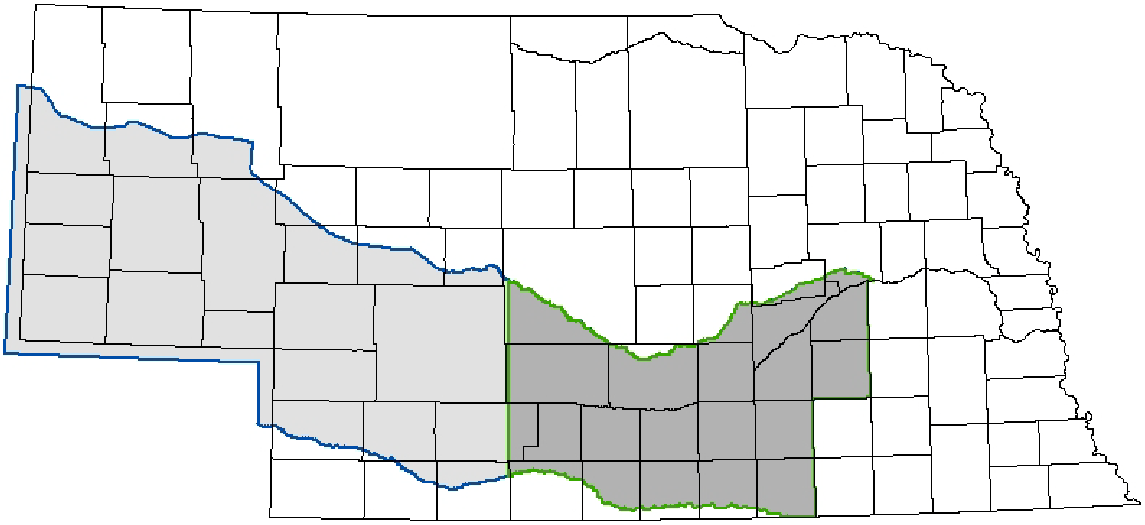
Groundwater Flow Model

of the Eastern Model Unit of the Nebraska

Cooperative Hydrology Study (COHYST) Area



Steven M. Peterson
Cooperative Hydrology Study Technical Committee
Approved by the Technical Committee, November 13, 2007

Major Funding Provided By
The Nebraska Environmental Trust
preserving NATURAL NEBRASKA™ for future generations

COoperative HYdrology STudy
COHYST

Acknowledgements

This study was supported by the various state and local agencies that make up the COHYST Sponsors, including:

Nebraska Department of Natural Resources
Nebraska Game and Parks Commission
Central Platte NRD
Little Blue NRD
North Platte NRD
South Platte NRD
Tri-Basin NRD
Twin Platte NRD
Upper Big Blue NRD
The Central Nebraska Public Power and Irrigation District
Nebraska Public Power District

Funding was also provided by the Nebraska Environmental Trust.

In addition, special thanks to Richard R. Luckey, U.S. Geological Survey, for his help throughout the project.

Table of Contents

List of Figures

List of figures (continued) Page

List of Tables

Executive Summary

The Cooperative Hydrology Study (COHYST) is a study of surface water and groundwater resources in 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 Natural Resources Districts in the study area with the management of groundwater, provide Nebraska with the basis for surface-water and groundwater 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 COHYST study area was divided into three overlapping areas, called Model Units, Western, Central, and Eastern (fig. 1) for the purpose of constructing groundwater flow models. This report describes the groundwater flow model that was constructed for the Eastern Model Unit.

The Eastern Model Unit is about 150 miles east to west and 100 is about miles north to south, and covers 10,400 square miles. Agriculture dominates the livelihood and landscape of the region, with land in both the valleys and upland plains irrigated with surface water and groundwater. As of 1950, approximately 70 percent (4,600,000 acres) of the total land area was farmed. The average slope of the land surface in the Eastern Model Unit is 6 to 7 feet per mile from west to east. The topography in the Eastern Model Unit varies from relatively flat areas, such as tablelands and the floodplain of the Platte River, to dissected plains of the Loup and Republican River basins. Climate in the Eastern Model Unit varies from moist sub-humid in the eastern part of the model area to dry sub-humid in the west. Average 1961-90 precipitation ranges from less than 22 inches per year in the west to more than 28 inches per year in the east and southeast. Abundant sunshine, frequent winds, and low humidity contribute to a high rate of evaporation.

The Platte River flows approximately through the center of the Eastern Model Unit. Other large streams in the interior of the area include the Little Blue River and the West Fork of the Big Blue River. The largest surface water reservoir in the model area is Harlan County Reservoir (6,300 acres), on the Republican River. Wetlands and other areas of high evapotranspiration are limited to the floodplain of the Platte River and areas near other surface-water bodies. Other small wetlands exist, but are limited to less than a few square miles in size.

The pre-groundwater development water table ranges from more than 2,700 feet above sea level in the northwestern part of the Eastern Model Unit to less than 1,500 feet above sea level in the east. The water table in the western part of the Eastern Model Unit generally slopes to the southeast at around 6 to 8 feet per mile, and in the eastern part, the water table generally slopes to the east at around 6 feet per mile.

The geologic units in the Eastern Model Unit that are important to the groundwater flow model consist of various Quaternary-age deposits and deposits of the Ogallala Group of Tertiary age. Both Quaternary-age and Tertiary-age deposits are developed as sources of water, though the Ogallala Group is absent from most of the eastern part of the Eastern Model Unit. Quaternary-age deposits are present throughout much of the Eastern Model Unit, and are frequently coarser-grained than Tertiary-age deposits.

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 documents the construction and calibration of a flow model for the Eastern Model Unit. This is a five-layer groundwater model with a grid of 160 acres. Model construction began with a conceptual flow model, which describes the state of the flow system at the beginning of the simulation period, the lateral and vertical boundaries of the model, what happens to the flow of water at these boundaries, and how the flow system interacts with external sources or sinks of water. The external boundaries of the Eastern Model Unit consist of fixed-flow boundaries at the eastern and western boundaries, a river boundary at the northern boundary, and a combination of fixed water level, fixed-flow, zero-flow, and river boundaries along the southern boundary. The Platte River, Loup River, South Loup River, North Loup River, and Republican River were simulated as river boundaries. All other perennial streams were simulated as stream boundaries in the model. Areas of wetlands, generally near the Platte River, were treated as evapotranspiration areas which acted as groundwater sinks; that is, locations where groundwater was removed from the model. Evapotranspiration areas were identified using 1997 land use mapping data and estimates of areas where the groundwater was on average 10 feet or less below land surface. The pre-groundwater development model simulated the groundwater system in 1895 as being in a long-term state of equilibrium, called steady state. A transient model was then developed, including recharge from canal and lateral leakage to simulate the pre-groundwater development period (1895-1950). Finally, a transient model was developed, including net pumpage and additional recharge, to simulate the groundwater development period (1950-98). Output groundwater levels derived from each model, in this sequence of development, are used as starting groundwater levels in subsequent models.

MODFLOW-2000 was selected as the groundwater flow modeling code for this study. The Groundwater Modeling System was the pre- and post-processor selected for managing MODFLOW-2000 input and output. The grid for the Eastern Model Unit consists of 204 rows, 300 columns, and 5 layers, with 41,904 active cells per layer for a total of 209,520 potentially active cells, each measuring 2,640 feet per side.

Hydraulic conductivity and specific yield were assigned to the model based on the COHYST testhole database and mapped hydraulic conductivities from the Cooperative Hydrology Study Hydrostratigraphic Units and Aquifer Characterization Report. Model layers 1 and 5 were each assigned a uniform conductivity of 10 feet per day and model layers 2 through 4 were assigned spatially distributed values. Mean hydraulic conductivities for model layers 2, 3, and 4 were 155 feet per day, 8 feet per day, and 33 feet per day, respectively. Model layer 2 was assigned a larger hydraulic conductivity than model layer 4 because it is comprised of coarser-grained materials. Specific yield was assigned based on the COHYST testhole database. Specific yield for model layer 1 was set to a uniform value of 0.16, and specific yield for model layers 2-5 varied spatially, with mean values of 0.22 for layer 2, 0.09 for layer 3, 0.18 for layer 4, and 0.08 for layer 5.

Recharge due to canal and lateral leakage was estimated based on available records from the Nebraska Department of Natural Resources, the Central Nebraska Public Power and Irrigation District, and Nebraska Public Power District. Where sufficient data were available, recharge due to canal and lateral leakage was estimated through a mass balance approach. For canals without sufficient data, recharge due to canal and lateral leakage was estimated to be 40 percent of the water diverted into the canal.

Rangeland recharge assigned to the pre-groundwater development model was based mainly on topography and regional precipitation. Rangeland recharge due to precipitation was highest in areas with sandiest soils and flattest areas and lowest in areas with silty or clayey soils and more steeply sloping topography. Recharge ranged from 0.30 inches per year on the westernmost plains to 2.50 inches per year on western Sand Hills. The mean rangeland recharge was 1.25 inches per year and the median was 0.78 inches per year.

Simulated 1950 water levels were from the transient pre-groundwater development period model were compared to observed water levels at 423 observation points. The mean difference was 2.00 feet, the mean absolute difference was 8.92 feet, and the root-mean-square difference was 12.08 feet. Simulated groundwater discharge to streams was within the estimated range for most streams. Simulated discharge was outside the estimated range for some streams, in most cases due to groundwater discharge from outside the model area. Simulated discharge to the Little Blue River was too large, but this is likely due to some area streams not included in the simulation.

The groundwater development period model simulated the 1950-98 period, starting with the 1950 simulated water levels from the pre-groundwater development simulation. Inputs from the pre-groundwater development model were retained and additional time-varying inputs were added to represent groundwater development and additional recharge in 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 using CropSim, a soil-water-balance model developed at the University of Nebraska-Lincoln.

To calibrate the model, additional time-varying recharge, above the amount of rangeland recharge used in the pre-groundwater development model, was added during the groundwater development period. This recharge was added only to cropped land, and more recharge was added to irrigated land than to dryland. This recharge varied through time because the amount of dryland and irrigated crop land changed over time. Recharge added to irrigated land also varied through time because land use practices changed over time. Recharge added to the eastern part of the model was more than that added to the western part of the model because precipitation increased from west to east. Additional recharge on dryland ranged from 0.8 to 1.0 inches per year, and the additional recharge on irrigated land ranged from 3.7 to 6.9 inches per year.

Simulated water-level changes were compared to measured water-level changes for five periods (1950-98, 1950-61, 1961-73, 1973-85, and 1985-98) with the number of observation points for each comparison ranging from 78 to 406 per period. For the 1950-98 period, the mean difference was -0.55 feet, the mean absolute difference was 5.76 feet, and the root-mean-square difference was 8.67 feet. For the remaining periods, the mean difference ranged from -2.63 to 2.11 feet, the mean absolute difference ranged from 2.96 to 4.19 feet, and the root-mean-square difference ranged from 3.78 to 5.80 feet. The weighted measure for the mean difference was 0.34 feet; for the mean absolute difference it was 3.64 feet; and for the root-mean-square difference it was 5.11 feet.

This model was compared with the pre-groundwater development model of the Central Model Unit to the west. Hydraulic conductivity applied to the two models was very similar, even though the models were calibrated independently. Hydraulic conductivity for the two models was most different for model layer 2. The mean hydraulic conductivity for layer 2 in the Eastern Model Unit was 155 feet per day, whereas for the Central Model Unit it was 79 feet per day. However, in the Central Model Unit, layer 2 is absent from virtually the entire southern half of the area, and is limited to the valley-fill along the North Platte, South Platte, and Platte Rivers, and areas north of those valleys, where it is related to the Sand Hills. Both models used similar recharge distributions based on topographic divisions. The mean recharge value for the Eastern Model Unit, at 1.25 inches per year, was larger than that of the Central Model Unit, at 1.05 inches per year, but this is reasonable given the overall wetter climate in the Eastern Model Unit. The same evapotranspiration input values were used for both models.

Separate analyses were performed to determine the sensitivity of the calibrated transient pre-groundwater development period and transient groundwater development period models to changes in model inputs. The pre-groundwater development period model was tested for sensitivity to hydraulic conductivity, rangeland recharge, the ratio of horizontal to vertical hydraulic conductivity, streambed conductance, and evapotranspiration. This model was nearly equal in sensitivity to changes in hydraulic conductivity and rangeland recharge, least sensitive to changes in streambed conductance and evapotranspiration, and was insensitive to changes in the ratio of horizontal to vertical hydraulic conductivity. The groundwater development period model was tested for sensitivity to changes in specific yield, net pumpage, dryland recharge, irrigated land recharge, and recharge due to canal and lateral leakage. This model was most sensitive to changes in irrigated land recharge and net pumpage, less sensitive to canal seepage recharge and dryland recharge, and least sensitive to changes in specific yield.

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, and over time scales of years to decades. Care should be exercised if this model is used beyond the purpose for which it was constructed. The model is better calibrated in areas with greater numbers of water-level or streamflow observations against which to calibrate, and is less calibrated to areas with little or no calibration information.

This report is the culmination of a multi-year effort to construct and calibrate a groundwater flow model for the Eastern Model Unit. As with all models, this model can only represent the flow system as it is 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 current pre-groundwater development simulation does not account for effects of irrigation wells prior to 1950. The effects of early pumping are probably important enough that these wells should be added in future simulations. The groundwater development period model was hampered by the lack of pumpage data. Recent advances in groundwater modeling software have provided new methods of representing geology, solving flow equations, and automated parameter estimation, which should lead to decreased computer run times and allow for comprehensive exploration of model uncertainty and sensitivity, and could lead to improvements to the conceptual model of the system.

Description and Purpose of COHYST

The Cooperative Hydrology Study (COHYST) is a 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);
2. Assist the Natural Resources Districts in the study area with management of groundwater;
3. Provide Nebraska with the basis for surface-water and groundwater 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 variations between simulated and actual 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 variations between simulated and actual groundwater flow across these boundaries will have minimal effect on the study results in Nebraska. Additionally, the southern boundary of the model along the Nebraska-Colorado border nearly follows a mapped groundwater flow line, so little groundwater is likely to flow across this boundary.

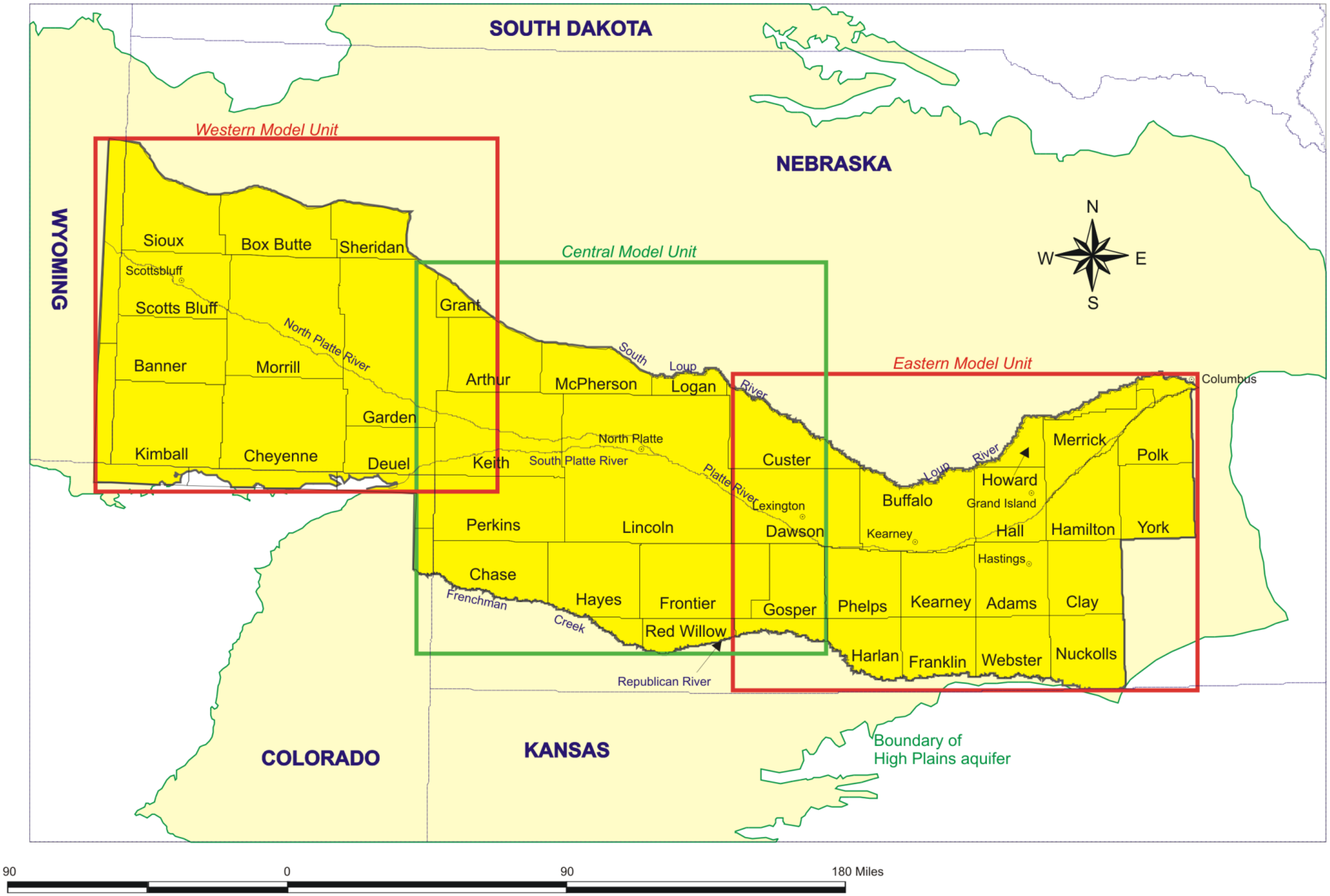


Figure 1. COHYST groundwater model area and model units.

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 Eastern Model Unit.

Previous Studies

The earliest studies of groundwater in central Nebraska were done by Darton (1898, 1905). Shortly thereafter, Condra (1907) studied the Republican valley and adjacent areas. Nebraska State Planning Board (1936) did a comprehensive hydrologic study of the state. Lugan and Wenzel (1938) studied the area between Gothenburg and Chapman while Wenzel (1940) investigated groundwater overdraft at Grand Island. Waite and others (1944a and 1944b) studied the Republican River basin and Waite and others (1949) studied the lower Platte River valley. Keech (1952) studied the area around the Wood River while Sniegocki (1955) studied the area around Prairie Creek. Bradley and Johnson (1957) studied the Republican River and Frenchman Creek valleys. Johnson and Keech (1959) studied the Big Blue River basin while Sniegocki (1959) studied the Loup River basin. Johnson (1960) studied the area where the Little Blue River, Platte River, and Republican River basins meet.

Bentall and others (1975) studied central Nebraska, including much of the area described in this report. Lichter and others (1980) investigated artificial recharge at several sites, including one near Aurora. Ellis (1981) updated previous studies of the Republican River basin. Bartz and Peckenpaugh (1986) compiled extensive data for the area of this report. Hardgree and McChesney (1995) compiled a bibliography on the Platte River basin in Nebraska which emphasized water-quality information but included other references as well.

A number of county-level studies were conducted in the study area from the 1940s into the 1980s. Adams County was studied by Keech and Dreeszen (1968) and Boyle Engineering Corp. (1983). Buffalo County was studied by Schreurs (1956). Clay County was studied by Keech and Dreeszen (1959). Franklin County was studied by Conservation and Survey Division (1957). Hall County was studied by Keech and Dreeszen (1964) and Spalding (1975). Hamilton County was studied by Keech (1962). Kearney County was studied by Conservation and Survey Division (1948). Phelps County was studied by Conservation and Survey Division (1953). Polk County was studied by Weakly (1966), Keech (1972), and Davis (1986). York County was studied by Keech and others (1967).

Large area studies after the Darton (1898, 1905) studies 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 and Chen (1983a and 1983b) did more detailed reports on the Nebraska portion of the High Plains aquifer.

Studies of central Nebraska that included a groundwater flow model or other detailed numerical analysis include Emery (1965), Huntoon (1974), Missouri River Basin Commission (1975), Cady and Ginsberg (1979), Lappala and others (1979), Burns (1981 and 1983), Missouri Basin States Association (1982a and 1982b), Peckenpaugh and Dugan (1983), Pettijohn and Chen (1984), Nguyen and Gilliland (1985), Luckey and others (1986 and 1988), Peckenpaugh and others (1987), Ayers (1990), Goeke and others (1992), Miller (1993), McLean and others (1997), McGuire and Kilpatrick (1998), and Chen and Yin (1999). Alley and Emery (1986) looked at how well a previous model of the Blue River basin performed. A groundwater model of the Republican River basin was constructed as part of an interstate lawsuit involving Colorado, Kansas, and Nebraska (Republican River Compact Administration, 2003). Details of that model are given by Nebraska Department of Natural Resources (2006). The northern part of that model coincided with the southern part of this study. 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 southern part of that study coincided with the northern part of this study.

Testhole descriptions have been published for all of the counties in the study area. These include Adams County (Wigley, 1999a), Buffalo County (Dreeszen, 2000), Clay County (Burchett and Smith, 1994), Custer County (Cast, 2000a), Dawson County (Smith, 1999a), Franklin County (Burchett and Summerside, 1997), Frontier County (Eversoll, 2000), Furnas County (Smith, 1998), Gosper County (Cast, 2000b), Hall County (Dreeszen, 1999a), Hamilton County (Wigley, 1999b), Harlan County (Burchett and Summerside, 1998a), Howard County (Dreeszen, 1999b), Kearney County (Summerside, 1999a), Merrick County (Smith, 1999b), Nance County (Burchett and Smith, 1992), Nuckolls County (Summerside, 2003), Phelps County (Summerside, 1999b), Platte County (Burchett and Summerside, 1998b), Polk County (Burchett and Smith, 1996), Webster County (Summerside, 2004), and York County (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 estimate the effects of implementing groundwater management alternatives. Effects of these alternatives include changes in groundwater levels with time and changes in streamflows due to changes in groundwater discharge to or from streams. COHYST developed a formal strategy for construction and calibration of groundwater 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). This report documents the construction and calibration of a flow model for the Eastern Model Unit. The Eastern Model Unit overlaps approximately 30 mi with the Central Model Unit to the west. 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 different schedules, some differences exist. Differences between this model and the adjacent model to the west are described in the “Comparison to Adjacent Model” section.

The strategy calls 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 is for a model grid of 160 acres and 5 layers. Models were constructed for two time periods. 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 is defined to be 1950 (fig. 2). Most of the surface-water development for irrigation was completed in the region covered by the Eastern Model Unit by 1950, though some continued until around 1960. Both the pre-groundwater development period model and the groundwater development period model are described.

Description of Eastern Model Unit

The COHYST Eastern Model Unit (fig. 1) included in the groundwater flow model extends from Columbus westward to a boundary that parallels the western edge of Dawson County, and covers about 10,400 mi^2. The southern boundary of the model follows the Republican River from the western edge of Furnas County to where the river leaves Nebraska in Nuckolls County. The southern boundary then continues eastward along the southern edge of Nuckolls County to the east edge of Nuckolls County. The eastern boundary of the model follows the eastern edge of Nuckolls and Clay Counties, the southern and eastern edges of York County, and the eastern edge of Polk County. The northern boundary of the model starts on the South Loup River near the western edge of Custer County, and continues eastward to the junction with the Middle Loup River in western Howard County, and continues along the Middle Loup River. The Middle Loup River merges with the North Loup River in northeastern Howard County to become the Loup River, which is the northern boundary of the model eastward to Columbus. The Platte River flows from west to east roughly through the center of the Eastern Model Unit.

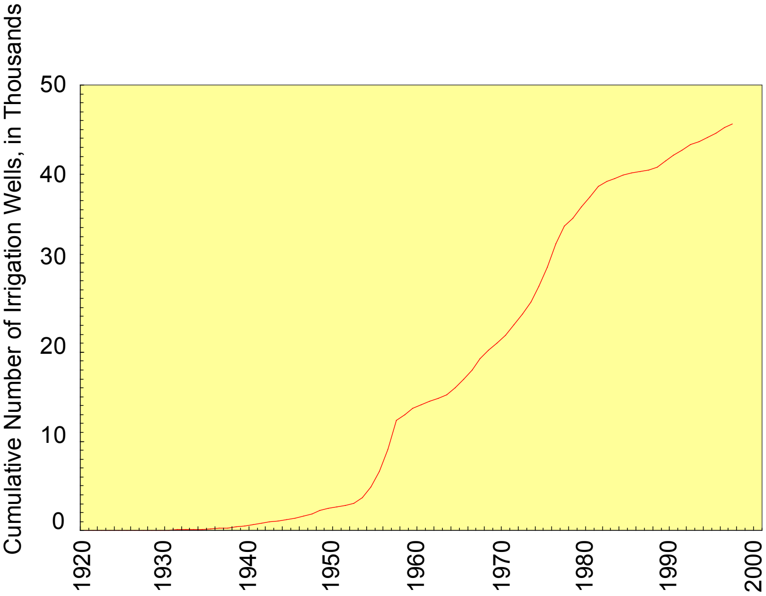


Figure 2. Irrigation well development in the COHYST area.

Major cities included in the Eastern Model Unit include (in order of 2000 population): Grand Island (42,940), Kearney (27,431), and Hastings (24,064), Lexington (10,011) and many other smaller communities of less than 10,000 population. Columbus (20,898) is just outside of the Eastern Model Unit. Counties, major streams, and lakes are shown in figure 3, and the eight Natural Resources Districts (NRDs) and major cities are shown in figure 4.

Agriculture dominates the livelihood and landscape of the region, with land in both the valleys and upland plains irrigated with surface water and groundwater. Areas where the groundwater aquifers are thin or non-existent are primarily used for grazing or dryland crops, and areas too topographically rough for crops are frequently used for pasture. As of 1950, the time considered to be the start of groundwater development in this study, approximately 70 percent (4,600,000 acres) of the total land area was farmed. Corn, wheat, and hay were the dominant crops at that time (Cooperative Hydrology Study, 2001a).

The average slope of the land surface in the Eastern Model Unit is 6 to 7 feet per mile (ft/mi) from west to east, although local variations exist. The topography in the Eastern Model Unit varies from relatively flat areas, such as tablelands and the floodplain of the Platte River, to dissected plains of the Loup and Republican River basins. The areas of dissected plains have considerably more topographic relief than the tablelands and floodplains. Canyons that are 30 to 160 feet (ft) deep are generally spaced at 10 to 20 mi intervals perpendicular to the east-west trending Republican River.

Climate in the Eastern Model Unit varies from moist sub-humid in the eastern part of the model area to dry sub-humid in the west (Conservation and Survey Division, 1998). Average 1961-90 precipitation ranges from less than 22 inches per year (in/yr) in the west to more than 28 in/yr in the east and southeast (fig. 5). Average 1895-1998 precipitation for the four climate divisions that cover the Eastern Model Unit is 24.2 in/yr (National Climatic Data Center, 2000). Annual precipitation may vary significantly, and has been recorded from as low as 13.2 inches (1934) in the southwest part of the model area (climate division 8) to as high as 48.3 inches (1993) in the southeast part of the area (climate division 9). Abundant sunshine, frequent winds, and low humidity contribute to a high rate of evaporation. Between 1950 and 1998, the average summer (May through September) pan evaporation in the Eastern Model Unit was about 45 in/yr, based on data collected at Grand Island and Harlan County Reservoir (Nebraska Department of Natural Resources, 2000; High Plains Regional Climate Center, 2003).

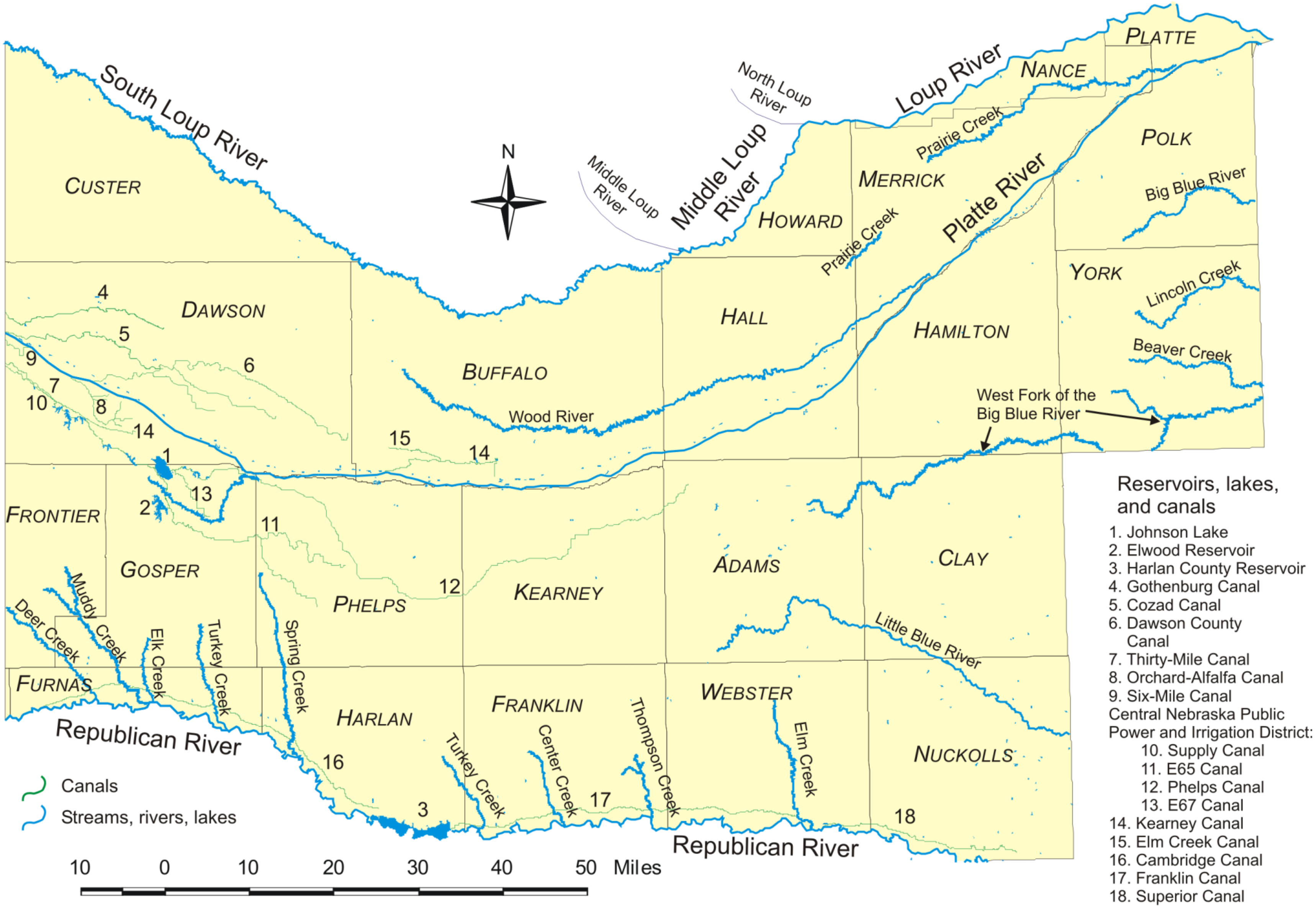


Figure 3. Counties, major streams, canals, and lakes in the Eastern Model Unit of COHYST.

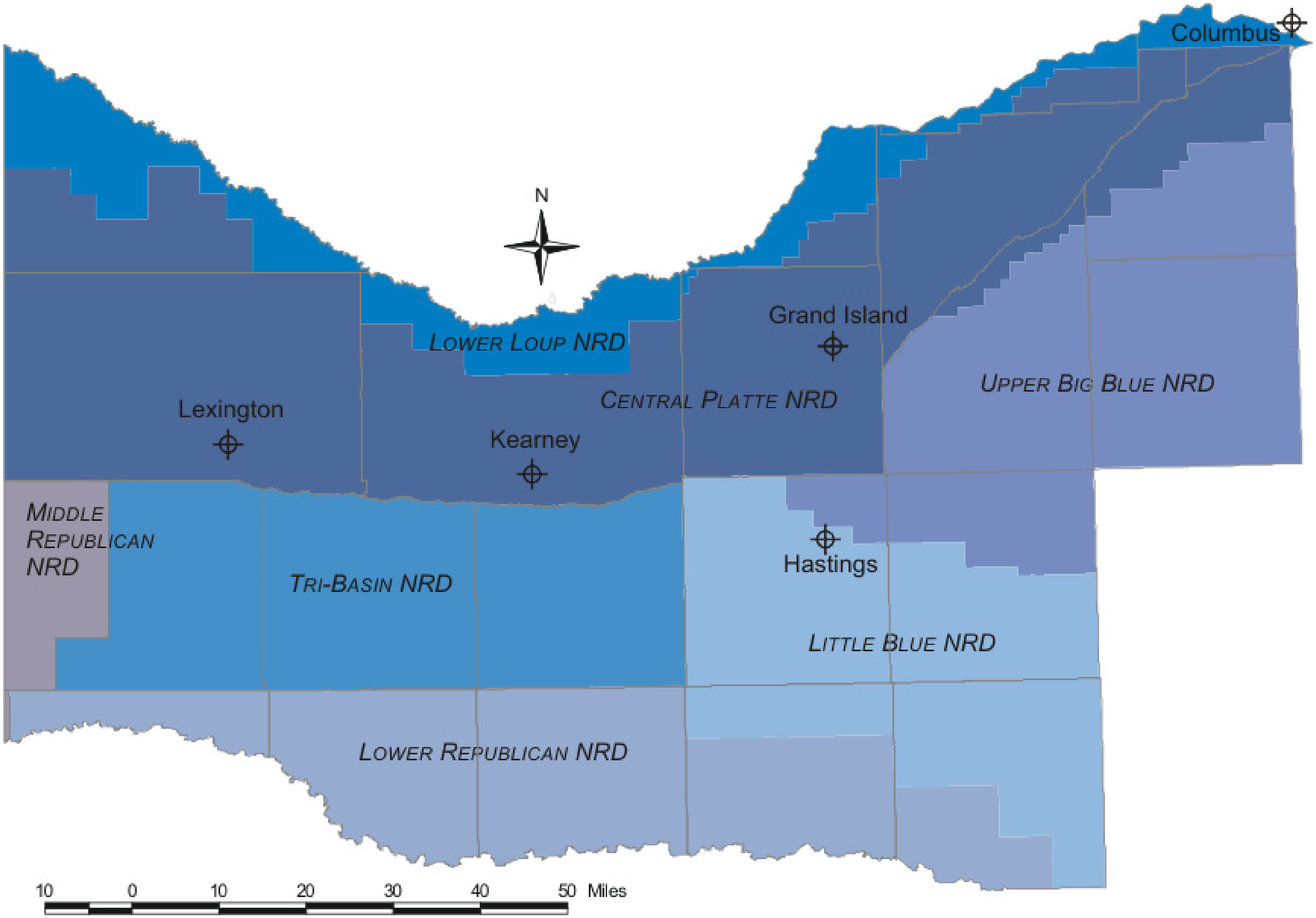


Figure 4. Natural Resources Districts (NRD) and major cities in the Eastern Model Unit of COHYST.

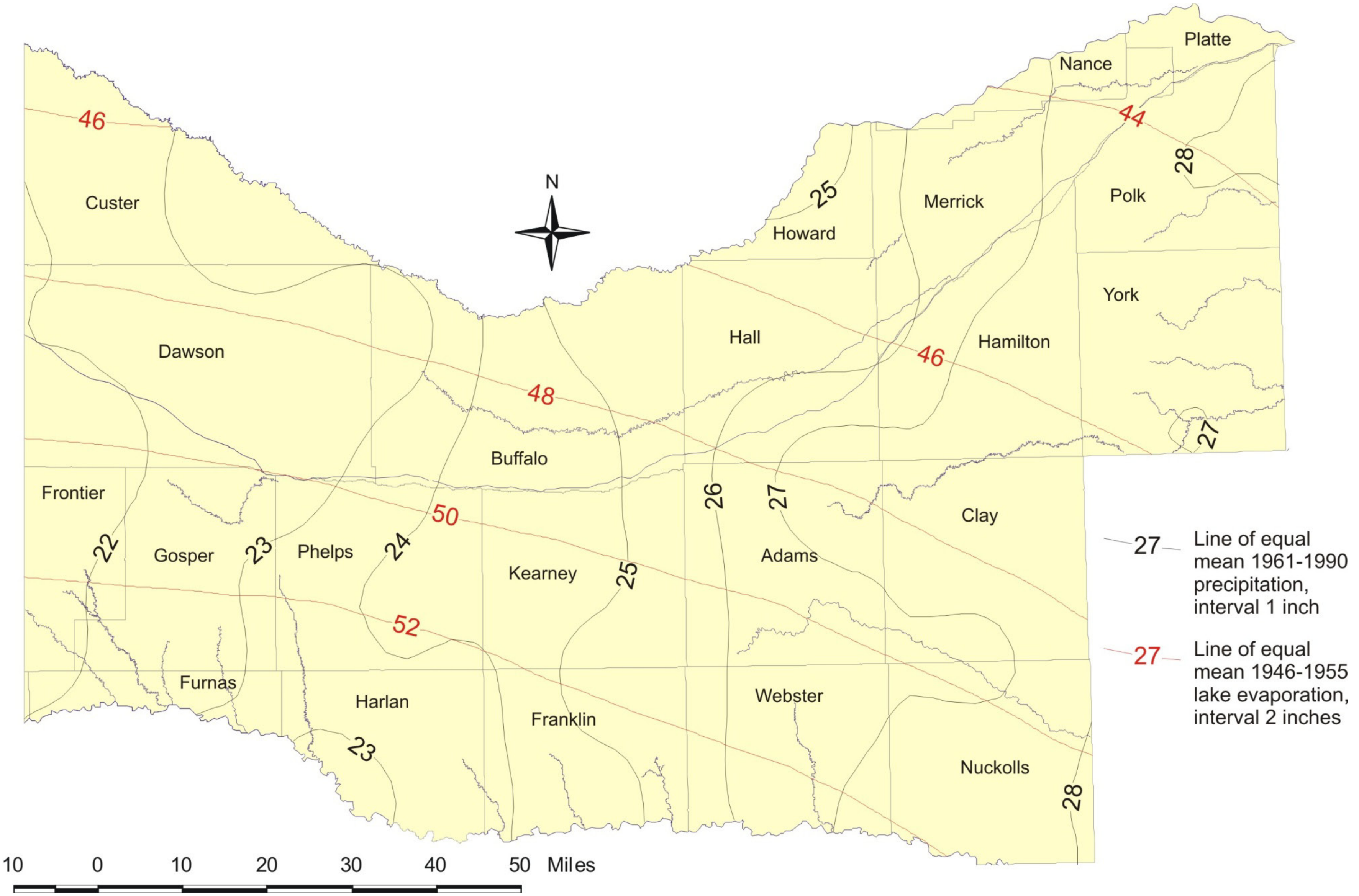


Figure 5. Average annual 1961-90 precipitation and 1946-55 lake evaporation in the Eastern Model Unit. Modified from Water and Climate Center of the Natural Resources Conservation Service (2000), and U.S. Weather Bureau (1959).

The Platte River flows approximately through the center of the Eastern Model Unit. As shown in figure 3, other major rivers in the interior of the area include the Little Blue River and the West Fork of the Big Blue River. The largest surface-water reservoir in the model area is Harlan County Reservoir (6,300 acres), on the Republican River. The only other large reservoirs in the model area are Johnson Lake (2,200 acres in Dawson and Gosper Counties), and Elwood Reservoir (1,100 acres in Gosper County), which are part of the Central Nebraska Public Power and Irrigation District system.

Wetlands and other areas of high evapotranspiration are limited to the floodplain of the Platte River and areas near other surface-water bodies. Other small wetlands exist in the eastern part of the Eastern Model Unit, in York and Clay Counties, but are limited to less than 1-2 mi^2 in size.

The pre-groundwater development water table ranges from more than 2,700 ft above sea level in the northwestern part of the Eastern Model Unit to less than 1,500 feet above sea level in the east (Gutentag and others, 1984; Cederstrand and Becker, 1999) (fig. 6). The water table in the western part of the Eastern Model Unit generally slopes to the southeast at around 6 to 8 ft/mi, and in the eastern part of the study unit the water table generally slopes to the east at around 6 ft/mi. In some areas, within 8 to 9 mi north of the Republican River, water table gradients can be as high as 30 to 60 ft/mi to the south.

Geologic and Hydrostratigraphic Units of the Eastern Model Unit

The geologic units in the Eastern Model Unit important to the groundwater flow model consist of various Quaternary-age deposits and deposits of the Ogallala Group of Tertiary age (table 1). Quaternary-age deposits consist of Pleistocene-age alluvial deposits, Pleistocene-age and Holocene-age loess, Holocene-age dune sand, and Holocene-age valley-fill deposits. The alluvial deposits, which typically yield large amounts of water to wells, are found throughout most of the Eastern Model Unit, though they may be thin or absent where the underlying bedrock is topographically higher than surrounding areas. Loess deposits are also found throughout the Eastern Model Unit, and tend to be thin or absent in active river valleys. Loess deposits are thickest in the west, in bluffs south of the Platte River, and in an area north of the Platte River valley. These deposits can be over 400 ft thick, but generally only the lowest 100 ft is below the water table. These deposits are capable of storing and slowly releasing large amounts of water. Dune sand is relatively thin in northern Phelps County, Kearney County, Custer County, Howard County, and northern Buffalo, Hall, and Merrick Counties, and is not developed as a source of groundwater in the Eastern Model Unit. The valley-fill deposits occur primarily along the Platte and Republican Rivers. These deposits and the Quaternary-age alluvial deposits are a heterogeneous mixture of gravels, sands, silts, and clays and typically yield large amounts of water to wells. The valley-fill deposits are nearly 20 mi wide along the Platte River in the vicinity of Grand Island. Two distinct separate paleo-channels also contain Quaternary-age valley-fill deposits (fig. 6). The upper end of one of these channels is located south of the Platte River near the western boundary of the Eastern Model Unit, and ends over 100 mi southeast near the Republican River. At the western end of the paleo-channel, Tertiary-age valley-fill deposits overlie older aquifers, however the Tertiary-age deposits are absent in the eastern half of this paleo-channel. The other paleo-channel containing Quaternary-age valley-fill deposits is south of the Platte River in Adams and Clay Counties. This paleo-channel is present for about 60 mi east to west in the Eastern Model Unit, and in places may be greater than 15 mi wide. Quaternary-age valley-fill deposits in this paleo-channel can be over 200 ft thick (Cannia and others, 2006).

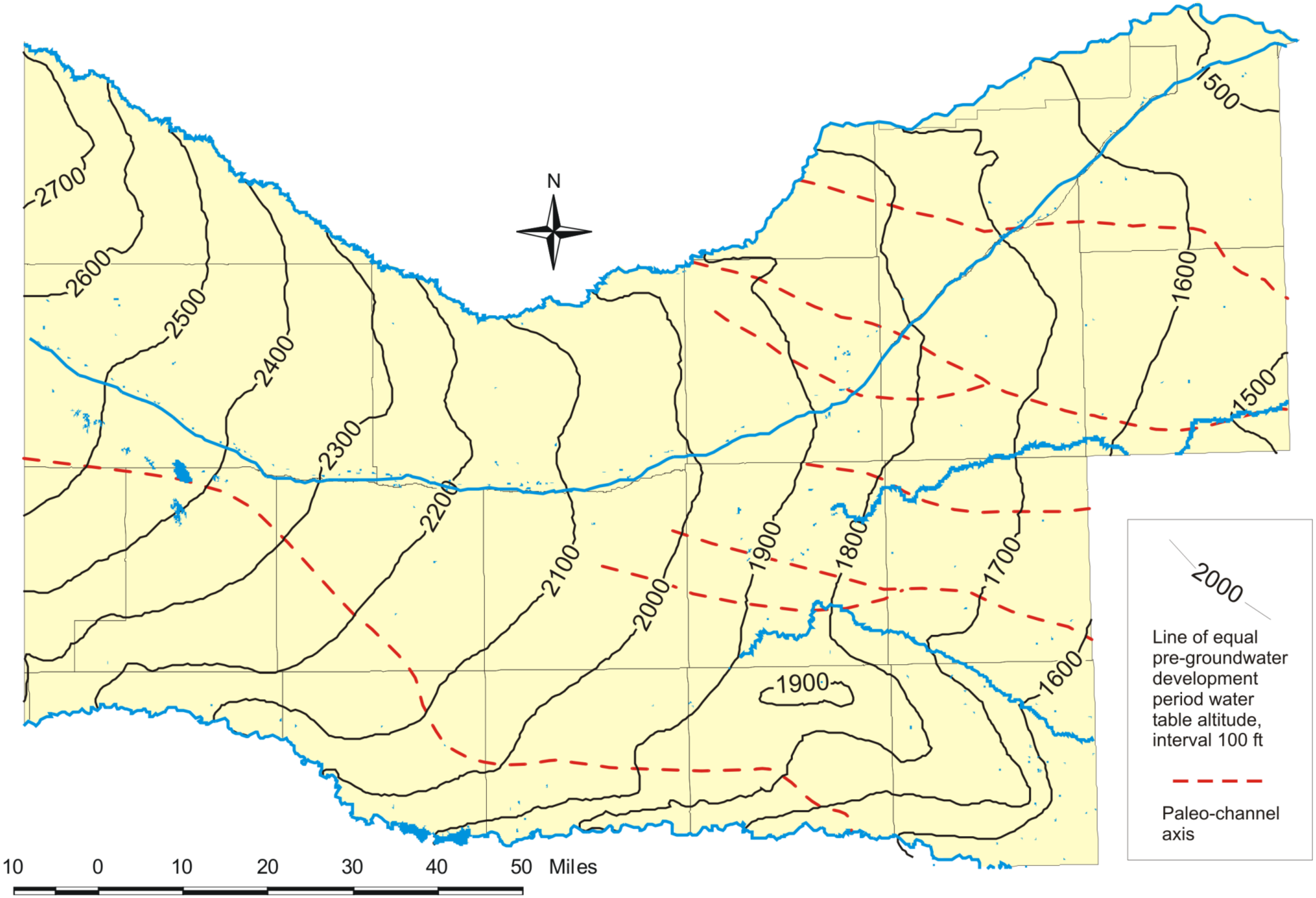


Figure 6. Pre-groundwater development period water table and paleo-channels in the Eastern Model Unit. Modified from generalized map by Gutentag and others (1984) and detailed digitized map by Cederstrand and Becker (1999).

Table 1. Generalized section of geologic units used in the Cooperative Hydrology Study (modified from Gutentag and others, 1984; Swinehart and others, 1985).

System	Series	Geologic Unit	Hydrostratigraphic Unit	Description
Quaternary	Holocene	Valley-fill deposits	Generally Unit 2	Gravels, sands, silts, and clays with coarser materials more common. Generally stream 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 180 ft thick.
		Dune sand	Unit 1	Wind-deposited fine to medium sand with small amounts of clay, silt, and coarse sand. Occurs in only a few locations in Hall, Howard, Phelps, and Kearney Counties, where it can be a few tens of ft thick.
	Pleistocene and Holocene	Loess deposits	Unit 1 when above Unit 2, otherwise Unit 3	Silt with small amounts of very fine sand and clay. Deposited as wind blown dust. Occurs almost everywhere in the Eastern Model Unit, and is generally thinnest in valleys of large, active rivers. Can be over 370 ft thick in bluffs and plains adjacent to the Platte River valley, but generally only the lowest 100 ft is beneath the water table.
	Pleistocene	Alluvial deposits	Generally Unit 2	Gravels, sands, silts, and clays with coarser materials more common. Generally stream deposits. Upper fine material, if present, is assigned to Hydrostratigraphic Unit 1. Lower fine material, if present, is assigned to Unit 3. Occurs throughout most of the Eastern Model Unit, except where underlying bedrock is topographically higher than surrounding areas, and can be over 300 ft thick.
Tertiary	Upper and middle Miocene	Ogallala Group	Units 4-6	Generally unconsolidated heterogeneous mixture of gravels, sands, silts, and clays. Generally stream deposits but also contains wind-blown deposits. Upper fine material, if present, is assigned to Unit 4. Center coarse material, if present, is assigned to Unit 5. Lower fine material, if present, is assigned to Unit 6. Occurs throughout the western half of the Eastern Model Unit, where the mean thickness is around 160 ft, though it can be over 500 ft thick. Thins eastward and is absent from the eastern part of the Eastern Model Unit.
	Lower Miocene and upper Oligocene	Arikaree Group	Unit 7	Predominately very fine to fine-grained sandstone but may also contain siltstones. Locally, may contain conglomerates, gravels, and sands. Fluvial deposits with some wind-blown volcanic deposits. Present in only one testhole in the Eastern Model Unit, in Custer County, where it is 35 ft thick.
	Lower Oligocene	Brule Formation of White River Group	Unit 8 of High Plains aquifer or Unit 9 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 Unit 8 only if fractured or contains sandstone or channel deposits, otherwise it is Unit 9 and forms the base of the High Plains aquifer. Wind-blown volcanic deposits with some fluvial deposits. Occur in only two testholes in the Eastern Model Unit, both in Dawson County, where it was 19 ft thick in one testhole and over 200 ft thick in the other testhole.
Cretaceous	Undifferentiated	Undifferentiated	Unit 10; below the High Plains aquifer	Shale, chalk, limestone, siltstone, and sandstone. Except for a few minor units in the extreme western part of the COHYST area and the Dakota Sandstone in the extreme eastern part of the area, generally forms an impermeable base of High Plains aquifer. Deep marine deposits to beach deposits.

The Ogallala Group consists of a heterogeneous mixture of gravels, sands, silts, and clays of the Ash Hollow, Valentine, and Runningwater Formations, though COHYST does not subdivide this unit below the group level. Outside of Nebraska, the Ogallala is treated as a single formation. The Ogallala Group typically yields large amounts of water to wells. The Ogallala Group is absent from most of the eastern part of the Eastern Model Unit.

The High Plains aquifer is underlain by shale, chalk, limestone, siltstone, and sandstone of Cretaceous age. Except for sandstones, these units generally transmit very little water and form a relatively impermeable base to the High Plains aquifer. The Dakota Sandstone underlies the aquifer in the extreme eastern part of the Eastern Model Unit and may exchange small amounts of water with the High Plains aquifer.

COHYST divides the High Plains aquifer into eight Hydrostratigraphic Units plus two additional units beneath the aquifer. These units are different from the geologic units discussed above. Geologic units are frequently grouped or subdivided on the basis of hydrostratigraphic characteristics, wherein geologic units that have similar water transmitting and storage characteristics are grouped together. No part of the COHYST area contains all ten Hydrostratigraphic Units and some of the units are discontinuous over large areas. Unit 1 consists of an upper Quaternary-age silt or clay; Unit 2 consists of a middle Quaternary-age sand or gravel; and Unit 3 consists of a lower Quaternary-age silt or clay. Some sands and gravels may occur in parts of Units 1 and 3 and some silts and clays 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 in test holes. Units 3 and 4 were grouped together for input to the groundwater model, and in that context are referred to as Unit 3-4. Unit 5 consists of a middle Tertiary-age sand or gravel; and Unit 6 consists of a lower Tertiary-age silt or clay. Some sands and gravels may occur in parts of Units 4 and 6 and some silts and clays may occur in parts of Unit 5. Unit 7 consists of very fine to fine-grained sandstone or siltstone of the Arikaree Group. Unit 8 consists of that part of the Brule Formation that is part of the High Plains aquifer because it is fractured or consists of channel deposits. Unit 9 is that part of the Brule Formation containing non-fractured silts and clays and the remainder of the White River Group. Unit 9 forms the generally impermeable base of the High Plains aquifer, though it only exists in two locations in the Eastern Model Unit. Unit 10 is Cretaceous-age materials that form the generally impermeable base of the aquifer where Unit 9 is absent. For more information on the geologic layers, refer to the COHYST Hydrostratigraphic Units and Aquifer Characterization Report (Cannia and others, 2006).

Conceptual Flow Model

A conceptual flow model is a narrative description of the characteristics of the groundwater flow system that are important to the intended use of the numerical model. The conceptual model includes descriptions of the state of the flow system at the beginning of the simulation period, the lateral and vertical boundaries of the model, what happens to the flow of water at these boundaries, and how the flow system interacts with external sources or sinks of water. An example of an important characteristic of the groundwater component of the flow system is how hydraulic conductivity (parameter describing the ability of the aquifer to transmit water) varies over the model area. The state of the groundwater flow system at the beginning of simulation describes whether the system is in a state of dynamic equilibrium or whether it is 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 study proceeds, but the basic framework generally is understood at the start of model construction.

The external boundaries of the Eastern Model Unit consist of fixed-flow boundaries at the eastern and western boundaries, a river boundary at the northern boundary, and a combination of fixed water level, fixed-flow, zero-flow, and river boundaries along the southern boundary (fig. 7). These boundaries are geographic boundaries of the model area, and were chosen to have relatively small influence on the internal area of the model.

A fixed-flow boundary is a boundary where a specified flow into or out of the model is 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. In addition to the eastern and western boundaries, part of the southern boundary in Nuckolls County was simulated as a fixed-flow boundary because the Republican River flows 1 mi south of and parallel to the model boundary, and it is likely that some flow moves from the model area south to the river. Further discussion on the use of fixed-flow boundaries can be found in the report on the COHYST Modeling Strategy (Cooperative Hydrology Study Technical Committee, 2000).

A fixed water-level boundary was used in this model to simulate Harlan County Reservoir. Further discussion on the use of fixed water-level boundaries can be found in the COHYST Modeling Strategy (Cooperative Hydrology Study Technical Committee, 2000). The lower boundary of the flow model is the base of the aquifer, and the upper boundary is the water table.

A zero-flow boundary is a boundary across which no flow is permitted throughout an entire simulation (McDonald and Harbaugh, 1988). Zero-flow boundaries were used in this model where groundwater flows parallel to the exterior boundary of the model, thus probably little or no water crosses those boundaries (southern border of York County, fig. 7).

Rivers and streams can be modeled as either river boundaries or as stream boundaries. Stream boundaries are allowed to gain or lose water from the aquifer, 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 potentially ephemeral drainages. 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 water table and estimated parameters that control the rate of movement between the aquifer and the streams. The Platte River, Loup River, South Loup River, North Loup River, and Republican River were simulated as river boundaries (fig. 7). All other perennial streams were simulated as stream boundaries. These include the West Fork of the Big Blue River, the Big Blue River, the Little Blue River, Deer Creek (Frontier and Furnas Counties), Muddy Creek, Elk Creek, Turkey Creek (Gosper and Furnas Counties), Spring Creek (Harlan County), Deer Creek (Harlan County), Foster Creek, School Creek, Flag Creek, Rope Creek, Turkey Creek (Franklin County), Center Creek, Thompson Creek, Elm Creek, Wood River, Buffalo Creek, Spring Creek (Dawson County), Plum Creek, North Dry Creek, Tributaries A, B, and C (Phelps County), Prairie Creek, Lincoln Creek, and Beaver Creek.

Drains and other enhanced ditches in the Platte River floodplain were simulated as drain boundaries (fig. 7). Drain boundaries are allowed to gain water from the aquifer but are not allowed to lose water to it. Interaction between a drain boundary and the groundwater system is controlled as it is in a river boundary. Most of these drains are a few miles in length, and were originally constructed to lower the local water table. Often drains of this size and extent would not be included in a regional groundwater simulation; however, due to the large number of drains south of the Platte River and their influence on the groundwater flow system, they were included in the Eastern Model Unit.

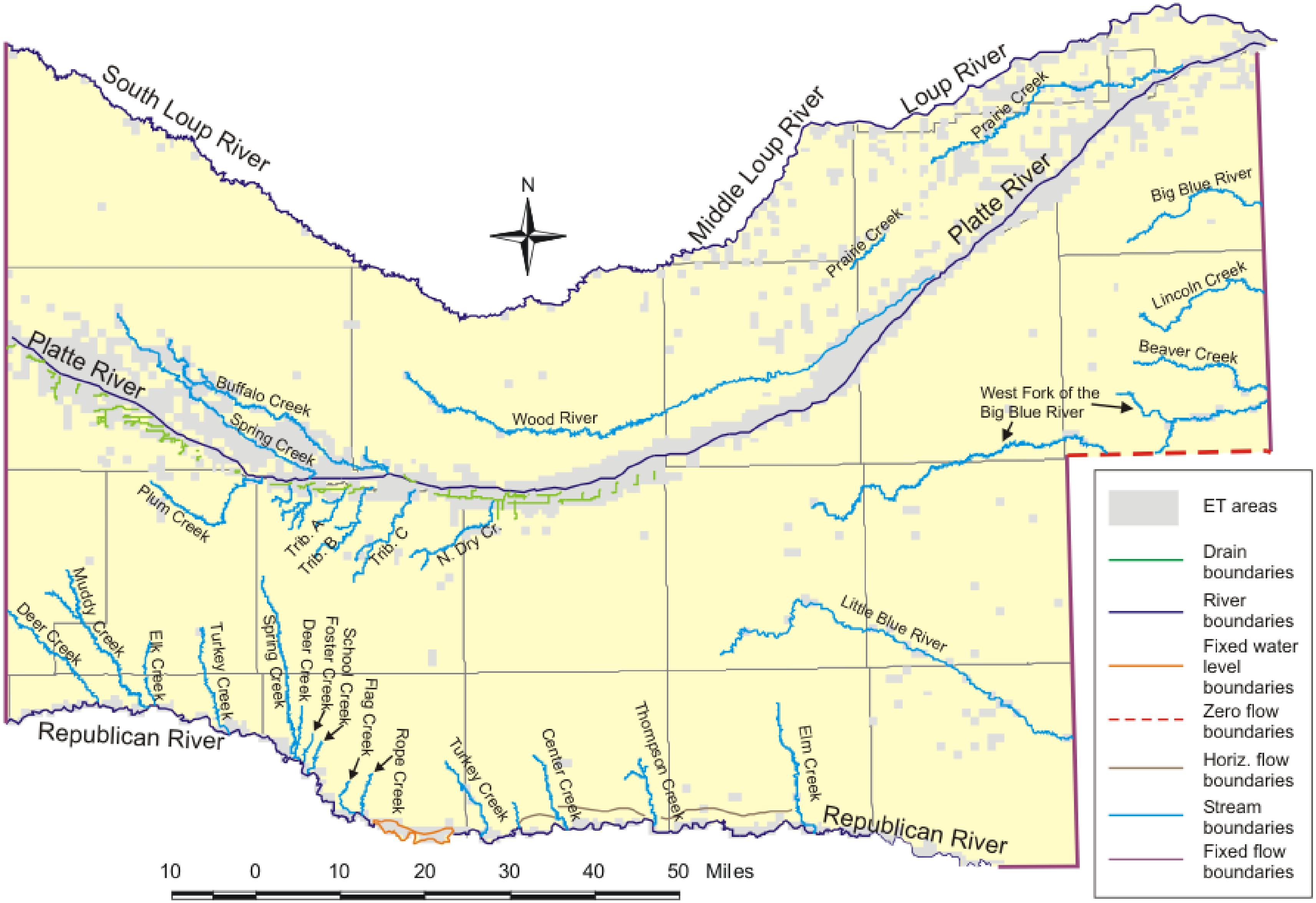


Figure 7. Conceptual model features for the Eastern Model Unit. Areas where evapotranspiration was simulated are shown by gray shading.

Areas of wetlands, generally near the Platte River, were treated as evapotranspiration areas (fig. 7) where groundwater was removed from the model. Evapotranspiration areas were defined using the 1997 land use map (Dappen and Tooze, 2001). Evapotranspiration was simulated in a model cell if more than 25 percent of the cell was classified as open water, riparian forest and woodlands, wetlands, or dryland alfalfa. Dryland alfalfa was included because it is usually grown in areas where the water table is shallow, and in those areas it is often sub-irrigated. Groundwater evapotranspiration areas in the groundwater model were also defined as areas where the groundwater was on average 10 ft or less below land surface, using long-term depth to water data (U.S. Geological Survey National Water Information System, 1999).

The interaction of the Republican River with the groundwater system north of the river changes from west to east in the Eastern Model Unit. In the western part of the model, the Ogallala aquifer adjoins Republican River valley-fill deposits. The Ogallala deposits thin eastward, and are generally absent near the Republican River valley downstream of Harlan County Reservoir. Overlying Quaternary-age alluvial deposits generally adjoin Republican River valley-fill deposits downstream of Harlan County Reservoir for about 8 mi. Eastward of this point, the Quaternary-age alluvial deposits thin as well, to the point where hydrologic connection to the Republican River alluvium is unlikely (Condra, 1907; Lugn and Wenzel, 1938; Waite and others, [1944]; Peckenpaugh and others, 1987). This disconnect between Quaternary-age alluvial deposits and Republican River valley-fill deposits is about 1-2 mi north of the Republican River and extends from western Franklin County about 30 mi eastward to the vicinity of Elm Creek, in Webster County (J. Goeke, Conservation and Survey Division, personal commun., 2002; L. Cast, Central Platte Natural Resources District, personal commun., 2003). This concept of the Republican River valley-fill deposits being separated from the Quaternary-age alluvial aquifer is also supported by testhole drilling performed in this area during 2001 (Summerside, 2004). Locations of COHYST testholes drilled in this area in 2001-02 are shown in figure 8, and an interpretive cross-section based on one group of testholes is shown in figure 9. As shown in figure 9, the zone of separation between the two aquifers could be up to ½ mi wide at this location. At the full possible width of ½ mi, this physical boundary to groundwater flow is somewhat smaller in width than the size of the model cells, because at the time this feature was added to the simulation, the model cell size was larger than ½ mi. Therefore, this barrier to groundwater flow was simulated with a Horizontal Flow Barrier (Hsieh and Freckleton, 1993). The amount of restriction provided by this barrier is based on estimated physical parameters that control the rate of water movement across the barrier. Downstream of Elm Creek, Quaternary valley-fill deposits in a paleo-channel (fig. 6) in the Cretaceous bedrock surface adjoin the Republican River alluvium (L. Cast, personal communication, 2003); therefore, the barrier was not simulated in the model east of Elm Creek.

Six Hydrostratigraphic Units (HU) were simulated as five layers in this model. The model layers, from top down, represent HU 1, HU 2, HU 3-4 combined, HU 5, and HU 6. Hydraulic conductivity is a mappable attribute for HU 2, 3-4, and 5 (Cannia and others, 2006). The mapped hydraulic conductivity distributions were used in model calibration. For HU 1 and HU 6, hydraulic conductivity was not a mappable attribute, therefore a uniform value was assigned to the entire layer. Specific yield used in model calibration was based on the testhole database (Cooperative Hydrology Study, 2003a). In addition, not all Hydrostratigraphic Units exist in all parts of the model (Cannia and others, 2006), though MODFLOW requires continuous layers. Where Hydrostratigraphic Units were absent, the corresponding model layers were assigned a default thickness of 1 foot; hydraulic conductivity and specific yield for these situations were averages of the units that were present above and below the absent Hydrostratigraphic Unit.

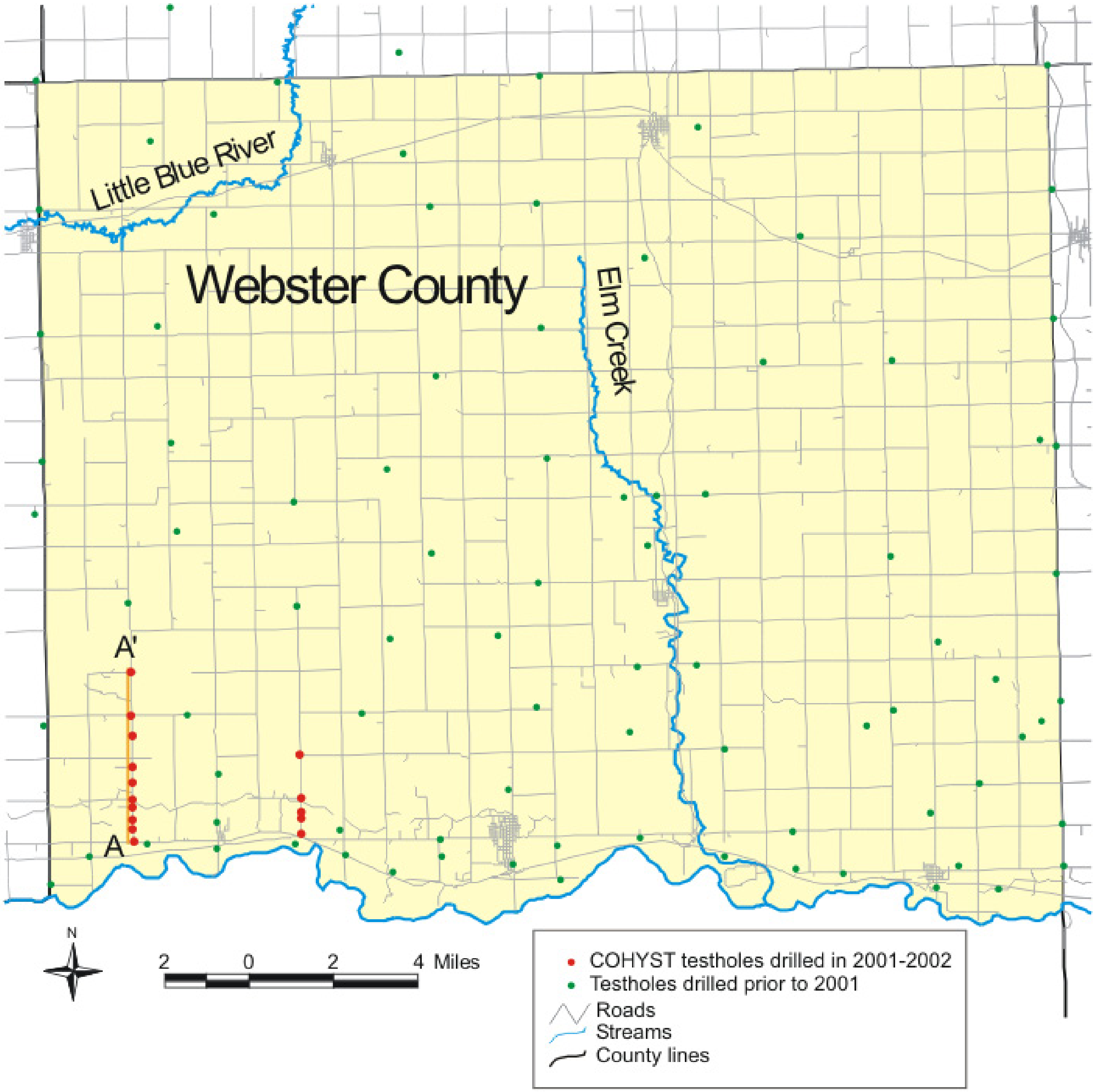


Figure 8. Locations of COHYST testholes drilled in Webster County in 2001-02. Line A-A' shows the location of the cross-section in figure 9. Green dots show testholes from the COHYST database (Cooperative Hydrology Study, 2003a).

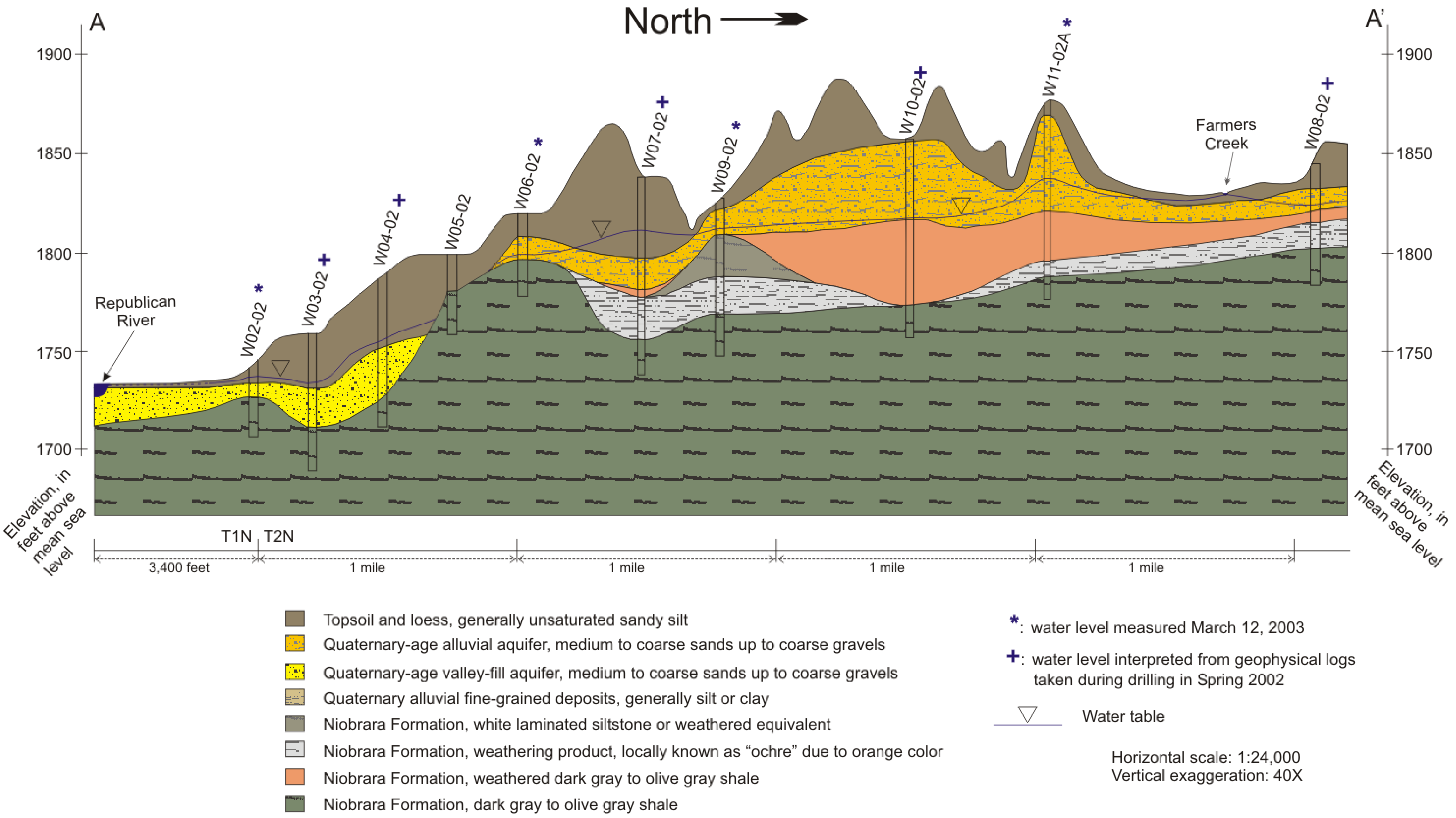


Figure 9. Interpretive geologic cross-section of selected COHYST testholes in Webster County. Location map shown in figure 7. No saturated materials were found above the Niobrara Formation in testhole W05-02. The Quaternary-age valley-fill aquifer was present in testhole W04-02, the Quaternary-age alluvial aquifer was present in W06-02, yet both were absent in W05-02.

Several irrigation canals were simulated in the model from 1895 to 1998 (fig. 3). The canal systems include Cambridge Canal, Franklin Canal, Superior Canal, the Central Nebraska Public Power and Irrigation District canals (Supply Canal, Phelps Canal, E65 Canal, E67 Canal), Gothenburg Canal, Cozad Canal, Dawson County Canal, Orchard-Alfalfa Canal, Six-Mile Canal, Thirty-Mile Canal, Elm Creek Canal, and Kearney Canal (State Board of Irrigation, 1899).

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 model necessarily simplifies and aggregates the true system but includes those features important to the intended use of the model. This numerical model was constructed to simulate and investigate the important effects of recharge to and discharge from the regional aquifer within the Eastern Model Unit. Important regional effects include changes in water levels and changes in groundwater discharge to or from streams.

This numerical flow model makes the following assumptions:

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 are masked by the uncertainties in model parameters.
3. Model parameters can be meaningfully averaged within 160-acre areas. This assumption is appropriate for a model designed as a regional representation of the groundwater flow system and because the spacing of testholes used 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 probably 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. Hydraulic conductivity is isotropic in the horizontal direction but can be anisotropic in the vertical direction. The assumption about isotropy in the horizontal directions probably is valid at the scale of this model. Vertical hydraulic conductivity for each cell is assigned values that are 10 percent of the horizontal hydraulic conductivity for the cell unless otherwise noted in the Model Calibration section.

MODFLOW-2000 (Harbaugh and others, 2000) was selected as the groundwater flow modeling code for this study. MODFLOW-2000 is a widely used flow code that employs block-centered finite-difference techniques to solve the three-dimensional partial differential equations that describe the flow of groundwater through porous media, such as 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 with the uncertainties associated with the real system.

To use the finite-difference technique, the aquifer is subdivided into a grid with individual blocks called cells. Although the flow code allows variation in cell size within a grid, a constant cell size of ½ mi by ½ mi is 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-2000 accounts for the flow of water between adjacent cells and water in 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 final solution. When the difference between successive approximations becomes negligible, a solution is reached.

The Department of Defense Groundwater Modeling System (GMS) developed by the Engineering Computer Graphics Laboratory at Brigham Young University (Environmental Modeling Systems, Incorporated, 2007) was the pre- and post-processor selected for managing MODFLOW-2000 input and output. GMS version 6.0 supports a number of groundwater flow and transport codes in addition to MODFLOW-2000. 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, images, borehole data, Triangulated Irregular Networks (TINs), and data sets of two and three-dimensional grids can be used. GMS allows such data sets to be created within the pre-processor. GMS uses the coverages and other data sets to prepare the input files required by MODFLOW-2000. The output from MODFLOW-2000 is imported into GMS, which then displays the results with maps, graphs, diagrams, cross sections, and tables. These capabilities allow GMS users to efficiently conceptualize and simulate flow in real groundwater systems. The conceptual models can evolve based on the comparison of results of the simulations with historic hydrologic data.

The grid for the Eastern Model Unit consists of 204 rows, 300 columns, and 5 layers, with 41,904 active cells per layer for a total of 209,520 potentially active cells (fig. 10). The grid lines are oriented in a north-south, east-west fashion, such that grid cells are squares measuring 2,640 ft on each side. This orientation is maintained for all model units to make it easier to compare results and inputs in the areas of model unit overlap.

The thickness of each cell is defined using contour maps of the bottom of Hydrostratigraphic Units 1-6 (Cannia and others, 2006). Figure 11 shows the elevation of the base of the aquifer. Cells are allowed to become inactive during calibration if the simulated water level drops below the bottom elevation of the cell. This allows cells that represent large areas of generally unsaturated layers to be removed from the simulation. Cells were allowed to re-activate in the simulation if the water level in the underlying cells rose to a predefined height above the bottom of an inactive cell (McDonald and others, 1991).

The MODFLOW River Package (McDonald and Harbaugh, 1988) was used to simulate river boundaries; the Drain Package (McDonald and Harbaugh, 1988) was used to simulate drain boundaries; the Stream Package (Prudic, 1989) was used to simulate stream boundaries. Drain, river, and stream boundary elevations were assigned from a digital elevation model (DEM) (Nebraska Department of Natural Resources, 1997) at selected locations, and GMS interpolated between those points. Stream and river locations followed generalized courses of the streams but did not duplicate exact details of the streams. The MODFLOW General Head Boundary Package (McDonald and Harbaugh, 1988) was used to simulate Harlan County Reservoir. The simulated extent and lake elevation approximated the area inundated by a moderately low stage, at 1,946 ft elevation. The Horizontal Flow Barrier Package (Hsieh and Freckleton, 1993) was used to simulate horizontal flow barriers.

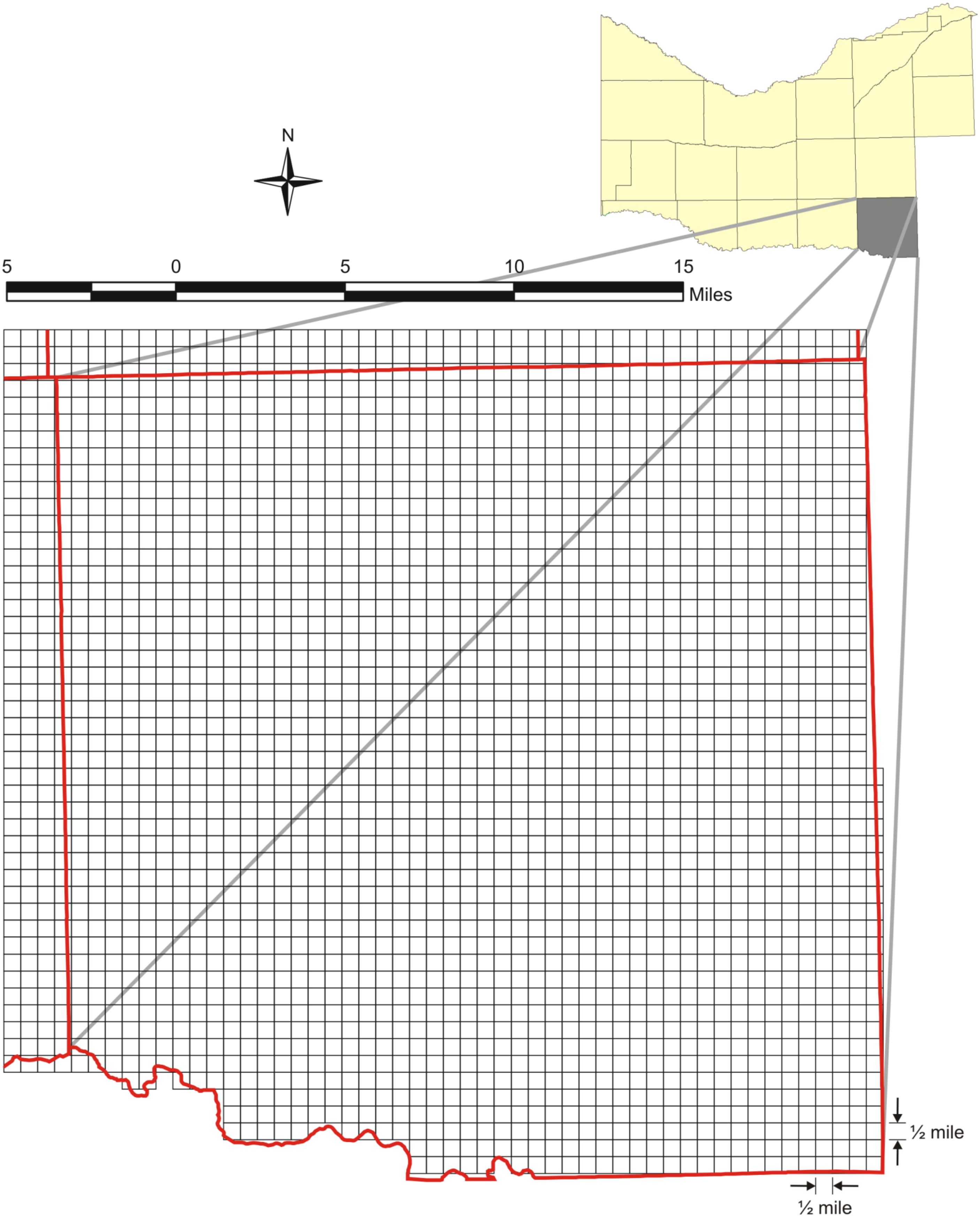


Figure 10. Active cells in the calibrated model in the Nuckolls County area.

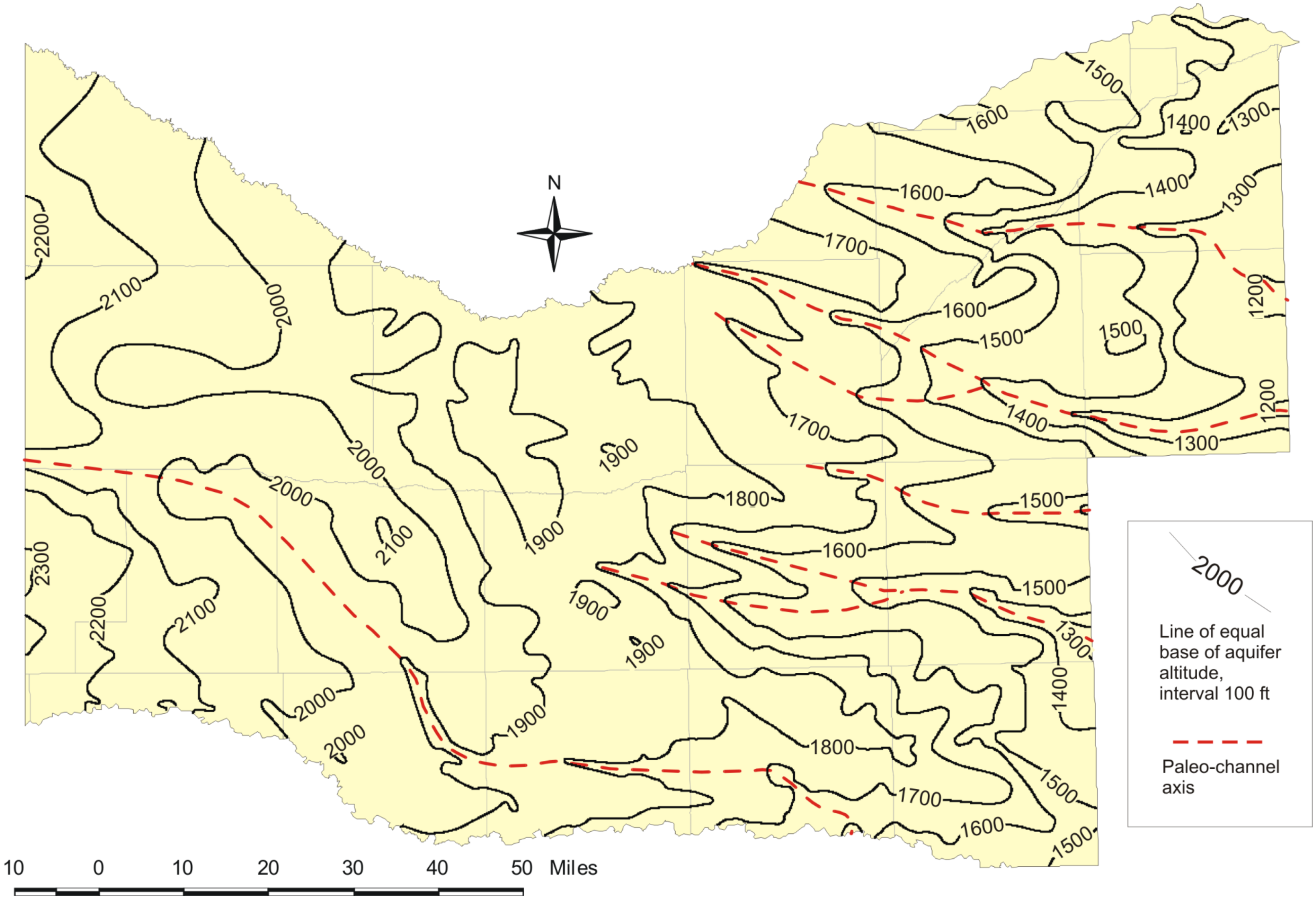


Figure 11. Base of Hydrostratigraphic Unit 6, corresponding to the base of the aquifer and the base of the groundwater flow model.

MODFLOW-2000 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 vertical hydraulic conductivity and thickness of the layer, feature width, and feature length in each drain, river, stream, or lake cell. Conductance controls the ease of interaction between the surface-water and groundwater systems. GMS automatically calculates the length of drain, stream, and river features, so the value input to GMS is conductance per unit length. In this report, conductance means the lumped parameter that accounts for layer vertical hydraulic conductivity, layer thickness, and feature width (for linear features only) to which GMS will apply feature length. Conductance for the drain, stream, and river boundaries was initially assigned according to the size and character of each stream. Large streams were assigned a conductance value of 10 feet per day per foot (ft/d/ft) length, and drains and small streams were assigned 1 ft/d/ft.

Recharge due to canal and lateral leakage (table 2) was estimated using different methods for different canal systems. For many of the canal systems, only diversion data were available, and data on deliveries were not available. Some of these canals (fig. 3) have returns back to the Platte River below the irrigated area, though those returns were not measured. For these canal systems, the recharge due to canal and lateral leakage was assumed to be 40 percent of the diversion, based on estimates made by various canal operators in the area. For canals where the annual diversion tended to be relatively constant, the average of all the annual diversion data was used to estimate recharge due to canal and lateral leakage. For some other canals, long-term trends were evident in the annual diversion data. For those canals, annual diversion data were plotted and regression lines were manually fit to represent the long-term trends, excluding data that appeared to be short-term outliers (fig. 12). From this technique, the long-term data could be represented by a relatively small number of points. Canal seepage recharge between those points was linearly interpolated. For some of these canals, data representing the early periods were either partially or totally absent. In these cases, the earliest data available were used to estimate the canal seepage recharge, and applied to the simulation as a constant rate.

For a few canals on the Central Nebraska Public Power and Irrigation District system, annual diversion and delivery data were available by major subdivisions of the system (Supply Canal, Phelps Canal, E65 Canal, Elwood Reservoir, E67 Canal). For Phelps Canal, E65 Canal, and E67 Canal, recharge due to canal and lateral leakage was estimated as the diversion minus the delivery for each sub-system. The Supply Canal is a large canal that flows through a series of lakes, and is operated year round for hydroelectric power generation, as well as to provide water for the downstream irrigation canals during the summer. Data from hydroelectric plant discharge from two plants on the Supply Canal were used along with other outflow data, such as returns to the river and irrigation canal diversions, as well as evaporation and precipitation data, to estimate the amount of water in the Supply Canal that went to groundwater recharge. For Elwood Reservoir, seepage recharge applied to the groundwater model for 1978-93 was based on a study by CH2MHill (written commun., 1993). Seepage recharge from Elwood Reservoir from 1994-98 was based on Central Nebraska Regional Water Conservation Task Force (2002). A summary of recharge due to canal and lateral leakage applied to the simulation is shown in table 2. This recharge was fixed during model construction and was not changed during model calibration.

The model first simulated the period prior to 1895 as a 1,000-year-long simulation to allow the groundwater system to come into dynamic equilibrium with recharge from precipitation. This 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 1,000-year period because highly permeable alluvial deposits in model layer 2 caused numerical instability that precluded direct simulation of steady state conditions by MODFLOW.

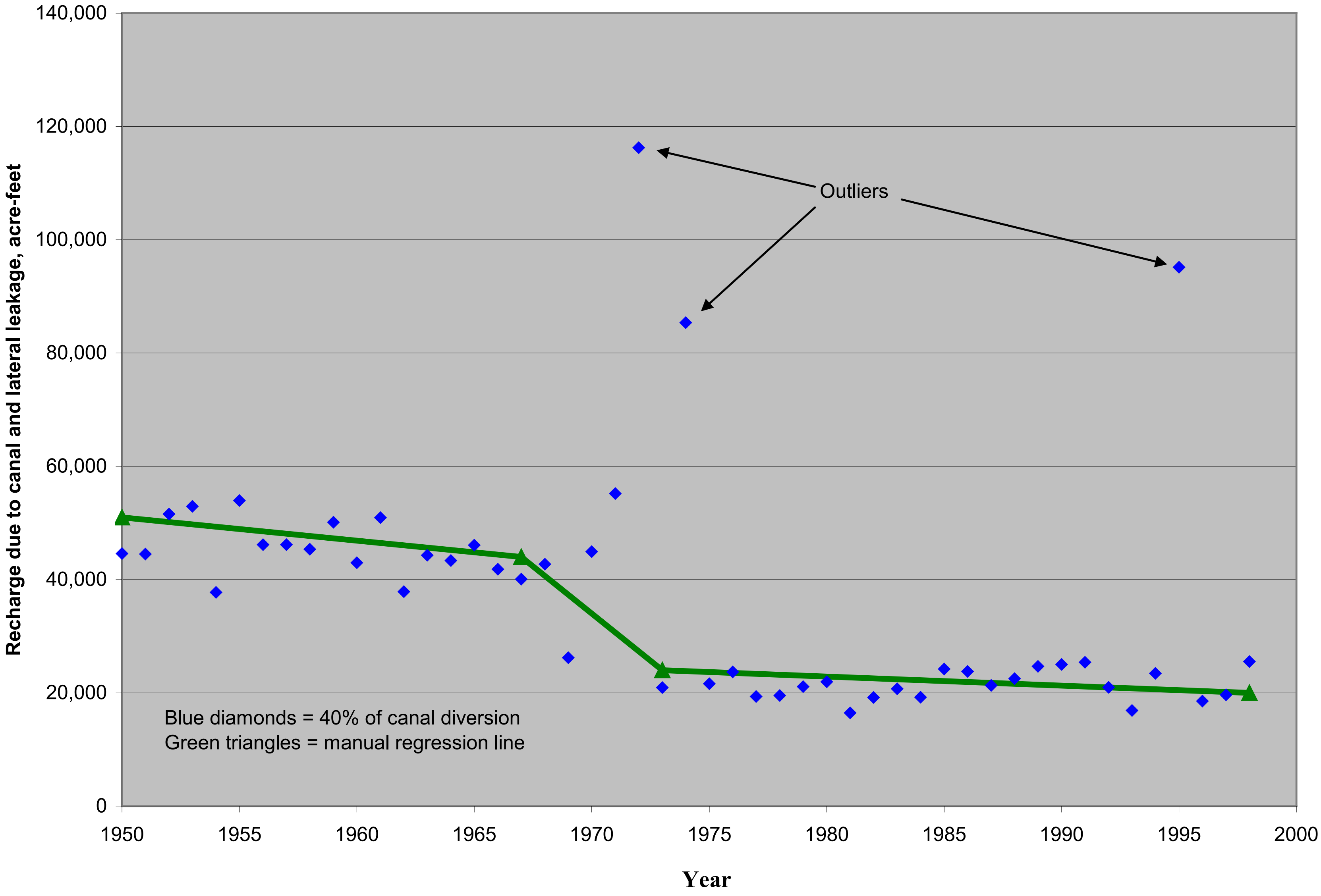


Figure 12. An example of a manual regression line used to represent historic recharge due to canal and lateral leakage of Gothenburg Canal.

Table 2. Summary of estimated recharge due to canal and lateral leakage applied to the simulation. Seepage volumes shown as ranges were linearly interpolated between listed years. Seepage is rounded to the nearest 1,000 acre-feet per year or to two significant figures.

Canal name	Year(s) applied to simulation	Estimated annual seepage, acre-feet
Cozad Canal	1895-1998	7,800
Dawson County Canal	1895-1998	21,000
Orchard-Alfalfa Canal	1895-1998	2,700
Gothenburg Canal	1895-1950	14,000 to 51,000
	1950-67	51,000 to 44,000
	1967-73	44,000 to 24,000
	1973-98	24,000 to 20,000
Six-mile Canal	1895-1950	380
	1950-64	380 to 400
	1964-69	400 to 860
	1969-79	860 to 1,000
	1979-98	1,000
Kearney Canal	1895-1950	4,600
	1950-55	4,600 to 5,700
	1955-68	5,700 to 9,200
	1968-98	9,200 to 9,600
Thirty-mile Canal	1928-98	11,000
Elm Creek Canal	1929-50	3,400
	1950-54	2,900 to 3,400
	1954-62	3,400 to 2,600
Central Nebraska Public Power and Irrigation District Supply Canal (only within Eastern Model Unit)	1942-98	209,000
Central Nebraska Public Power and Irrigation District Phelps Canal	1942-49	54,000
	1949-50	54,000 to 82,000
	1950-59	82,000 to 117,000
	1959-78	117,000 to 100,000
Central Nebraska Public Power and Irrigation District Phelps Canal (continued)	1978-84	100,000 to 71,000
	1984-98	71,000
Central Nebraska Public Power and Irrigation District E65 Canal	1942-49	42,000
	1949-50	42,000 to 57,000
	1950-75	57,000 to 55,000
	1975-79	55,000 to 32,000
	1979-98	32,000
Cambridge Canal	1951-57	7,600 to 9,700
	1957-68	9,700 to 12,000
	1968-98	12,000 to 11,000
Superior Canal	1952-98	5,100
Franklin Canal	1954-59	3,300 to 5,800
	1959-60	5,800 to 8,200
	1960-72	8,200 to 11,000
	1972-98	11,000
Central Nebraska Public Power and Irrigation District E67 Canal	1954-64	5,300 to 4,600
	1964-75	4,600 to 7,000
	1975-90	7,000 to 6,400
	1990-97	6,400 to 6,500
	1997-98	6,500
Elwood Reservoir	1978-93	25,000
	1993-94	25,000 to 20,000
	1994-98	20,000

Next, the model simulated the period 1895-1950 as a transient period when extra recharge from canal leakage and surface-water irrigation was added to the model, affecting much of the area north and south of the Platte River in the western half of the Eastern Model Unit. This part of the simulation was broken into five different stress periods. The first two stress periods had identical inputs and were used only to break the 1895 to 1928 period into roughly equal halves. The remaining stress periods were selected to coincide with the different times when various canals started operation (stress periods from 1895 to 1928, 1928 to 1929, 1929 to 1942, and 1942 to 1950). Finally, the model simulated the period 1950-98 as a transient period when groundwater irrigation and additional recharge from precipitation on cultivated land were added to the model.

The initial groundwater level for the 1,000-year simulation was set to a small distance below land surface to control numerical stability early in the period. The model was then run for 1,000 years so the groundwater levels changed until they came into dynamic equilibrium (called steady state) with recharge from precipitation. Steady state was verified in the 1895 simulation by running the model an additional 100 years and noting that water levels changed only a negligible amount over the additional 100 years. Because equilibrium was reached, the 1895 simulated water table was independent of the initial water levels. The simulated 1,000-year water level was set as the initial water level for the 1895-1950 period. The simulated 1950 water level was the initial water level for the 1950-98 period.

The 1,000-year period prior to 1895 was simulated with 2,000 time steps of about 183 days. The 1895-1950 transient period was simulated with 5 stress periods using 201 time steps of about 98 days. The small time steps prevented problems with model convergence related to cells wetting and drying as water levels rose and fell across layers according to the model stresses.

Beginning May 1, 1950, the transient model simulated each year with two stress periods: an irrigation season stress period (May-September) and a non-irrigation season stress period (October-April). Pumpage and recharge were constant throughout each stress period. The irrigation season stress period was simulated with 200 time steps and the non-irrigation season stress period was simulated with 224 time steps; this resulted in a time step length of about 0.8 days during the irrigation season and about 1.0 day during the non-irrigation season. The small time steps prevented problems with model convergence. Although the October-April period is called the non-irrigation season, some irrigation on alfalfa and wheat was simulated during this period. Because the groundwater development period started on May 1, 1950, the last non-irrigation season ended on April 30, 1998.

The period 1950-98 was subdivided into four shorter periods for calibration. 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 (R.R. Luckey, 2002, electronic commun.). More water-level change data were available for calibration of the shorter periods, particularly the last two periods, than were available for 1950-98.

Pumpage for groundwater-irrigated crops was estimated for the irrigation seasons beginning May 1 of 1950 through 1997 (1950-97). The estimates were based on changes in land uses 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 due to over-application of water.

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, irrigated acres by crop were estimated, because only total irrigated acres were reported. Not all crops were reported for all years, so dryland and irrigated acres had to be estimated in some cases. This was usually the case with minor crops. When more acres were planted, 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 percentage of the county located within 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, dryland, and rangeland within a county for 1950-97 was estimated based on the 26 land uses in the 1997 land use map (Dappen and Tooze, 2001), location of surface-water irrigated land, registered irrigation wells (Cooperative Hydrology Study, 2004), and topographic regions (Conservation and Survey Division, 1998, figure 2). Six land uses were assumed not to change over time, including urban, open water, woodlands, wetlands, other agricultural land, and roads. While minor changes may have occurred over time, these land uses, when combined, cover less than 7 percent of the study area, with wetlands and woodlands being the dominant land uses in this group. Two minor 1997 land uses, dryland potatoes and dryland sugar beets, were assumed to be irrigated, because these crops normally are irrigated for full development on the High Plains. The remaining 18 land uses were modified over time as described below.

The 1997 land uses (Dappen and Tooze, 2001), originally output at 2.5-meter resolution, were aggregated to 640-acre cells that covered the entire COHYST area. The number of acres of 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 described below. The 640-acre cells are coincident with four 160-acre cells of the model described in this report. Pumpage was calculated for the 640-acre cells and equally distributed to the four 160-acre cells in the groundwater model. The 1997 land uses also were aggregated to 10-acre cells and saved for potential future use.

The process of estimating 1950-96 land use by 640-acre cells started with 1997 land use (Dappen and Tooze, 2001) and worked backwards from 1997, one year at a time, until the land use for all years was estimated. For example, if total acres for a particular land use in a county was 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 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, based on the weighting procedure, that had been previously removed. If the increase in land uses was greater than the decreases in land use, the net increase in land uses were added by removing rangeland.

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 (and alfalfa), grain/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 weighting was generally based on the premise that when farmers chose new ground to develop for crop land, flat ground near large streams would be most preferred, and hilly or steep ground far from large streams would be least preferred.

The process of re-assigning land uses 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 for the Eastern Model Unit was computed with an unpublished soil water balance model developed by Dr. Derrel Martin, University of Nebraska-Lincoln. This model, referred to as CropSim, attempts to deal with the spatial variations of soils, land uses, and the spatial and temporal variations in meteorology. CropSim uses daily time steps to account for precipitation, computed crop evapotranspiration, and computed remaining available soil moisture. When modeled soil moisture decreases to a specified level in CropSim, 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 as it requires daily inputs for precipitation and meteorological data to compute potential evapotranspiration, which is also known as reference crop evapotranspiration. It also requires data that are not continuously or universally available or are very sparse. CropSim has been calibrated to natural conditions only to a very limited extent.

The data to compute daily potential evapotranspiration, the most critical data input to CropSim, is not available for much of the 1950-98 period. For this period the daily potential evapotranspiration was estimated indirectly from meteorological data using Hargreaves method (Hargreaves, 1994) adjusted to each meteorological station. The calculated potential evapotranspiration changed several inches on an annual basis from one meteorological station to the next. This variation is attributed to limitations of calibrating the Hargreaves method to the meteorological stations, some of which may be due to substandard site locations. To correct for this, potential evapotranspiration was averaged over the entire COHYST area on a daily basis. This calculated value was greater than generally accepted values, so daily potential evapotranspiration values determined by this method were reduced by 10 percent to bring them into the accepted range. Net pumpage was then reduced by an additional 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. For more information on the processing of acres and pumpage data, see Kern (2004).

Recharge due to over-application of surface-water irrigation was estimated for the groundwater development period using Bureau of Reclamation on-farm delivery estimates (D. Woodward, Central Platte Natural Resources District, personal commun., 2004) compared with CropSim estimated net irrigation requirement. When the on-farm delivery was greater than the net irrigation requirement, the extra delivered water was applied to the groundwater development period simulation as recharge (R. Kern, Nebraska Department of Natural Resources, personal commun., 2004). When on-farm delivery was less than the net irrigation requirement, the amount of water necessary to meet the net irrigation requirement was withdrawn as groundwater pumpage (simulated as negative recharge). The average value for the 1950-52 surface-water irrigation over-application was applied to the 1895-1950 simulation because CropSim net irrigation requirement was not estimated for the 1895-1950 period. This recharge was fixed during model construction and was not changed during model calibration, and amounted only about 1 percent of the magnitude of the recharge due to canal leakage shown in table 2.

Numerical Model Calibration

A groundwater flow model should be calibrated prior to being used for analysis or 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. The model was calibrated for both the pre-groundwater development period (pre-1950) and the groundwater development period (1950-98). In the pre-groundwater development model, rangeland recharge, hydraulic conductivity, properties of horizontal flow barriers, and streambed conductance were adjusted. In the groundwater development period model, dryland recharge, irrigated land recharge, and specific yield were adjusted. Boundary flows were initially fixed using preliminary model output data, and were later adjusted slightly during calibration of the groundwater development period model. Other model inputs, including stream, river and drain elevations, river stages, canal leakage, surface-water irrigation recharge, Hydrostratigraphic Unit elevations, and net pumpage were not modified during calibration.

A groundwater flow model may not be unique in that different combinations of model inputs can 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 produce reasonable groundwater levels if the ratio between the two input values were correct. Fortunately, simulated recharge and hydraulic conductivity are not interrelated with respect to simulated groundwater discharge to or from streams. Therefore, both groundwater levels and groundwater discharge to streams were used to determine whether the model was correctly calibrated.

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. As the modeling process evolved, 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.

Observed water levels from U.S. Geological Survey and Nebraska Department of Natural Resources databases and data-based estimates of groundwater discharge to streams (Peterson and Carney, 2002) were used to calibrate the pre-groundwater development model. Observed water-level changes were used to calibrate the groundwater development period model. Water-level changes rather than absolute water levels were used in the development period so that any errors in the 1950 simulated water levels were not propagated into the development period. Changes in streamflows were used only in a qualitative manner because groundwater discharge to most streams changed only slightly between 1950 and 1998 (Peterson and Carney, 2002).

Observed water levels used in calibration of the pre-groundwater development period model were selected from water levels measured in wells during 1946-55, 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 calculating the water level are due to errors in location or land-surface elevation, the most reliable water level is the level associated with the most accurate location and land-surface elevation. After screening values in all the 4-mi by 4-mi cells, a few water levels 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 the pre-groundwater development calibration consisted of 423 water levels.

Observed water-level changes were used in calibration of the groundwater development period model. These changes were selected from water levels measured near the beginning and end of the periods 1950-98, 1950-61, 1961-73, 1973-85, and 1985-98. A 4-mi by 4-mi grid was overlain on the entire COHYST area and the observation well with the most water levels in the cell, including ones near the beginning and ending date, was selected. The number of water levels in the Eastern Model Unit for each period were:

Period	Number
1950-98	78
1950-61	132
1961-73	219
1973-85	280
1985-98	405

Due to the limited number of available water levels in the 1950-98, 1950-61, and 1961-73 periods, there were some areas that had more observed change data than others. For instance, no observed change data were available for Frontier County and the western part of Gosper County except in the 1985-98 period. Fortunately, water levels exist in every time period for some heavily developed areas (for example, Hamilton, York, and Polk Counties).

Groundwater model calibration is commonly evaluated by comparing either the mean difference, the mean absolute difference, or the root mean square of the differences between simulated and observed water levels.

The mean difference (MD) is defined as:

$$MD = \frac{1}{n}\sum_{1}^{n}(h_s - h_o)_i$$

where h_s is the simulated water level and h_o is the measured or observed water levels at each observation point. The mean difference is not commonly regarded as the best measure of calibration because differences 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:

$$MAD = \frac{1}{n}\sum_{1}^{n}\left|(h_s - h_o)_i\right|$$

The mean absolute difference is a useful measure of model calibration because positive and negative differences do not cancel each other out. Furthermore, all differences are given equal weight, so a few measurements with large error will not dominate the measure of error. Root mean square (RMS) difference is another commonly used measure of calibration. RMS difference is defined as:

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

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

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.

Groundwater discharge to streams was estimated using streamflows recorded at gaging stations during the fall (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 Peterson and Carney (2002). A minimum, mean, and maximum estimate of observed groundwater discharge was made for each stream or segment of stream with a gaging station. 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 Elm Creek, have relatively narrow ranges of observed groundwater discharges, whereas other streams, such as the 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.

Pre-Groundwater Development Period Calibration

Hydraulic conductivity is a coefficient describing the quantity of groundwater that can flow through an aquifer. Hydraulic conductivity is a function of the physical properties of the aquifer and the viscosity of the water passing through it (Fetter, 1994). The rate at which groundwater moves through the aquifer is controlled by hydraulic conductivity as well as gradient and porosity.

Several distributions of hydraulic conductivity and rangeland recharge were tested to determine which produced the best model calibration. Early in model development, simple conceptual distributions of hydraulic conductivity were tested against the hydraulic conductivity data set of Gutentag and others (1984). However, subdivision of the single-layer model into multiple layers allowed for a more accurate representation of hydraulic conductivity within the Hydrostratigraphic Unit configuration recently produced by Cannia and others (2006). The conceptual distributions used early in model development focused on the regional geology, whereas Cannia and others (2006) provided locally refined information about distinct Hydrostratigraphic Units (HU). Based on the multi-layer conceptual model, values of hydraulic conductivity were initially applied uniformly to each layer based on Hydrostratigraphic Units. For example every cell that represented some saturated thickness of HU 1 was assigned the same hydraulic conductivity value. For model layers 1 and 5 (corresponding to HU 1 and HU 6), no additional variation was considered because testhole information indicated little spatial variation in hydraulic conductivity. For model layers 2-4, corresponding to HU 2, HU 3-4, and HU 5, testhole information was used to produce a spatial distribution of hydraulic conductivity within each model layer represented by polygon areas (Cannia and others, 2006). Hydraulic conductivity values defined by these distributions were uniformly modified upward or downward by layer within the estimated range of uncertainty until the best model calibration was identified. Table 3 shows a summary of the hydraulic conductivity values used in the simulation, and figure 13 shows the thickness-weighted hydraulic conductivity from the calibrated model. Figure 14 shows 1950 saturated thickness from the calibrated simulation.

Table 3. Hydraulic conductivity for the calibrated pre-groundwater development period model, for portions of model layers where the corresponding Hydrostratigraphic Units (HU) were present. Where a HU represented by a model layer was absent, that model layer was assigned hydraulic conductivity representative of HUs present above and below that model layer (not represented in this table).

Model Layer	HU	Mean hydraulic conductivity (ft/d)	Minimum hydraulic conductivity (ft/d)	Maximum hydraulic conductivity (ft/d)
1	1	10	--	--
2	2	155	5	240
3	3-4	8	5	25
4	5	33	25	125
5	6	10	--	--

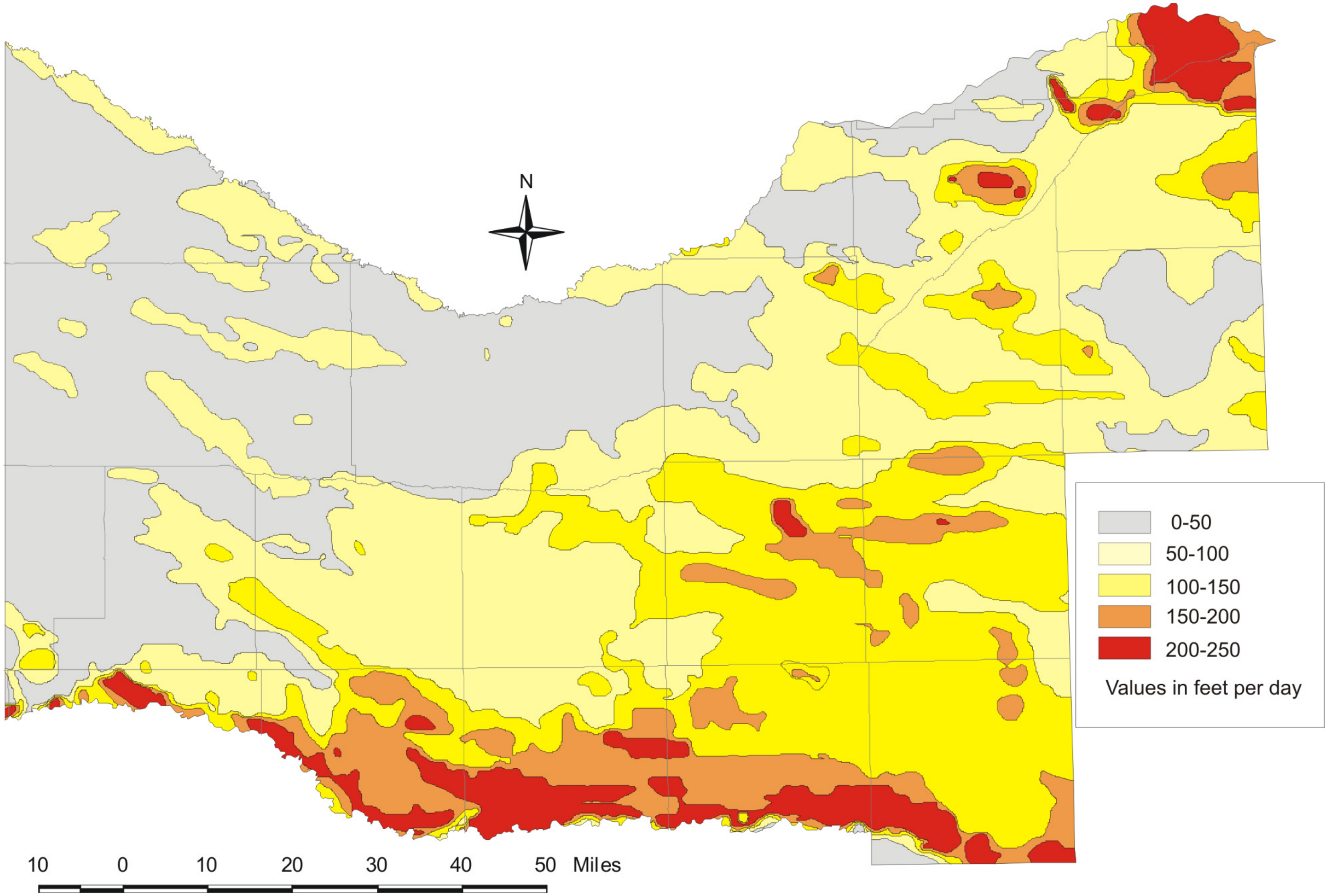


Figure 13. Composite hydraulic conductivity distribution applied to the calibrated model. Values from each layer were weighted by saturated thickness of the layer and divided by the total saturated thickness to show an effective composite hydraulic conductivity.

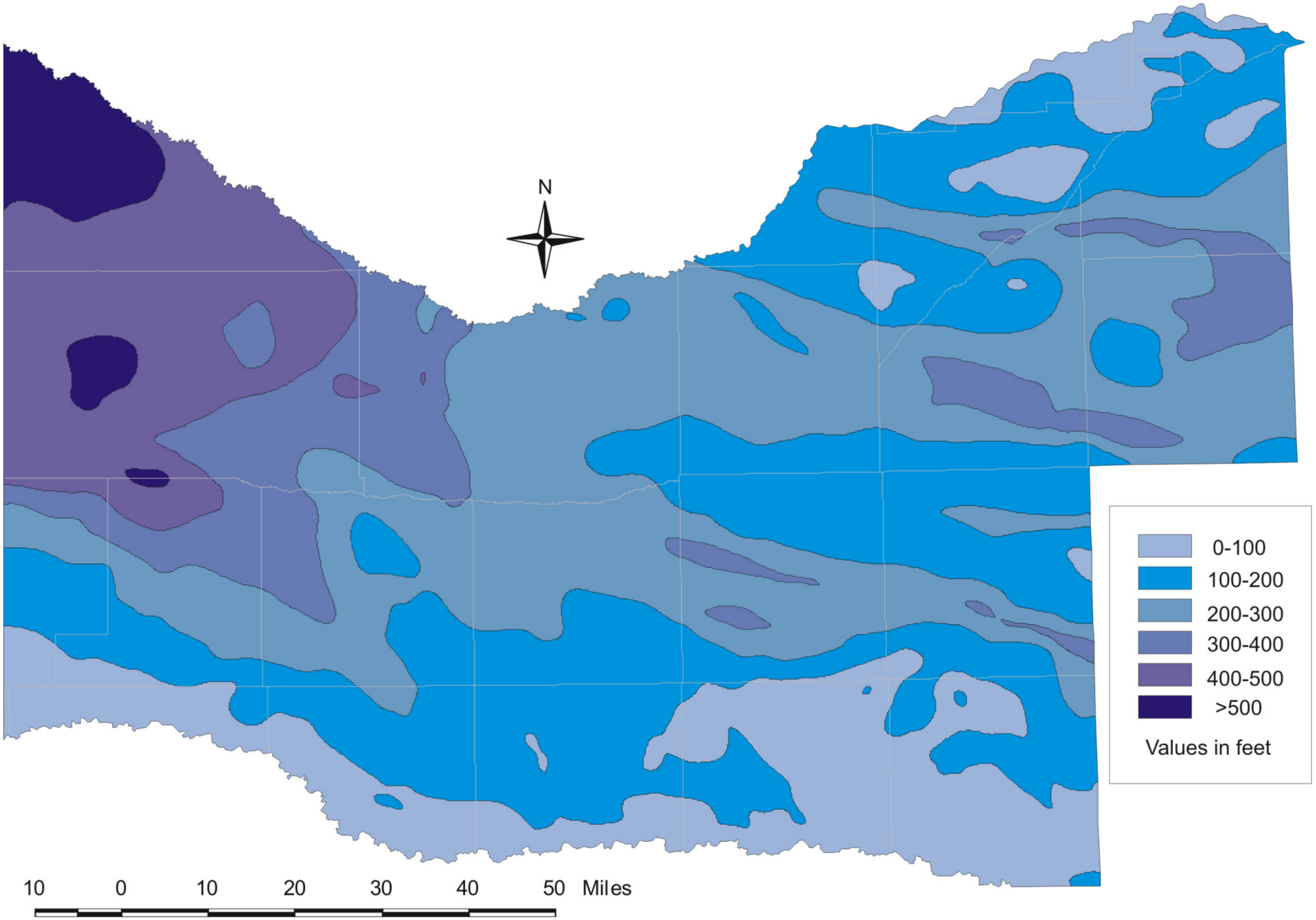


Figure 14. Simulated 1950 saturated thickness of combined Hydrostratigraphic Units in the Eastern Model Unit.

During model construction, streams were classified as large or small and were assigned an initial conductance based on the size classification. The conductance for each stream classification was separately calibrated (fig. 15) to obtain the best match between simulated and observed stream baseflow (Peterson and Carney, 2002). Conductance for all small streams was initially adjusted from 10 ft/d/ft down to 0.4 ft/d/ft to make the simulated baseflow to these streams better match observed baseflow. Conductance was then further calibrated by using streambed cores collected during the summer and fall of 2000 (Cooperative Hydrology Study, 2001b) as a guide for the adjustment of streambed conductance using conductance multipliers. Conductance multipliers were generated for each coring location based on grain size and stratigraphy of shallow streambed sediments. Streambed cores at 7 of the 25 coring sites in the Eastern Model Unit showed the shallow streambed sediments to be fine-grained. These streams were assigned a conductance multiplier of 0.5. Streambed cores at 13 of the 25 sites showed coarse-grained sediments; these streams were assigned conductance multipliers of 2 or 3. The remaining 5 sites had neither very fine-grained nor very coarse-grained sediments and thus were assigned a multiplier of 1. The conductance of 0.4 ft/d/ft for small streams was then multiplied by the conductance multiplier to produce a revised estimate of conductance for that stream or section of that stream. For instance, Spring Creek (Phelps and Harlan Counties, fig. 15) was assigned a conductance multiplier of 1 based on the streambed core logs. Therefore the final conductance value for the Spring Creek stream boundary was 0.4 ft/d/ft length ((base conductance of 0.4 ft/d/ft length)*1 = 0.4 ft/d/ft length). Some streams were added after the initial calibration of conductance values. Streams added subsequent to the initial stream calibration were assigned a value equal to the base value or were assigned a modified value based on the character of similar streams nearby. For example, Elk Creek, Turkey Creek in Furnas County, Lincoln Creek, and Beaver Creek were all added during later stages of model calibration and development. Elk Creek and Turkey Creek in Furnas County were assigned a conductance value of 0.4 ft/d/ft length, whereas Lincoln Creek and Beaver Creek were assigned a conductance value of 1.0 ft/d/ft length. Calibrated streambed conductances are shown in figure 15.

In many cases there were multiple streambed cores described for a stream at different locations. For instance, Muddy Creek (fig. 15) was assigned a conductance multiplier of 0.25 on the upstream half of the perennial reach, and assigned a conductance multiplier of 0.5 on the downstream half of the perennial reach, based on streambed cores from those areas of the stream. When the original base conductance for the class (small streams in this example) was multiplied by the conductance multiplier based on streambed cores, the resulting streambed conductances were 0.1 ft/d/ft (base conductance of 0.4 ft/d/ft*0.25 = 0.1 ft/d/ft) and 0.2 ft/d/ft (base conductance of 0.4 ft/d/ft*0.5 = 0.2 ft/d/ft) for the upstream and downstream sections, respectively. Using multiple cores to assign conductance multipliers to a stream required the assumption that if the conductance multipliers were different at the separate locations, the transition between the two values took place at an equal distance between the two core locations. This could introduce a degree of inaccuracy in some cases, but cannot be better constrained without further data collection.

Rangeland recharge rates used in the calibrated model are shown in figure 16. The distribution of rangeland recharge due to precipitation was based mainly on topography (Cooperative Hydrology Study, 2000). Each topographic region was also combined with a trend based on long-term average rainfall values by Climate Division (National Climatic Data Center, 2000). Precipitation generally increased from west to east, and to a lesser degree, from south to north (National Climatic Data Center, 2000). These trends are also evident in the rangeland recharge used in the calibrated model (fig. 16). The zones labeled “other sandy deposits,” in the eastern part of the area, were modified using a shaded relief image (Cooperative Hydrology Study, 2003b). While areas of “other sandy deposits” are not as sandy as Sand Hills terrains, they are still substantially sandier than the remainder of the area, and can be easily identified from shaded relief imagery due to characteristic “hummocky” landforms. Rangeland recharge was highest in the areas with the sandiest soils. Recharge in the Platte River valley was smaller than that simulated for the sandy soils but larger than that simulated for the South-central plains. Rangeland recharge in the Republican River valley was the same as that simulated for the adjoining dissected plains.

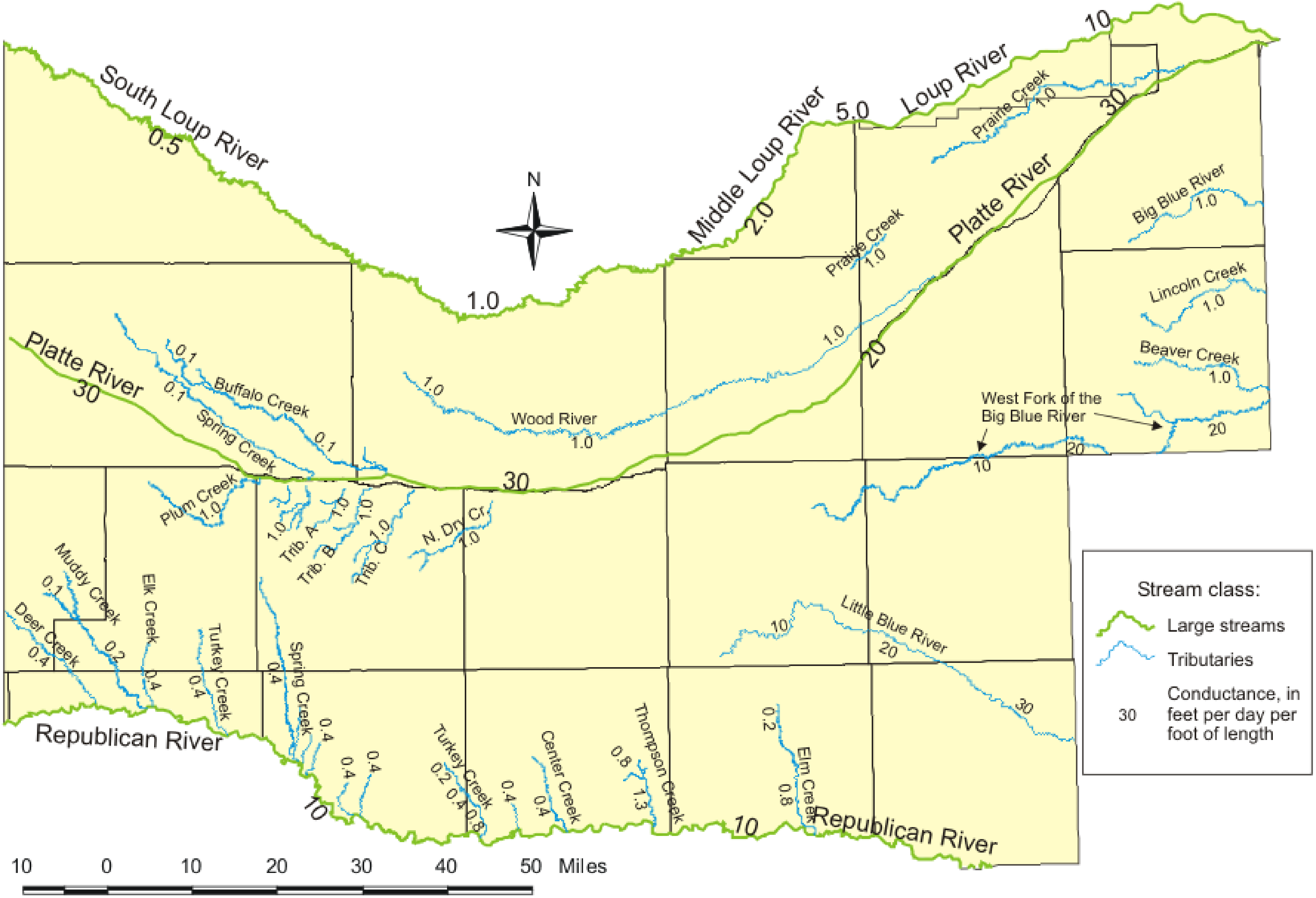


Figure 15. Stream classifications and calibrated streambed conductance values. Conductances are shown in ft/d/ft length.

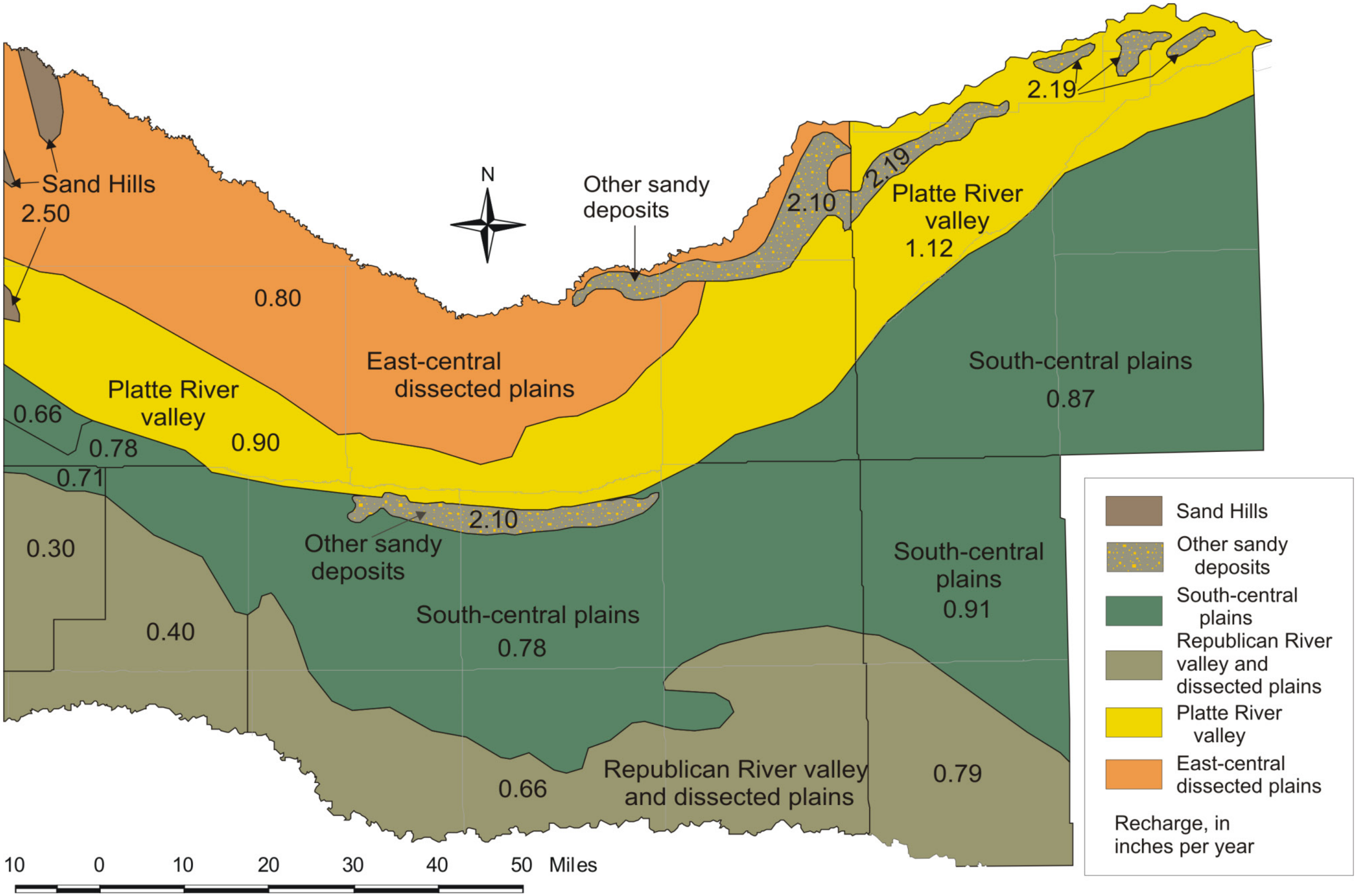


Figure 16. Rangeland recharge distribution used in the calibrated pre-groundwater development model of the Eastern Model Unit. Topographic regions (modified from Cooperative Hydrology Study, 2000 by adding other sandy deposits) are shown with corresponding applied recharge. Counties are shown by gray lines, except those shown by black lines where they correspond to recharge divisions.

Evapotranspiration from groundwater (fig. 7) was simulated in areas identified as riparian vegetation or wetlands (Dappen and Tooze, 2001) and in areas where the water table was close to land surface, based on long-term depth to water data (U.S. Geological Survey National Water Information System, 1999). The maximum groundwater evapotranspiration rate in the Eastern Model Unit was 13.1 in/yr in the western part of the model and decreased linearly to 7.7 in/yr in the easternmost part 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, personal commun., July, 2004), accounting for the fact that vegetation evapotranspiration rates are less than open-water rates. The maximum evapotranspiration rate occurred when the simulated water table was at or above the evapotranspiration surface. The evapotranspiration surface was estimated as the average of 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 within a model cell 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 riparian and wetland areas because of the deeply rooted cottonwood trees, and 3 ft in areas defined as shallow groundwater evapotranspiration areas, because of less deeply rooted grasses and wetland plants.

Figure 17 shows the comparison between simulated and observed 1950 water levels for the calibrated pre-groundwater development model. Positive values indicate simulated water levels are above measured water levels, whereas negative values indicate simulated water levels are below measured water levels. Simulated water levels are within ±25 ft of measured or interpolated water levels for 400 of the 423 total observation points (95 percent). Of those that differ by more than ±25 feet, no regional trends are evident, indicating that there are no trends of bias in the regional flow system conceptualization. The largest differences are -45.5 ft in southwestern Phelps County and 38.1 ft in north-western Nuckolls County.

As shown by figure 17, the observed water levels do not uniformly cover all parts of the simulation area. Therefore, additional pre-groundwater development water-table data (referred to as interpolated observation points) were obtained as an additional check on calibration. Figure 18 shows the comparison between simulated water levels and water-level contours from the Groundwater Atlas of Nebraska (representing water levels measured in 1979), along with interpolated points based on the published contours (Conservation and Survey Division, 1998). The simulated contours match the Conservation and Survey Division (CSD) contours reasonably well in most places, with the exception of the west-central portion of the Eastern Model Unit. In this area, groundwater levels had risen significantly by 1979, due to surface-water irrigation, whereas the simulation only accounts for rises up to 1950. Figure 19 shows a comparison of the simulated water-level contours with the High Plains Regional Aquifer System Analysis (RASA) water-level contours (Cederstrand and Becker, 1999), along with the associated interpolated observation points. The simulated contours are consistent with the RASA contours in most places, except in the northwest and southeast parts of the model area. However, the points at which the simulated water levels are greater than 25 ft different from the RASA water-level contours are different from the points where the simulated water levels are greater than 25 ft different from the CSD contours, indicating that the simulated water levels are probably within the range of error associated with the CSD and RASA contours.

Table 4 shows difference statistics for the simulated versus observed 1950 water levels for the three observation point sets. The mean difference of 2.00 feet for the observed water-level data set indicates that the simulated water levels averaged somewhat above observed water levels at calibration points, though the mean difference for the two interpolated observation point sets is closer to zero. Mean absolute difference was considered to be the most appropriate measure of error for these simulations. The mean absolute difference between observed and simulated values is 8.92 feet, which is small compared to the gradient of the water table (about 1,400 feet change across the model area) combined with potential measurement errors. The mean absolute difference between the simulated water levels and the interpolated observations is larger than it was for the observed water levels. However, the two published water table maps upon which the interpolated values were based are not in total agreement with each other, so the larger mean absolute difference is not of concern.

Table 4. Observed versus simulated water-level differences for the 1950 calibrated model.

Statistic	Simulated water levels compared with observed water levels (feet)	Simulated water levels compared with interpolated water levels from published sources (feet)	
		RASA (Cederstrand and Becker, 1999)	Groundwater Atlas of Nebraska (Conservation and Survey Division, 1998)
Number of points	423	212	223
Mean difference	2.00	0.26	1.22
Mean absolute difference	8.92	16.60	15.20
Root mean squared difference	12.08	21.54	20.76

Table 5 shows the 1950 estimated and simulated groundwater discharge to streams for the calibrated model. Table 6 shows simulated groundwater discharge to streams for which estimated discharge could not be computed because of a lack of data. Simulated discharge is within the estimated range for most streams. Discharge was either too large or too small for some streams, such as the Platte River from Brady to Cozad, the Loup River system from St. Michael to St. Paul, and the Little Blue River. The difference for the Platte River from Brady to Cozad is not of concern, because 9 mi of that reach are actually outside the model area. Similarly, the Loup River system from St. Michael to St. Paul probably receives groundwater discharge from outside the model area. The source of the difference for the Little Blue River is not clear, but it may be related to the absence of Liberty Creek (Clay and Nuckolls Counties) and Elk Creek (Nuckolls County) in the simulation. These streams were not recognized to be important until late in the calibration process, but discussions with some persons familiar with the area (S. Summerside, Conservation and Survey Division, University of Nebraska-Lincoln, personal commun., 2004; K. Orvis, Little Blue Natural Resources District, personal commun., 2004) suggest that these streams together may receive an amount of groundwater discharge that is similar to the amount by which the simulated discharge to the Little Blue River is too high. The remaining six streams for which simulated discharge is outside the estimated range are within 5.3 ft^3/s of the estimated range; for five of those six streams 5.3 ft^3/s is 28 to 147 percent of the total stream discharge (Muddy Creek, Turkey Creek at Edison, Center Creek, Thompson Creek, and Elm Creek). Furthermore, simulated discharge to Center Creek was low by 3.1 ft^3/s, but simulated discharge to the neighboring Turkey Creek in Franklin County was 4.2 ft^3/s, and personal observations (by S.M. Peterson and C.P. Carney, March 2001) suggest simulated discharge to Turkey Creek in Franklin County is probably high. It appears that some of the groundwater discharge that should be simulated as going to Center Creek is being simulated as discharge to Turkey Creek, perhaps due to local-scale geologic features not represented in the regional simulation.

Table 7 shows the overall water budget for the calibrated model. Recharge comprises the single largest inflow (99 percent of total inflow), whereas discharge to evapotranspiration comprises the single largest outflow (34 percent of total outflow). The only other substantial inflow is from fixed-flow boundaries (1 percent of total inflow). Other large outflows include river boundaries (21 percent of total outflow), stream boundaries (18 percent of total outflow), and water entering storage (25 percent of total outflow).

The calibrated pre-groundwater development period model is considered a reasonable representation of the system, given the data available and the size of the grid. Final results from this model were used as starting conditions for the groundwater development period model.

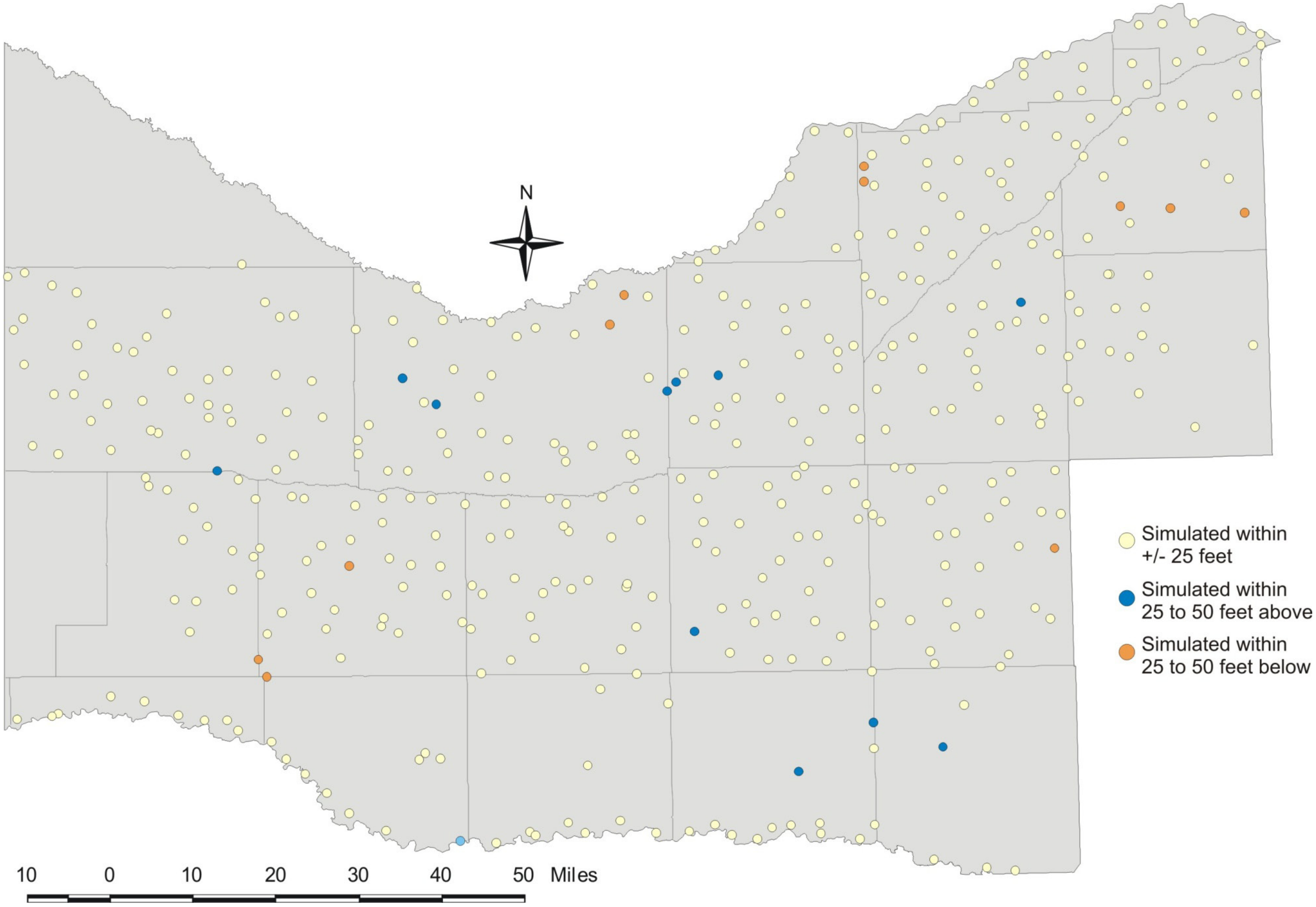


Figure 17. Comparison between simulated water levels for the calibrated model and measured pre-groundwater development water levels (Cooperative Hydrology Study, unpublished).

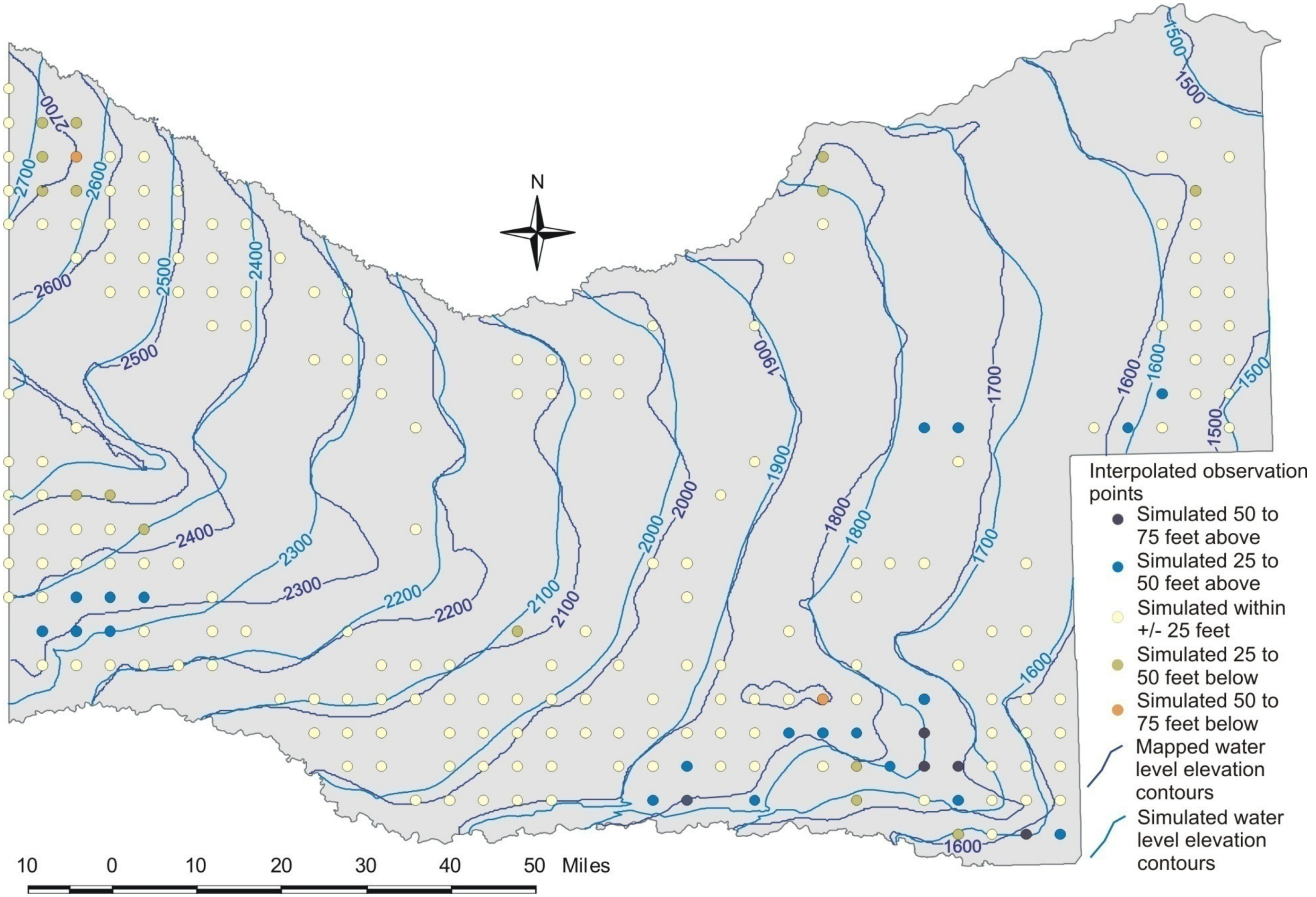


Figure 18. Comparison between simulated 1950 water levels for the calibrated model and pre-groundwater development water levels from the Groundwater Atlas of Nebraska (Conservation and Survey Division, 1998). Contours published in the Groundwater Atlas were used to generate interpolated observation points, to allow for comparison with simulated water levels in locations were no measured data exist. Contour elevations are in feet above mean sea level.

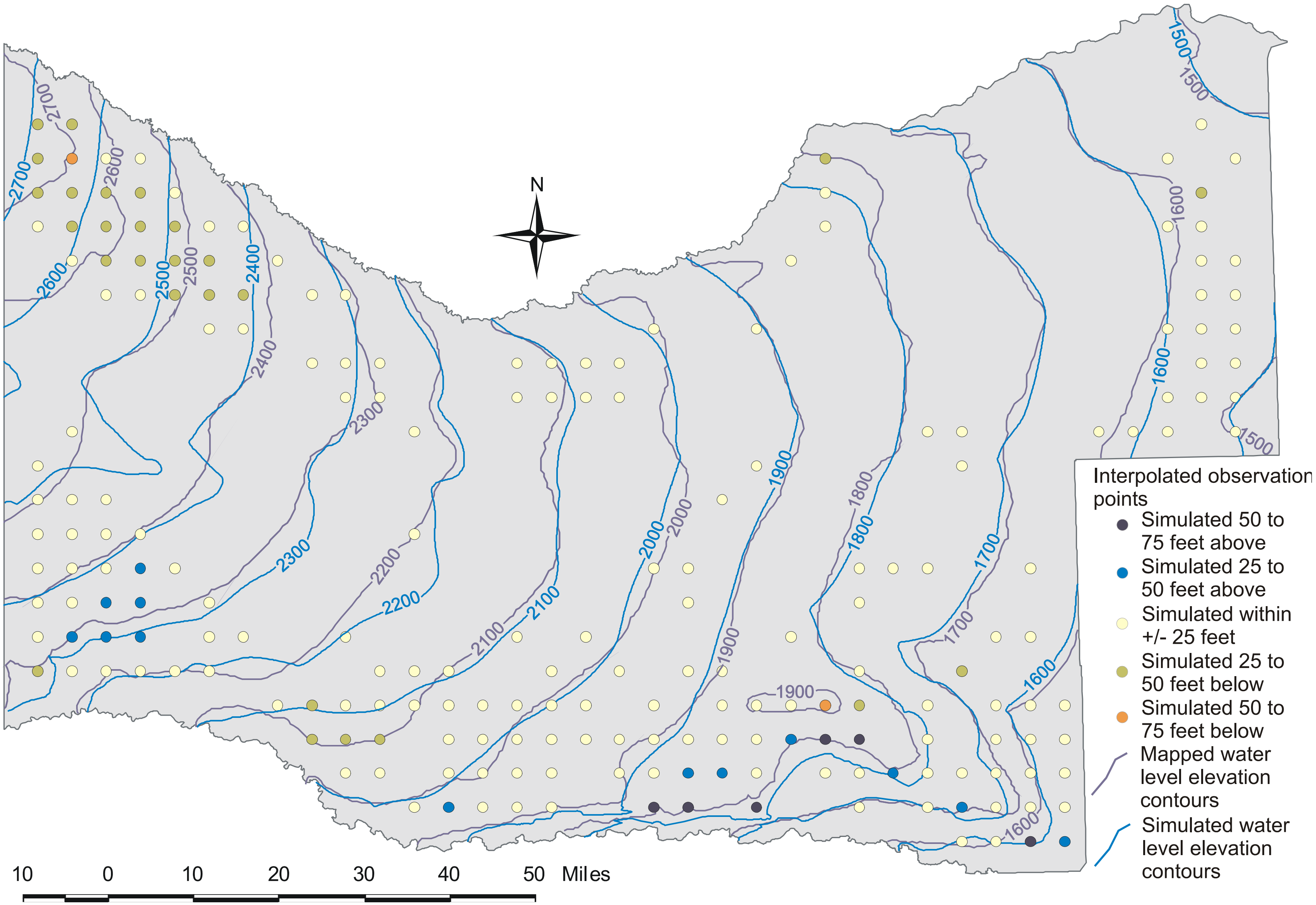


Figure 19. Comparison between simulated 1950 water-level elevations for the calibrated model and pre-groundwater development water-level contours from the High Plains Regional Aquifer System Analysis (RASA) (Cederstrand and Becker, 1999). Published High Plains RASA contours were used to generate interpolated observation points to allow for comparison with simulated water levels in locations where no measured data existed. Contour elevations are in feet above mean sea level.

Table 5. Estimated and simulated pre-groundwater development discharge to streams. Gain is positive number and loss is negative number.

Surface-water feature	Estimated range (ft^3/s)			Simulated gain or loss (ft^3/s)	Remarks
	Low	Mean	High		
Platte River, Brady to Cozad	65	100	180	51	-14 (Below range). There are 9 miles of this stream outside of model area
Platte River, Cozad to Overton	-100	20	200	33	Within range
Platte River, Overton to Odessa	-80	-20	50	-8	Within range
Platte River, Odessa to Grand Island	-750	-150	300	-51	Within range
Platte River, Grand Island to Duncan	-80	20	260	-18	Within range
Republican River, Cambridge to Orleans	-20	0	40	17	Within range. Stream probably receives water from outside of model area
Republican River, Orleans to Hardy	-50	0	240	45	Within range. Stream probably receives water from outside of model area
Loup River, upper end to St. Michael	130	160	180	140	Within range. Stream probably receives water from outside of model area
Loup River, St. Michael to St. Paul	40	810	1100	13	-27 (Below range). Stream probably receives water from outside of model area
Loup River, St. Paul to Genoa	-180	-50	70	18	Within range. Stream probably receives water from outside of model area
West Fork of the Big Blue River	38	49	60	64	4 (Above range)
Big Blue River (Polk County)	0.0	0.2	0.3	0.0	Within range
Little Blue River	51	56	60	79	19 (Above range)
Muddy Creek	3.6	4.5	5.4	6.1	-0.5 (Below range)
Turkey Creek (at Edison, Furnas County)	2.4	3.6	4.8	1.9	-0.5 (Below range)
Center Creek	4	5.1	5.7	0.9	-3.1 (Below range)
Thompson Creek	17	19	20	15	-1.8 (Below range)
Elm Creek (at Amboy, Webster County)	11	12	12	5.7	-5.3 (Below range)
Buffalo Creek (Dawson County)	0.0	0.9	1.8	0.8	Within range

Table 6. Pre-groundwater development simulated groundwater discharge to streams for which quantitative discharge estimates could not be computed. Comparisons are based on field observations by S.M. Peterson in most cases, and published information (U.S. Geological Survey 1:100,000 topographic maps) in a few cases.

Surface-water feature	Simulated gain (positive) or loss (negative) (ft^3/s)	Author's evaluation of simulated flow
Wood River	11	Reasonable value
Deer Creek	4.7	Reasonable value
Spring Creek (Harlan County)	0.5	Reasonable value
Turkey Creek (near Naponee, Franklin County)	4.2	Probably high
Other small Republican River tributaries	1.8	Reasonable value
Spring Creek (near Overton, Dawson County)	0.2	Reasonable value
Small drains near Platte River above Lexington	23	Reasonable value
Small drains near Platte River from Lexington to Grand Island	1.5	Reasonable value
Plum Creek	0.8	Reasonable value
N. Dry Creek, Tributaries A, B, and C, and a nearby unnamed tributary	0.0	Reasonable value
Prairie Creek	2.4	Reasonable value
Lincoln Creek (York County)	0.0	Reasonable value
Beaver Creek (York County)	1.3	Reasonable value

Groundwater Development Period Calibration

The groundwater development period model simulated the period May 1, 1950, through April 30, 1998. The simulated water levels for April 30, 1950 were the starting water levels for this model. All of the inputs to the pre-groundwater development period model were retained and other time- and spatially-varying inputs were added for the 1950-98 period. 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. Time-varying recharge on cultivated land also was added to the model and the values were determined during calibration.

Table 7. Simulated 1950 water budget for the calibrated pre-groundwater development period model. Individual items may not sum to total because of rounding. River boundaries include the Platte River, Republican River, South Loup River, Middle Loup River, and Loup River. Stream boundaries include all other natural streams. Drain boundaries include constructed artificial drains and modified stream channels. Where items may be both inflow and outflow (such as river boundaries), a net value was computed and placed on the side of the budget with the larger value.

Inflow	Rate, in cubic feet per second	Volume, in thousands of acre-feet per year	Percent of budget
Fixed-flow boundaries	13	10	1
Recharge (pre-settlement)	660	480	55
Recharge (canal seepage)	510	370	43
Recharge (surface-water irrigation over- and under-application)	6	4	1
TOTAL IN	1,200	860	100
Outflow	**Rate, in cubic feet per second**	**Volume, in thousands of acre-feet per year**	**Percent of budget**
Increase in storage	300	220	25
River boundaries	250	180	21
Stream boundaries	210	150	18
Drain boundaries	25	18	2
Evapotranspiration	410	290	34
TOTAL OUT	1,200	860	100

Specific yield is the ratio of the volume of water that drains from a saturated aquifer due to gravity drainage to the water-level decline in the aquifer (Fetter, 1994). Specific yield is a dimensionless number. Numerous specific yield distributions were tested in calibrating this model. The best fit between simulated and observed water-level changes occurred when a uniform specific yield was assigned to model layer 1 and spatially-varying specific yield was assigned individually to model layers 2 through 5. Specific yield for model layers 2-5 was based on the various Hydrostratigraphic Units (HU) which comprise those model layers, using spatially-distributed values estimated at testhole locations (Cannia and others, 2006). Model layer 1, corresponding to HU1, was assigned a uniform value of specific yield of 0.16. Hydrostratigraphic Unit 1 is typically comprised of silt or loess deposits that are not saturated everywhere throughout the model area. Where HU1 is thick, only the lower portion is saturated, and it is often coarser-grained. Therefore, the specific yield assigned to HU1 is between that which is usually used for silts (around 0.03-0.19) and that which is usually estimated for sands and gravels (0.15-0.35) (Fetter, 1994). Model layer 2, which is comprised mainly of Quaternary-age alluvial sands and gravels, had the largest mean specific yield among model layers at 0.22. The mean for the distributed values for model layer 4 was lower, at 0.18; model layer 4 corresponds with HU5, which is sand and gravel of the Ogallala Group. These sands and gravels are finer grained than those of HU2. Specific yields for model layers 3 and 5, which are comprised of silt and clay, were lower, with means of 0.08 and 0.09, respectively. Specific yield values for model layers 2-5 were not modified during the calibration process, and were used for all simulation periods. Specific yield for model layer 1 was determined during the 1950-98 calibration. Table 8 shows a summary of the specific yield values used in the calibrated simulation.

Table 8. Specific yield for the calibrated model for portions of model layers where the corresponding Hydrostratigraphic Unit (HU) was present. Where a HU represented by a model layer was absent, that model layer was assigned specific yield representative of HU's present above and below that model layer (not represented in this table).

Model Layer	HU	Specific yield, dimensionless		
		Mean	Minimum	Maximum
1	1	0.16	0.16	0.16
2	2	0.22	0.02	0.30
3	3-4	0.09	0.01	0.20
4	5	0.18	0.09	0.27
5	6	0.08	0.01	0.21

The specific storage term represents the amount of water an aquifer can receive or release per unit volume of aquifer for a change in water level. This volume is related to the expansion/compressibility of water and the compressibility of the aquifer material. Specific storage only applies to those cells which are entirely below the water table. Fetter (1994) suggests specific storage values less than 0.0001 for sediments comprising the High Plains aquifer. A specific storage value of 0.00001 was applied to the Eastern Model Unit model. As shown in the Model Sensitivity section, model results were insensitive to values of specific storage below 0.0001.

Additional recharge from precipitation, above the amount in the pre-groundwater development period model, was added during the groundwater development period to achieve calibration. This recharge was applied only to cropped land, including dryland (fallow and active) and irrigated land. More recharge was added to irrigated land than to dryland. The recharge on dryland varied over time because the amount of dryland varied over time. The justification for adding extra recharge to dryland is that dryland, when fallow, is cultivated to capture and maintain soil moisture. Because of this, the soil moisture profile on dryland regularly exceeds that on rangeland. Therefore, when precipitation falls on dryland, it has a better chance to become recharge than when precipitation falls on uncultivated rangeland.

The soil moisture profile on irrigated crop land is maintained by irrigation and precipitation, thus precipitation on irrigated land has a better chance of becoming recharge than precipitation on either dryland or rangeland. Note that 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 in the net pumpage estimate from the CropSim analysis. The amount of additional recharge on cropped land was not varied according to soil type, because the distribution of rangeland recharge for the pre-groundwater development model was based partially upon topographic regions, which are similar to the distribution of soils. This recharge was increased from west to east to account for west to east increases in precipitation. The additional recharge on irrigated land and dryland west of the western boundary of Hall, Adams, and Webster Counties was 16 percent less than that applied east of that line.

Recharge on irrigated land was also varied through time, in addition to the variation caused by the changes in the amount of irrigated crop land. Recharge applied to the eastern portion of the model for the 1950-73 period was 2.5 in/yr less than that applied from 1973-98, and recharge applied to irrigated land in the western portion of the model for the 1950-73 period was 2.1 in/yr less than that applied during the 1973-98 period. This change in the additional recharge rate accounted for changes in agricultural land management practices that in more recent times have generally enhanced the capability of cropped land to capture and retain soil moisture. In the 1950s, row crops were spaced widely apart, allowing considerable evaporative loss of soil moisture directly from the soil. However, from 1950 to 1998, agricultural practices gradually changed; crops in 1998 were planted at higher densities, rows were planted closer together, crop canopies closed earlier in the growing season, and surface residue increased. These changes have substantially reduced the amount of moisture that could evaporate directly from the soil and increased moisture holding capability (M. Trompke, Central Nebraska Public Power and Irrigation District, personal commun., 2004). Center-pivot sprinkler irrigation increased significantly in the 1970s through the 1990s, which in some cases was accompanied by a moderate reduction in tillage (D. Ford, Central Nebraska Public Power and Irrigation District, personal commun., 2004). Tillage and other agricultural practices may have caused compaction of underlying soil layers; compaction tends to reduce recharge. However, a compaction-reducing practice called "deep chiseling" came into widespread use in the 1970s (D. Ford, Central Nebraska Public Power and Irrigation District, personal commun., 2004). Optimally, deep chiseling produces widespread fracturing of compacted soil layers down to a depth of a few feet. Farmers in Gosper and Phelps Counties tend to deep-chisel fields every few years (V. Fastenau, Central Nebraska Public Power and Irrigation District, personal commun., 2004). Row spacing is probably only a minor component in these modifications, and changes in row spacing have been sporadic and local, and not as widespread as other factors mentioned above. In addition to these changes, additional recharge was added to an area of dense agricultural development between Kearney (Buffalo County) and Grand Island (Hall County). In this area, farmers generally construct small dikes around the edges of fields to enhance recharge (D. Woodward, Central Platte Natural Resources District, personal commun., 2004), so an additional 1 in/yr of recharge was added to the model in this area.

A considerable number of simulations were made in which the additional recharge was some function of precipitation, both spatially and temporally, but these simulations were not as good as the calibrated model, which has a simple distribution of the recharge based on land use. Table 9 summarizes the recharge added to the 1950 simulated recharge to calibrate the 1950-98 period.

Calibration statistics for the simulated versus observed water-level change in the calibrated 1950-98 groundwater development period model are shown in table 10. Weighted measure was used to serve as an overall measure of calibration to all water-level change observations for all time periods, and was the primary indicator of model calibration during the final model calibration process. Weighted measure was calculated by multiplying the mean difference, mean absolute difference, and root-mean-square difference for each time period times the number of points used to calculate the statistic for that time period, summing the results from all the periods, then dividing by the total number of observations in all periods. Therefore, the time periods with more observations have more of an effect on the weighted measure, and time periods with fewer observations have less of an effect on the weighted measure.

Simulated water-level changes and graphical comparison to measured water-level changes are shown in figures 20, 21, and 22. For the 1950-98 period, simulated water-level changes were less than 5 ft for much of the area. Areas in Dawson, southern Buffalo, Gosper, Phelps, and Kearney Counties were affected by recharge due to canal and lateral leakage, and both simulated and observed water levels rose in those areas. North of the Platte River, in Custer, eastern Dawson, Buffalo, Hall, and Merrick Counties, simulated water levels declined, whereas observed water levels increased slightly or did not change. This is probably related to irrigation well pumpage that took place prior to 1950, which occurred mainly in the bottomlands of the Platte River valley. Irrigation well pumpage prior to 1950 was not simulated in this model.

Table 9. Recharge added on cropped land to calibrate the 1950-98 period. Eastern portion is east of western boundary of Hall, Adams, and Webster Counties.

Time period	Land use	Additional recharge (in/yr)	
		Eastern portion	Western portion
1950-98	Dryland	1.0	0.8
1950-73	Irrigated land	4.4	3.7
1973-98	Irrigated land	6.9	5.8

Table 10. Calibration statistics for the calibrated groundwater development period model.

Time period	Number of points	Mean difference	Mean absolute difference	Root-mean-square difference
1950-98	78	-0.55	5.76	8.67
1950-61	132	-2.64	3.70	4.75
1961-73	219	-0.27	2.96	3.78
1973-85	281	2.12	4.19	5.80
1985-98	406	0.57	3.19	4.77
Weighted Measure	1,116	0.34	3.64	5.11

Some simulated 1950-98 water-level rises occur in Nuckolls County, in the southeastern part of the Eastern Model Unit. These rises may be due to the fixed-flow boundary effects; the model boundary in that area was specified to have a constant flow throughout all the simulations. Constant flow is inaccurate for this area because the groundwater system was affected by water diverted into Superior Canal, which started operations in 1952 (table 2). Furthermore, the aquifer is only a few tens of feet thick in this area, so a water level rise of a few tens of feet could have doubled the water-table gradient in this area, which would increase flows across this boundary from 1952 to 1998. This issue was not discovered until after the calibration process was complete, but it is limited to a small area. Inaccurate flow in this area does not affect any simulation result near the Platte River, the main feature for which these simulations were constructed.

Figure 20 shows the simulated groundwater level changes for the Eastern Model Unit from 1950 to 1998. Figures 21 and 22 show the incremental changes for this period. Figure 21 shows the changes from 1950 to 1961 and 1961 to 1973. Figure 22 shows the changes from 1973 to 1985 and 1985 to 1998. Simulated water-level changes generally agree with observed changes in these figures. Two areas appear important to all four periods; one in Gosper, Phelps, and Kearney Counties, and one in York, Polk, and Hamilton Counties. The area in Gosper, Phelps, and Kearney Counties is affected by recharge due to canal and lateral leakage; simulated water-level increases are too large towards the western side of this area in all four periods, though little observed water-level change information was available to use in calibration for this area except for the 1985-98 period. Simulated water-level changes in the eastern half of this area are generally the same as observed water-level changes in all four periods.

There were many observed water-level changes available for York, Polk, and Hamilton Counties during calibration. Simulated water-level changes match more closely with the observed water-level changes in this area in the 1961-73 and 1985-98 periods, and match less closely in the 1950-61 and 1973-85 periods. In the 1950-61 period, observed water-level changes in this area tended to show declines of several feet, whereas the simulated water-level changes tended to show either very small declines or increases (fig 21-A). Simulated water-level declines for the 1961-73 period match reasonably well with observed declines (fig 21-B). Observed water-level changes in this area for the 1973-85 period tended to show increases up to several feet, whereas the simulated changes for that period tended to show declines of a few feet (fig. 22-A). Observed water-level changes in this area for the 1985-98 period were increases of up to 10 ft, and were matched reasonably well by simulated water-level increases (fig. 22-B).

Simulated streamflow for the groundwater development period model was larger for some streams than simulated streamflow for the pre-groundwater development model, resulting in a slightly improved comparison with estimated groundwater discharge to streams. For instance, in the pre-groundwater development period model, simulated discharge for Turkey Creek (near Edison), Center Creek, and Elm Creek were too low; by 1998 in the groundwater development period simulation, simulated discharge to Turkey Creek (near Edison) was within the estimated range, and simulated discharge to Center Creek and Elm Creek were slightly closer to the estimated range. Stream discharge data does not exist for Wood River for the pre-groundwater development period, and recent data suggests that Wood River flows are minimal where it joins the Platte River. Therefore, simulated discharge to Wood River improved as it decreased from 11 ft^3/s to 6.1 ft^3/s from 1950 to 1998, possibly as a result of groundwater pumping, though it may still be too large. Simulated discharge to Plum Creek and other streams that drain the Central Nebraska Public Power and Irrigation District area increased from 1950 to 1998, as water levels in that area increased due to recharge from canal and lateral leakage. Simulated discharge to the Little Blue River and the West Fork of the Big Blue River were too large in 1950, and the 1998 simulated discharges was even larger on the West Fork of the Big Blue River. Simulated discharge to the Little Blue River in 1998 was the same as it was for 1950.

The simulated water budget for the groundwater development period is shown in table 11. Simulated inflows are dominated by recharge, which amounts to 96 percent of the inflow budget. The largest component of simulated outflows was net pumpage (49 percent), followed by evapotranspiration (17 percent), river boundaries (16 percent), and outflows to storage (increases in storage) (8 percent). Simulated inflows are the same as simulated outflows, indicating that the model is in balance. However, storage is increasing over the 48-year period, indicating that inflows other than storage are greater than outflows other than storage. When compared with the simulated budget from the pre-groundwater development model, inflow components were very similar, though inflows from storage and from cropped land recharge were not important components of the pre-groundwater development budget. With regard to outflows, budgets were also similar between the pre-groundwater development model and the groundwater development model, except for outflows to net pumpage. However, in the latter period, outflows to rivers, streams, and evapotranspiration decreased as a percentage of the total budget.

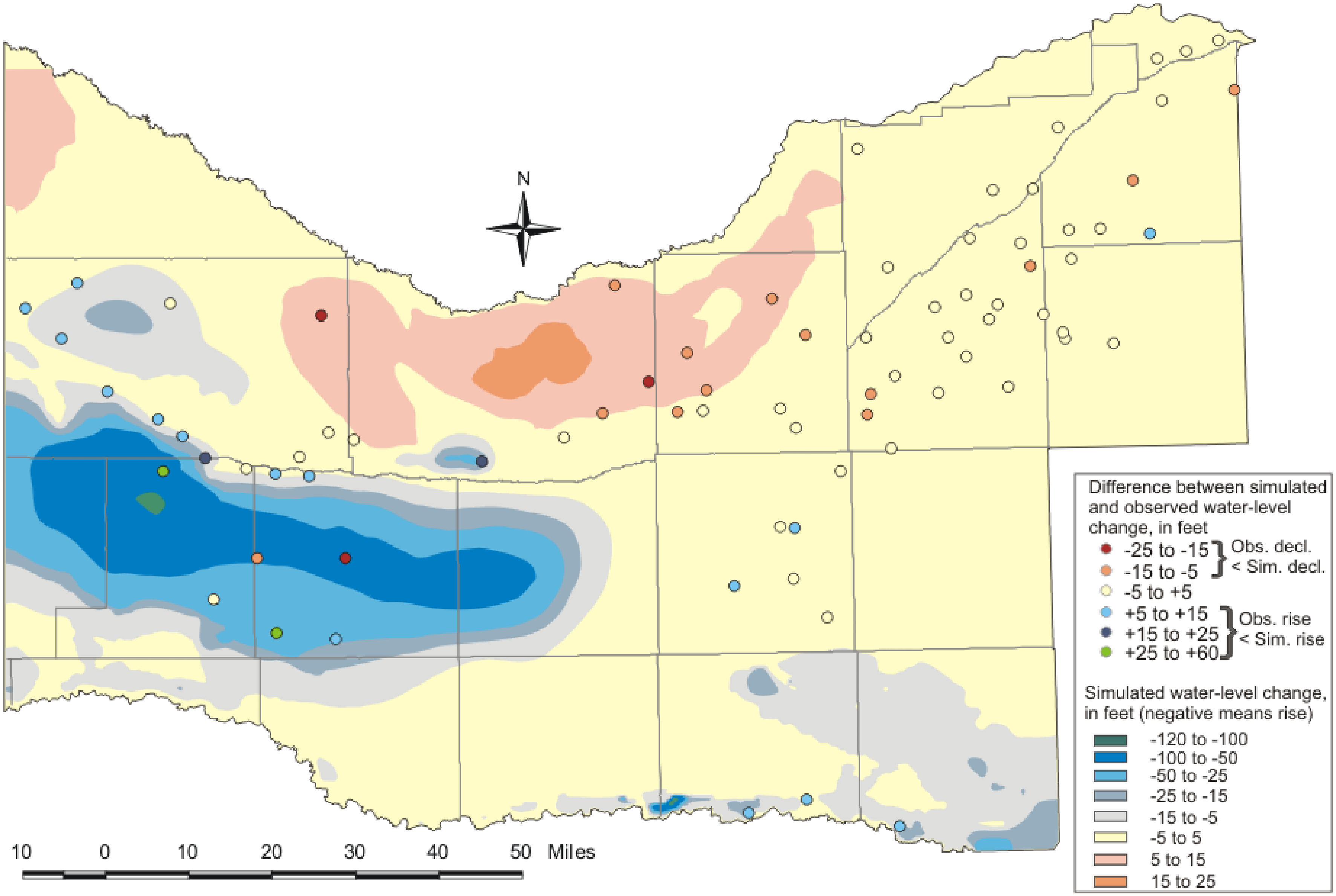


Figure 20. Simulated 1950-98 water-level change for the calibrated groundwater development period model and comparison between simulated and observed water-level change at observation points in the Eastern Model Unit.

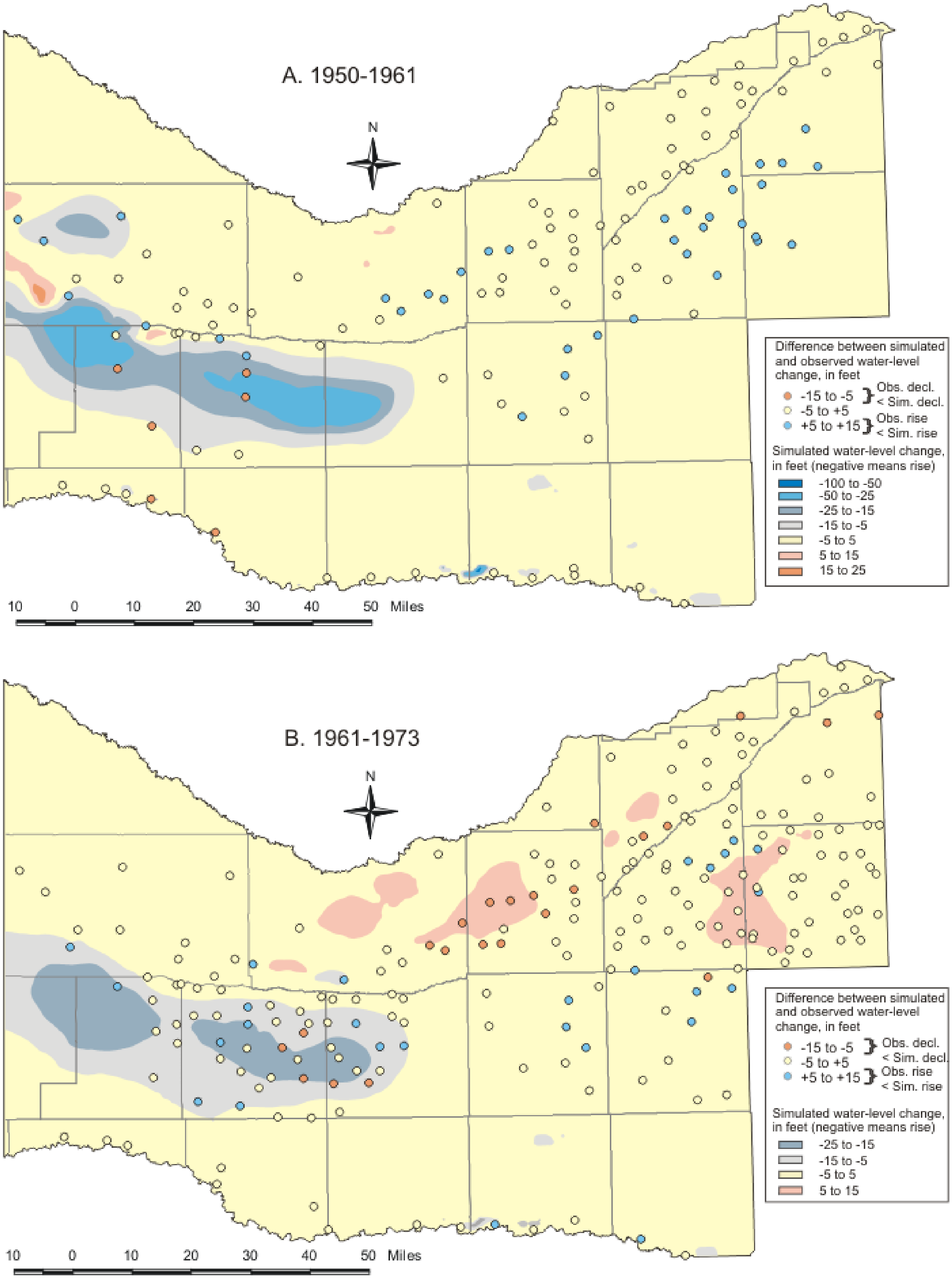


Figure 21. Simulated water-level change for the 1950-61 period (A) and 1961-73 period (B) and comparison between simulated and observed water-level change at observation points for the Eastern Model Unit.

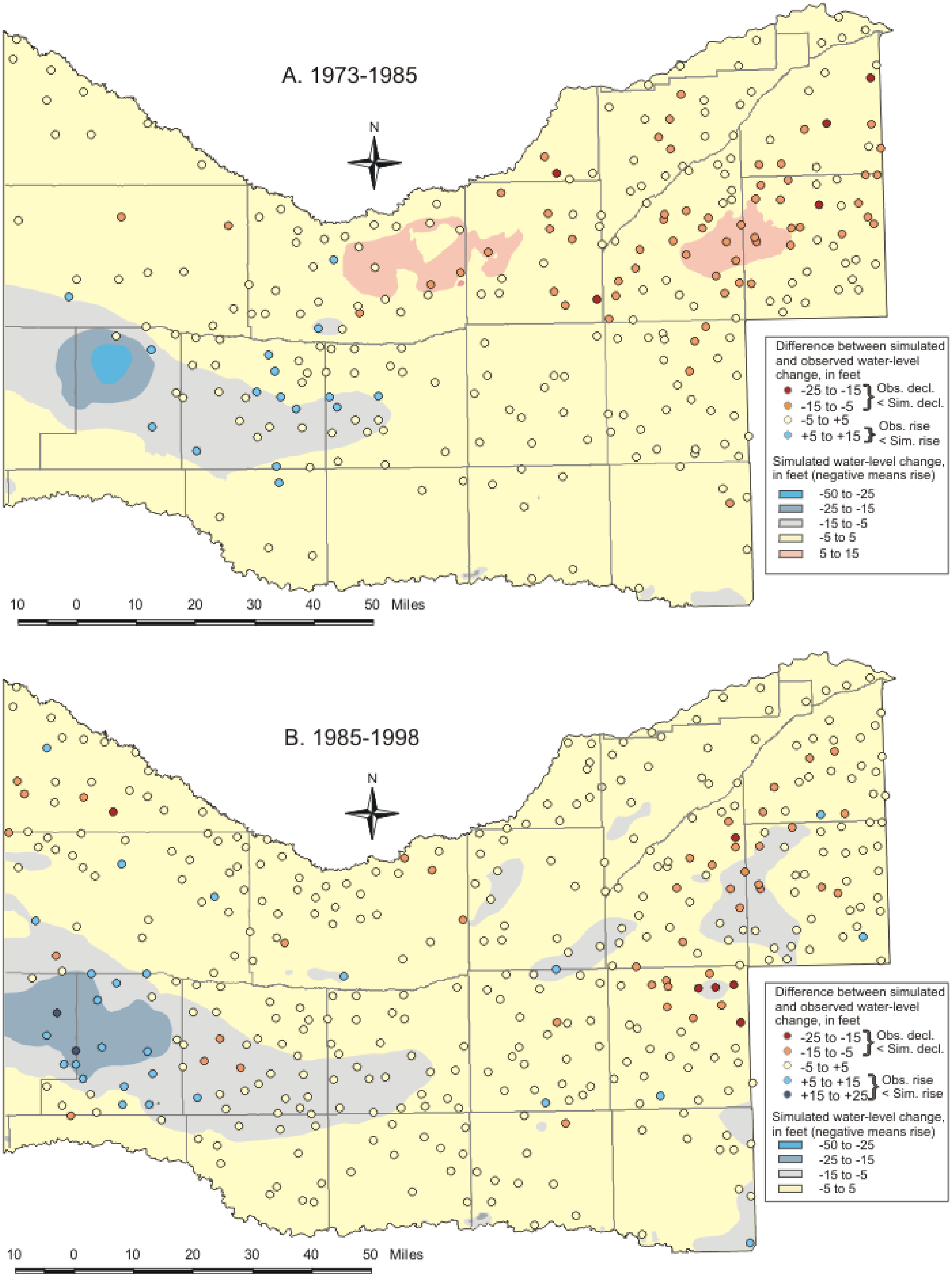


Figure 22. Simulated water-level change for the 1973-85 period (A) and 1985-98 period (B) and comparison between simulated and observed water-level change at observation points for the Eastern Model Unit.

Table 11. Simulated average water budget for the calibrated groundwater development period model of the Eastern Model Unit using CropSim net pumpage. Values are averages for the 48-year period. Individual items may not sum to total because of rounding. Where items may be both inflow and outflow (such as river boundaries), a net value was computed and placed on the side of the budget with the larger value.

Inflow	Rate, in cubic feet per second	Volume, in thousands of acre-feet per year	Percent of budget
Fixed water-level boundaries (from Harlan County Reservoir)	98	71	4
Recharge (pre-settlement) applied to non-agricultural lands	290	210	11
Recharge (canal seepage)	580	420	23
Recharge (surface-water irrigation over- and under-application)	76	55	3
Recharge (dryland/irr. land, including recharge from field diking practices)	1,500	1,100	59
TOTAL IN	2,500	1,800	100
Outflow	**Rate, in cubic feet per second**	**Volume, in thousands of acre-feet per year**	**Percent of budget**
Increase in storage	210	150	8
River boundaries	400	290	16
Stream boundaries	220	160	8
Drain boundaries	47	34	2
Evapotranspiration	440	320	17
Net pumpage (including fixed-flow boundaries)	1,200	900	49
TOTAL OUT	2,500	1,800	100

Outflows to storage increased in the development period, which may be related to high recharge rates in areas affected by canal seepage recharge. Cropped land recharge provided increased inflows, but net pumpage in the groundwater development period model created an increase in inflows from storage and a decrease in outflows to rivers, streams, and evapotranspiration. Outflows to net pumpage (900,000 acre-feet per year) are relatively the same magnitude as the inflows from cropped land recharge (1,100,000 acre-feet per year). This is consistent with the small magnitude of observed and simulated water-level changes across much of the area for the 1950-98 period. The overall volume of the water budget of the groundwater development period model is 2.1 times larger than the overall volume of the water budget of the pre-groundwater development period model. The water budgets for these models (tables 7 and 11) show that the groundwater development period model has more recharge, more groundwater pumping, and less flow into storage than the pre-groundwater development model. The amount of recharge applied to non-agricultural lands in the development period was less that the recharge applied to non-agricultural lands in the pre-development period because the acres of rangeland decreased during the development period, as more acres were converted to cropped land.

Recharge due to canal and lateral leakage is an important component of the inflow budget of the groundwater development period model (table 11). In particular, the groundwater mound in Gosper, Phelps, and Kearney Counties is an important sub-regional groundwater resource caused by recharge due to surface-water irrigation. The simulated water-level rises from 1950-98 along the edge of the mapped mound are greater than the observed rises (Stanton, 1999). Only two measured 1950-98 water-level changes exist near the mapped center of the mound; at one of these, the simulated water-level rise was 57 ft, about 15 ft less than observed rise. At the other point, simulated water-level rise was 62 ft, about 12 ft less than observed water-level rise. At a point near Johnson Lake (fig. 3, fig. 20), observed water-level rise was about 36 ft, about 37 ft less than the simulated 1950-98 water-level rise of about 73 ft. As shown by figure 20 for the groundwater development period, measured water-level rises were smaller than simulated water-level rises for nearly all of the observation points around the edge of the mapped mound, whereas simulated rises were smaller than measured water-level rises in the middle of the mapped mound. Extensive testing of hydraulic parameters was conducted during calibration of the groundwater development period model to try to remedy this problem. However, no values within reasonable ranges for hydraulic conductivity or specific yield were found that improved the model in this area.

Canal seepage was estimated using Central Nebraska Public Power and Irrigation District records, and is thought to be reasonably accurate. However, because the simulated groundwater development period water-level rises in the area of the mound did not match observed rises as well as desired, the volume of water contained in the observed mound was estimated and compared with the volume contained in the simulated mound. Estimated volume of the observed mound was calculated by subtracting pre-development water-level data (Cederstrand and Becker, 1999) from a water table map representing 1995 (Conservation and Survey Division, 2003). The results were contoured, and average thicknesses of the water table rises were calculated for the areas between the contours. The average thicknesses for these areas were then multiplied by an average specific yield (0.16) to estimate the volume. The estimated volume of water in the observed groundwater mound was 8,340,000 acre-feet, whereas the volume of the simulated mound was approximately 9,200,000 acre-feet. The difference between simulated volume of the mound and the estimated volume of the mound could be accounted for by relatively small errors in estimated canal seepage recharge, groundwater pumping, groundwater discharge to streams, groundwater that flowed out of the mound area, inaccuracies in the maps used to estimate the volume of the observed mound, or most likely, some combination of these factors. It is possible that some aspect of local hydrology might not be represented in the simulation, because the simulated height of the groundwater mound appeared to be less than the observed height, and the simulated volume of the mound was a little more than the estimated volume of the mound. However, neither the height nor the volume of the mound is well known because of lack of early pre-mound water-level data in the area, so the model may be a reasonable representation of the mound.

The calibrated groundwater development model is considered 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.

Comparison to Adjacent Model

The model west of this model, in the area of 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. A development period model was later produced and documented (Carney, 2008) after this report was prepared. The pre-groundwater development period is compared in this report.

The model representing the Central Model Unit contained 6 layers and simulated identical time frames in both the pre-groundwater development period and the groundwater development period. The Eastern Model Unit and the Central Model Unit overlap in a 30-mi area from the Lincoln-Dawson County line to the Gosper-Phelps County line. Although development and calibration of the two models occurred at different times, the modelers for each area communicated frequently to share data and discuss calibration strategies and obstacles.

Hydraulic conductivity applied to the two models was very similar, even though the models were calibrated independently and calibration procedures for the Central and Eastern models were somewhat different. For the Central Model Unit, hydraulic conductivity distribution polygons within Hydrostratigraphic Units were adjusted individually, whereas for the Eastern Model Unit, all hydraulic conductivity polygons for a Hydrostratigraphic Unit were adjusted in the same way. Both models used variations of the COHYST hydraulic conductivity maps (Cannia and others, 2006) for simulation of HU 2, HU 3-4, and HU 5, though the values used for HU 2 in the Eastern Model Unit were increased somewhat more than they were in the Central Model Unit. The mean hydraulic conductivity for HU 2 in the Eastern Model Unit was 155 ft/d, whereas for the Central Model Unit it was 79 ft/d. However, it is important to note that in the Central Model Unit, HU 2 is absent from virtually the entire southern half of the area, and is limited to the valley-fill along the North Platte, South Platte, and Platte Rivers, and areas north of those valleys, where it underlies the Sand Hills. The mean, minimum, and maximum values for hydraulic conductivity used for HU 3-4 in the Eastern Model Unit was lower than that used in the Central Model Unit. For HU 5, both models used similar values, though the maximum value used in the Eastern Model Unit was less than the maximum value used in the Central Model Unit. Uniform hydraulic conductivities were used in both models for HU 1 and HU 6, though those used in the Eastern Model Unit (10 ft/d for both units) were lower than those used in the Central Model Unit (23 ft/d and 27.5 ft/d respectively).

Similar recharge was applied to the two models. Both models used recharge distributions based on topographic divisions. Central Model Unit recharge rates in the overlap area ranged from 0.35 to 2.20 in/yr, whereas Eastern Model Unit recharge rates in the overlap area ranged from 0.3 to 2.50 in/yr. However, as shown in figure 16, in the Eastern Model Unit only a few small areas were assigned recharge of 2.50 in/yr, whereas in the Central Model Unit several large sand dune areas were assigned values of 2.20 in/yr or greater. For the Eastern Model Unit, the mean recharge value was 1.25 in/yr and the median was 0.78 in/yr, contrasted with a mean of 1.05 in/yr and median of 0.35 in/yr for the Central Model Unit. The larger mean and median are reasonable given the overall wetter climate in the Eastern Model Unit.

Some areas of groundwater evapotranspiration in the two model units lie in the area of overlap. The same parameter values were used for evapotranspiration for both models.

Streambed conductances used in the two models differed only slightly. Stream discharges for streams mutual to both models were found to be consistent between models, with the exception of the South Loup River in Custer County and Spring Creek and Buffalo Creek in Dawson County. For the Eastern Model Unit, simulated South Loup River stream discharges were larger than those simulated for the Central Model Unit. Investigation of this difference suggested that the larger discharge in the Eastern Model Unit was most likely related to the larger values of HU 2 hydraulic conductivity. For Spring Creek and Buffalo Creek in Dawson County, groundwater discharge simulated in the Eastern Model Unit was much lower than that simulated by the Central Model Unit. Simulated discharge to Buffalo Creek was within the estimated range for the Eastern Model Unit, but for the Central Model Unit simulated discharge to Buffalo Creek was higher than the estimated range. Furthermore, the Central Model Unit included one tributary in that area (West Buffalo Creek) that was not simulated in the Eastern Model Unit. Groundwater discharge to two of these three streams could not be estimated due to a lack of basic flow data, however, personal observations (by S.M. Peterson and C.P. Carney, March, 2001) suggested that discharge to Spring Creek and Buffalo Creek would be unlikely to be greater than several cubic feet per second, and simulated discharge was approximately in that range for both models.

The overlap area and simulated water levels from the two models are shown in figure 23. The simulated water levels generally agree between the two models. The overall calibration of the Eastern Model Unit to 1950 water levels, at a mean absolute difference of 8.92 feet, was slightly better than the 9.38 feet for the Central Model Unit, but both represented reasonable calibration.

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 model and the groundwater development period model, 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 hydraulic conductivity, the ratio of horizontal to vertical hydraulic conductivity, maximum evapotranspiration rate, streambed conductance, and rangeland recharge were investigated. For the groundwater development period, changes in specific yield, net pumpage, canal seepage recharge (grouped with surface-water irrigation over-application), dryland recharge, and irrigated land recharge were investigated. Changes in the spatial distribution of model parameters and stresses were not investigated because the spatial distributions were based on generally well-defined, known conditions.

The pre-groundwater development period model sensitivity to 1950-water-level statistics was analyzed (fig. 24). At calibration (input multiplier equals 1.0), the mean difference between simulated and observed water levels was 2.00 ft. The mean difference increased as rangeland recharge increased and reached 6.14 ft when this recharge was increased 30 percent. The mean difference decreased as this recharge decreased and reached –2.38 ft when this recharge was decreased 30 percent. The mean difference was closest to zero when rangeland recharge was decreased 10 percent. At calibration, the mean absolute difference between simulated and observed water levels was 8.92 ft. This difference was 10.32 ft when rangeland recharge was increased 30 percent and was 9.28 ft when this recharge was decreased 30 percent. This difference was at a minimum when rangeland recharge was decreased 5 percent. At calibration, the root-mean-square difference between simulated and observed water levels was 12.08 ft. This difference was 13.71 ft when rangeland recharge was increased 30 percent and was 12.87 ft when this recharge was decreased 30 percent. This difference was at a minimum when rangeland recharge was decreased 5 percent. The sensitivity of the simulation to recharge suggests that a 5 percent reduction in rangeland recharge might have been beneficial to calibration. However, such a change would have degraded some of the simulated groundwater discharge to some streams, so this change was not made.

The pre-groundwater development period model showed a similar sensitivity to hydraulic conductivity (fig. 24), although for the mean difference, the effect was in the opposite direction, which is hydrologically correct. The mean difference decreased as hydraulic conductivity increased and reached 1.23 ft when hydraulic conductivity was increased 30 percent. The mean difference increased as hydraulic conductivity decreased and reached 3.25 ft when hydraulic conductivity was decreased 30 percent. The mean difference was closest to zero when hydraulic conductivity was increased 30 percent. The mean absolute difference was 8.67 ft when hydraulic conductivity was increased 30 percent and was 9.72 ft when hydraulic conductivity was decreased 30 percent. This difference was at a minimum when hydraulic conductivity was increased 30 percent. The root-mean-square difference was 11.91 ft when hydraulic conductivity was increased 30 percent and was 13.47 ft when hydraulic conductivity was decreased 30 percent. This difference was at a minimum when hydraulic conductivity was increased 20 percent. The sensitivity analysis of hydraulic conductivity suggests that an increase in hydraulic conductivity might have been beneficial to calibration. However, this change was not made because it would have degraded the simulated groundwater discharge to some streams.

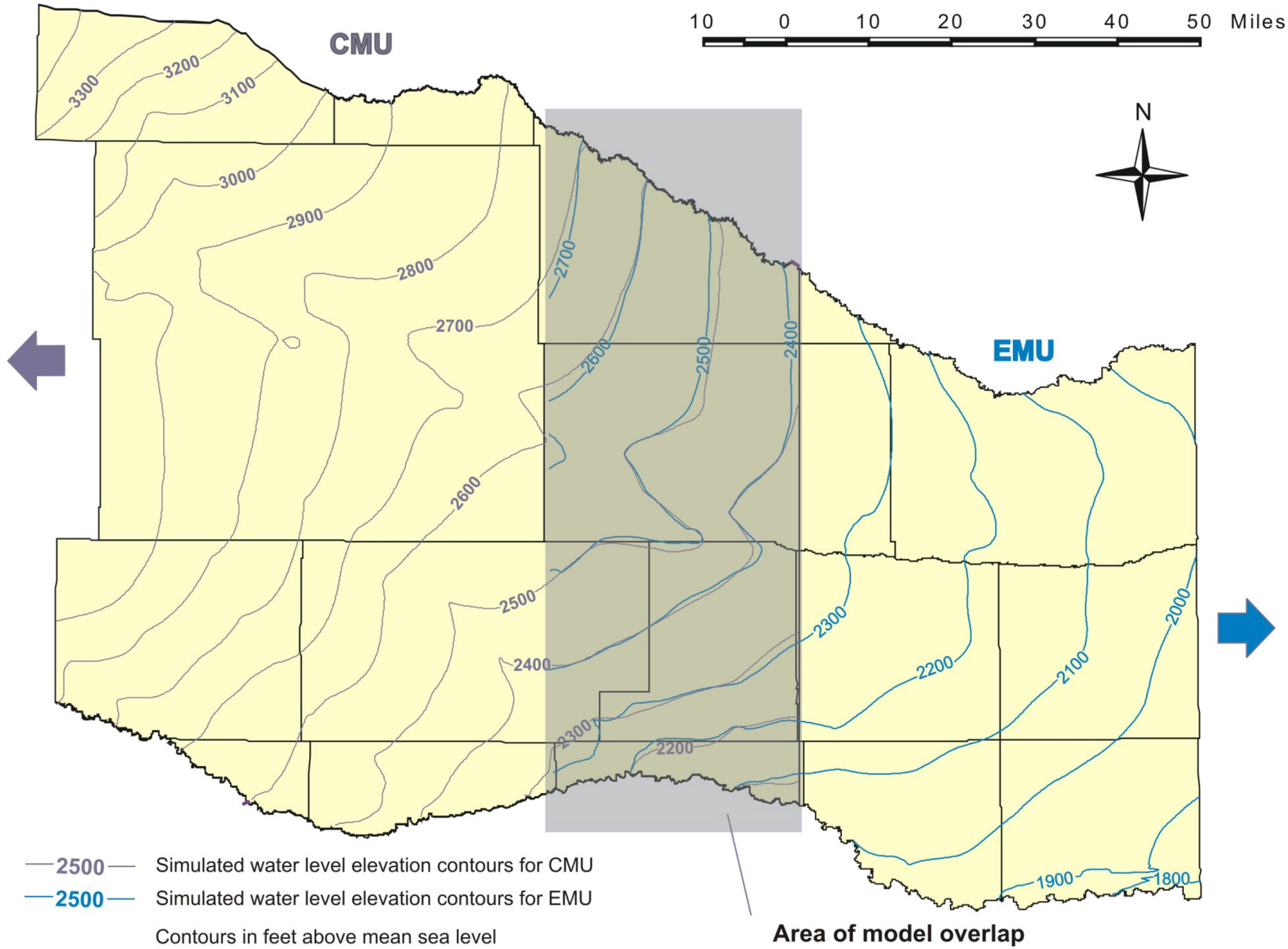


Figure 23. Comparison of simulated 1950 water-level contours in the overlap area of the Central Model Unit (CMU) and Eastern Model Unit (EMU). The model areas extend beyond what is shown in this figure, as indicated by the arrows. Central Model Unit contours were as of August 16, 2007, and could be slightly different from the final documented version.

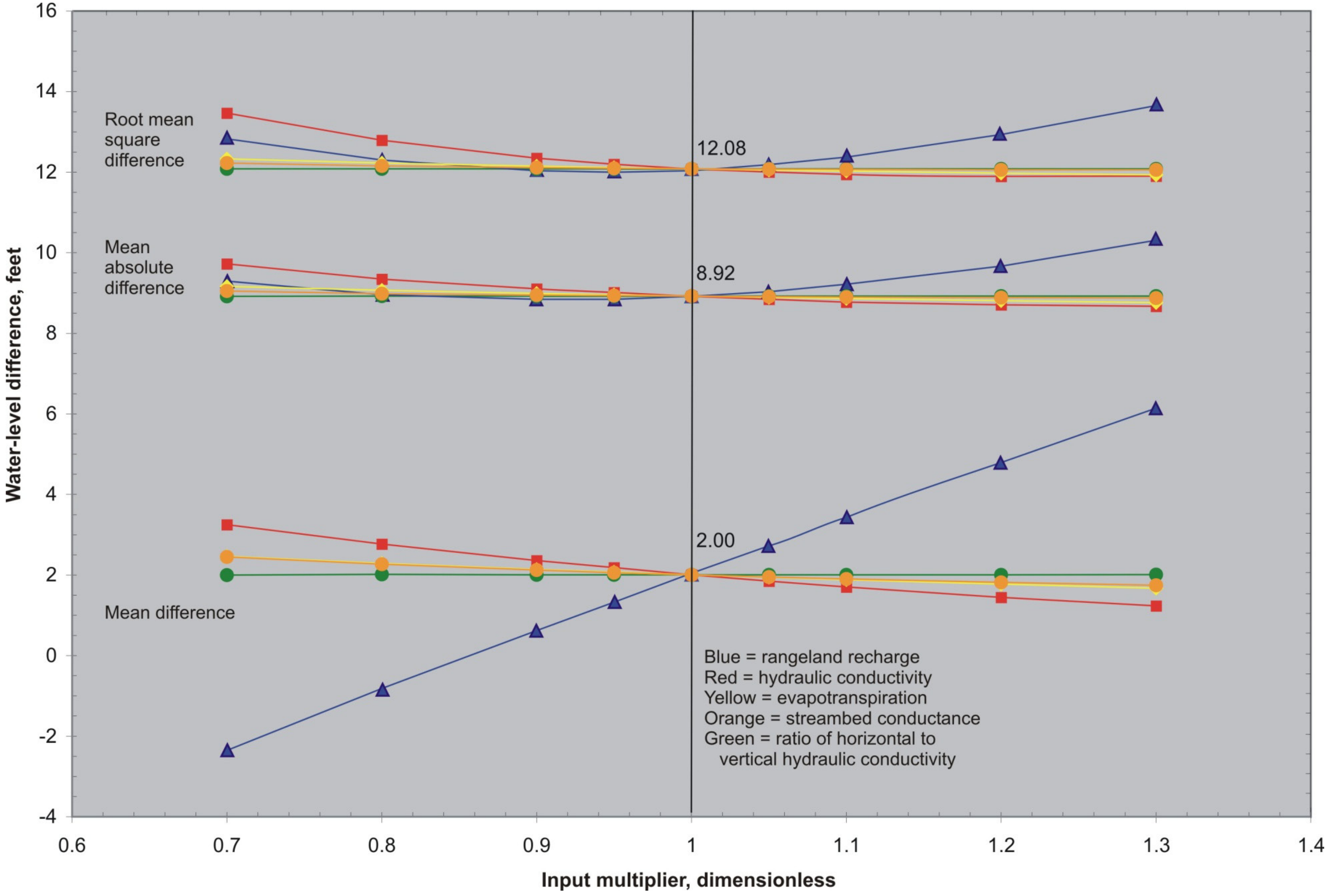


Figure 24. Effects of varying rangeland recharge, hydraulic conductivity, evapotranspiration, streambed conductance, and the ratio of horizontal to vertical hydraulic conductivity on simulated 1950 water levels.

The mean difference decreased as streambed conductance increased and reached 1.75 ft when streambed conductance was increased 30 percent. The mean difference increased as streambed conductance decreased and reached 2.45 ft when streambed conductance was decreased 30 percent. The mean difference was closest to zero when streambed conductance was increased 30 percent. The mean absolute difference was 8.88 ft when streambed conductance was increased 30 percent and was 9.05 ft when streambed conductance was decreased 30 percent. This difference was at a minimum when streambed conductance was increased 30 percent. The root-mean-square difference was 12.06 ft when streambed conductance was increased 30 percent and was 12.23 ft when streambed conductance was decreased 30 percent. This difference was at a minimum when streambed conductance was increased 30 percent. The sensitivity analysis of streambed conductance suggests that a 30 percent increase in streambed conductance might have been beneficial to calibration. However, this change was not made because it would have degraded the simulated groundwater discharge to streams.

The mean difference decreased as the maximum evapotranspiration rate increased and reached 1.67 ft when the maximum rate was increased 30 percent. The mean difference increased as the maximum evapotranspiration rate decreased and reached 2.46 ft when the maximum rate was decreased 30 percent. The mean difference was closest to zero when maximum evapotranspiration rate was increased 30 percent. The mean absolute difference was 8.76 ft when the maximum evapotranspiration rate was increased 30 percent and was 9.17 ft when the maximum rate was decreased 30 percent. This difference was at a minimum when the maximum evapotranspiration rate was increased 30 percent. The root-mean-square difference was 11.93 ft when the maximum evapotranspiration rate was increased 30 percent and was 12.33 ft when the maximum rate was decreased 30 percent. This difference was at a minimum when the maximum evapotranspiration rate was increased 30 percent. The sensitivity analysis of the maximum evapotranspiration rate suggests that a 30 percent increase in the maximum rate might have been beneficial to calibration. However, the maximum rate used in the simulation was based on recent studies of riparian evapotranspiration (M.K. Landon, U.S. Geological Survey, personal commun., July, 2004), and was not adjusted to improve calibration.

The sensitivity analysis of the ratio of horizontal to vertical hydraulic conductivity shows that effects of changes to the ratio of horizontal to vertical hydraulic conductivity in the model were negligible. Therefore, no changes to the ratio of horizontal to vertical hydraulic conductivity would have been beneficial to calibration.

The sensitivity of streamflow to hydraulic conductivity rangeland recharge, evapotranspiration, streambed conductance, and the ratio of horizontal to vertical hydraulic conductivity in the pre-groundwater development period was investigated for four streams: the Platte River from Brady to Cozad, Thompson Creek, Turkey Creek in Furnas County, and the Platte River from Overton to Odessa (fig. 25). The simulated flow to the Platte River from Brady to Cozad at calibration was 51 ft^3/s. The simulated flow was 67 ft^3/s when rangeland recharge was increased 30 percent and 35 ft^3/s when rangeland recharge was decreased 30 percent. The simulated flow was 52 ft^3/s when hydraulic conductivity was increased 30 percent, and 47 ft^3/s when hydraulic conductivity was decreased 30 percent. The simulated flow was 43 ft^3/s when the evapotranspiration was increased 30 percent, and 60 ft^3/s when the evapotranspiration was decreased by 30 percent. The simulated flow was 50 ft^3/s when the ratio of horizontal to vertical hydraulic conductivity was increased 30 percent, and was 51 ft^3/s when the ratio of horizontal to vertical hydraulic conductivity was decreased by 30 percent. The simulated flow was 51 ft^3/s when streambed conductance was increased by 30 percent, and was 49 ft^3/s when streambed conductance was decreased by 30 percent. The Platte River from Brady to Cozad was most sensitive to changes in rangeland recharge and evapotranspiration, least sensitive to hydraulic conductivity and streambed conductance, and relatively insensitive to changes in the ratio of horizontal to vertical hydraulic conductivity.

The simulated flow to Thompson Creek at calibration was 15 ft^3/s. The simulated flow was 17 ft^3/s when rangeland recharge was increased 30 percent and 13 ft^3/s when rangeland recharge was decreased 30 percent. The simulated flow was 15 ft^3/s when hydraulic conductivity was increased 30 percent, and

15 ft^3/s when hydraulic conductivity was decreased 30 percent. The simulated flow was 15.1 ft^3/s when the evapotranspiration was increased 30 percent, and 15 ft^3/s when the evapotranspiration was decreased by 30 percent. The simulated flow was 15 ft^3/s for all changes to the ratio of horizontal to vertical hydraulic conductivity. The simulated flow was 16 ft^3/s when streambed conductance was increased by 30 percent, and was 13 ft^3/s when streambed conductance was decreased by 30 percent. Thompson Creek was sensitive to changes in rangeland recharge and streambed conductance, but relatively insensitive to changes in hydraulic conductivity, evapotranspiration and the ratio of horizontal to vertical hydraulic conductivity.

The simulated flow to Turkey Creek at calibration was 1.9 ft^3/s. The simulated flow was 2.9 ft^3/s when rangeland recharge was increased 30 percent and 1.0 ft^3/s when rangeland recharge was decreased 30 percent. The simulated flow was 1.5 ft^3/s when hydraulic conductivity was increased 30 percent and 2.3 ft^3/s when hydraulic conductivity was decreased 30 percent. The simulated flow was 1.8 ft^3/s when the evapotranspiration was increased 30 percent, and 1.9 ft^3/s when the evapotranspiration was decreased by 30 percent. The simulated flow was 1.9 ft^3/s for all changes to the ratio of horizontal to vertical hydraulic conductivity. The simulated flow was 2.0 ft^3/s when streambed conductance was increased by 30 percent, and was 1.7 ft^3/s when streambed conductance was decreased by 30 percent. Turkey Creek was most sensitive to changes to hydraulic conductivity and streambed conductance, but insensitive to changes to rangeland recharge, the ratio of horizontal to vertical hydraulic conductivity, and evapotranspiration.

The simulated flow to the Platte River from Overton to Odessa at calibration was -8.0 ft^3/s. The simulated flow was -4.0 ft^3/s when rangeland recharge was increased 30 percent and -12 ft^3/s when rangeland recharge was decreased 30 percent. The simulated flow was steady at -8.0 ft^3/s for all hydraulic conductivity changes. The simulated flow was -13 ft^3/s when the evapotranspiration was increased 30 percent, and -3.0 ft^3/s when the evapotranspiration was decreased by 30 percent The simulated flow was -8.0 ft^3/s for all changes to the ratio of horizontal to vertical hydraulic conductivity. The simulated flow was -8.0 ft^3/s for all changes to streambed conductance. Platte River from Overton to Odessa was sensitive to changes in rangeland recharge and evapotranspiration, but insensitive to changes in hydraulic conductivity, the ratio of horizontal to vertical hydraulic conductivity and streambed conductance.

For the groundwater development period, sensitivity analysis was done for the entire 1950-98 period, using the weighted measure calculated as described in the Groundwater Development Period Calibration section. The weighted measure represents the difference of the simulated changes from the observed changes for all simulation periods, thus displaying the sensitivities using 1,116 points instead of only using a portion of the calibration points or only using points for one time period. Therefore, examination of the weighted measure response to various input changes should provide the most useful insight into model sensitivities. The model was most sensitive to irrigated land recharge followed closely by net pumpage, and was least sensitive to specific yield, followed closely by dryland recharge (fig. 26). The model was fairly insensitive to canal seepage recharge. The insensitivity to canal seepage recharge may be due to a small number of water-level observation points in the area of the groundwater mound in 1950. The mound grew more rapidly prior to 1950 and in the 1950-61 period, than it did in the 1961-73, 1973-85, and 1985-98 periods when observation points were more numerous.

At calibration, the mean difference between simulated and observed water-level changes was 0.34 ft. This difference was -2.05 ft when net pumpage was reduced 30 percent and was 2.96 ft when net pumpage was increased 30 percent. This difference was closest to zero when net pumpage was increased 5 percent. The mean absolute difference between simulated and observed water-level changes was 3.64 ft at calibration; this difference was 3.94 ft when net pumpage was reduced 30 percent and was 5.02 ft when net pumpage was increased 30 percent. This difference was at a minimum when net pumpage was reduced 5 percent. At calibration the root-mean-square difference between simulated and observed water-level changes was 5.11 ft; this difference was 5.30 ft when net pumpage was reduced 30 percent and was 6.66 ft when net pumpage was increased 30 percent. This difference was at a minimum when net pumpage was reduced 5 percent.

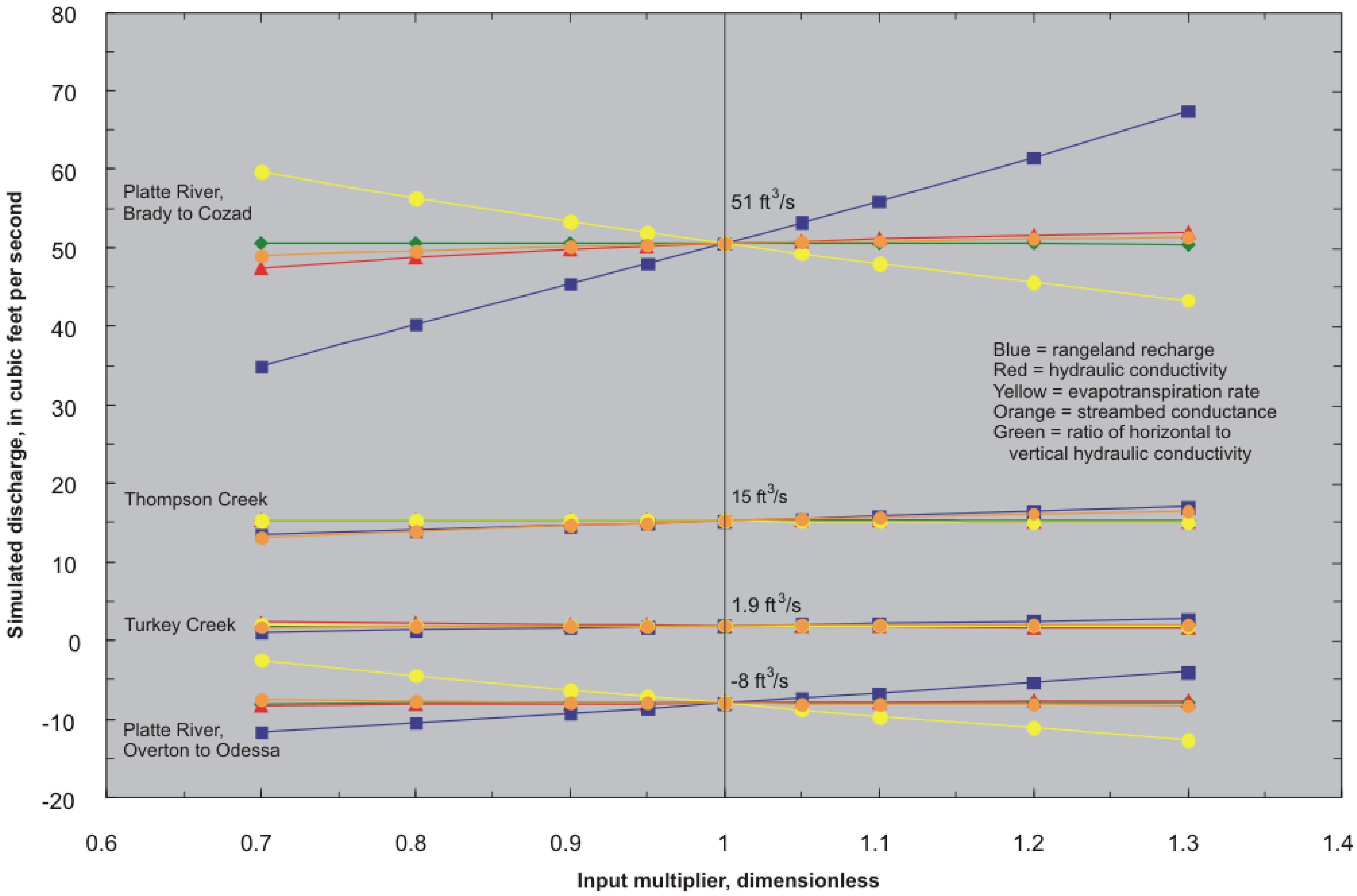


Figure 25. Effects of varying hydraulic conductivity, rangeland recharge, ratio of horizontal to vertical hydraulic conductivity, evapotranspiration and streambed conductance on simulated flow of the Platte River from Brady to Cozad and Overton to Odessa, Turkey Creek (Furnas County), and Thompson Creek.

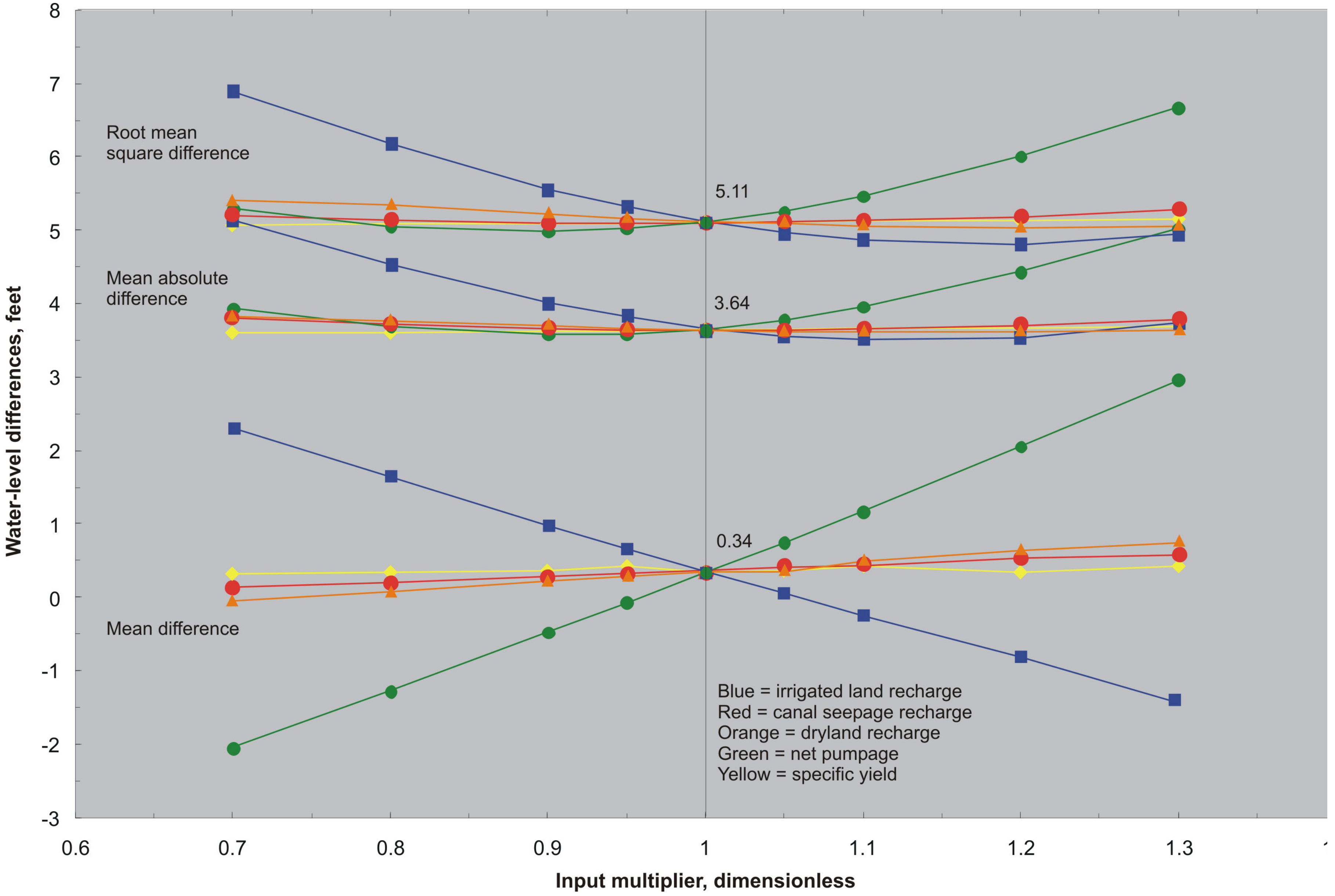


Figure 26. Effects of varying specific yield, net pumpage, dryland recharge, irrigated land recharge, and canal seepage recharge on simulated 1950-98 water-level changes. Canal seepage recharge included recharge from the over- and under-application of surface-water irrigation.

The groundwater-development period model showed a similar sensitivity to irrigated land recharge, though in the opposite direction, which is hydrologically correct. The mean difference was 2.29 ft when irrigated land recharge was reduced 30 percent, and was -1.47 ft when irrigated land recharge was increased by 30 percent. This difference was closest to zero when irrigated land recharge was increased 5 percent. The mean absolute difference was 5.13 ft when irrigated land recharge was reduced 30 percent, and was 3.72 ft when irrigated land recharge was increased 30 percent. The mean absolute difference was at a minimum when irrigated land recharge was increased 5 percent. The root-mean-square difference between simulated and observed water-level changes was 6.89 ft when irrigated land recharge was reduced 30 percent, and was 4.94 ft irrigated land recharge was increased 30 percent. This difference was at a minimum when irrigated land recharge was increased 5 percent.

The model was least sensitive to changes in canal seepage recharge and dryland recharge. The mean difference was 0.11 ft when canal seepage recharge was decreased by 30 percent, and was 0.55 ft when canal seepage was increased by 30 percent. This difference was closest to zero when canal seepage recharge was decreased by 30 percent. The mean absolute difference was 3.80 ft when canal seepage recharge was decreased by 30 percent, and 3.77 ft when canal seepage recharge was increased by 30 percent. This difference was at a minimum when canal seepage recharge was decreased by 5 percent. The root mean square difference was 5.20 ft when canal seepage recharge was decreased by 30 percent, and 5.29 ft when canal seepage recharge was increased by 30 percent. This difference was at a minimum when canal seepage recharge was decreased by 5 percent.

The mean difference for dryland recharge was -0.08 ft when decreased by 30 percent, and 0.73 ft when dryland recharge increased by 30 percent. This difference was closest to zero when dryland recharge decreased by 20 percent. The mean absolute difference was 3.81 ft when dryland recharge decreased by 30 percent, and was 3.63 ft when dryland recharge increased by 30 percent. This difference was at a minimum when dryland recharge decreased by 5 percent. The root mean square difference was 5.41 ft when dryland recharge decreased by 30 percent, and was 5.03 ft when dryland recharge increased by 30 percent. This difference was at a minimum when dryland recharge increased by 5 percent.

The groundwater-development period model was relatively insensitive to changes in specific yield, especially for changes of 10 percent or less.

The sensitivity of simulated 1950-98 stream discharge with respect to model parameters was not investigated during the sensitivity runs.

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 look at the effects of water management plans over scales of years to decades. It should not be viewed as capable of predicting effects through one year or less.

This groundwater flow model is an aggregation and simplification of the natural system, and contains 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 the Eastern Model Unit of the COHYST study area, as well as providing the framework for construction of other models with different time factors or smaller spatial resolution. 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 potentially non-unique in that a different set of model inputs could have produced similar results. This uncertainty was reduced by calibrating the pre-groundwater development model to both streamflows and observed water levels, which fixed the hydraulic conductivity and the pre-groundwater development rangeland recharge. Those parameters were not adjusted during calibration of the groundwater development period simulation.

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 maximum evapotranspiration rate might fall into this category for some uses of this model. As was shown in the Model Sensitivity section, simulated water levels were somewhat insensitive to the maximum evapotranspiration rate. The simulated discharges to streams were somewhat sensitive to evapotranspiration rate, but the observed discharges to some streams were only known within fairly broad ranges (table 5). 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 model is better calibrated in areas with greater numbers of water-level or streamflow observations against which to calibrate, and may be less well calibrated to areas with little or no 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.

The Platte River was simulated as a river boundary in the model described in this report. This is appropriate because this stream seldom goes dry, and when it does, the period during which it is dry is short compared to the 48 years of analysis. As a result of how this stream was simulated, this model should not be used to calculate effects of management scenarios that may cause this stream to go dry for months or years. If there is a need to investigate such management scenarios in the future, the Platte River should first be converted to a stream boundary.

This model should not be used to simulate contaminant 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 (Luckey and Cannia, 2005). As a result, this regional flow model might not adequately simulate solute transport without specific calibration for that purpose.

Further Work

This report is the culmination of a multi-year effort to construct and calibrate a groundwater flow model for the Eastern 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 should benefit from incorporating those changes.

For instance, data collected during recent testhole drilling in southern Gosper County (R. Holloway, Tri-Basin Natural Resources District, personal commun., 2004) has shown the actual configuration of hydrostratigraphic units to be tens of feet different in elevation at some locations from what was mapped by Cannia and others (2006). This suggests that adding more testhole or irrigation well log data could improve those maps, which in turn could be expected to improve the models.

Canal seepage recharge is an important model input for the Eastern Model Unit, but is only generally constrained in spatial distribution and volume. Any additional data collected to better define the distribution of canal seepage or to improve estimates of the volume of canal seepage should improve the model or lead to an improved conceptual model of the system.

The groundwater development period simulation starts in 1950; however, many irrigation wells were already operating in the Platte River valley prior to this time (Cooperative Hydrology Study, 2004). Within the bottomlands of the Platte River valley in the Eastern Model Unit, over 3,600 irrigation wells were drilled prior to 1950, with over 1,000 drilled prior to 1940. Furthermore, these wells were not required to be registered in those times, so the actual number of operational wells in the Platte River valley may have been even larger. The current pre-groundwater development simulation does not simulate any of the effects of early irrigation wells, though it appears that the impact of those wells is probably important enough that they should be added in future simulations.

The groundwater development period model was hampered by the lack of pumpage data. Better pumpage data is something that the Natural Resources Districts in some parts of the COHYST area have identified as a priority. A number of years of pumpage data would be needed before such pumpage data could be used to improve the model. In addition to better pumpage data, better estimates are needed for deep percolation from pumped irrigation water as well as recharge from precipitation on irrigated fields. These processes need further research and refinement.

Recent advances in groundwater modeling software have provided new methods of representing geology (Anderman and Hill, 2000) and solving flow equations (Mehl and Hill, 2001). If the simulation were modified to work with this new software, computer run time should decrease, which would allow for easier testing of model improvements. Also, recent advances in automated parameter estimation using MODFLOW-2000 (Harbaugh and others, 2000) and PEST (Doherty, 2004) allow for comprehensive exploration of model uncertainty and sensitivity, and could lead to an improved conceptual model of the system.

References Cited

Alley, W.M., and Emery, P.A., 1986. Groundwater model of the Blue River basin, Nebraska – Twenty years later. Journal of Hydrology, v. 85, p. 225-249.

Anderman, E.R., and Hill, M.C., 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model – Documentation of the Hydrogeologic-Unit Flow (HUF) Package. U.S. Geological Survey Open-File Report 00-342, 89 p.

Ayers, J. F., 1990. Hydrogeology of the lower Platte valley alluvial aquifer, part II – Groundwater flow model update. Conservation and Survey Division, University of Nebraska-Lincoln, Open-File Report 43, 242 p.

Bartz, P.A., and Peckenpaugh, J.M., 1986. Hydrologic data for the south-central area, Nebraska. U.S. Geological Survey Open-File Report 86-246, 78 p.

Bentall, Ray, and others, 1975. Hydrology, Nebraska mid-state division and associated areas. Conservation and Survey Division, University of Nebraska-Lincoln, 256 p.

Boyle Engineering Corp., 1983. Adams County water supply study, reconnaissance level investigation. Central Nebraska Public Power and Irrigation District and Little Blue Natural Resources District, 40 p.

Bradley, Edward, and Johnson, C.R., 1957. Geology and ground-water hydrology of the valleys of the Republican and Frenchman Rivers, Nebraska. U.S. Geological Survey Water-Supply Paper 1360-H, p. 589-713

Burchett, R.R., and Smith, F.A., 1992. Nance County test-hole logs. Nebraska Water Survey Test-Hole Report No. 63, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 28 p.

Burchett, R.R., and Smith, F.A., 1994. Clay County test-hole logs. Nebraska Water Survey Test-Hole Report No. 18, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 35 p.

Burchett, R.R., and Smith, F.A., 1996. Polk County test-hole logs. Nebraska Water Survey Test-Hole Report No. 72, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 44 p.

Burchett, R.R., and Summerside, S.E., 1997. Franklin County test-hole logs. Nebraska Water Survey Test-Hole Report No. 31, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 92 p.

Burchett, R.R., and Summerside, S.E., 1998a. Harlan County test-hole logs. Nebraska Water Survey Test-Hole Report No. 42, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 115 p.

Burchett, R.R., and Summerside, S.E., 1998b. Platte County test-hole log.: Nebraska Water Survey Test-Hole Report No. 71, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 117 p.

Burns, A.W., 1981. Simulated hydrologic effects of possible ground-water and surface-water management alternatives in and near the Platte River, south-central Nebraska. U.S. Geological Survey Open-File Report 81-1116, 41 p.

Burns, A.W., 1983. Simulated hydrologic effects of possible ground-water and surface-water management alternatives in and near the Platte River, south-central Nebraska. U.S. Geological Survey Professional Paper 1277-G, 30 p.

Cady, R. E, and Ginsberg, M. H., 1979. Interpretative study and numerical model of the hydrogeology, Upper Big Blue Natural Resources District. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 185 p.

Cannia, J.C., Woodward, D.W., and Cast, L., 2006. Cooperative Hydrology Study Hydrostratigraphic Units and Aquifer Characterization Report. Cooperative Hydrology Study, 91 p.

Carney, P.G., 2008. Groundwater flow model of the Central Model Unit of the Nebraska Cooperative Hydrology Study (COHYST) area. Cooperative Hydrology Study, 87 p.

Cast, L.D., 2000a. Custer County test-hole logs. Nebraska Water Survey Test-Hole Report No. 21, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 201 p.

Cast, L.D., 2000b. Gosper County test-hole logs. Nebraska Water Survey Test-Hole Report No. 37, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 68 p.

Cederstrand, J.R., and Becker, M.F., 1999. Digital map of predevelopment water levels for the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. U.S. Geological Survey Open-File Report 99-264.

Central Nebraska Regional Water Conservation Task Force, 2002. Supplement IV to the comprehensive water conservation plan. Central Nebraska Public Power and Irrigation District, Holdrege, Nebraska. 66 p.

Chen, Xun-Hong, and Yin, V., 1999. Modeling of groundwater flow and analysis of stream-aquifer interactions, Franklin County, south-central Nebraska. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Open-File Report 69, 139 p.

Condra, G.E., 1907. Geology and water resources of the Republican River valley and adjacent areas, Nebraska. U.S. Geological Survey Water-Supply and Irrigation Paper No. 216, 71 p.

Conservation and Survey Division, 1948. Preliminary groundwater study of Kearney County, Nebraska. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Open-File Map Report, Scale 1:125,000.

Conservation and Survey Division, 1953. Preliminary groundwater study of Phelps County, Nebraska. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Open-File Map Report, Scale 1:125,000.

Conservation and Survey Division, 1957. Preliminary groundwater study of Franklin County, Nebraska. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Open-File Map Report, Scale 1:125,000.

Conservation and Survey Division, 1998. The groundwater atlas of Nebraska. Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. Resource Atlas No. 4a/1998, 44 p.

Conservation and Survey Division, 2003. 1995 water table contours. Accessed February 28, 2003 at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Cooperative Hydrology Study Technical Committee, 2000. Flow modeling strategy for COHYST. Accessed March 15, 2000 at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Cooperative Hydrology Study Technical Committee, 2004. Pre-groundwater development multi-layered groundwater flow model with 1-square mile cells – Central Model Unit – COHYST study area. Cooperative Hydrology Study unpublished report dated October 25, 2004, 51 p.

Cooperative Hydrology Study, 2000. Topographic regions. file g002toporeg_97. Accessed March 31, 2000, at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Cooperative Hydrology Study, 2001a. Land use and irrigation – Graphical compilation of crop irrigation data within COHYST. Accessed February 1, 2001, at URL http://cohyst.nrc.state.ne.us/

Cooperative Hydrology Study, 2001b. Streambed coring results. file g012strmbdcor_01. Posted January 17, 2001 at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Cooperative Hydrology Study, 2003a. Testhole database. Accessed June 17, 2003, at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Cooperative Hydrology Study, 2003b. Shaded relief image of the COHYST area. Accessed March 15, 2003, at http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Cooperative Hydrology Study, 2004. File g003regwell_04. Accessed May 25, 2004 at URL http://cohyst.dnr.state.ne.us/cohyst_data.html

Dappen, P., and Tooze, M., 2001. Delineation of land use patterns for the Cooperative Hydrology Study in the central Platte River basin. Center for Advanced Land Management Information Technologies (CALMIT), Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 73 p.

Darton, N.H., 1898. Underground waters of a portion of southeastern Nebraska. U.S. Geological Survey Water Supply and Irrigation Paper 12, 56 p.

Darton, N.H., 1905. Preliminary report on the geology and underground water resources of the central Great Plains. U.S. Geological Survey Professional Paper 32, 433 p.

Davis, R.K., 1986. Hydrogeologic interpretations of the Platte River basin and the upper Big Blue River basin, in the Polk County area of Nebraska. University of Nebraska-Lincoln M.S. thesis, 120 leaves.

Doherty, J.E., 2004. PEST – model-independent parameter estimation user's guide, 5th ed. 333 p. Accessed December 21, 2004, at URL http://www.sspa.com/PEST

Dreeszen, V.H., 1999a. Hall County test-hole logs. Nebraska Water Survey Test-Hole Report No. 40, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 125 p.

Dreeszen, V.H., 1999b. Howard County test-hole logs. Nebraska Water Survey Test-Hole Report No. 47, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 90 p.

Dreeszen, V.H., 2000. Buffalo County test-hole logs. Nebraska Water Survey Test-Hole Report No. 10, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 251 p.

Ellis, M. J., 1981. Hydrogeologic reconnaissance of the Republican River basin in Nebraska. U.S. Geological Survey Open-File Report 81-531, 3 sheets, scales 1:330,000 and 1:500,000.

Emery, P.A., 1965. Effect of ground-water pumping on streamflow and ground-water levels, Blue River basin, Nebraska. U.S. Geological Survey Open-File Report 65-55, 11 p.

Environmental Modeling Systems, Incorporated, 2007. The Department of Defense groundwater modeling system. GMS 6.0. Environmental Modeling Research Laboratory, Brigham Young University, Provo, Utah. Accessed October 15, 2007, at URL http://www.xmswiki.com/index.php?title=GMS:GMS

Eversoll, D.A., 2000. Frontier County test-hole logs. Nebraska Water Survey Test-Hole Report No. 32, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 93 p.

Fetter, C.W., 1994. Applied hydrogeology (3d. ed.). Upper Saddle River, N.J., Prentice Hall, 691 p.

Goeke, J.W., Peckenpaugh, J.M., Cady, R.E., and Dugan, J.T., 1992. Hydrogeology of parts of the Twin Platte and Middle Republican Natural Resources Districts, southwestern Nebraska, *with a section on* Water Quality by R.A. Engberg. Nebraska Water Survey Paper No. 70, Conservation and Survey Division, University of Nebraska-Lincoln, 89 p.

Governors of Wyoming, Colorado, and Nebraska, and the Secretary of the Interior, 1997. Cooperative agreement for Platte River research and other efforts relating to endangered species habitat along the central Platte River, Nebraska. Signed July 1, 1997. Copy available at http://www.platteriver.org/

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

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

Hardgree, Melissa, and McChesney, Jennifer, 1995. A selected bibliography on the hydrology of the Platte River basin in Nebraska through 1991. U.S. Geological Survey Open-File Report 94-496, 80 p.

Hargreaves, G.H., 1994. Defining and using reference evapotranspiration. Journal of Irrigation and Drainage Engineering, American Society of Civil Engineers, v. 120, no. 6, p. 1132-1139.

High Plains Regional Climate Center, 2003. Climatic data database. Accessed March 28, 2003 at URL http://www.hprcc.unl.edu/data.htm for stations in COHYST study area.

Hsieh, P.A., and Freckleton, J.R., 1993. Documentation of a program to simulate horizontal flow barriers using the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model. U.S. Geological Survey Open File Report 92-477, 32 p.

Huntoon, P.W., 1974. Predicted water-level declines for alternative groundwater developments in the upper Big Blue River basin, Nebraska. Resources Report No. 6, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 106 p.

Johnson, C.R., 1960. Geology and ground water in the Platte-Republican Rivers watershed and the Little Blue River basin above Angus, Nebraska, *with a section on* Chemical quality of the ground water by Robert Brennen. U.S. Geological Survey Water-Supply Paper 1489, 142 p.

Johnson, C.R., and Keech, C.F., 1959. Geology and ground-water resources of the Big Blue River basin above Crete, Nebraska, *with a section on the* Chemical quality of the ground water by Robert Brennan. U.S. Geological Survey Water-Supply Paper 1474, 94 p.

Keech, C.F., 1952. Ground-water resources of the Wood River unit of the lower Platte River basin, Nebraska. U.S. Geological Survey Circular 139, 96 p.

Keech, C.F., 1962. Ground-water resources of Hamilton County, Nebraska, *with a section on the* Chemical quality of water by P.G. Rosene. U.S. Geological Survey Water Supply Paper 1539-N, 64 p.

Keech, C.F., 1972. Ground water in Polk County, Nebraska. U.S. Geological Survey Hydrologic Investigations Atlas HA-389, scale 1:125,000, 1 sheet.

Keech, C.F., and Dreeszen, V.H., 1959. Geology and ground-water resources of Clay County, Nebraska, *with a section on* Chemical quality of water by F.H. Rainwater. U.S. Geological Survey Water Supply Paper 1468, 157 p.

Keech, C.F., and Dreeszen, V.H., 1964. Availability of ground water in Hall County, Nebraska. U.S. Geological Survey Hydrologic Investigation Atlas HA-131, scale 1:125,000, 1 sheet.

Keech, C.F., and Dreeszen, V.H., 1968. Availability of ground water in Adams County, Nebraska. U.S. Geological Survey Hydrologic Investigations Atlas HA-287, scale 1:125,000, 1 sheet.

Keech, C.F., Dreeszen, V.H., and Emery, P.A., 1967. Availability of ground water in York County, Nebraska. U.S. Geological Survey Water Supply Paper 1839-F, 17 p.

Kern, R., 2004. Development of pumpage/recharge estimates. Nebraska Department of Natural Resources unpublished report. Lincoln, Nebraska. 2 p. plus 5 supporting documents.

Lappala, E.G., Emery, P.A., and Otradovsky, F.J., 1979. Simulated changes in ground-water levels and streamflow resulting from future development (1970 to 2020) in the Platte River basin. U.S. Geological Survey Water-Resources Investigations Report 79-26, 82 p.

Lichter, W.F., Stannard, D.I., and Kouma, Edwin, 1980. Investigation of artificial recharge of aquifer in Nebraska. U.S. Geological Survey Water Resources Investigations Report 80-93 112 p.

Luckey, R.R., and Cannia, J.C., 2006. Groundwater flow model of the western model unit of the Nebraska Cooperative Hydrology Study (COHYST) area. 63 p.

Luckey, R.R., Gutentag, E.D., Heimes, F.J., and Weeks, J.B., 1986. Digital simulation of ground-water flow in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. U.S. Geological Survey Professional Paper 1400-D, 57 p.

Luckey, R.R., Gutentag, E.D., Heimes, F.J., and Weeks, J.B., 1988. Effects of future ground-water pumpage on the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. U.S. Geological Survey Professional Paper 1400-E, 44 p.

Lugn, A.L., and Wenzel, L.K., 1938. Geology and ground-water resources of south-central Nebraska, with special reference to the Platte River valley between Chapman and Gothenburg. U.S. Geological Survey Water-Supply Paper 779, 242 p.

McDonald, M.G., and Harbaugh, A.W., 1988. A modular three-dimensional finite-difference ground-water flow model. U.S. Geological Survey Techniques of Water-Resources Investigations, Chapter A1, Book 6, 586 p.

McDonald, M.G., Harbaugh, A.W., Orr, B.R., Ackerman, D.J., 1991. A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water flow model. U.S. Geological Survey Open-File Report 91-536, 99 p.

McGuire, V.L., and Kilpatrick, J.M., 1998. Hydrogeology in the vicinity of the Nebraska Management Systems Evaluation Area site, central Nebraska. U.S. Geological Survey Water-Resources Investigations Report 97-4266, 25 p.

Mehl, S.E. and Hill, M.C., 2001. MODFLOW-2000, the U.S. Geological Survey modular ground-water model – User guide to the LINK-AMG (LMG) Package for solving matrix equations using an algebraic multigrid solver. U.S. Geological Survey Open-File Report 01-177, 33 p.

Miller, C.A., 1993. Modeling of the Kearney well field using a three-dimensional groundwater model. University of Nebraska-Lincoln, M.S. thesis, 14 leaves.

Missouri Basin State Association, 1982a. Technical Paper, Ground water depletion. Omaha, Missouri River Basin hydrology study, 94 p. plus 2 appendices.

Missouri Basin State Association, 1982b. Transmissivity and stream depletion factor maps; Platte and Kansas River basins, Colorado-Kansas-Nebraska-Wyoming, Appendix II of Technical Paper, Ground water depletions (Missouri Basin State Association, 1982a). Omaha, Missouri River Basin hydrology study, 16 pls.

Missouri River Basin Commission, 1975. Stream-aquifer hydrology, technical paper, Platte River basin, Nebraska, Level B Study. Missouri River Basin Commission, 67 p.

National Climatic Data Center, 2000. Climate division drought data, including precipitation data and various drought indexes. Accessed November 1, 1999, at URL http://www.ncdc.noaa.gov/onlineprod/drought/main.html for Nebraska climate divisions 1, 2, and 5 through 9.

Nebraska Department of Natural Resources, 1997. Digital elevation model. Metadata accessed January 22, 2001 at URL http://www.nrc.state.ne.us/databank/doqqs/dem_doc.html.

Nebraska Department of Natural Resources, 2000. Evaporation database. Accessed February 29, 2000, at URL http://www.dnr.state.ne.us/ for stations 1684, 3395, 3595, 3660, 3911, 5388, and 7330.

Nebraska Department of Natural Resources, 2006. Republican River settlement implementation. Accessed September 21, 2006, at URL http://www.dnr.ne.gov/legal/kansasvs.html .

Nebraska State Planning Board, 1936. Water resources of Nebraska – Preliminary report. Nebraska State Planning Board, 695 p. plus 28 general plates.

Nguyen, Q.M., and Gilliland, M.W., 1985. A surface water- groundwater interaction model for the Platte River wellfield of the city of Grand Island, Nebraska. Department of Civil Engineering, University of Nebraska-Lincoln, 179 p. Unpublished report available for inspection at Central Platte Natural Resources District and City of Grand Island.

Peckenpaugh, J.M., and Dugan, J.T., 1983. Hydrology of parts of the Central Platte and Lower Loup Natural Resources Districts, Nebraska. U.S. Geological Survey Water-Resources Investigations Report 83-4219, 125 p.

Peckenpaugh, J.M., Dugan, J.T., Kern, R.A., and Schroeder, W.J., 1987. Hydrogeology of the Tri-Basin and parts of the Lower Republican and Central Platte Natural Resources Districts, Nebraska; U.S. Geological Survey Water-Resources Investigations Report 87-4176, 117 p.

Peterson, S.M., and Carney, C.P., 2002. Estimated groundwater discharge to streams from the High Plains aquifer in the eastern model unit of the COHYST study area for the period prior to major groundwater irrigation. Posted March 4, 2002, at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Pettijohn, R.A., and Chen, H.H., 1983a. Geohydrology of the High Plains aquifer system in Nebraska. U.S. Geological Survey Open-File Report 82-502, map, scale 1:705,000, 3 sheets.

Pettijohn, R.A., and Chen, H.H., 1983b. Hydraulic conductivity, specific yield, and pumpage–High Plains aquifer system, Nebraska. U.S. Geological Survey Water-Resources Investigations Report 82-4014, map, scales 1:750,000 and 1:1,000,000, 3 sheets.

Pettijohn, R.A., and Chen, H.H., 1984. Hydrologic analysis of the High Plains aquifer system in Box Butte County, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 84-4046, 54 p.

Prudic, D.E., 1989. Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model. U.S. Geological Survey Open-File Report 88-729, 113 p.

Republican River Compact Administration, 2003. Republican River Compact Administration ground water model, June 30, 2003. Accessed September 27, 2006, at URL http://www.republicanrivercompact.org

Schreurs, R.L., 1956. Geology and ground-water resources of Buffalo County and adjacent area, Nebraska, *with a section on* Chemical quality of ground water by F.H. Rainwater. U.S. Geological Survey Water-Supply Paper 1358, 175 p.

Smith, F.A., 1998. Furnas County test-hole logs. Nebraska Water Survey Test-Hole Report No. 33, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 266 p.

Smith, F.A., 1999a. Dawson County test-hole logs. Nebraska Water Survey Test-Hole Report No. 24, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 119 p.

Smith, F.A., 1999b. Merrick County test-hole logs. Nebraska Water Survey Test-Hole Report No. 61, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 35 p.

Smith, F.A., 2000. York County test-hole logs. Nebraska Water Survey Test-Hole Report No. 93, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 60 p.

Sniegocki, R.T., 1955. Ground-water resources of the Prairie Creek unit of the Lower Platte River basin, Nebraska *with a section on* Chemical quality of ground water by F.H. Rainwater. U.S. Geological Survey Water-Supply Paper 1327, 133 p.

Sniegocki, R.T., 1959. Geologic and ground-water reconnaissance of the Loup River drainage basin, Nebraska, *with a section on* Chemical quality of the water by R.H. Langford. U.S. Geological Survey Water-Supply Paper 1493, 106 p.

Spalding, R.F., 1975. Effects of land use and river seepage on groundwater quality in Hall County, Nebraska. Nebraska Water Supply Paper 38, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 95 p.

Stanton, J., 1999. Groundwater-level changes in Nebraska, predevelopment to spring 1997. Conservation and Survey Division Water Survey Map GM-62, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln., 1 sheet.

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

Summerside, S.E., 1999a. Kearney County test-hole logs. Nebraska Water Survey Test-Hole Report No. 50, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 53 p.

Summerside, S.E., 1999b. Phelps County test-hole logs. Nebraska Water Survey Test-Hole Report No. 69, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 68 p.

Summerside, S.E., 2003. Nuckolls County test-hole logs. Nebraska Water Survey Test-Hole Report No. 65, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 63 p.

Summerside, S.E., 2004. Webster County test-hole logs. Nebraska Water Survey Test-Hole Report No. 91, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 126 p.

Swinehart, J.B., Souders, V.L., DeGraw, H.M., and Diffendal, R.F. Jr., 1985. Cenozoic paleogeography of western Nebraska, *from* Cenozoic paleogeography of west-central United States, *in* Proceedings of Rocky Mountain Paleogeography Symposium 3, Denver, Colorado, 1985, R.M. Flores and S.S. Kaplan, eds. p. 209-229.

U.S. Department of Agriculture, 1997. Census of Agriculture for Nebraska. National Agricultural Statistical Services. 536 p., 6 appendices.

U.S. Department of Commerce, 1949-92. Census of Agriculture for Nebraska. Bureau of the Census, agricultural data for 1949, 1954, 1959, 1964, 1969, 1974, 1978, 1982, 1987, and 1992.

U.S. Geological Survey National Water Information System, 1999. Accessed December, 1999, at URL http://waterdata.usgs.gov/ne/nwis/gw

U.S. Weather Bureau, 1959. Evaporation maps for the United States. U.S. Weather Bureau Technical Paper 37, plate 2.

Waite, H.A, and others, 1949. Progress report on the geology and groundwater hydrology of the lower Platte River valley, Nebraska, U.S. Geological Survey Circular 20, 211 p.

Waite, H.A., Reed, E.C., and Jones, D.S. Jr., 1944a. Ground water in the Republican River basin in Nebraska, Part I, Nuckolls, Webster, Franklin, and Harlan Counties. Nebraska Water Supply Paper 1.1, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 46 p.

Waite, H.A., Reed, E.C., and Jones, D.S. Jr., 1944b. Ground water in the Republican River basin in Nebraska, Part II, Furnas County. Nebraska Water Supply Paper 1.2, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 32 p.

Waite, H.A., Reed, E.C., and Jones, D.S., Jr., [1944]. Groundwater in the Republican River basin in Nebraska, part 1. Nuckolls, Webster, Franklin, and Harlan counties. Nebraska Water Resources Survey Water Supply Paper 1. Conservation and Survey Division, University of Nebraska-Lincoln. 46 p.

Water and Climate Center of the Natural Resources Conservation Service, 2000. Central United States average annual precipitation. Accessed April 8, 2003, at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html.

Weakly, E.C., 1966. Geology and ground-water resources of Polk County, Nebraska. University of Nebraska-Lincoln M.S. thesis, 77 leaves.

Weeks, J.B., Gutentag, E.D., Heimes, F.J., and Luckey, R.R., 1988. Summary of the High Plains regional aquifer-system analysis in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. U.S. Geological Survey Professional Paper 1400-A, 30 p.

Wenzel, L.K., 1940. Local overdevelopment of ground-water supplies, with special reference to conditions at Grand Island, Nebraska. U.S. Geological Survey Water-Supply Paper 836-E, p. 233-281.

Wigley, P.B., 1999a. Adams County test-hole logs. Nebraska Water Survey Test-Hole Report No. 1, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 46 p.

Wigley, P.B., 1999b. Hamilton County test-hole logs. Nebraska Water Survey Test-Hole Report No. 41, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 34 p.