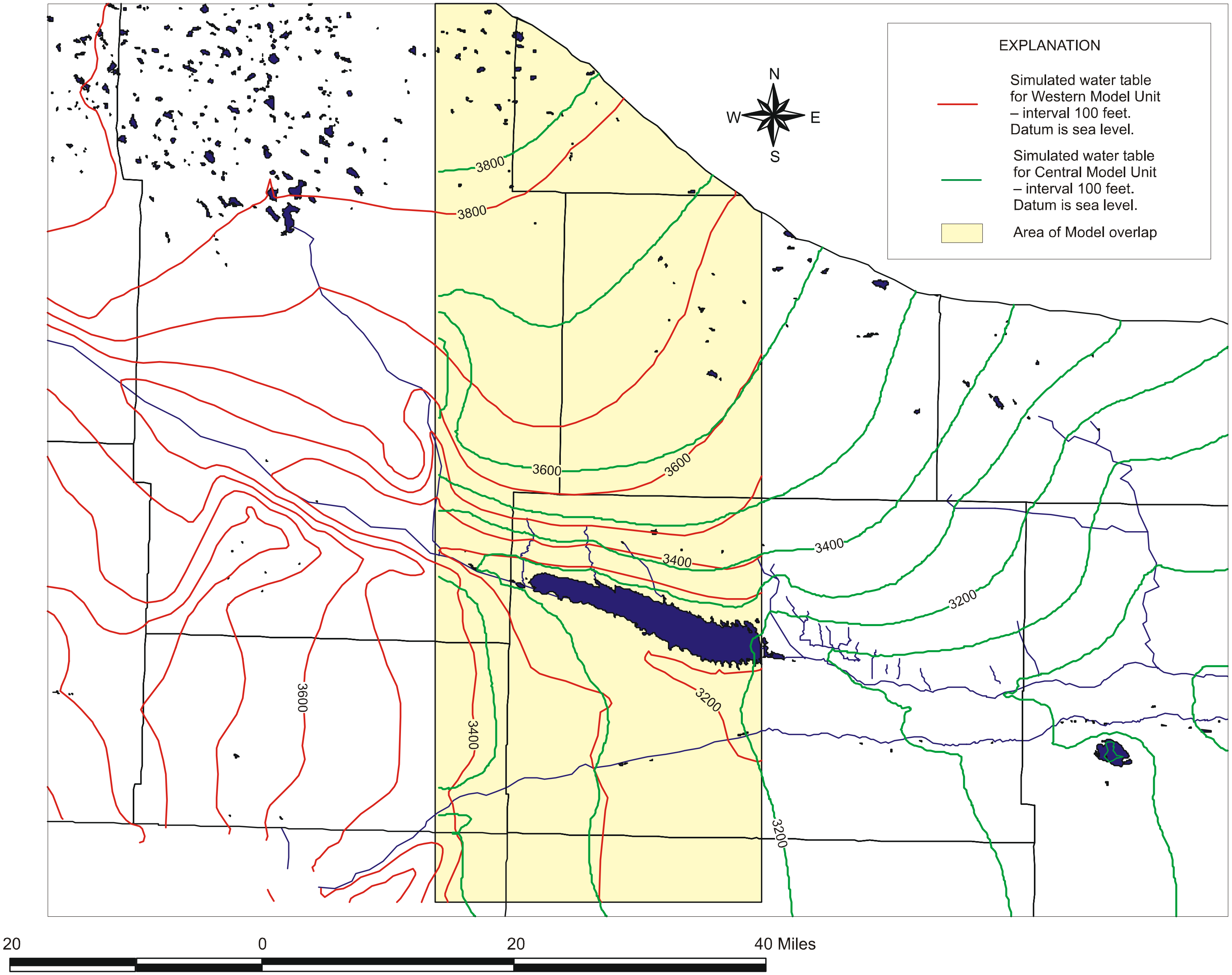

Figure 19. Comparison of simulated 1950 water tables for the Western Model Unit and the Central Model Unit.

The 25-mi wide overlap area between the Western Model Unit and the Central Model Unit contains the North Platte River, the South Platte River, and three short tributaries to the North Platte River. The streams were simulated in a similar manner in both models and similar values for streambed conductances were used.

Model Sensitivity

An analysis was performed to determine the sensitivity of the calibrated model to changes in model inputs. A separate analysis was performed for the pre-groundwater development period and the groundwater development period, and different inputs were investigated for different periods. The sensitivity analysis consisted of uniformly increasing or decreasing a single model parameter or stress and looking at the effects on observed water-level or water-level-change statistics and at simulated groundwater discharge to selected streams. For the pre-groundwater development period, changes in evapotranspiration rate, hydraulic conductivity, rangeland recharge, and streambed conductance (including riverbed conductance) were investigated. For the groundwater development period, changes in dryland recharge, irrigated land recharge, net pumpage, and specific yield were investigated. Changes in the areal distribution of model parameters and stresses were not investigated because the areal distributions were based on generally well-defined, known conditions. Changes in model inputs in only one area, such as rangeland recharge in the Sand Hills, also were not investigated because such changes would generally only affect simulated water levels and groundwater discharge to streams in that particular area.

The pre-groundwater development period model sensitivity was analyzed using 1950-water-level statistics (fig. 20). At calibration (input multiplier equals 1.00), the mean difference between simulated and observed water levels was 2.20 ft. The mean difference increased as evapotranspiration rate decreased and reached 4.76 ft when this rate was decreased 20 percent. The mean difference decreased as this rate increased and reached 1.21 ft when this rate was increased 20 percent. The mean difference was closest to zero when evapotranspiration rate was decreased 20 percent.

At calibration, the mean absolute difference between simulated and observed water levels was 10.33 ft (fig. 20). This difference was 11.41 ft when evapotranspiration rate was decreased 20 percent and was 10.29 ft when this rate was increased 20 percent. This difference was at a minimum when evapotranspiration rate was decreased 5 percent.

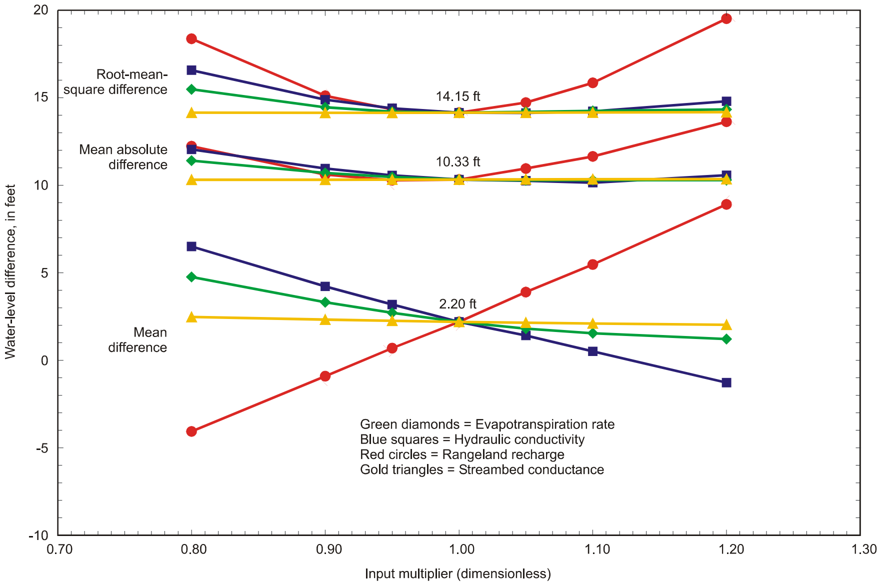

Figure 20. Effects of varying evapotranspiration rate, hydraulic conductivity, rangeland recharge, and streambed conductance on simulated 1950 water levels for the pre-groundwater development period model.

At calibration, the root-mean-square difference between simulated and observed water levels was 14.15 ft (fig. 20). This difference was 15.49 ft when evapotranspiration rate was decreased 20 percent and was 14.33 ft when this rate was increased 20 percent. This difference was at a minimum when evapotranspiration rate was at calibration.

The sensitivity of the mean difference and mean absolute difference to evapotranspiration rate suggested that a 5 to 20 percent reduction in this rate might have been beneficial to calibration. However, such a change would have degraded the root-mean-square difference, so this change was not made. Figure 20 shows that the calibration of the model was less sensitive to evapotranspiration rate than to some of the other model inputs.

The pre-groundwater development period model was more sensitive to hydraulic conductivity than to evapotranspiration rate (fig. 20). The mean difference increased as hydraulic conductivity was decreased and reached 6.50 ft when hydraulic conductivity was increased 20 percent. The mean difference decreased as hydraulic conductivity was increased and reached -1.28 ft when hydraulic conductivity was increased 20 percent. The mean difference was closest to zero when hydraulic conductivity was increased 10 percent.

The mean absolute difference was 12.04 ft when hydraulic conductivity was decreased 20 percent and was 10.57 ft when hydraulic conductivity was increased 20 percent. This difference was at a minimum when hydraulic conductivity was increased 10 percent.

The root-mean-square difference was 16.57 ft when hydraulic conductivity was decreased 20 percent and was 14.80 ft when hydraulic conductivity was increased 20 percent. This difference was at a minimum when hydraulic conductivity was increased 5 percent.

The sensitivity analysis of hydraulic conductivity suggested that a 5 to10 percent increase in hydraulic conductivity might have been beneficial to calibration. However, this was not done because the hydraulic conductivity of most zones (fig. 13) was an even multiple of five or ten, and changing hydraulic conductivity by 5 to 10 percent would not preserve the even multiples of five or ten and would suggest more precision in hydraulic conductivity than the model calibration warranted.

The pre-groundwater development period model showed a similar sensitivity to rangeland recharge as to hydraulic conductivity (fig. 20), although for the mean difference, the effect was in the opposite direction, which is hydrologically correct. The mean difference decreased as rangeland recharge decreased and reached -4.07 ft when rangeland recharge was decreased 20 percent. The mean difference increased as rangeland recharge increased and reached 8.91 ft when rangeland recharge was increased 20 percent. The mean difference was closest to zero when rangeland recharge was decreased 5 percent.

The mean absolute difference was 12.23 ft when rangeland recharge was decreased 20 percent and was 13.63 ft when rangeland recharge was increased 20 percent. This difference was at a minimum when rangeland recharge was increased 5 percent.

The root-mean-square difference was 18.37 ft when rangeland recharge was decreased 20 percent and was 19.52 ft when rangeland recharge was increased 20 percent. This difference was at a minimum when rangeland recharge was at calibration.

The sensitivity analysis of rangeland recharge suggested that a 5 percent decrease would improve the mean difference and a 5 percent increase would improve the mean absolute difference, so no changes were made.

The pre-groundwater development period model was less sensitive to streambed conductance than to rangeland recharge (fig. 20). The mean difference increased as streambed conductance decreased and reached 2.48 ft when streambed conductance was decreased 20 percent. The mean difference decreased as streambed conductance increased and reached 2.03 ft when streambed conductance was increased 20 percent. The mean difference was closest to zero when streambed conductance was increased 20 percent.

The mean absolute difference was 10.32 ft when streambed conductance was decreased 20 percent and was 10.35 ft when streambed conductance was increased 20 percent. This difference was at a minimum when streambed conductance was decreased 10 percent.

The root-mean-square difference was 14.15 ft when streambed conductance was decreased 20 percent and was 14.18 ft when streambed conductance was increased 20 percent. This difference was at a minimum when streambed conductance was decreased 10 percent.

The sensitivity analysis of streambed conductance suggested that a 20 percent increase would improve the mean difference and a 10 percent decrease would improve the mean absolute difference and root-mean-square difference, so no change was made. Figure 20 shows that the calibration of the model to is less sensitive to streambed conductance than to some of the other model inputs.

The sensitivity of streamflow to evapotranspiration rate, hydraulic conductivity, rangeland recharge, and streambed conductance (including riverbed conductance) in the pre-groundwater development period was investigated for five streams: Blue Creek, Lodgepole Creek, North Platte River, Sheep Creek, and South Platte River (fig. 21). Blue Creek predominately reflects conditions in the Sand Hills; Lodgepole Creek predominately reflects conditions on the tablelands; and Sheep Creek predominately reflects conditions in the North Platte Valley. The North Platte and South Platte River analyses were for the main stem only and did not include tributaries.

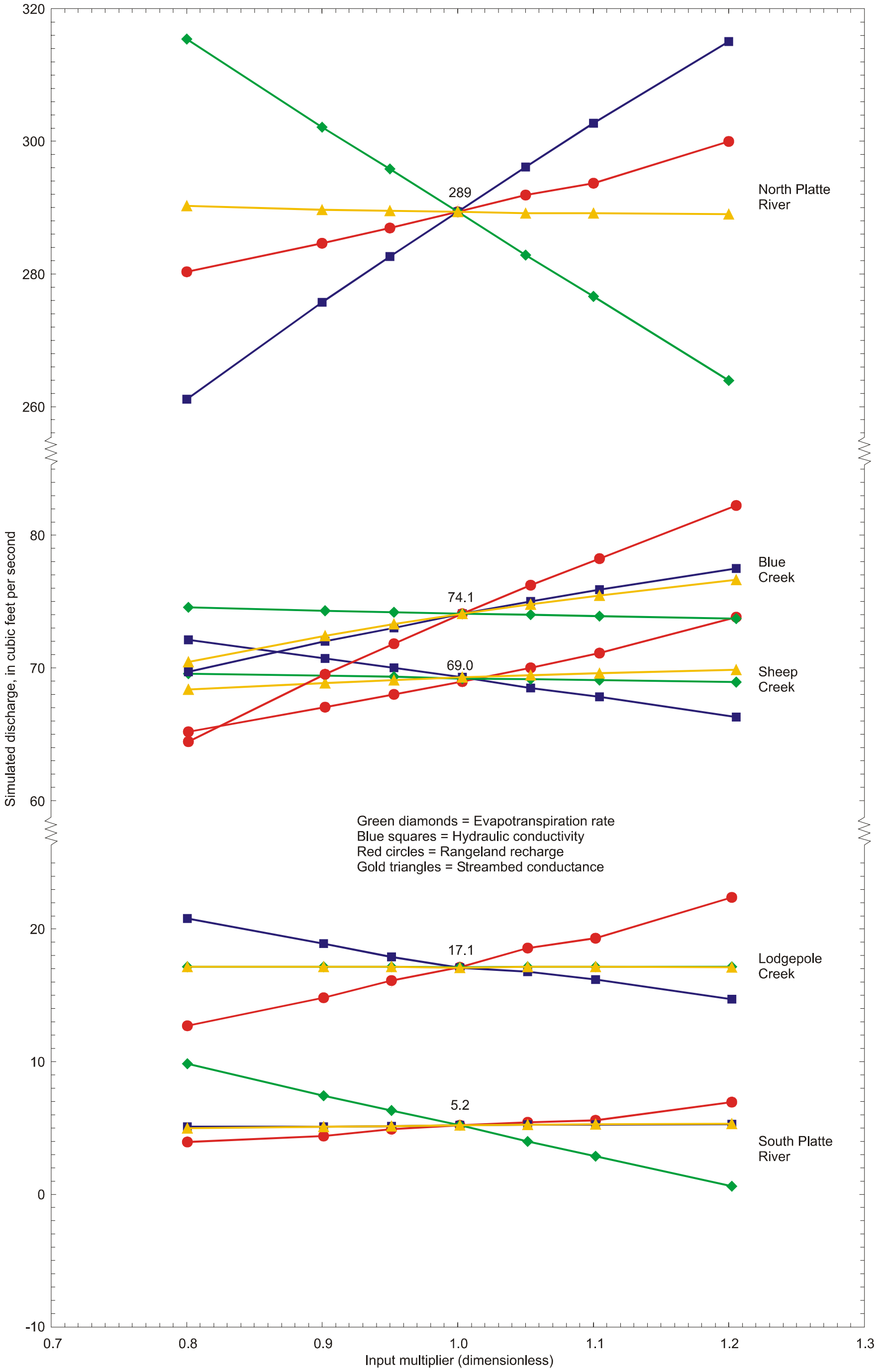

Figure 21. Effects of varying evapotranspiration rate, hydraulic conductivity, rangeland recharge, and streambed conductance on simulated flow of Blue Creek, Lodgepole Creek, North Platte River, Sheep Creek, and South Platte River for the pre-groundwater development period model. Note that scale for North Platte River is twice the scale for other streams.

The simulated flow to North Platte River at calibration was 289 ft^3/s. The flow increased to 314 ft^3/s when evapotranspiration rate was decreased 20 percent and the flow decreased to 263 ft^3/s when evapotranspiration rate was increased 20 percent (fig. 21). The simulated flow to Blue Creek at calibration was 74.1 ft^3/s. The simulated flow was 74.7 ft^3/s when evapotranspiration rate was decreased 20 percent and was 73.7 ft^3/s when evapotranspiration was increased 20 percent. The simulated flow to Sheep Creek at calibration was 69.0 ft^3/s. The simulated flow was 69.3 ft^3/s when evapotranspiration rate was decreased 20 percent and was 68.6 ft^3/s when evapotranspiration was increased 20 percent.

The simulated flow to Lodgepole Creek at calibration was 17.1 ft^3/s. The simulated flow was 17.1 ft^3/s when evapotranspiration rate was decreased 20 percent and was 17.1 ft^3/s when evapotranspiration was increased 20 percent. The simulated flow to South Platte River at calibration was 5.2 ft^3/s. The simulated flow was 9.9 ft^3/s when evapotranspiration rate was decreased 20 percent and was 0.6 ft^3/s when evapotranspiration was increased 20 percent.

The simulated discharge to North and South Platte Rivers was sensitive to evapotranspiration rate because of the riparian corridors along these streams. Blue Creek was insensitive to evapotranspiration rate in spite of a large evapotranspiration area near its headwaters. Lodgepole Creek and Sheep Creek were insensitive to evapotranspiration rate because they are generally far from evapotranspiration area.

Simulated flow to streams was generally more sensitive to hydraulic conductivity than to evapotranspiration rate (fig. 21). Simulated flow to the North Platte River decreased to 260 ft^3/s when hydraulic conductivity was decreased 20 percent and increased to 314 ft^3/s when hydraulic conductivity was increased 20 percent. Simulated flow to Blue Creek decreased to 69.7 ft^3/s when hydraulic conductivity was decreased 20 percent and increased to 77.5 ft^3/s when hydraulic conductivity was increased 20 percent. Simulated flow to Sheep Creek increased to 71.8 ft^3/s when hydraulic conductivity was decreased 20 percent and decreased to 66.0 ft^3/s when hydraulic conductivity was increased 20 percent. Simulated flow to Lodgepole Creek increased to 20.8 ft^3/s when hydraulic conductivity was decreased 20 percent and decreased to 14.7 ft^3/s when hydraulic conductivity was increased 20 percent. Simulated flow to South Platte River decreased to 4.7 ft^3/s when hydraulic conductivity was decreased 20 percent and increased to 5.6 ft^3/s when hydraulic conductivity was increased 20 percent. Decreasing hydraulic conductivity decreased the simulated flow to some streams and increased the flow to others, but overall decreased flow to streams and increased evapotranspiration along the riparian corridors.

Simulated flow to streams was about as sensitive to rangeland recharge as it was to hydraulic conductivity but in some cases, the effect was in the opposite direction (fig. 21). Simulated flow to the North Platte River decreased to 280 ft^3/s when rangeland recharge was decreased 20 percent and increased to 299 ft^3/s when rangeland recharge was increased 20 percent. Simulated flow to Blue Creek decreased to 64.5 ft^3/s when rangeland recharge was decreased 20 percent and increased to 82.3 ft^3/s when rangeland recharge was increased 20 percent. Simulated flow to Sheep Creek decreased to 65.3 ft^3/s when rangeland recharge was decreased 20 percent and increased to 74.0 ft^3/s when rangeland recharge was increased 20 percent. Simulated flow to Lodgepole Creek decreased to 12.7 ft^3/s when rangeland recharge was decreased 20 percent and increased to 22.5 ft^3/s when rangeland recharge was increased 20 percent. Simulated flow to South Platte River decreased to 3.9 ft^3/s when rangeland recharge was decreased 20 percent and increased to 6.9 ft^3/s when rangeland recharge was increased 20 percent. Decreasing rangeland recharge decreased the simulated flow to streams and increasing rangeland recharge increased the simulated flow to streams, as would be expected.

Simulated flow to streams was generally insensitive to streambed conductance, with Blue Creek being the exception (fig. 21). Simulated flow to the North Platte River increased to 289 ft^3/s when streambed conductance was decreased 20 percent and decreased to 288 ft^3/s when streambed conductance was increased 20 percent. Simulated flow to Blue Creek decreased to 70.5 ft^3/s when streambed conductance was decreased 20 percent and increased to 76.6 ft^3/s when streambed conductance was increased 20 percent. Simulated flow to Sheep Creek decreased to 68.1 ft^3/s when streambed conductance was decreased 20 percent and increased to 69.6 ft^3/s when streambed conductance was increased 20 percent. Simulated flow to Lodgepole Creek remained essentially the same when streambed conductance was decreased 20 percent or was increased 20 percent. Simulated flow to South Platte River decreased to 4.9 ft^3/s when streambed conductance was decreased 20 percent and increased to 5.3 ft^3/s when streambed conductance was increased 20 percent. Decreasing streambed conductance decreased overall simulated flow to streams slightly and increasing streambed conductance increased overall flow to streams slightly. Changing streambed conductance changed different streams in different ways.

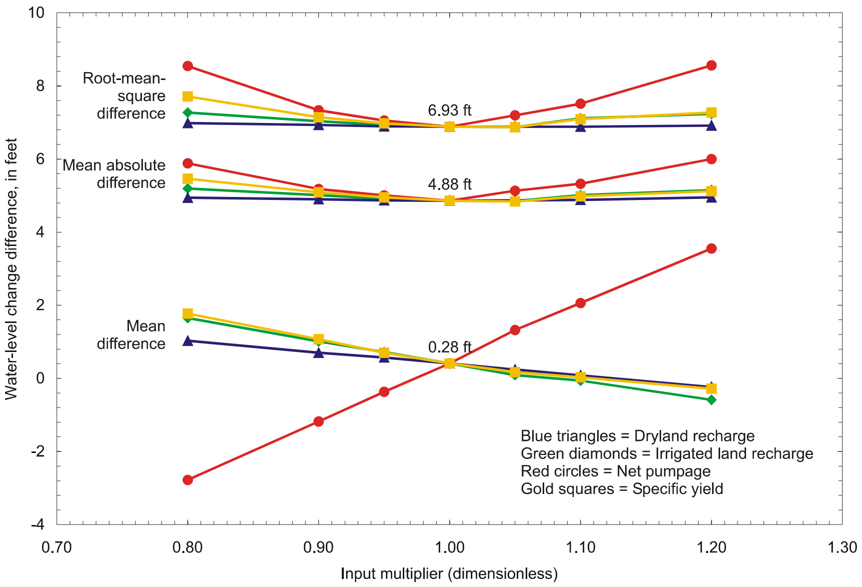

Figure 22. Effects of varying dryland recharge, irrigated land recharge, net pumpage, and specific yield on simulated 1950-98 water-level changes for the groundwater development period model.

For the groundwater-development period, sensitivity analysis was done for the entire 1950-98 period. There were too few measured 1950-98 water-level changes to allow meaningful analysis, so only the estimated 1950-98 water-level changes were used. The model was most sensitive to changes in CropSim net pumpage and least sensitive to changes in dryland recharge (fig. 22). The model was about equally sensitive to changes in irrigated crop land recharge and specific yield, with the mean difference more sensitive to irrigated land recharge and the mean absolute difference and root-mean-square difference more sensitive to specific yield.

Of the three streams investigated in the groundwater development period sensitivity analysis, only Lodgepole Creek was sensitive to changes in model inputs, and even Lodgepole Creek was relatively insensitive to changes in specific yield, with simulated discharge changing only 0.4 ft^3/s over the full range tested. Lodgepole Creek was most sensitive to changes in net pumpage with the simulated discharge ranging from 13.2 ft^3/s when net pumpage was decreased 20 percent to 6.8 ft^3/s when net pumpage was increased 20 percent. When irrigated land recharge was decreased 20 percent, simulated flow to Lodgepole Creek was 8.2 ft^3/s, and when irrigated land recharge was increased 20 percent, simulated flow was 10.5 ft^3/s. When dryland recharge was decreased 20 percent, simulated flow to Lodgepole Creek was 8.4 ft^3/s, and when dryland recharge was increased 20 percent, simulated flow was 10.2 ft^3/s.

Limitations on Use of this Model

This model was designed to be a regional representation of the groundwater flow system. As such, it is useful for investigating the effects of water-management plans over townships or counties. It should not be used to investigate effects over a few square miles or less. The model also was designed to evaluate the effects of water-management plans over scales of years to decades. It should not be viewed as capable of predicting effects over a year or less.

This groundwater flow model is an aggregation and simplification of the natural system, but does contain the best available information and essential features of the natural flow system. It was constructed for the purpose of simulating water-management scenarios for the Platte River Basin in western Nebraska. Care should be exercised if this model is used beyond the purpose for which it was constructed.

As with all models, the calibration of this model is not unique in that a different set of model inputs could have produced similar results. This uncertainty was reduced by using both water levels and streamflows in the calibration.

This model is better calibrated in regions with greater numbers of water-level or streamflow observations to calibrate against, and is less precise in regions without calibration information. The inputs to which the model is more sensitive are naturally better calibrated than those inputs to which the model is less sensitive.

One particular type of model error, called Type IV Error, can limit the usefulness of a model. A Type IV Error refers to a model input to which the model calibration is insensitive, but to which the model use is sensitive. Simulated evapotranspiration might fall into this category for some uses of this model. As was shown in the Model Sensitivity section, simulated water levels were insensitive to the evapotranspiration rate, as were simulated tributary streamflows. The simulated discharges to the North and South Platte Rivers were somewhat sensitive to evapotranspiration rate, but the observed discharges to these streams were only known within fairly broad ranges (table 3). The best that can be done with a Type IV Error is to make the input as realistic as possible and attempt to reduce the uncertainty of the input.

The North Platte River and South Platte River were simulated as river boundaries in the model described in this report. This is appropriate because these streams seldom go dry, and when they do, the period that they are dry is short compared to the 48 years of analysis. As a result of how these streams were simulated, this model should not be used to calculate effects of management scenarios that may cause these streams to go dry for months or years. If there is a need to investigate such management scenarios in the future, the North and South Platte Rivers should first be converted to stream boundaries.

Evapotranspiration from the water table was simulated as an annual rate in the model described in this report, when in reality, evapotranspiration is much higher in the middle of the summer and may be negligible in the middle of winter. Simulating evapotranspiration on an annual basis is appropriate for simulating the effects of water-management plans over scales of years or decades, but is not appropriate for scales of less than a year. If information is needed on a seasonal basis, evapotranspiration should be simulated on a seasonal basis.

This model should not be used to simulate solute transport without specifically calibrating it for that purpose. Flow models tend to be most sensitive to average inputs in a region whereas solute transport models tend to be most sensitive to the extreme inputs in a region. As a result, flow models frequently do not adequately simulate solute transport.

Further Work

This report is the culmination of a multi-year, team effort to construct and calibrate a groundwater flow model for the Western Model Unit. As with all models, this model can only represent the flow system as it was understood at the time the model was constructed. As more information is collected and the understanding of the flow system improves, this model should be updated. Small changes in inputs are not likely to change the model, but as data suggesting large changes or many small changes become available, this model would benefit from incorporating those changes.

The groundwater development period model was severely hampered by the lack of pumpage data. Improving the accuracy of pumpage data is something that the Natural Resources Districts in the area have identified as a priority. A number of years of pumpage data would be needed before this model or an improvement on this model can be calibrated. Even when better pumpage data are available, it will still be difficult to estimate recharge from deep percolation of pumped irrigation water as well as recharge from precipitation on irrigated fields. These processes also need further research and refinement.

Recharge from precipitation on dryland fields was poorly defined in this model, although the model clearly needed some extra recharge in order to complete the calibration. Estimates of recharge from precipitation on dryland fields could be improved with additional water-level data. However, to be useful, such data would have to be collected for many years well away from any pumpage or irrigation locations.

Evapotranspiration parameters for areas where the water table is near land surface also were poorly defined in this model, although the areas where evapotranspiration occurs were somewhat better defined by the model. Unfortunately, some of the management scenarios that this model was designed to test may be sensitive to evapotranspiration. The representations of evapotranspiration in the model, as well as evapotranspiration parameters, also need further research and refinement.

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