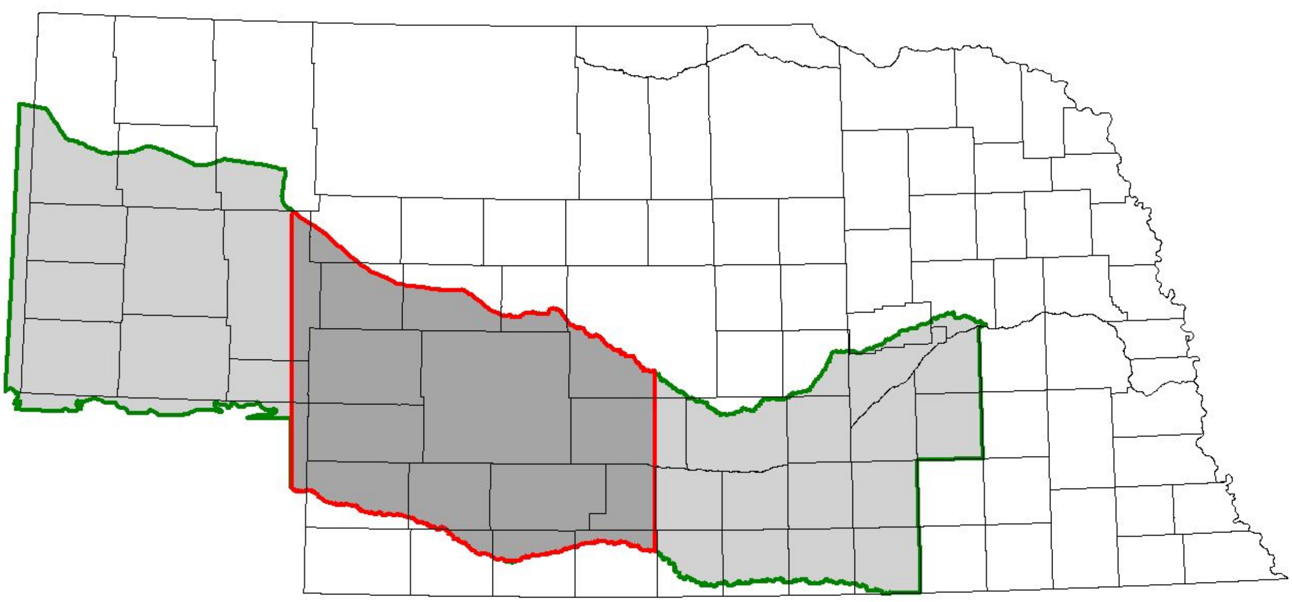
Groundwater Flow Model of the Central Model Unit of the Nebraska Cooperative Hydrology Study (COHYST) Area



Clint P. Carney, P.G.
Nebraska Public Power District

September 2008

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

Acknowledgments

This study was supported by the various state and local agencies that make up the Cooperative Hydrology Study (COHYST) Sponsors, including two state agencies, seven natural resources districts, and two public power districts. The Sponsors include:

Central Nebraska Public Power and Irrigation District

Central Platte Natural Resources District

Nebraska Department of Natural Resources

Nebraska Game and Parks Commission

Nebraska Public Power District

North Platte Natural Resources District

South Platte Natural Resources District

Tri-Basin Natural Resources District

Twin Platte Natural Resources District

Upper Big Blue Natural Resources District

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

The author would like to express deep gratitude to Richard R. Luckey, High Plains Hydrology, LLC (formerly of the U.S. Geological Survey), Steven M. Peterson, U.S. Geological Survey (formerly of the Central Nebraska Public Power and Irrigation District), and James C. Cannia, U.S. Geological Survey (formerly of the North Platte Natural Resources District) for their guidance and support during the entirety of this project. The author also recognizes Doug Hallum of the Nebraska Department of Natural Resources and Kevin Spelts of the Twin Platte Natural Resources District for their comments on the contents and format of this documentation. In addition, the author would also like to acknowledge NPPD Water Resources Management and the COHYST Sponsors for allowing the author to complete this modeling project and documentation while simultaneously attending further graduate studies at the Colorado School of Mines in Golden, CO. Their patience and openness to allow this arrangement will not be forgotten.

Table of Contents

Page

List of figures iv

List of tables vi

Abbreviation, unit, and conversion guide.................... vii

Executive summary 1

Description and purpose of COHYST.................... 5

Previous studies 5

Modeling strategy 7

Description of Central Model Unit.................... 8

Geologic and hydrostratigraphic units in the Central Model Unit 15
- Geologic units.................... 15
- Hydrostratigraphic units.................... 18

Conceptual flow model 20
- Boundaries....................20
- Groundwater flow....................21
- Flow system history....................21

Numerical model construction 23
- Groundwater model concepts and development....................23
- Spatial discretization 25
- Temporal discretization....................25
- Model feature inputs....................28
  - Rivers and streams....................28
  - Drains 29
  - Reservoirs....................29
  - Recharge....................30
    - Canal seepage estimates 30
  - Groundwater pumpage 34
    - COHYST pumpage development....................34
    - Net irrigation requirement 35
  - Evapotranspiration....................36
  - Model cell rewetting....................36

Numerical model calibration 37
- Pre-groundwater development period calibration 39
  - Hydraulic conductivity 39
  - Specific yield....................41
  - Specific storage 41
  - Bed conductance....................41
  - Recharge from precipitation 44
  - Evapotranspiration....................44
  - Simulation results....................47
    - Simulated groundwater levels 47
    - Water-level calibration statistics 50
    - Simulated stream discharges 50
    - Model budget....................50

Groundwater development period calibration 54
Model parameters 54
Specific yield 54
Recharge from canal seepage 55
Land-use based recharge 55
Simulation results 58
Simulated groundwater level changes 58
Calibration statistics 65
Simulated stream discharge 67
Model budget 67
Groundwater mound volume 67

Comparison to adjacent models 68
Central-Eastern Model Unit comparison 68
Central-Western Model Unit comparison 71

Model sensitivity 72

Limitations on use of this model 77

Further work 78

References cited 80

List of Figures

Figure 1. COHYST study area and model units 6

Figure 2. Irrigation well development in the COHYST area 8

Figure 3. Major surface water features in the Central Model Unit 9

Figure 4. Natural resources districts, cities, and major roads within the Central Model Unit.................. 10

Figure 5. Average 1961-90 precipitation, average lake evaporation, and meteorological stations in the Central Model Unit.. 12

Figure 6. Average monthly precipitation for 1948-1999 at three stations in the Central Model Unit illustrating the temporal distribution of precipitation by month…………………......................13

Figure 7. Hydrographs comparing annual average flow of streams draining the Sand Hills and the Republican River basin 14

Figure 8. Pre-groundwater development water table in the Central Model Unit 16

Figure 9. Elevation and geologic units of the High Plains aquifer base in the Central Unit Model........... 19

Figure 10. Central Model Unit conceptual model features 22

Figure 11. Active cells for the Central Model Unit 160-acre cell grid with Lake McConaughy, the North Platte River, and the South Platte River highlighted in Keith County 26

Figure 12. Correspondence of COHYST Hydrostratigraphic Units with a sample view of model layers 27

Figure 13. An example of a manual line used to represent historic recharge due to canal and lateral leakage of Gothenburg Canal ....……………..32

Figure 14. Zones within the Central Model Unit receiving additional groundwater groundwater recharge from canal seepage 33

Figure 15. Composite hydraulic conductivity distribution applied to the calibrated model.......................42

Figure 16. Streambed conductance values applied to the calibrated model 43

Figure 17. Rangeland recharge distribution applied to the calibrated pre-groundwater development period flow model. 45

Figure 18. Shaded relief image showing the dune type and spatial distribution in the eastern Sand Hills of the Central Model Unit.. 46

Figure 19. Simulated 1950 water table for the calibrated pre-groundwater development period model and comparison between simulated and observed water levels at observation points in the Central Model Unit 48

Figure 20. Comparision between simulated 1950 water levels for the calibrated model and pre-groundwater development water levels from the Groundwater Atlas of Nebraska 49

Figure 21. Comparision between simulated 1950 water levels for the calibrated model and pre-groundwater development water levels from the U.S. Geological Survey 51

Figure 22. Simulated 1950 saturated thickness of all layers in the Central Model Unit 52

Figure 23. 1997 land-use categories based on satellite imagery exemplifying the variability in dryland, irrigated lands, and rangeland. 56

Figure 24. Zone delineation for additional recharge during the development period in the Central Model Unit........ 57

Figure 25. Simulated water-level change for the calibrated groundwater development period model & comparison between simulated and observed water-level change at observation points with records available for the entire model period 60

Figure 26. Simulated water-level change 1950-61 sub-period of the groundwater development period simulation 61

Figure 27. Simulated water-level change for the 1961-73 sub-period of the groundwater development period simulation 62

Figure 28. Simulated water-level change for the 1973-85 sub-period of the groundwater development period simulation 63

Figure 29. Simulated water-level change for the 1985-98 sub-period of the groundwater development period simulation 64

Figure 30. Comparison of simulated water-tables withing the overlap area of the Central, Western, and, Eastern Model Units........ 70

Figure 31. Effects of varying rangeland recharge, hydraulic conductivity, the ratio of horizontal to vertical hydraulic conductivity, evapotranspiration, and streambed conductance on simualted 1950 water levels 73

Figure 32. Effects of varying hydraulic conductivity, rangeland recharge, bed conductance, and evapotranspiration on groundwater discharge to Muddy Creek, Red Willow Creek, Birdwood Creek, and the North Platte River between gages at Sutherland NE, and North Platte, NE at 1950 74

Figure 33. Effects of varying specific yield, net pumpage, dryland recharge, irrigated land recharge, and canal seepage recharge on simulated 1950-1998 water-level changes........76

List of Tables

Table 1. Generalized section of geologic units used in Cooperative Hydrology Study 17

Table 2. Stress periods and time steps for the Central Model Unit pre-groundwater development period simulation 28

Table 3. Summary of estimated recharge from canal and lateral leakage applied to the simulation 31

Table 4. The number of water-level observation points available by sub-period of the groundwater development period simulation 38

Table 5. Hydraulic conductivity values for the calibrated pre-groundwater development period model 40

Table 6. Simulated and observed discharge to streams for the calibrated pre-groundwater development model at 1950 53

Table 7. Calibration statistics for the 1950 simulated water levels 53

Table 8. Simulated 1950 water budget for the calibrated pre-groundwater development period model 54

Table 9. Specific yield values applied to the calibrated model 55

Table 10. Additional recharge applied to the development period model by time frame and land use for both NebGuide and CropSim pumpage simulations 57

Table 11. Calibration statistics for the development period simulation showing results using both NebGuide and CropSim pumpage data sets 66

Table 12. Error statistics of simulated versus observed water-level changes for Chase & Perkins Counties from 1973-85 and 1985-98 with NebGuide pumpage data 67

Table 13. Simulated average budget for the calibrated development period groundwater model using NebGuide net pumpage. 68

Abbreviation, Unit, and Conversion Guide

Abbreviations/Acronyms

CMU	Central Model Unit
CNPPID	Central Nebraska Public Power and Irrigation District
COHYST	Platte River *Cooperative Hydrology Study*
DNR	Department of Natural Resources
HU	Hydrostratigraphic Unit
NPPD	Nebraska Public Power District
NRD	Natural Resources District
RASA	Regional Aquifer Systems Analysis
UNL-CSD	University of Nebraska-Lincoln (UNL) Conservation and Survey Division
USGS	United States Geological Survey

Units and Rates

ft	feet
mi	mile
in	inch
yr	year
d	day
ac-ft	acre-feet
ft^3/s	cubic-feet per second

Common Conversions

1 cubic foot = 7.5 gallons

1 acre-foot = 43,560 cubic feet (the amount of water at a depth of 1 foot covering a single acre)

1 cubic foot per second = 449 gallons per minute

1 square mile = 640 acres

Other Comments

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1983 – a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly call Sea Level Datum of 1929.

Elevation: In this report, "elevation" refers to distance above sea level in feet.

Groundwater: In this report, water in the saturated subsurface is termed groundwater (spelled as one word).

Executive Summary

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

The COHYST study area covers 29,300 square miles (mi²) and extends from the Republican River and Frenchman Creek on the south to the Loup River, South Loup River, and a mapped groundwater divide on the north. The eastern boundary follows county lines. The western boundary and part of the southern boundary are 6 miles (mi) inside Colorado and Wyoming. For modeling the groundwater flow system, the COHYST study area was divided into three overlapping units. This report describes the groundwater flow model that was constructed for the Central Model Unit.

The Central Model Unit is approximately 132 mi east-west by 90 mi north-south and covers 11,230 mi². The 2000 U.S. Census indicates that approximately 90,000 people live within the Central Model Unit, with over half residing in the cities of North Platte (23, 878), Lexington (10,011), McCook (7,994), Ogallala (4,930), Cozad (4,163), and Gothenburg (3,619) (U.S. Census Bureau). Agriculture dominates the livelihood and landscape of the region, with land in the valleys irrigated with both surface water and groundwater. Upland areas are used primarily for grazing, dryland crops, and irrigated crops using groundwater pumped from the High Plains aquifer. The topography varies from relatively flat areas such as tablelands and floodplains to hummocky sand dunes. Climate is generally semiarid. Average 1961-90 precipitation ranges from 16 to over 23 inches per year (in/yr). Most of the precipitation occurs in the summer with about two-thirds of the annual total occurring in May through September. Abundant sunshine, frequent winds, and low humidity contribute to a relatively high rate of evaporation.

The North Platte and South Platte Rivers, with headwaters in the Rocky Mountains of southeastern Wyoming and north-central Colorado, join to form the Platte River near the center of the Central Model Unit just east of the city of North Platte. The valleys of these three rivers approximately divide the Central Model Unit into northern and southern halves. Unless otherwise specified, these valleys are collectively termed the “Platte River system valley” hereafter in this document. The Republican River and Frenchman Creek form the southern boundary of the Central Model Unit, and the South Loup River forms the boundary on the eastern half of the northern boundary. Other major streams in the area include Birdwood Creek, Whitetail Creek, Red Willow Creek, and Medicine Creek. Lake McConaughy in Keith County is the largest reservoir in the Central Model Unit. In addition, several smaller reservoirs exist along the Platte River system valley and along Republican River tributary valleys. Numerous small lakes and wetlands occur in the Sand Hills in the northwestern part of the model area.

Within the Central Model Unit, the water table in the High Plains aquifer ranges from more than 3,800 feet (ft) above mean sea level in the northwest to less than 2,100 ft in the east. Depth to water ranges from less than 5 ft near streams to almost 400 ft in the western Keith County. In the mid-1990s, the regional water table in the northwest quarter of the model sloped generally between 7 and 13 feet per mile (ft/mi) towards the southeast. South of the Platte River system valley, the water table slopes between 6 and 12 ft/mi, and in the northeast quarter of the model area the water table slopes between 6 and 8 ft/mi.

The geologic units in the Central Model Unit important to the flow model consist of various Pliocene and Quaternary age deposits, and the Miocene age Ogallala Group. The Oligocene to Miocene age Arikaree Group exists in limited areas of the Central Model Unit, but is generally

not relied upon as a water source as there are typically several hundred feet of saturated Ogallala Group where the Arikaree Group is present. The Arikaree Group generally yields only minor amounts of water to wells, but where sufficient saturated thickness exists, it can yield large amounts of water to wells. In limited areas of the Central Model Unit, permeable zones within the Eocene to Oligocene White River Group (e.g. Chadron Formation) produce minor amounts of water. This water is often of poor quality and is not considered a major resource within the Central Model Unit. Pliocene and Quaternary age deposits typically yield large amounts of water to wells. The Ogallala Group also typically yields large amounts of water to wells, but aquifer productivity can vary considerably within short distances. The Oligocene Brule Formation and the Cretaceous age Pierre Shale form the base of the aquifer in the Central Model Unit.

In 1998, the COHYST Technical Committee developed a formal strategy for construction and calibration of flow models. The overall strategy followed the principle of parsimony: initial simple models constructed that gain detail and complexity as required during the calibration process. This report describes only the final model for the Central Model Unit. This model has a grid cell size of 160 acres and six layers. Three separate models were constructed for the Central Model Unit. The initial model simulated aquifer conditions prior to any European-American influence on the hydrologic system of the High Plains aquifer (pre-1895). The second stage of the model uses the water levels from the initial model as the starting water levels and incorporates canal seepage estimates as additional recharge to the aquifer as the area became further settled and developed between 1895 and 1950. The third and final stage of model development (1950-1998) incorporates groundwater pumpage and modified recharge rates due to land-use modifications.

The process of constructing a flow model begins with a conceptual flow model, which is a description of the characteristics and major processes of the flow system that are important to the numerical model. The conceptual model includes the state of the flow system at the beginning of the simulation period, the influence of external sources or sinks of water, the lateral and vertical boundaries of the model, and what happens to the flow of water at these boundaries.

The external boundaries of the Central Model Unit consist of fixed-flow boundaries at the eastern, western, and a portion of the northern boundary, and river boundaries along the eastern half of the northern boundary (South Loup River) and the entire southern boundary (Frenchman Creek and the Republican River). The western one-third of the northern boundary is a zero flow boundary. Within the model interior, the North Platte, South Platte, and Platte Rivers were treated as river boundaries. All other perennial streams are stream boundaries. The areas of numerous lakes in the Sand Hills were treated as groundwater evapotranspiration areas, as were 1 to 10 mi wide corridors along the Platte River system. Time-varying recharge from surface-water irrigation and canal leakage was included in the model beginning in 1895. Surface water reservoirs were added to the simulation as either additional recharge or fixed-head boundaries when they became operational.

MODFLOW-96, developed by the U.S. Geological Survey (USGS), was selected as the groundwater flow modeling code for this study. The Groundwater Modeling System (GMS version 3.1) was selected as the pre- and post-processor for MODFLOW-96 input and output data. The final Central Model Unit model grid consists of 252 rows, 264 columns, and 44,918 160-acre cells per layer, resulting in 269,508 potentially active cells for the entire grid.

The pre-groundwater development period model started with the period prior to 1895. This was a 5,000-year simulation to allow the groundwater system to come into dynamic equilibrium with precipitation-derived recharge on rangeland. The distribution of this recharge was based on soils and topography. The recharge ranged from 2.50 in/yr in the Sand Hills to 0.15 in/yr year on the clay-loam mantled plains. Recharge due to canal leakage and surface-water irrigation was added to the model beginning in 1895.

Hydraulic conductivity was assigned based on the COHYST testhole database and mapped hydraulic conductivities from the Cooperative Hydrology Study Hydrostratigraphic Units and Aquifer Characterization Report in which layers 1-6 are defined. Model layers 1, 5, and 6 were applied uniform values of 23, 27.5, and 27.5 feet per day (ft/d), respectively. Model layers 2, 3, and 4 were assigned variable hydraulic conductivity values with means of 81, 21, and 27.5 ft/d, respectively. Layer 2 had a higher mean value than all other layers because of coarse unconsolidated sediment within the Pliocene Broadwater Formation and Platte River system alluvial deposits. Individual zones of hydraulic conductivity within layers 2 and 4 were adjusted during calibration. Specific yield was assigned based on the COHYST testhole database. Adjustments in specific yield were made for individual layers as necessary during calibration. All layers were assigned uniform values. A specific yield of 0.11 is assigned to layer 1. Layer 2 is assigned a value of 0.18. Layers 3-6 are assigned a value of 0.17.

Maximum groundwater evapotranspiration ranged from 17 in/yr in the northwestern portion of the model dominated by Sand Hills lakes and wetlands to 13 in/yr in the remainder of the model. This rate was reduced to zero when the water table depth reached 7 ft along riparian corridors and 5 ft elsewhere.

Simulated 1950 water levels were compared to observed water levels at 205 observation points. The mean difference was 1.59 ft, the mean absolute difference was 9.38 ft, and the root-mean-square difference was 11.69 ft. Groundwater discharge to surface drainages was estimated by a low-flow (groundwater contribution to streamflow, also termed *baseflow*) analysis calculated by Carney and Peterson (2001). Simulated groundwater discharge to the Platte River was within the calibrated range for both the Brady, NE to Cozad, NE (baseflow simulated at 72 ft^3/s (cubic feet per second), range of 55 – 119 ft^3/s) and Cozad to the eastern boundary reaches (baseflow simulated at 33 ft^3/s, range of -131 – 133 ft^3/s). Groundwater discharge on the North Platte River between Sutherland, NE and North Platte, NE was below calibration range (baseflow simulated at 44 ft^3/s, range of 69 – 119 ft^3/s). Simulated discharge to the South Platte River between Julesburg, CO and Paxton, NE was simulated higher than the calibrated range (baseflow simulated at 28 ft^3/s, range of -42 – 14 ft^3/s), and flows between Paxton and North Platte, NE was below calibration range. Simulated groundwater discharge to Sand Hills drainages Birdwood (baseflow simulated at 151 ft^3/s, range of 138 – 152 ft^3/s) and Whitetail (baseflow simulated at 29 ft^3/s, range of 14 – 43 ft^3/s) Creeks were within calibration range. Simulated discharge to Republican River tributaries Stinking Water (baseflow simulated at 27 ft^3/s, range of 23 – 32 ft^3/s), Red Willow (baseflow simulated at 27 ft^3/s, range of 22 – 27 ft^3/s), and Medicine Creeks (baseflow simulated at 44 ft^3/s, range of 34 – 51 ft^3/s) were all within calibration range.

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

Additional time-varying recharge, above the amount in the pre-groundwater period model, was applied on certain land-use areas during the groundwater development period. This recharge was added only to cropped land, with more recharge added to irrigated land than to dryland. This recharge changed over time because the amount of dryland and irrigated crop land changed over time. This additional recharge on both dryland and irrigated land increased from west to east across the Central Model Unit. The additional recharge on dryland ranged from 0.15 to 0.9 in/yr and additional recharge on irrigated land ranged from 1.3 to 5.8 in/yr when NebGuide net pumpage was applied to the model. When CropSim net pumpage was simulated, additional dryland recharge ranged from 0 to 0.4 in/yr and irrigated land recharge ranged from 2.3 to 6.8

in/yr. This difference in cropland recharge compensated for differences in the net pumpage estimates for both pumpage estimate methods.

Simulated water-level changes were compared to measured water-level changes for five periods (1950-61, 1961-73, 1973-85, 1985-98, and 1950-98), with the number of available observation points per period ranging from 47 to 227. The mean difference with NebGuide net pumpage ranged from -1.23 to 1.09 ft, the mean absolute difference ranged from 1.29 to 3.19 ft, and the root-mean-square difference ranged from 1.73 to 4.46 ft. Results obtained with CropSim net pumpage varied slightly from results using NebGuide pumpage. With CropSim net pumpage, the mean difference ranged from -1.56 to 0.56 ft, the mean absolute difference ranged from 1.56 to 4.56 ft, and the root-mean-square difference ranged from 2.07 to 7.18 ft. The 1950-98 changes were also compared at 47 points where estimated changes were available. The mean difference with NebGuide pumpage was -2.5 ft, the mean absolute difference was 5.34 ft, and the root-mean-square difference was 8.83 ft. With CropSim pumpage, the mean difference with was -3.84 ft, the mean absolute difference was 6.18 ft, and the root-mean-square difference was 9.98 ft.

This model was compared to the pre-groundwater development period model of the Western and Eastern Model Units. Final hydraulic conductivity values were developed with different methods for the three models, but the ranges of values were similar. Rangeland recharge was based on topographic setting in each model and similar results were obtained. Evapotranspiration rates varied slightly when compared to the neighboring model units, but were similar in the overlap areas within each model unit. The simulated 1950 water tables were generally similar in the southern half of the area of overlap with the Western Model Unit. In the northern half of the area of overlap, the 100-ft contours were parallel but displaced from each other by approximately 3 mi. This difference is possibly due to differences in simulated evapotranspiration. Simulated water tables for the Central Model Unit were similar to those produced in the Eastern Model Unit with only minor deviations 2 mi or less in parts of Gosper and Dawson Counties. This difference is possibly due to slight differences in parameter inputs or boundary conditions of each model.

An analysis was performed to determine the sensitivity of the calibrated model to changes in model parameter inputs by varying one parameter while holding all other parameters constant. A separate analysis was performed for the pre-groundwater development period model and the groundwater development period model, and different inputs were investigated for different periods. For the pre-groundwater development period, changes in hydraulic conductivity, rangeland recharge, the ratio of horizontal to vertical hydraulic conductivity, evapotranspiration, and bed conductance were investigated. The model was about equally sensitive to hydraulic conductivity and rangeland recharge. For the groundwater development period, changes in specific yield, net pumpage, dryland recharge, and irrigated land recharge were investigated. The groundwater development period model was most sensitive to canal seepage and net pumpage and was about equally sensitive to the other inputs.

The final 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 township and county-size areas. This model should not be used beyond its intended purpose without a complete evaluation of model applicability or refinement by a qualified professional. This model is better calibrated in regions with greater numbers of water-level or streamflow observations to calibrate against, and is less precise in regions that lack calibration information.

This model can only represent the flow system as it was understood at the time the model was constructed. As more information is collected and the understanding of the flow system improves, this model should be updated. Calibration of the groundwater development period model was hampered by the lack of pumpage data. Recharge from precipitation on dryland fields is not well defined. This model input could be improved with additional water-level and stream-flow data. Further refinement and understanding of evapotranspiration processes in riparian and wetland areas would also improve the representation of evapotranspiration in the model.

Description and Purpose of COHYST

The Cooperative Hydrology Study (COHYST) is a hydrologic study of surface water and groundwater resources in the Platte River basin of Nebraska upstream from Columbus, NE. 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 Platte River Recovery Program (Governors of Wyoming, Colorado, and Nebraska, and the Secretary of the Interior, 1997; for more information, see http://www.platteriver.org/);
2. Assist the Natural Resources Districts (NRD's) in the study area with regulation and management of groundwater;
3. Provide Nebraska with the basis for groundwater and surface-water policy; and
4. Help Nebraska analyze the hydrologic effects of proposed activities of the Three-State Cooperative Agreement.

The COHYST study area (fig. 1) covers 29,300 mi^2 and extends from the Republican River and Frenchman Creek on the south to the Loup River, South Loup River, and a previously documented groundwater divide on the north. The eastern boundary is a geographic boundary that follows county lines and was located sufficiently to the east such that errors in estimated groundwater flow across this boundary are likely to have minimal effect on water management planning in the densely developed areas or on groundwater discharge to the Platte River at Columbus. The western boundary and part of the southern boundary are also geographic boundaries that are located 6 mi inside Colorado and Wyoming. The remainder of the southern boundary in Colorado is the known extent of the aquifer. These boundaries are sufficiently far from Nebraska that errors in estimated groundwater flow across these boundaries would likely have minimal effect on the study results in Nebraska. Additionally, the southern boundary along the Nebraska panhandle in Colorado approximately follows a mapped groundwater flow line (Nebraska Conservation and Survey Division, 1995). Zero rates of groundwater flow are assumed to cross this boundary, although negligible rate of groundwater movement may occur at some locations.

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 Central Model Unit, shown by the green boundary on fig. 1.

Previous Studies

The earliest studies of groundwater in west-central Nebraska were by **Darton (1905)**. Not long after Darton's work, **Condra (1907)** investigated ground water conditions in the Republican River valley. Other studies in the first half of the 20th Century within the Central Model Unit include work by **Lugn and Wenzel (1938)** that focused on geology and groundwater resources of south-central Nebraska. **Wenzel and Waite (1941)** investigated the groundwater conditions of Keith County. **Waite and others (1946, 1948)** completed a series of investigations of groundwater in the Republican River basin within the Central Model Unit. **Waite (1949)** also investigated groundwater conditions in Dawson County.

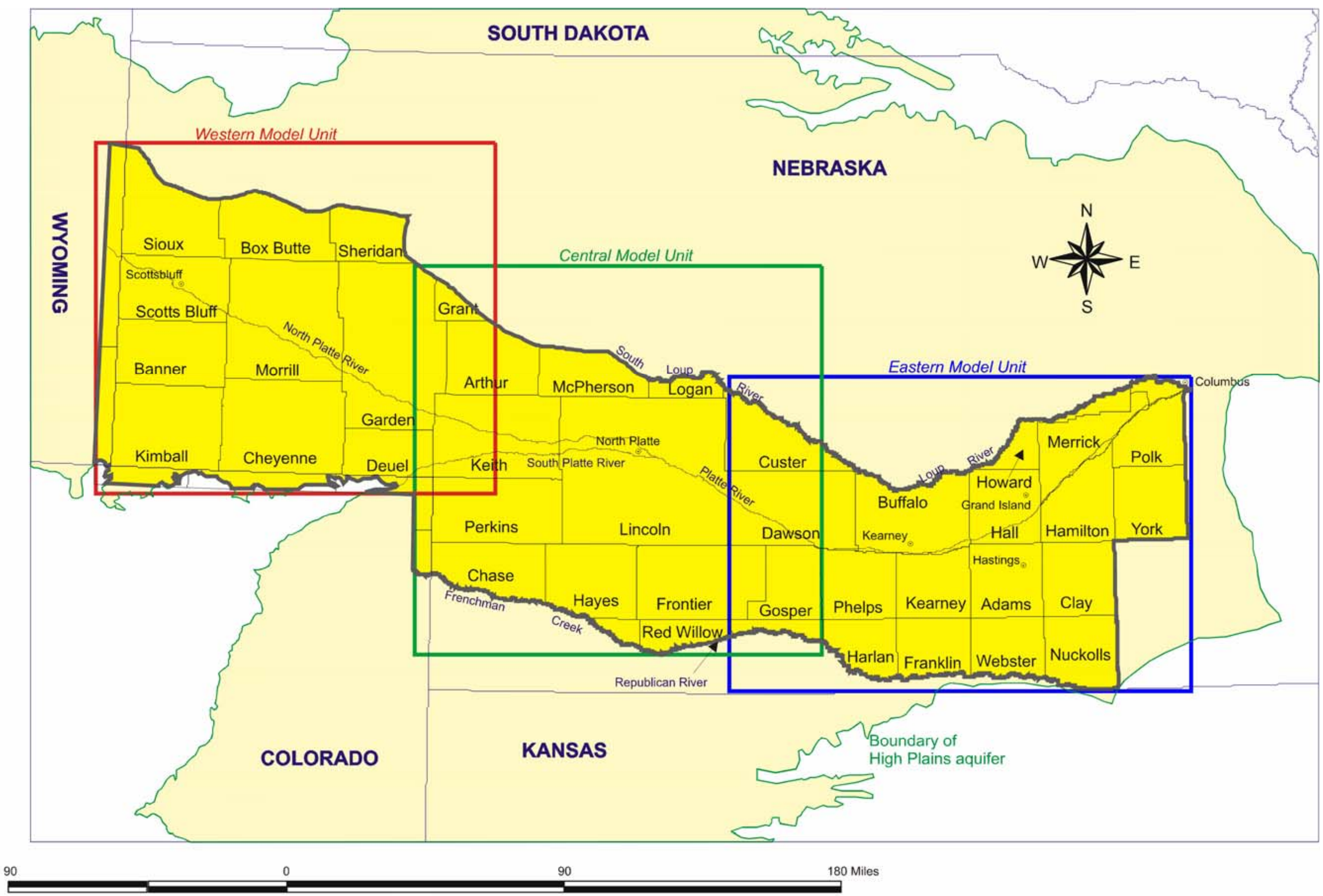


Figure 1. COHYST study area and model units.

In the second half of the 20th Century, a large number of regional and local investigations were conducted in the Central Model Unit, many of which included numerical simulations of groundwater conditions to address the impacts of the rapidly increasing use of groundwater for irrigation. The first large-scale study of the region 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)**. Included in this investigation were large-scale numerical simulations of the aquifer by **Luckey and others (1986, 1988)**. **Pettijohn (1983a and 1983b)** published more detailed reports on the Nebraska portion of this study of the High Plains aquifer. **Dugan and Zelt (2000)** conducted work on soil water conditions of the entire Great Plains area that benefited the calibration process of the Central Model Unit development period model.

Several smaller scale studies since 1950 have benefited the development of the COHYST model. In the southwestern portion of the Central Model Unit, **Bradley and Johnson (1957)** and **Cardwell and Jenkins (1963)** investigated the ground water geology of the Frenchman Creek and Republican River basins. **Bjorklund and Brown (1957)** described the hydrogeologic conditions of the South Platte River valley. **Redell (1967)** discussed ground-water recharge in the Colorado portion of the Central Model Unit. Other investigations of the Colorado portion of the Central Model Unit include modeling studies by **Luckey (1973)** and **Luckey and Hofstra (1974)**. **Leonard and Huntoon (1974)** investigated the groundwater geology of Chase County, and **Lappala (1978)** completed a detailed hydrogeologic investigation (including a digital simulation) of Chase and Perkins Counties. **Peckenpaugh and others (1995)** produced numerical simulations of the same area. **Goeke and others (1992)** investigated the hydrogeology and surface water conditions of much of the area south of the Platte River system in the Central Model Unit. Several studies were also conducted in the eastern Central Model Unit, **Johnson (1960)** described hydrogeologic conditions in much of the southeastern Central Model Unit. **Marlette and Lewis (1974)** and **Keasling (1975)** produced numerical conjunctive-use simulations of the aquifer for irrigation in Dawson County. **Peckenpaugh and Dugan (1983)** investigated hydrologic conditions in parts of Dawson and Custer Counties. **Peckenpaugh and others (1987)** completed a study of the hydrogeology of much of the eastern portion of the Central Model Unit. North of the Platte River system, **McLean and others (1997)** simulated aquifer conditions in the southern Sand Hills including areas of Lincoln, Logan, and McPherson Counties.

Testhole descriptions have been published for every county in the Central Model Unit with the exception of Grant County. These include Arthur County **(Diffendal and Goeke, 2000)**, Chase County **(Dreezen, 2000a),** Custer County **(Cast, 2000a),** Dawson County **(Smith, 1999a)**, Deuel County **(Diffendal, 1999)**, Frontier County **(Eversoll, 2000a)**, Furnas County **(Smith, 2003b)**, Garden County **(Smith and Swinehart, 2000)**, Gosper County **(Cast, 2000b)**, Hayes County **(Eversoll, 2000b)**, Hitchcock County **(Eversoll, 2004)**, Keith County **(Diffendal and Goeke, 2004)**, Lincoln County **(Goeke, 2004a)**, Logan County **(Wigley, 2001)**, McPherson County **(Goeke 2004b)**, Perkins County **(Dreezen, 2000b)**, and Red Willow County **(Eversoll, 2003)**.

Modeling Strategy

Groundwater flow models are one of the primary tools being developed by COHYST to help meet project objectives (p. 11). Flow models can be used to predict the effects of implementing groundwater management alternatives. Effects of these alternatives include changes in water levels over time and changes in groundwater contributions to streamflow (baseflow). The overall COHYST strategy for model development is to start with simple representations and add detail to the models as required to reach the best fit between simulated and observed groundwater levels and baseflow values (the concept of parsimony). The strategy calls for constructing flow models for three overlapping areas (fig. 1). The Central Model Unit (CMU) overlaps with the Eastern Model Unit to the east and the Western Model Unit to the west. Within the areas of overlap the models were coordinated so as to maintain consistency with each other in terms of model inputs, simulated water levels, and groundwater flows. However, because the models were developed on different schedules, some inconsistency in overlapping zones remains. Differences between this Central Model Unit model and adjacent models are described in the "Comparison to Adjacent Models" section (p. 68).

The strategy called for initially developing models with a fixed grid having cells of 4 mi^2 in size and a single layer and eventually decreasing grid size to 160 acre cells and including one to eight layers. This report is for a model grid of 160 acres and six layers. The grid for the CMU was built with six layers instead of eight, because of the combination of materials defining layers with similar hydraulic properties (layers 3 and 4), and the lack of Arikaree Group in the CMU. Models were constructed for three time periods. The first period simulated the time prior to any influence of Euro-American settlers on the hydrologic system. The second period simulated conditions prior to large-scale development of the aquifer for irrigation (pre-groundwater development period). The third period simulated conditions after the beginning of large-scale utilization of the aquifer (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 CMU by 1950, but some areas continued to be developed until the 1960s. Both the pre-groundwater development period model and the groundwater development period model are described in this report.

Description of Central Model Unit

The Central Model Unit (CMU) covers 11,230 mi^2 in west-central Nebraska and is bounded by both hydrologic and political boundaries (fig. 3). The western boundary is an extension of the north-south segment of the Colorado-Nebraska state line and extends from northern Garden County southward into Colorado and terminates at Frenchman Creek. The eastern boundary coincides with the eastern county line of Furnas County and extends northward to the South Loup River in Custer County. The northern boundary lies along the South Loup River from the eastern boundary through Logan County. From western Logan County, the boundary follows a groundwater divide through central McPherson County, northeast Arthur County, and southwest Grant County to the western boundary. The southern boundary follows Frenchman Creek from the western boundary to its confluence with the Republican River. From this point, the boundary follows the Republican River to the eastern boundary.

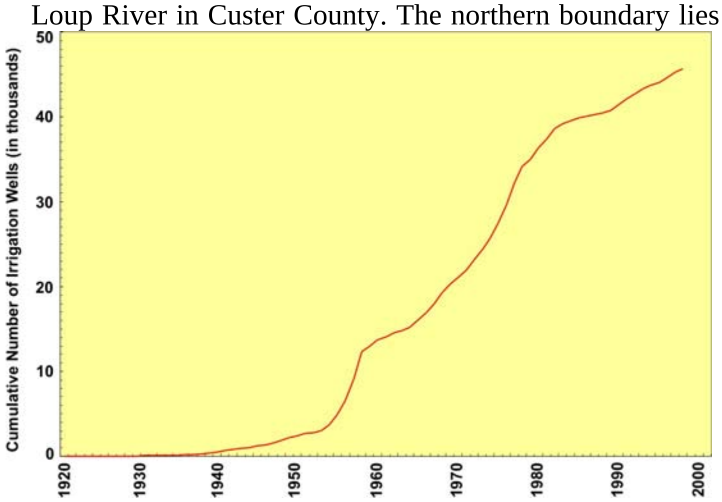


Figure 2. Irrigation well development in the COHYST area.

The 2000 Census indicates approximately 90,000 people live within the CMU with over half residing in the cities of North Platte (23,878), Lexington (10,011), McCook (7,994), Ogallala (4,930), Cozad (4,163) and Gothenburg (3,619). The remaining population is primarily rural or in small towns and villages. Nine Natural Resources Districts (fig. 4) exist entirely or partially within the CMU including the Twin Platte, Central Platte, North Platte, Upper Republican, Middle Republican, Lower Republican, Upper Loup, Lower Loup, and Tri-Basin Natural Resources Districts.

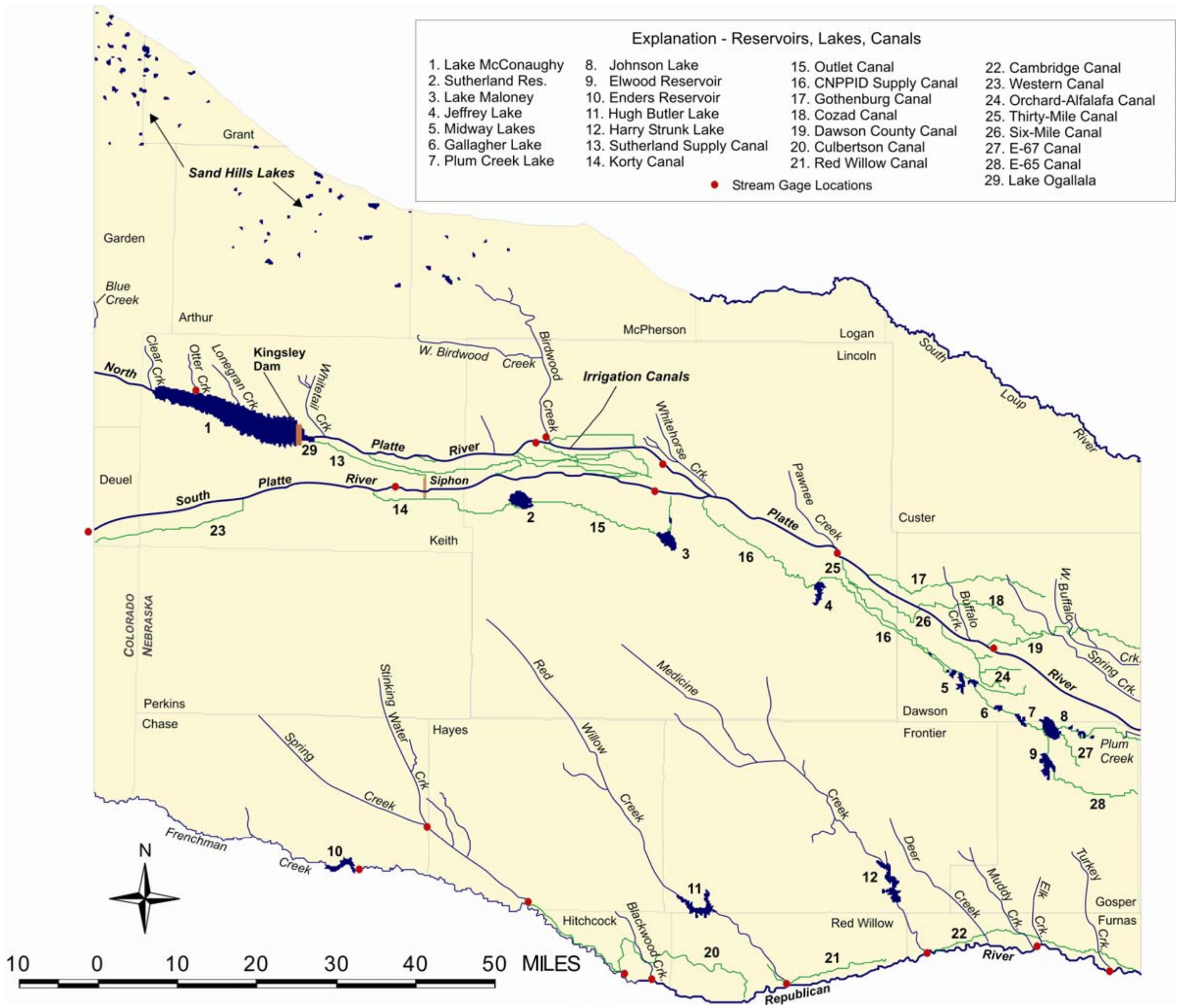


Figure 3. Major surface-water features in the Central Model Unit. Note that numerous drains exist along the Platte River system valley but are too numerous to show on the scale of this map. Drain locations are shown in the conceptual model on figure 9.

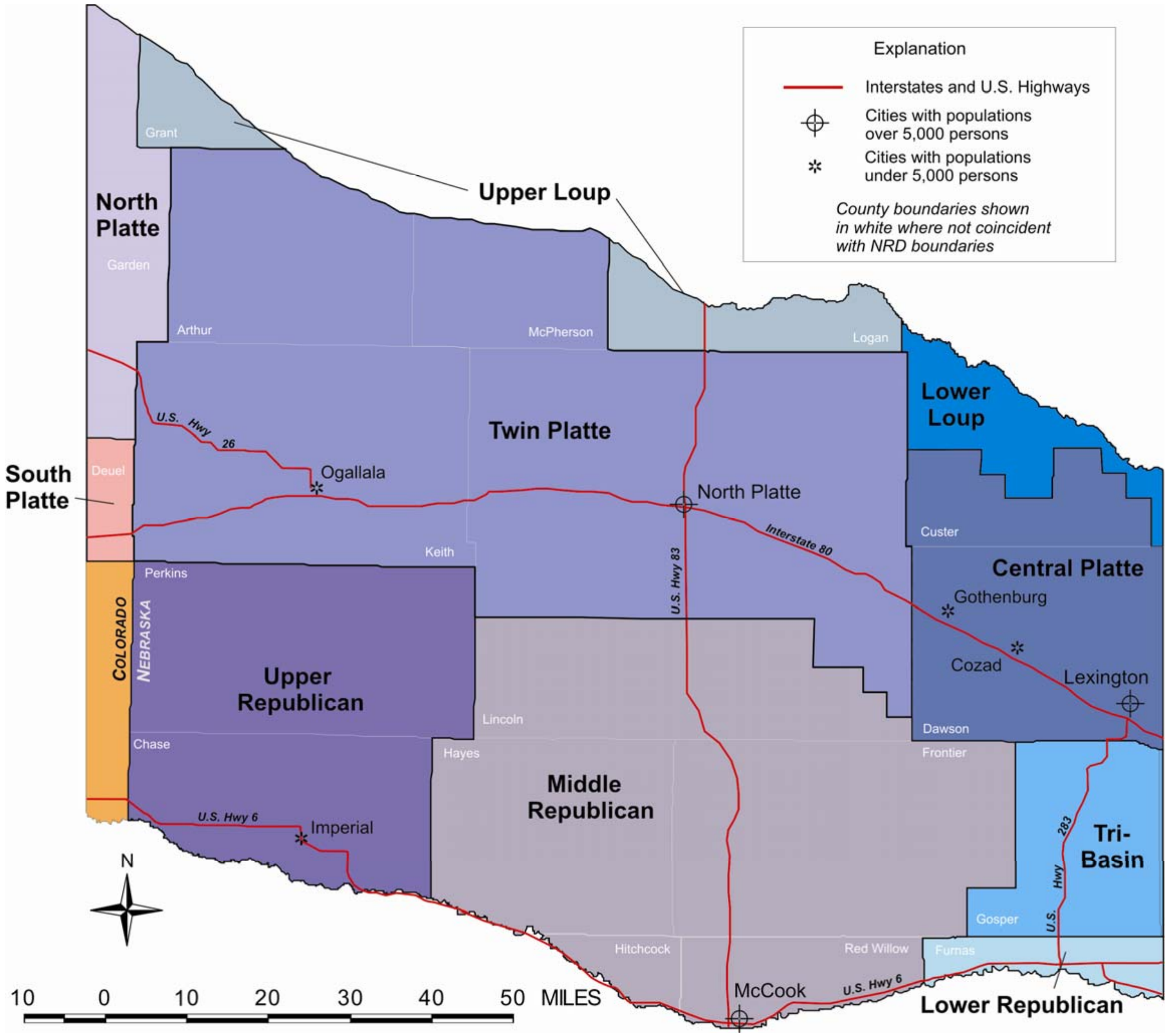


Figure 4. Natural Resource Districts (in bold), cities, and major roads within the Central Model Unit.

Agriculture plays a pivotal role in the livelihood and economy of the Central Model Unit and dominates the landscape of the region. Land in the valleys can be irrigated from both surface water (canals) and groundwater. Upland areas are used primarily for grazing, dryland crops, or row crops where wells tapping the High Plains aquifer allow irrigation. As of 1946, near the end of the time period considered pre-groundwater development for this study, approximately 24 percent (1,743,000 acres) of the total Central Model Unit land area (7,187,200 acres) was harvested, with crops including corn, soybeans, hay, wheat, sorghum, and other minor crops such as oats, sugar beets, and dry beans (COHYST, 2000a).

Broad valleys, rolling uplands, and narrow canyons form the general topography of the Central Model Unit. The Platte River system roughly divides the area in half, and east of the city of North Platte, it lies within a valley ranging from 5 to 15 mi in width. Similar but narrower valleys exist upstream of the confluence of the North and South Platte Rivers. The southern extent of the Sand Hills, a large topographic region consisting of sand dunes stabilized by short grasses in western Nebraska, comprises most of the area north of the Platte River system valley in the Central Model Unit. The southwest quarter of Lincoln County and small areas of Hayes, Chase, and Perkins Counties are also covered by sand dunes. South of the Platte River system, the topography consists of relatively flat to gently rolling uplands divided by steep valleys of tributary drainages to the Republican River. The valley of the Republican River lies along the eastern half of the southern boundary. In many areas, the valley walls are comprised of exposed Ogallala Group units, and in limited areas, Cretaceous bedrock (Waite and others, 1948).

Land surface elevations within the model area range from about 4,100 ft above mean sea level in the northwest corner to just over 2,000 ft in the southeast corner in the Republican River valley, resulting in a total relief in the study area of approximately 2,100 ft. Between the eastern and western boundary, the land slopes between 6 and 10 ft/mi.

Middle-latitude dry continental climate conditions persist in the present-day central COHYST area. This type of climate is characterized by low humidity, high evapotranspiration, abundant sunshine, moderate precipitation, and persistent winds (Gutentag and others, 1984). For the period of 1961 to 1990, mean annual precipitation ranged from 16 in/yr in the northwest corner of the CMU to over 23 in/yr near the eastern boundary (fig. 5) (Nebraska Department of Natural Resources, 2000a). The 100th Meridian, commonly referred to on the Great Plains as the "Line of Aridity," passes through the town of Cozad and roughly coincides with the 22 in/yr contour for annual precipitation (Nebraska State Historical Society website). East of this line, more humid conditions exist. From this line to the western Central Model Unit boundary, annual average precipitation drops nearly 6 in/yr. Roughly seventy percent of precipitation falls in the crop-growing months of April through August. Figure 5 shows data from weather stations at three locations trending northwest to southeast across the Central Model Unit (Nebraska Department of Natural Resources, 2000a). Each location reveal similar trends with peak precipitation in the months of May to July, and an overall higher amount of precipitation each month in the eastern part of the study area.

Figure 5 shows annual lake evaporation ranges from approximately 46 in/yr to 52 in/yr from north the south (Nebraska Department of Environmental Quality, 1981). Average annual minimum to maximum temperature in the study area ranges from 34 to 62° Fahrenheit (F) at Arthur, NE to 37 to 66° F at Cambridge, NE (Worldclimate website, 2000). The combination of high summer temperatures and dry windy conditions creates high evapotranspiration rates.

Several major surface water features within the Central Model Unit, including the drainages that comprise portions of the model area boundaries, have significant influence on the groundwater flow system. The Platte River system, including the South Platte, North Platte, and Platte Rivers, and the hydrologically-connected underlying aquifers are the primary focus of the current study.

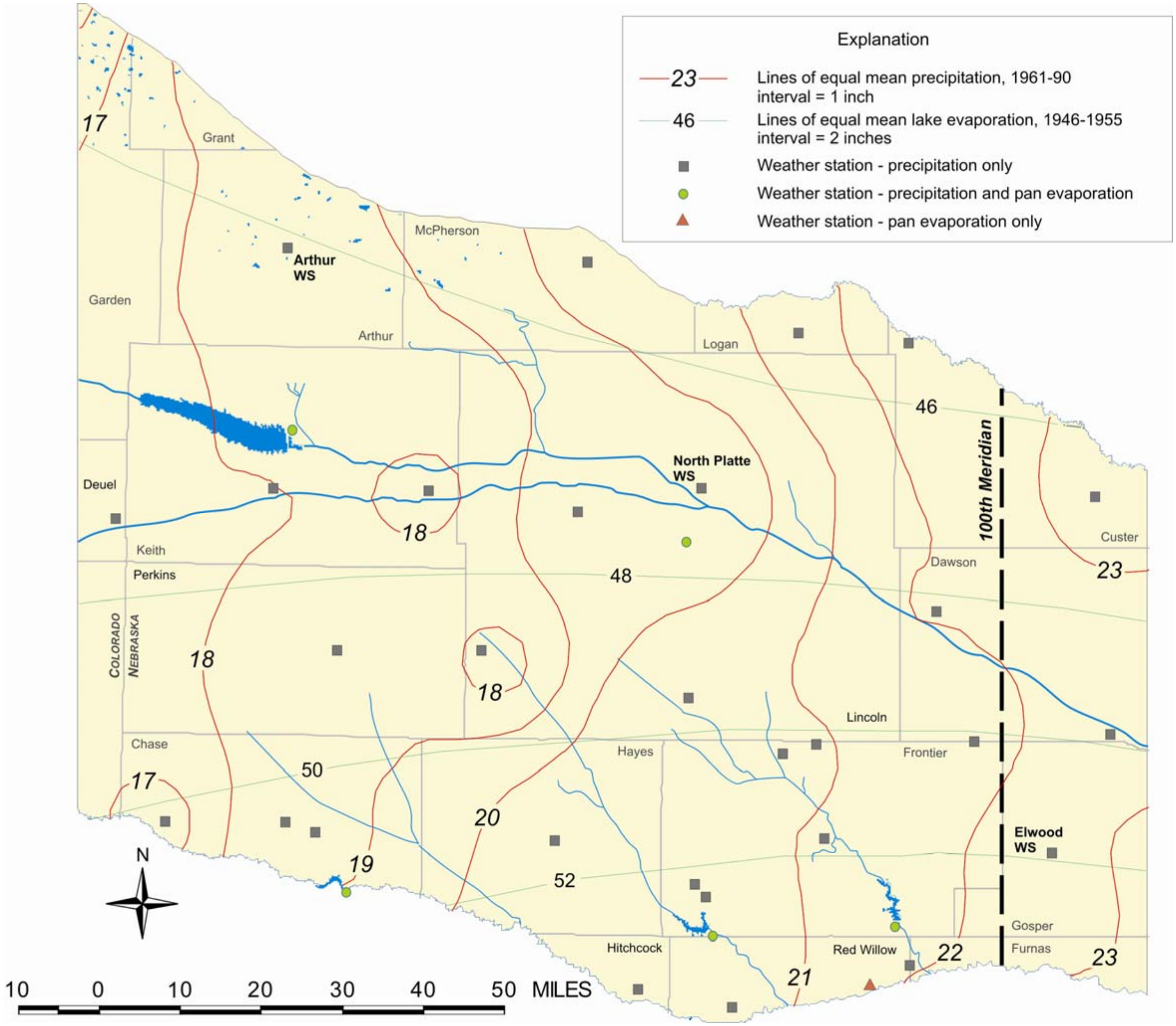


Figure 5. Average 1961-90 precipitation, average lake evaporation, and meteorological stations in the Central Model Unit. Note station locations shown are those with at least 20 years of record since 1889.

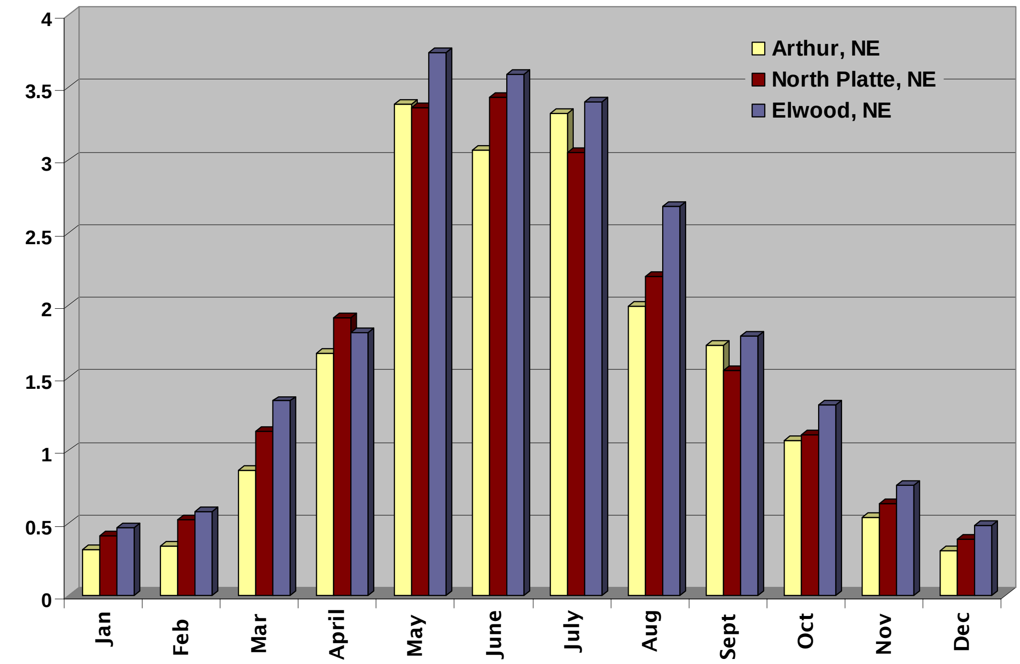


Figure 6. Average monthly precipitation for 1948-1999 at three stations in the Central Model Unit illustrating the temporal distribution of precipitation by month. Note locations of gages on figure 5. (Nebraska Department of Natural Resources, 2000a).

The North Platte and South Platte Rivers, which drain the Rocky Mountains of north-central Colorado and southeastern Wyoming, join near the center of the CMU just east of the city of North Platte to form the Platte River (fig. 3). To contrast discharges in the three rivers, flow in the South Platte River from 1932 to 1946 (a time period prior to major groundwater development) at North Platte averaged 352 ft^3/s (Nebraska Department of Natural Resources, 2000c) and flow in the North Platte River at North Platte averaged 984 ft^3/s. Flow in the Platte River for the same time period near Overton averaged 1,357 ft^3/s (U.S. Geological Survey, 2000). Although flows at these gages could have been influenced by upstream impoundments and diversions, these values give a general comparison of the magnitude of flow in each river. Although Overton is approximately 6 miles east of the model boundary, it is the closest station available with pre-groundwater development-era flow records.

The North Platte and Platte Rivers in the Central Model Unit have several smaller tributary streams that drain the Sand Hills from the north and the valley floodplain. These streams, which derive flow from steady groundwater seepage and springs, have very consistent flows throughout the year, including periods of drought (Nebraska Conservation and Survey Division, 1990). The most prominent of these streams are Birdwood, Pawnee, and Whitetail Creeks. For example, from 1932 to 1946, Birdwood Creek had a mean flow of 145 ft^3/s, with a range of monthly averages from 130 to 180 ft^3/s (Nebraska Department of Public Works, 1933-1946). This time period included the severe droughts of the Dust Bowl years in the mid 1930s. Blue Creek, another tributary to the North Platte River, also originates in the Sand Hills, and flows within the CMU for a 4-mile stretch along the western boundary in Garden County (fig. 3).

The southern half of the model area is drained by several tributaries to the Republican River and Frenchman Creek. Many of these streams are spring fed in areas where the water table in the High Plains aquifer intersects valley walls. However, several of these streams are not perennial at

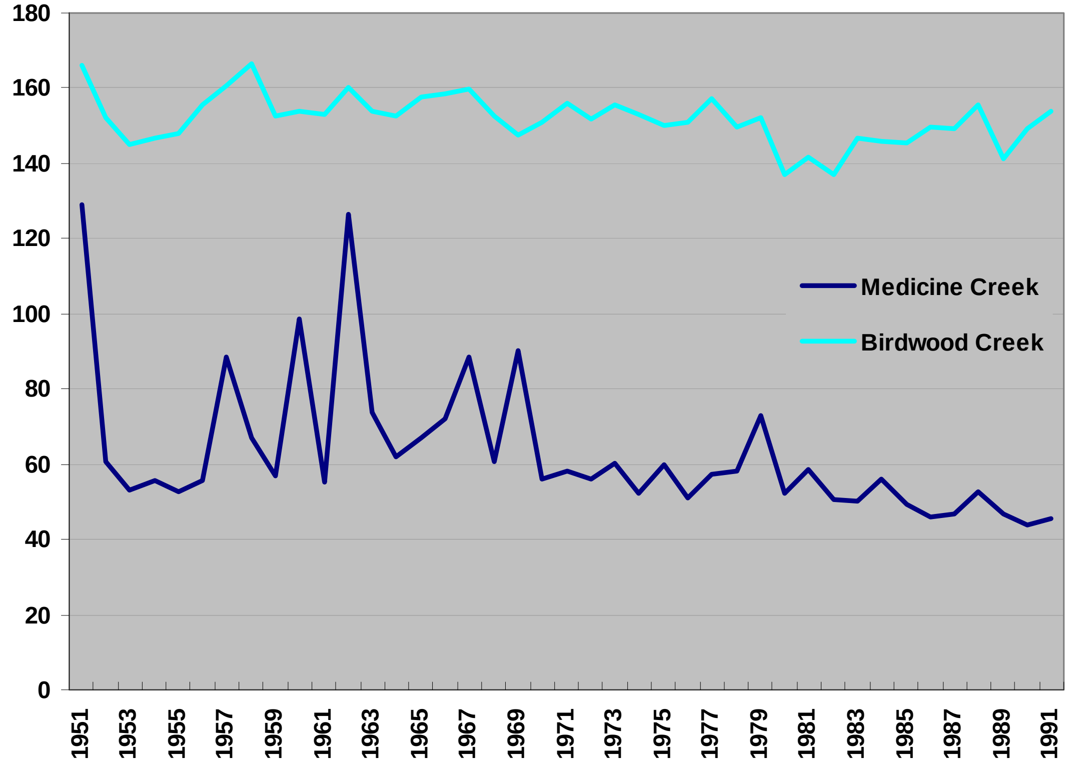


Figure 7. Hydrographs comparing annual (1951-1991) average flow of streams draining the Sand Hills (Birdwood Creek) and the Republican River basin (Medicine Creek). Rates (y-axis) are in cubic feet per second. (Nebraska Department of Natural Resources, 2000c).

their headwaters. Many small canyons exist north of the Republican valley, but most do not contain perennial streams. As illustrated in fig. 7, flows in the Republican River tributaries, such as Medicine Creek, are more erratic than those draining the Sand Hills, such as Birdwood Creek. The trend of Medicine Creek may exemplify the influence of groundwater pumping for irrigation on stream flows starting in the 1970s. This trend is not as evident in Birdwood Creek due to the lack of groundwater irrigation development and highly permeable soils that allow for higher potential amounts of groundwater recharge. Influential drainages in the Republican River basin are Stinking Water, Red Willow, and Medicine Creeks.

The demand for irrigation water storage and hydroelectric power in the early decades of the 20th Century prompted the development of several reservoirs in the Central Model Unit. The largest of these is the 35,700-acre Lake McConaughy created by Kingsley Dam located near the town of Ogallala in northwest Keith County (fig. 3). Kingsley Dam began storing water in 1941, and the dam was officially completed in 1943. In 1943, there were 50,686 acres irrigated from Lake McConaughy storage, and by 2003 that number doubled to over 100,000 acres. Other large lakes within the Central Model Unit in the Platte River basin include Sutherland Reservoir (3,050 acres) in western Lincoln County, Lake Maloney (1,650 acres) located near the city of North Platte, and a chain of lakes along the Central Nebraska Public Power and Irrigation District (CNPPID) Supply Canal, including Jeffrey (575 acres), Midway (457 acres), Plum Creek (252 acres), and Johnson Lakes (2,060 acres). Also in the Central Model Unit, but not along the CNPPID Supply Canal, is Elwood Reservoir (1,140 acres) south of Johnson Lake. Three reservoirs were created by damming tributaries to the Republican River, including Enders Reservoir (1,707 acres) on Frenchman Creek, Hugh Butler Lake (1,628 acres) on Red Willow Creek, and Harry Strunk Lake (1,850 acres) on Medicine Creek.

The northwest quarter of the Central Model Unit contains numerous small natural lakes and wetlands within the Sand Hills. These lakes and wetlands are considered to be the surface expression of the local water table. Wetlands and other areas of high evapotranspiration also exist throughout the Central Model Unit, particularly along floodplains of the major rivers.

Figure 8 shows that the pre-groundwater development water table in the High Plains aquifer ranges from more than 3,800 ft above sea level in the southwest to less than 2,100 ft in the east (Gutentag and others, 1984; Cederstrand and Becker, 1999). Depth to water ranges from nearly zero close to streams to almost 400 ft in western Keith County. The water table in the northwest quarter of the model area slopes between 7 and 13 ft/mi. South of the Platte River system valley, the water table slopes between 6 and 12 ft/mi, and in the northeast quarter of the model area the water table slopes between 6 and 8 ft/mi. The water table contours in northwest Lincoln County and McPherson County steepen in the vicinity of Birdwood Creek, which indicates the influence the stream has on the regional groundwater flow system in the Sand Hills.

Geologic and Hydrostratigraphic Units of the Central Model Unit

Following is a description of the geologic units present in the Central Model Unit and the conceptualization of them into hydrostratigraphic units.

Geologic Units

The geologic units in the Central Model Unit consist of various unconsolidated Quaternary age deposits, Pliocene age deposits, and the Tertiary age Ogallala Group (table 1). Quaternary deposits consist of Pleistocene alluvial deposits, Pleistocene and Holocene loess, Holocene dune sand, and Holocene alluvial deposits. Pliocene deposits of importance in the area consist of coarse alluvium typically overlain by finer Quaternary materials. Quaternary loess deposits are found throughout the Central Model Unit. These deposits are thickest south of the Platte River valley in southeastern Lincoln County and north of the valley in northeastern Lincoln County and southwestern Custer County. The loess deposits have thicknesses exceeding 400 ft in some locations. In general, these deposits are saturated in the lowermost 100 ft. and are capable of storing and slowly releasing large amounts of water. North of the Platte River system valley, extensive Pleistocene and Pliocene alluvial deposits are present and can exceed 150 ft in thickness. Thick deposits of Pleistocene alluvium, which typically yield large volumes of water to wells, are found within the major river valleys and larger tributaries. South of the Platte River system valley, extensive Quaternary alluvial deposits are thin to absent in the Central Model Unit. The Holocene alluvial deposits occur primarily along the Platte and Republican Rivers. These deposits and the underlying Pleistocene-age alluvial deposits are a heterogeneous mixture of gravels, sands, silts, and clays with permeabilities that allow for highly productive wells throughout much of the Central Model Unit.

Extensive deposits of Holocene dune sand exist north of the Platte system valley in the Central Model Unit, which comprise the southern extent of the Nebraska Sand Hills. These deposits exist in various dune shapes and sizes, with some individual dunes exceeding 300 ft in height. South of the Platte system valley, thinner, less extensive dune sand deposits exist. Dune sand will yield minor amounts of water because the saturated thickness of dune sand generally is small to non-existent and typically much larger volumes of water can be developed from underlying units. These deposits typically exist above the water table throughout the Central Model Unit, but do provide for areas of potentially substantial groundwater due to the extensive permeable soils present in this region.

The Ogallala Group consists of a heterogeneous mixture of gravels, sands, silts, and clays of the Ash Hollow, Valentine, and Runningwater Formations. However, COHYST does not

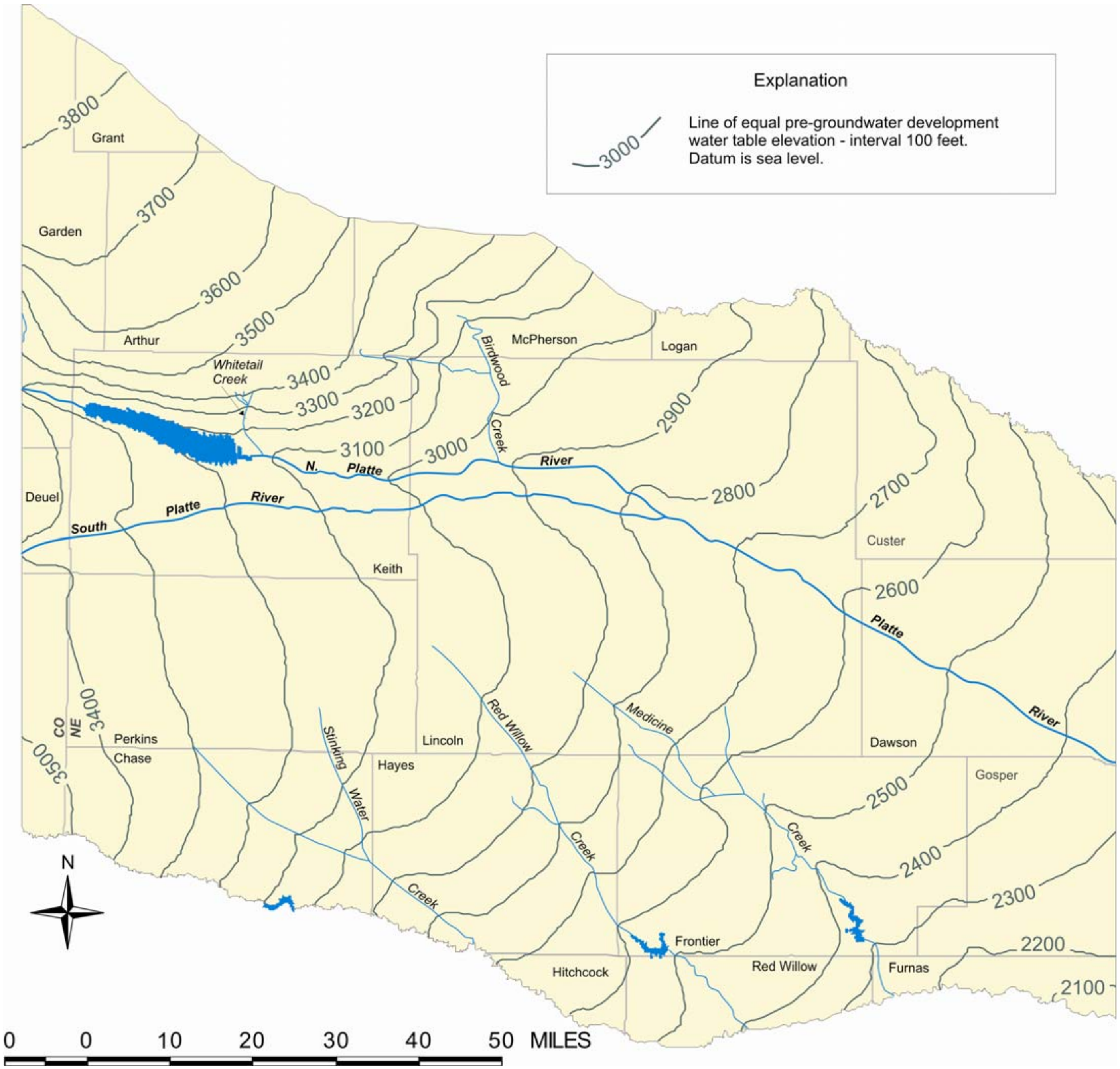


Figure 8. Pre-groundwater development water table in the Central Model Unit. Modified from a generalized map by Gutentag and others (1984) and detailed digital map by Cederstrand and Becker (1999).

System	Series	Geologic unit	Hydrostratigraphic unit	Description
Quaternary	Holo-cene	Alluvium and colluvium	Generally unit 2	Gravel and sand, with some silt, and clay deposits. Generally fluvial deposits. Upper fine material, if present, is assigned to Hydrostratigraphic unit 1. Lower fine material, if present, is assigned to unit 3. Occurs in major river valleys where thicknesses can exceed 150 ft.
	Pleistocene and Holocene	Dune sand	Generally unit 1	Generally fine sand but may contain some medium to coarse sand. May also contain some finer material. Primarily eolian deposits. Thickness may exceed 300 ft in Arthur, Grant, and McPherson Counties, but generally sit above the regional water table .
		Loess deposits	Unit 1 when above unit 2, otherwise unit 3	Generally silt, but may contain some very fine sand and clay. Deposited as eolian dust. Can range from 1 to nearly 400 ft in thickness in the Central Model Unit, with the areas of greatest thickness south of the Platte valley in Dawson and Gosper Counties. The water table exists typically within the lower 100 ft of this unit. Areas of considerable thickness also exist in eastern Lincoln County and southwestern Custer County.
	Pleistocene	Alluvial deposits	Generally unit 2	Gravel, sand, silt, and clay with coarser materials more common. Generally fluvial deposits. Upper fine material, if present, is assigned to Hydrostratigraphic unit 1. Lower fine material, if present, is assigned to unit 3. Primarily exists within the Platte valley in the Central Model Unit and in minor tributary valleys of the Republican and Platte Rivers. Exists in places beneath dune and loess deposits of Units 1 and 2 adjacent to the Platte valley. Thicknesses can exceed 200 ft in areas of the Central Model Unit.
Tertiary	Pliocene	Broadwater Formation	Unit 2	Coarse gravel and sand with some silt and clay. Fluvial deposits. Generally exists in deposits north of the North Platte River and Platte River valleys where it can be over 150 ft thick. Generally increases in saturated thickness from west to east in the Central Model Unit and provides highly productive zones for irrigation wells when saturated.
	Upper and middle Miocene	Ogallala Group	Units 4-6	Heterogeneous mixture of unconsolidated gravel, sand, silt, and clay. Generally fluvial deposits but also contains eolian deposits. Upper fine material, if present, is assigned to Hydrostratigraphic unit 4. Middle coarse material, if present, is assigned to unit 5. Lower fine material, if present, is assigned to unit 6. Typically 200-400 ft thick, but may exceed 600 ft thick. Present throughout nearly all of the Central Model Unit with the exception of an area in the North Platte River valley in the vicinity of Lake McConaughy and the town of Keystone. In addition, not present in some areas along the southern boundary along the Republican River valley.
	Lower Miocene and upper Oligocene	Arikaree Group	Unit 7	Primarily very fine to fine-grained sandstone but may also contain siltstone and eolian volcanic ash deposits. Locally, may contain conglomerates, gravels, and sands of fluvial origin. Occurs in very limited areas in the northwestern part of the Central Model Unit.
	Lower Oligocene	Brule Formation of White River Group	Unit 8 if High Plains aquifer or Unit 9 if below High Plains aquifer	Predominately siltstone, but may contain sandstone and channel deposits. Sometimes highly fractured with areas of fracturing difficult to predict. Upper part of Brule Formation is included in High Plains aquifer and Hydrostratigraphic unit 8 only if fractured or contains sandstone or channel deposits, otherwise considered unit 9 and is excluded from the High Plains aquifer. Eolian volcanic ash deposits with some fluvial deposits.
	Upper Eocene	Chadron Formation of White River Group	Unit 9; below the High Plains aquifer	Silt, siltstone, clay, and claystone. Generally forms impermeable base of High Plains aquifer. Fluvial deposits and eolian volcanic deposits. Some fluvial deposits exist at the base of this unit.
K[1]	Undif-feren-tiated	Undifferentiated	Unit 10; below the High Plains aquifer	Shale, chalk, limestone, siltstone, and sandstone originating as shallow to deep marine deposits as well as beach sediments.. Except for a few minor areas of Fox Hills Sandstone in the extreme western part of the COHYST area and the Dakota Group in the extreme eastern part of the area, generally forms an impermeable base of High Plains aquifer.

1 – Cretaceous Period

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

subdivide this unit below the group level. Outside of Nebraska, the Ogallala is considered a single formation. The saturated portion of the Ogallala Group is capable of providing large volumes of water to wells throughout much of the region, so much so that an entire economy of groundwater-irrigated agriculture developed in the Central Model Unit starting in the 1960s when well and pivot technology created the capacity for water extraction from depths of several hundred feet. The Ogallala Group is present throughout most of the Central Model Unit, with the exception of areas in the Republican River valley and in the vicinity of Kingsley Dam on Lake McConaughy. The Ogallala Group can be viewed in outcrops at several locations in the western half of the Central Model Unit, primarily in valleys of Republican River tributaries and along the North and South Platte River valleys in Keith County.

The Arikaree Group exists in limited areas of the Central Model Unit, but is not relied upon as a water source as there are typically several hundred feet of saturated Ogallala Group above the Arikaree Group where present in the Central Model Unit. The Arikaree Group is predominately a very fine to fine-grained sandstone that yields only minor amounts of water to wells. It is however relied upon as a water source in parts of the Western Model Unit, where the Arikaree Group can yield beneficial amounts of water to wells.

The Brule Formation is predominately a siltstone that forms the base of the High Plains aquifer in the northern half of the Central Model Unit (fig. 12). In some areas to the west of the Central Model Unit, the upper portion of the Brule Formation can be fractured and yield appreciable amounts of water to wells. These conditions are not known to exist in the Central Model Unit.

The High Plains aquifer is underlain by shale, chalk, limestone, siltstone, and sandstone of Cretaceous age. Except for sandstones (which are not included in the model), these units transmit very little water and form a relatively impermeable base to the High Plains aquifer.

Hydrostratigraphic Units

COHYST divided the High Plains aquifer into eight Hydrostratigraphic Units plus two additional units beneath the High Plains 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 typically consists of an upper Quaternary age silt or clay; Unit 2 consists of a middle Quaternary age or Pliocene age sand and/or gravel; and Unit 3 consists of a lower Quaternary age silt or clay. 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 an upper Miocene-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 of lower Miocene or upper Oligocene age. Unit 8 consists of that part of the Brule Formation that is part of the High Plains aquifer because of the presence of water-bearing fractures and/or 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 in the Central 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).

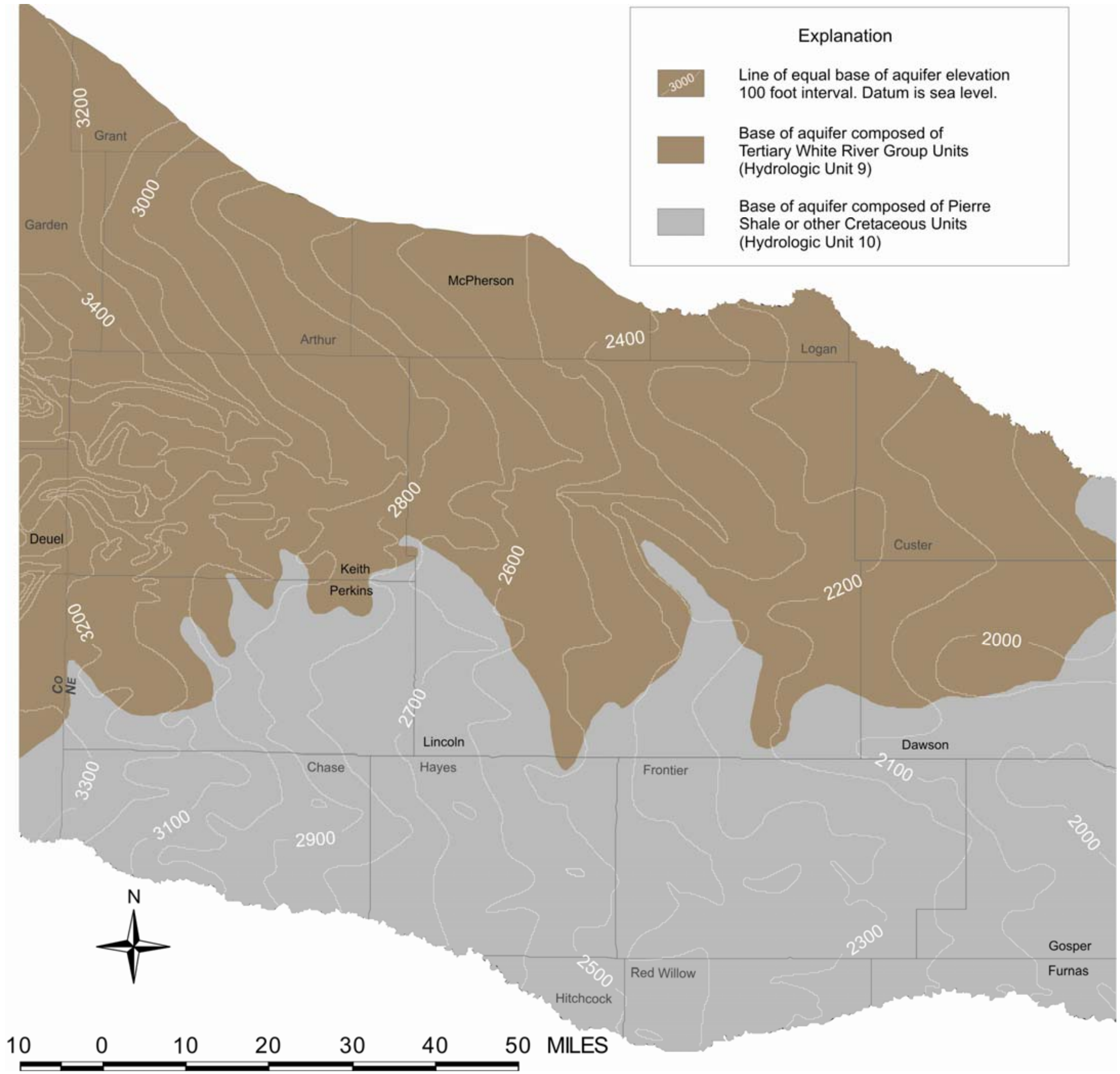


Figure 9. Elevation and geologic units of the High Plains aquifer base in the Central Model Unit.

Conceptual Flow Model

A conceptual flow model is a narrative description of the characteristics of the flow system that are commensurate with the intended use of a model. The conceptual model includes the state of the flow system at the beginning of the simulation period, definition of lateral and vertical boundaries of the model, and specification of the location and flow characteristics of sources and sinks of water. An example of an important characteristic of the flow system is the variation of hydraulic conductivity (a parameter describing the ability of the aquifer to transmit water) over the model area. The state of the flow system at the beginning of simulation describes whether the system is in a state of dynamic equilibrium or whether it is in a state of change. An example of an external source of water would be recharge from applied irrigation water and an example of an external sink of water would be evapotranspiration by a stand of cottonwood trees whose roots directly tap the aquifer. The details of the conceptual model can evolve as the model calibration proceeds, but the basic framework generally is understood at the start of model construction.

Boundaries

Definition of boundaries is typically the first step in conceptual model development. A boundary in this type of setting is simply a feature or area where water either enters or leaves the flow system. These features can be large surface areas (irrigated croplands), specified linear features (rivers), or isolated local features (pumping wells). Surface water features, including rivers, streams, engineered drains/ditches, lakes, and wetlands are considered boundaries of a system if they are in connection with the water table. Water also typically enters and leaves an aquifer in a defined model area. The subsurface flow of water through these boundaries is called fixed-flow and can be defined in areas where fluxes across a defined boundary can be estimated. A variation of this type of boundary is a zero-flow boundary, in which no groundwater movement is expected across a specified area. Recharge to the system, whether precipitation-derived, lake/canal seepage, or excess irrigation water is also considered a boundary. The aquifer in the Central Model Unit is considered unconfined. In such settings, the water table is in connection with the atmosphere and is also considered a boundary. Each of these features can be uniquely represented numerically in a model code. The methodology for defining these features is described in the following section Numerical Model Construction.

The upper boundary of the model was the water table and the lower boundary of the model was the surface of either the White River Group or Cretaceous bedrock. The external boundary of the Central Model Unit (fig. 10) consisted of subsurface fixed-flow boundaries along the eastern and western boundaries and a river along the entire southern boundary (Republican River and Frenchman Creek). The northern boundary was also assigned subsurface flow and river boundaries (South Loup River), as well as zero-flow boundary. The east and west bounds of the Central Model Unit were geographic boundaries of the model area where subsurface flows could be easily estimated from water table elevations. At the selected locations, these boundaries were expected to have relatively small influence on the internal area of the model. The zero-flow boundary along the northern border was delineated along lines where water-table maps indicated that little or no groundwater cross these boundaries. Much of the northern boundary coincides with either a groundwater divide or a flow line, so no groundwater crosses this boundary (Nebraska Conservation and Survey Division, 1995). Early simulations of the Central Model Unit indicated that portion of the northern boundary in McPherson County was not a zero-flow boundary, but rather a fixed-flow boundary with a total inflow of 23 ft^3/s or 1.4 ft^3/s per mile. This flow was estimated based on aquifer parameters and the gradient of the water table. Rather than altering the model grids, the boundary was changed to a subsurface flow boundary.

Internal boundaries in which water has the potential to both enter and leave the system within the Central Model Unit consisted of numerous surface water features including major rivers, smaller streams, drains, wetlands, riparian woodlands and vegetation directly tapping the water table (evapotranspiration), and lakes. In addition to these surface features, areal recharge boundaries were defined over the entire model area as well as pumping boundaries where water is removed from the system.

Groundwater Flow

Groundwater movement across the Central Model Unit is generally from west to east (fig. 8, p. 16) . Water movement is through the pore spaces within the sediments that make up the geologic units in the subsurface. This movement can be very slow, typically on the order of a few tens of feet per year in the Central Model Unit. North of the Platte River system valley, water enters across the western subsurface flow boundary (and to a lesser extent, the northern subsurface flow boundary) and moves southeast towards the North Platte River. This general west-northwest to east-southeast movement of groundwater is altered by the surface drainages Whitetail and Birdwood Creeks. These features modify the regional gradient and serve as consistently flowing, major tributaries to the North Platte River. East of Birdwood Creek, groundwater movement continues east-southeast towards the eastern boundary. Approximately halfway between the Platte River and the northern boundary is divide in the flow regime. North of this divide, groundwater movement is northeastward towards the South Loup River, and south of this divide groundwater flow is towards the Platte River. South of the Platte River system valley, water movement is generally west to east. A presumed groundwater flow divide exists through northern Perkins County and southern Lincoln County. North of this divide, groundwater movement is towards the South Platte and Platte Rivers. South of this divide, groundwater movement is towards Frenchman Creek and the Republican River. Groundwater is also captured by several tributaries of Frenchman Creek and the Republican River in this part of the Central Model Unit, with the most influential of these drainages being Stinking Water, Red Willow, and Medicine Creeks. In the southeast section of the Central Model Unit, groundwater movement is generally towards the southeast, where water exits the system through the eastern subsurface flow boundary as the Republican River and its tributary drainages in Gosper and Furnas County.

As groundwater flows easterly-southeasterly through the aquifer in the Central Model Unit, numerous opportunities exist within the interior of the model for water to leave the system via rivers, streams, engineered drains, and areas of evapotranspiration where vegetation roots are in direct contact with the water table. During the development period (1950-1998), water also exits the aquifer though pumping wells tapping the aquifer for agricultural purposes. The aquifer also gains water in parts of the Central Model Unit. Large fluxes of water seep into the aquifer from canals used for delivering irrigation water for crops as well as water for power generation.

Flow System History

The dynamics of a groundwater flow system often change over time, and major changes should be considered in a conceptual model of an area. Such changes include modification of surface water flows via diversion or storage structures, changes in land use practices, or climatic changes, all of which are often interrelated factors. For example, an extended drought (climatic influence) could change land use practices that either encourage more groundwater pumpage for irrigation, or, possibly cause a reduction in planted acres when irrigation water from surface diversions are unavailable.

Modifications similar to those described above have occurred since the end of the 19th Century and must be accounted for in the numerical model development. Prior to the 1890s, the system was considered to be in a condition of dynamic equilibrium, also known as steady state. During the 1890s however, the first permanent diversions from the Platte River system occurred

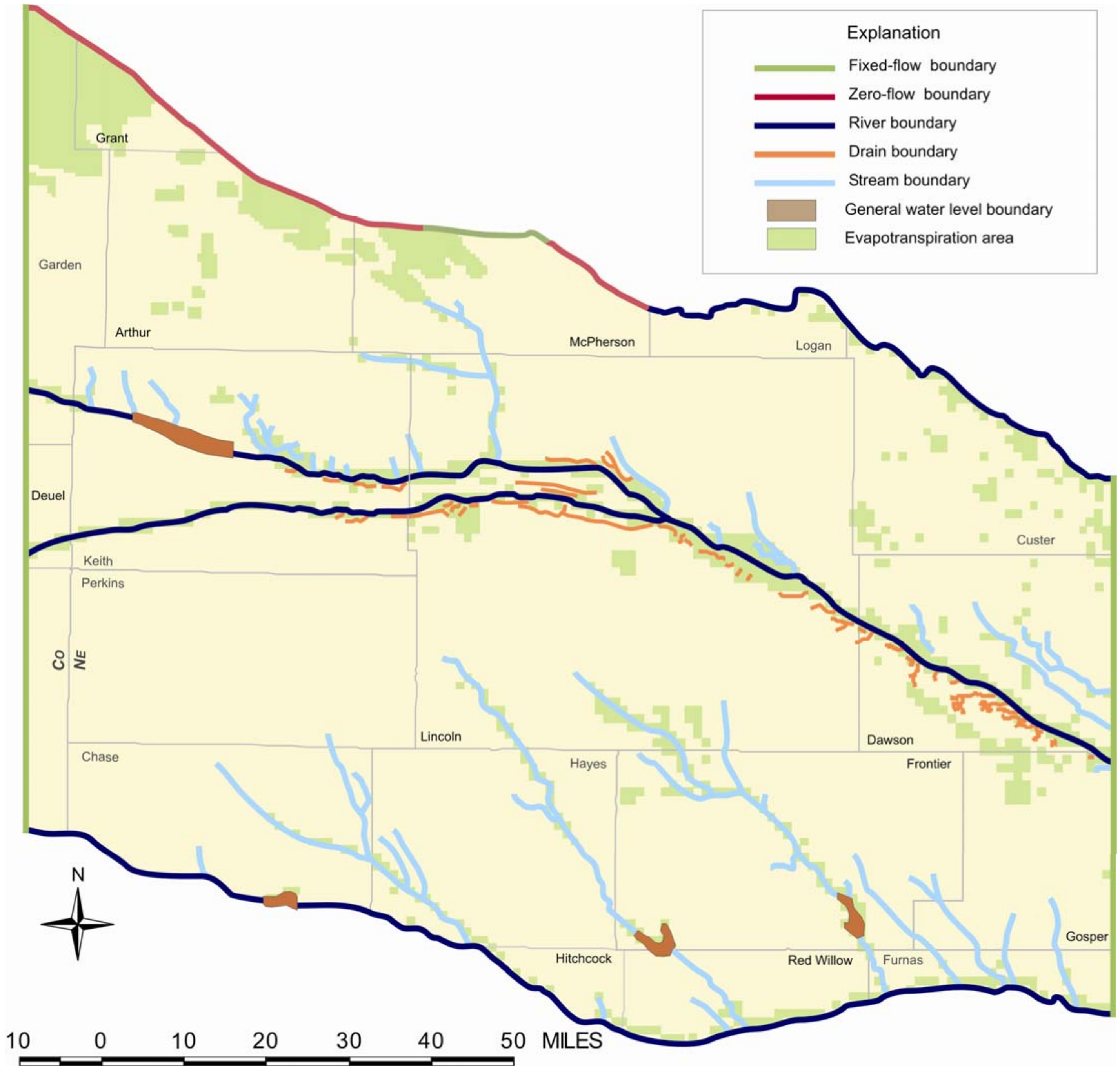


Figure 10. Central Model Unit conceptual model features.

in the Central Model Unit. Throughout the first half of the 20th Century, construction of numerous diversions from the Platte River system as well as the Republican River continued to modify the flow system as settlers converted the grasslands of the river valleys to agricultural lands. In addition to irrigated agriculture in the valley, dryland cropping practices developed in the upland plains beyond the major river valleys. Starting in the late 1930s, several water diversion and storage projects for both irrigation and energy generation further changes the flow system in the Central Model Unit. Seepage of diverted river water from these large projects created
large zones of increased water levels starting in the 1940s in two separate areas of the Central Model Unit. These projects were partially a response to the infamous drought years of the 1930s Dust Bowl. In the 1950s, breakthroughs in pumping well and water distribution system technology allowed for center-pivot irrigated agriculture to take root on the High Plains. With this spreading technology, the Central Model Unit once again saw major changes in land use practice starting in the mid-1960s as thousands of wells went into use in areas that were formerly rangeland or dryland cropped. Distribution of these wells was widespread in the central Model Unit, with the exception of the Sand Hills and other areas with highly sandy soils. This development in from the 1960s to the end of the 1990s caused appreciable declines in the saturated thickness of the aquifer in some areas of the Central Model Unit, primarily in Chase, Perkins, and Custer Counties.

To account for these modifications, the numerical model of the site was divided into two major timeframes, with the first accounting for the beginning of surface water diversions in the 1890s until 1950. A second time period was then defined using the final conditions at 1950 as the initial conditions. This second time period accounted for the changes in the system due to agricultural practices based on center pivot agriculture and the accompanying modifications in water entering the system as groundwater recharge under these lands. Although much less in scale compared to the pre-1950 time period, modifications in surface features continued to occur between 1950 and 1998.

Numerical Model Construction

Upon completion of initial conceptual model development, the next step was construction of the numerical model. This process involved creating appropriate input datasets that numerically describe the boundaries of the system defined during system conceptualization. This process is often done with preprocessing software and GIS tools. The following section describes the process in model development for the Central Model Unit.

Groundwater Model Concepts and Development

A groundwater flow model is a numerical representation of flow within an aquifer and the exchange of water between the aquifer and the external environment. The model necessarily simplifies and aggregates the true system, but includes those features important to the intended uses of the model. This model was constructed to simulate and understand the important regional effects of recharge to and discharge from the aquifer within the Central 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 would be masked by the uncertainties in model parameters.

3. Model parameters are uniform within 160-acre areas. This assumption is appropriate because the model is intended as a regional representation of the groundwater flow system and because the spacing of testholes to define model parameters is large compared to the 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.
5. Groundwater flow through the model is three-dimensional. Multiple-layering of the model grid allows for both vertical and horizontal movement of water, although the horizontal two-dimensional movement of water is the primary component of flow in the Central Model Unit
6. Hydraulic conductivity is isotropic in the horizontal direction, but is anisotropic in the vertical direction. Because of the fluvial origin of most of the deposits in the aquifer, the anisotropy is likely to occur in the vertical direction. With the three-dimensional model grid, the vertical component of flow is set as a model parameter that can be adjusted.

MODFLOW-96 was selected as the groundwater flow modeling code for this study. MODFLOW-96 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 (Harbaugh and McDonald, 1996).

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

The Groundwater Modeling System (GMS version 3.1), developed for the U.S. Department of Defense by the Environmental Modeling Research Laboratory at Brigham Young University (Aquaveo, 2000), was selected as the pre- and post-processor for MODFLOW. GMS supports a number of groundwater flow and transport codes in addition to MODFLOW. GMS allows a wide variety of data inputs and outputs, including Geographic Information System (GIS) coverages and data tables of points, lines, and polygons. In addition, GMS supports images, borehole data, Triangulated Irregular Networks (TIN's), and data sets for modeling with two and three-dimensional grids. Such data sets can be created within the preprocessor or imported from external sources. GMS uses the GIS coverages and other data sets to prepare the input files required by MODFLOW. The output from MODFLOW can be read by GMS, and the GMS post-processor displays the results with maps, graphs, diagrams, cross sections, and tables. These capabilities allow GMS users to efficiently conceptualize and simulate flow in groundwater systems. The conceptual and numerical models can evolve as the simulations are compared to actual historic hydrologic data.

Spatial Discretization

The grid for the Central Model Unit model in this report consisted of 252 rows, 264 columns, and 6 layers, with 44,918 active cells per layer for a total of 269,508 potentially active cells. The grid lines were 2,640 ft (fig. 13) apart in the north-south and east-west directions such that they formed 160-acre square cells. This orientation is maintained for all model units to simplify comparisons of results and inputs in the areas of model unit overlap. The thickness of each cell was defined using contour maps of the bottom of Hydrostratigraphic Units 1-6 (Cannia and others, 2006). Figure 14 shows the correspondence of the previously described hydrostratigraphic units and the six model layers. Figure 9 (p. 19) shows the elevation of the base of the aquifer. Similar maps are available for the base of other Hydrostratigraphic Units. Cells were allowed to become inactive during calibration if the simulated water level drops below the bottom elevation of a cell. This allows cells that represent large areas of generally unsaturated layers to be removed from the simulation. For the Central Model Unit, large areas of cells for model layers 1, 2, and 3 south of the Platte River system are dry at the onset of the simulation as the ambient starting water levels exist below the top 3 layers.

Temporal Discretization

In defining time, numerical models are divided into stress periods and time steps. A stress period is any segment of time in which model stresses such as recharge or pumping are constant. A time step is a segment within a stress period in which the numerical solution calculates an update of the solution to the flow equation. The first simulation of the Central Model Unit was for the period prior to 1895. This 5,000-year simulation allowed the groundwater system to come into dynamic equilibrium with precipitation-based recharge. This long period was required so that equilibrium was assured throughout the model area. This equilibrium, called *steady state*, is commonly simulated directly by MODFLOW, but had to be achieved indirectly using the 5,000-year period because small saturated thicknesses within Ogallala Group (model layers 4-6) in Keith County caused numerical instability that precluded direct simulation of steady state conditions. This long term transient simulation was run with 182,500 time steps of 10 days in length. The small time steps used to achieve steady state prevented cells from going dry due to the use of numerical methods.

Water levels from this steady state model at 1895 were used as the starting water levels for a simulation representing the period 1895-1950. During this period, additional recharge was added to the model to account for canal seepage (see Model Feature Inputs section) in many areas of the Platte and Republican River valleys. This period was divided into seven separate stress periods (1895-1928, 1928-1940, 1940-1942, 1942-45, 1946, 1947-1949, 1950), each accounting for times when canals began operation within the Central Model Unit (table 2). Each year starts on May 1 and ends on April 30th. For example, 1950 indicated a year of time ending April 30th, 1950. Table 2 shows the length of time of each stress period and the number of time steps used within each stress period for the 1895-1950 simulation. As seen in table 2, a large number of time steps were required to reach calibration during the 1895-1950 transient simulation. As with the pre-1895 simulation, this was required to prevent cells from drying due to numerical approximations.

Beginning May 1, 1950, the model was modified to incorporate an irrigation season stress period (May-September) and a non-irrigation season stress period (October-April). Within a stress period, pumpage and recharge were held constant. The 153-day irrigation season stress period was simulated with 70 time steps of about 2.2 days in length and the 212- or 213-day non-irrigation season stress period was simulated with 85 time steps of about 2.5 days in length. Every fourth non-irrigation season contained one extra day to account for leap years.

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,

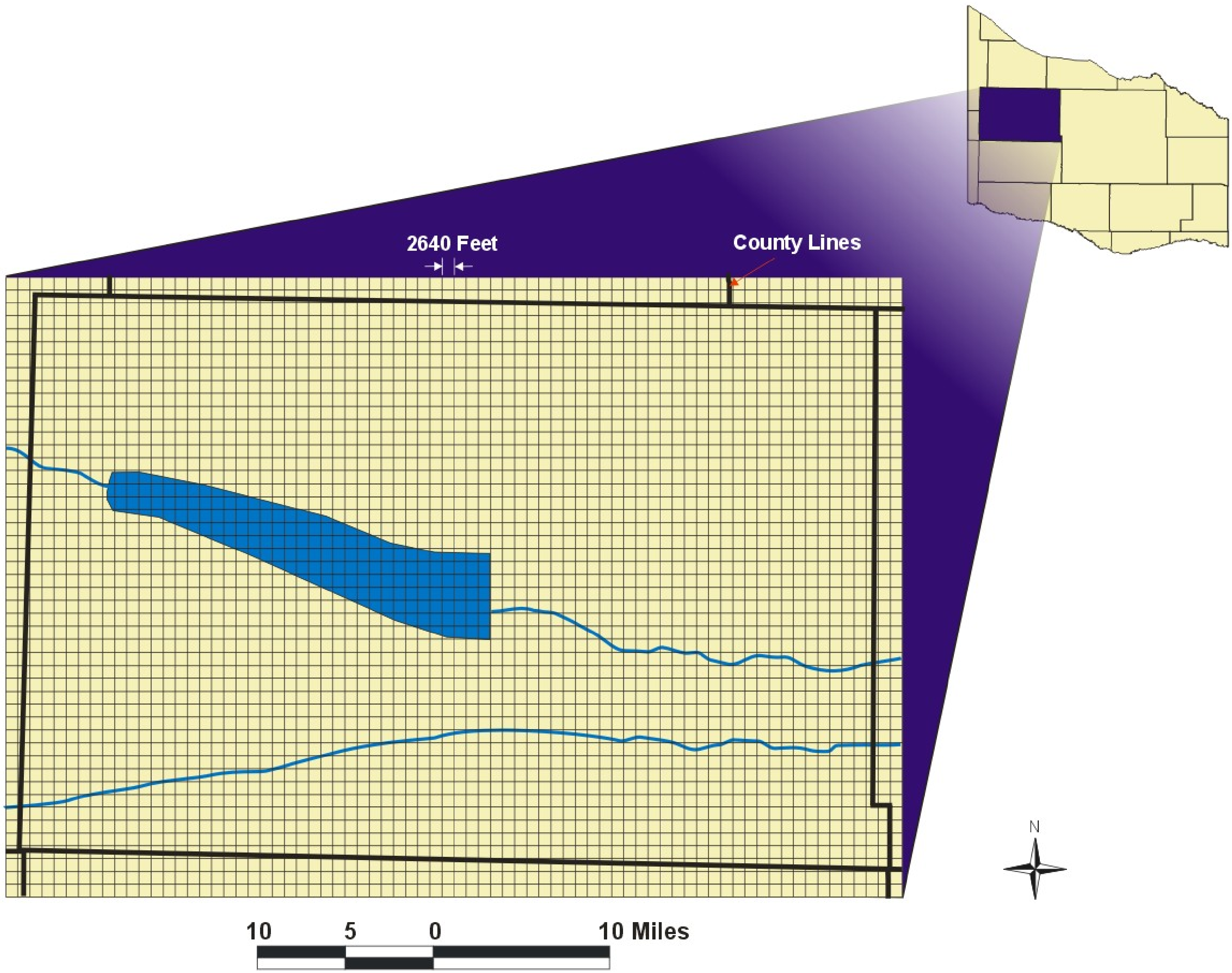


Figure 11. Active cells for the Central Model Unit 160-acre cell grid with Lake McConaughy, the North Platte River, and the South Platte River highlighted in Keith County.

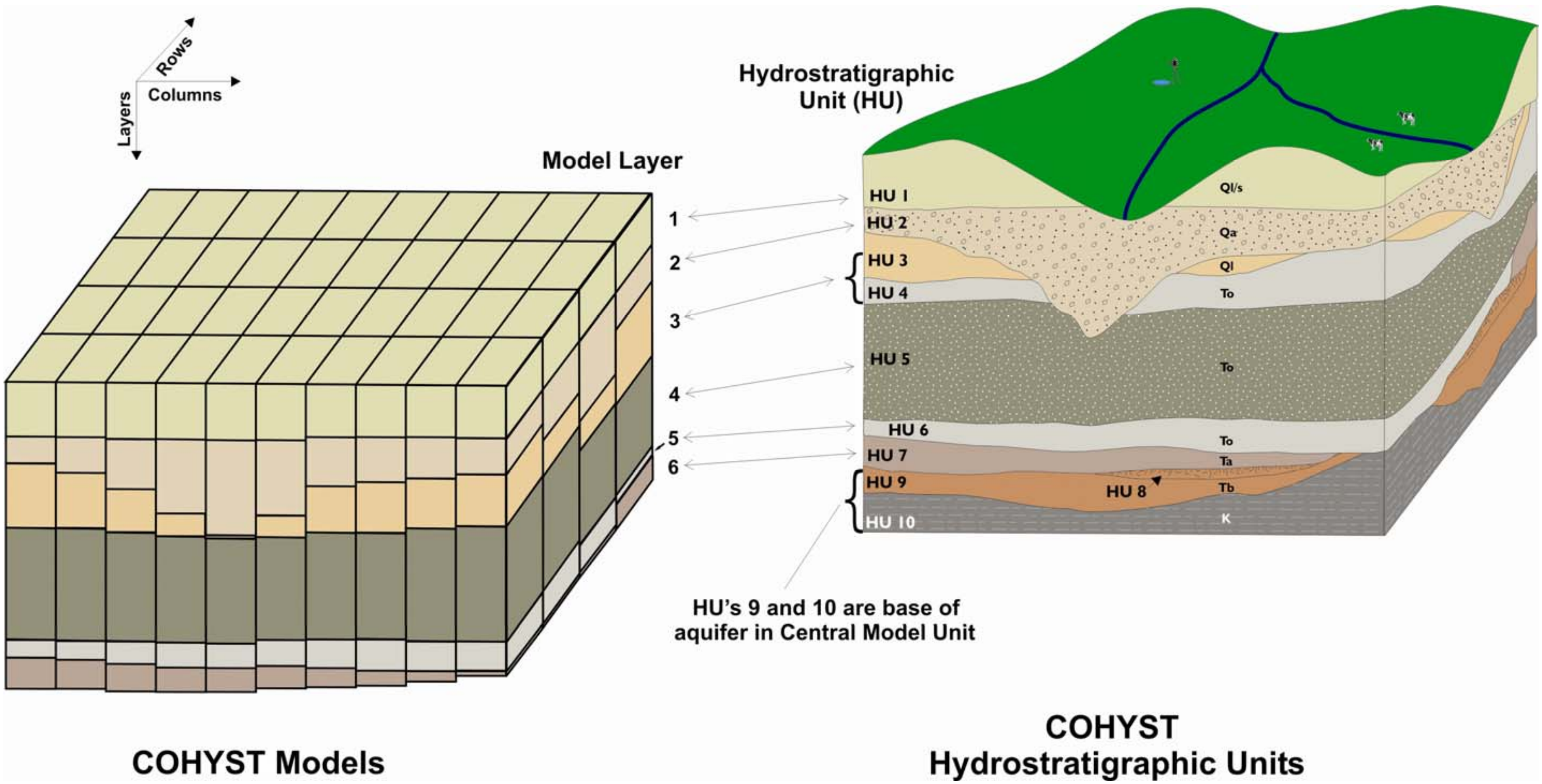


Figure 12. Correspondence of COHYST Hydrostratigraphic Units (right) with a sample view of model layers (left).

Table 2. Stress periods and time steps for the Central Model Unit pre-groundwater development period simulation.

Stress Period	Stress period time	Length (years)	No. of time steps	Time step length (days)
1	1895-1928	33	9,039	1.3
2	1928-1940	12	4,383	2.7
3	1940-1941	2	365	2.0
4	1941-1945	4	2,192	0.7
5	1946	1	548	0.7
6	1947-1949	3	1,644	0.7
7	1950	1	548	0.7

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 the 1950-98 period.

Model Feature Inputs

MODFLOW accounts for different system features and stresses through individual modules called packages. These packages arrange model inputs and parameters of various system stresses for the code to use while calculating a solution. MODFLOW simulates the interaction between the groundwater system and the surface water system as flow through a hypothetical bed layer with properties potentially different from those of the aquifer. This applies to streams, rivers, drains, and lakes. A lumped parameter termed "bed conductance" accounts for the hydraulic conductivity (k) and thickness (t) of the layer, and feature width (w), and feature length (l) in each stream, river, or lake cell. The equation is expressed as

$$C = (k / t) * lw \qquad \text{(Eq. 1)}$$

Conductance controls the ease of interaction between the surface water and groundwater systems. GMS automatically calculates the length of stream and river features and the area of lake features in each model cell, so the value input to GMS actually is conductance per unit length or unit area. In this report, conductance means the lumped parameter that accounts for layer hydraulic conductivity, layer thickness, and feature width (for linear features only) to which GMS will apply feature length or area.

Rivers and Streams

Both MODFLOW Stream (Prudic, 1989) and River (McDonald and Harbaugh, 1988) Packages were used to simulate stream and river boundaries. Stream boundaries are allowed to gain water from the aquifer or to lose water to it, up to the amount of water in the stream. River boundaries are similar to stream boundaries except that the amount of water in the river is not tracked by the flow model. River boundaries are appropriate for large features that seldom go dry whereas stream boundaries are appropriate for smaller drainages that may have periodic conditions of no flow. The interaction between the rivers or streams and the underlying aquifer is controlled in the flow model by relative elevations in the feature and the simulated adjacent water table and estimated (using Darcy's Law) conductance values. Stream and river locations followed the generalized courses of the streams but did not duplicate exact details of the stream. Stream and river water elevations were estimated at all contour crossings from 1:24,000 scale topographic maps and GMS performed linear interpolations between points. Streambed and riverbed conductance values were determined during calibration and are discussed in the Numerical Model Calibration section. Surface features simulated with the MODFLOW River

Package include the North Platte, South Platte, Platte, South Loup, and the Republican Rivers. Those features simulated as stream boundaries include Clear Creek, Otter Creek, Lonegran Creek, Whitetail Creek, West Birdwood and Birdwood Creeks, Whitehorse Creek, Pawnee Creek, Buffalo Creek, Spring Creek (Dawson County), West Buffalo Creek, Plum Creek, Sand Creek, Spring Creek (Chase County), Stinking Water Creek, Blackwood Creek, Red Willow Creek, Medicine Creek, Deer Creek, Muddy Creek, Elk Creek, Turkey Creek, and several unnamed streams draining the southern edge of the Sand Hills in Keith County north of the North Platte River. Since this model is configured with multiple layers, not all rivers and streams existed in the same model layer. Various levels of incision by drainages across the Central Model Unit forced many of the drainages to be assigned to different model layers. Most drainages were assigned to model layer 2, but some were placed in model layer 4 where the drainage cuts below the top of the Ogallala Group.

Drains

Engineered and natural drains and ditches, located mostly in the Platte River system, were simulated with the MODFLOW Drain Package. Simulated drain boundaries are allowed to gain water from the groundwater flow system, but cannot release water back to the aquifer. This boundary type was assigned to drains or other engineered features on the Platte River system floodplain. Most drains are only a few miles in length and were originally constructed to lower the local water table. Typically, drains of this small size and extent would not be included in a regional groundwater simulation. However, due to the density of these features south of the Platte and South Platte Rivers in the Central Model Unit, they were included because early simulations indicated significant influence on the regional groundwater flow system. Within the model grid, most drains were assigned to model layers 1 or 2.

Reservoirs

The MODFLOW General Head Boundary Package (McDonald and Harbaugh, 1988) was used to simulate general water-level boundaries within the model area, including Lake McConaughy, Harry Strunk Lake, Hugh Butler Lake, and Enders Reservoir. These types of boundaries allow water to flow across a boundary based on the water level difference across the boundary, with a user-specified conductance that controls the amount of flow across the boundary. The pre-groundwater development model represented Lake McConaughy throughout the entire simulation, but only as active after 1940 when a non-zero conductance value was applied. The simulated extent approximated the area inundated by a moderately low stage and the lake elevations of the boundary were set at the long-term average for various model periods. The General Head package was applied to all layers in the area representing Lake McConaughy. This was designed to account for all layers that may have become saturated at the reservoir boundary. Conceptually, most of the hydrostratigraphic units are relatively thin and are exposed in the valley walls where Kingsley Dam was constructed. To simulate this condition using MODFLOW-96, all layers were set to contain the General Head boundary, since each layer, regardless of thickness, will become saturated adjacent to the lake. During transient simulations, the average elevation was 3,240 ft for 1940-54, 3,230 ft for 1954-60, 3,257 ft for 1960-89, 3,240 ft for 1989-94, and 3,257 ft for 1994-98. The elevation was changed at the beginning of the irrigation season for the indicated year. The remaining lakes using this package are located on-channel and include Harry Strunk Lake (constructed in 1948 on Medicine Creek), Hugh Butler Lake (completed on Red Willow Creek in 1961), and Enders Reservoir (completed in 1952 on Frenchman Creek). The long-term average elevation for each reservoir was applied for the entire transient stress period for each of these reservoirs in the model.

Recharge

The MODFLOW Recharge Package accounts for all water that enters the system from the land surface that is either from precipitation that has traveled through the unsaturated zone, from canal and reservoir seepage, or flow into or out of the model on the western and eastern boundaries. The estimated boundary flows are applied only to the westernmost and easternmost columns of the model grid. Recharge from canal and reservoir seepage was applied to model cells that correspond to areas where canals and off-channel reservoirs exist. Precipitation-derived recharge is discussed in the Numerical Model Calibration section (p. 44).

Canal Seepage Estimates

Recharge due to canal and lateral leakage (table 3) 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 canals have returns back to the river of origin downstream of the irrigated areas, but those returns also were unmeasured. For these canal systems, the recharge due to canal and lateral leakage was assumed to be 40 percent of the diversion and was spread uniformly along the length of the canal in the model. 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 other canals, long-term trends were evident in the annual diversion data. For those canals, annual diversion data were plotted and lines were manually fit to represent the long-term trends, excluding data that appeared to be short-term outliers (fig. 14). 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 pre-groundwater development period 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.

The Nebraska Public Power District Sutherland Project (fig. 15, p. 35) utilizes North Platte River water (diverted at the Keystone diversion dam approximately a half mile downstream of Lake McConaughy) for energy production at Gerald Gentleman Power Station and a hydroelectric plant at North Platte. This canal re-enters the South Platte River at North Platte (fig. 11). Seepage rates from this system were applied from seepage estimates reported in an engineering feasibility study by Harza, Inc. (1993). These values vary by different reaches along the canal system and reservoirs, particularly between the diversion dam and Sutherland Reservoir. Sutherland Reservoir had the greatest seepage along the entire Sutherland Project with estimated rates exceeding 90 ft^3/s (Harza Engineering, Inc 1993). The upper reach of the Central Nebraska Public Power and Irrigation District's Tri-County Supply Canal from the diversion to the Lincoln-Dawson County line used seepage estimates modified (converted to rate over area terms) from Goeke and others (1992). These and the Sutherland Project seepage estimates were both adjusted during calibration.

For several canals in the eastern Central Model Unit, annual diversion and delivery data were available by major sub-systems of the CNPPID system (Tri-County 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 Tri-County Supply Canal is a large feature 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. Discharge data from two hydroelectric plants on the Supply Canal were used along with other outflow data, such as returns to the river, irrigation canal diversions, evaporation data, and precipitation data to estimate the amount of water in the Supply Canal that was lost to groundwater recharge. For Elwood Reservoir, seepage recharge applied to the groundwater model for 1978-1993 was based on a study by CH2MHill (written commun., 1993). Seepage recharge from Elwood Reservoir from 1994-1998 was based on Central Nebraska Regional Water Conservation Task Force (2002).

Canal/Service area	Year first applied to simulation	Estimated annual seepage (ac-ft)
[1]NPPD Sutherland Project – Supply Canal	1940	1,445-5,782
NPPD Sutherland Project - Sutherland Reservoir	1940	36,208
NPPD Sutherland Project - Outlet Canal	1940	30,353
NPPD Sutherland Project - Lake Maloney to South Platte River	1940	20,236
NPPD Sutherland Project - Korty Canal	1940	5,059-9,395
[2]CNPPID Supply Canal (Central Model Unit Only)	1942	290,563
CNPPID E65 Canal	1942	10,629
	1949	10,629
	1950	14,201
	1975	13,739
	1979	7,915
	1997	7,876
CNPPID E67 Canal	1954	5,302
	1964	4,591
	1975	6,979
	1990	6,382
	1997	6,474
CNPPID Phelps Canal	1942	629
	1949	629
	1950	3,209
	1959	4,569
	1978	3,925
	1984	2,778
CNPPID Elwood Reservoir	1978	24,926
	1993	24,926
	1994	20,325
	1998	20,325
Cambridge Canal	1951	4,915
	1957	6,267
	1968	7,782
	1998	7,163
Sixmile Canal	1895	1,140
	1950	1,140
	1964	1,200
	1969	2,580
	1979	3,060
	1998	3,075
Gothenburg Canal	1895	13,419
	1950	51,000
	1967	44,000
	1973	24,000
	1998	20,000
Cozad Canal	1895	7,849
Dawson County Canal	1895	17,323
Western Canal	1895	4,306
Keith-Lincoln Canal	1946	3,349
Sheridan-Wilson Canal	1946	65
Birdwood Canal	1946	1,141
Cody-Dillon Canal	1946	678
Suburban Canal	1946	2,852
North Platte Canal	1946	6,973
Orchard-Alfalfa Canal	1895	3,357
Hershey-Paxton Canal	1946	2,872
Thirtymile Canal	1928	14,678
Culbertson Canal	1946	5,754

Table 3. Summary of estimated recharge from canal and lateral leakage applied to the simulation. Values for canal areas located in both the Central and Eastern Model Units from Peterson, 2005.

[1] Nebraska Public Power District [2] Central Nebraska Public Power and Irrigation District

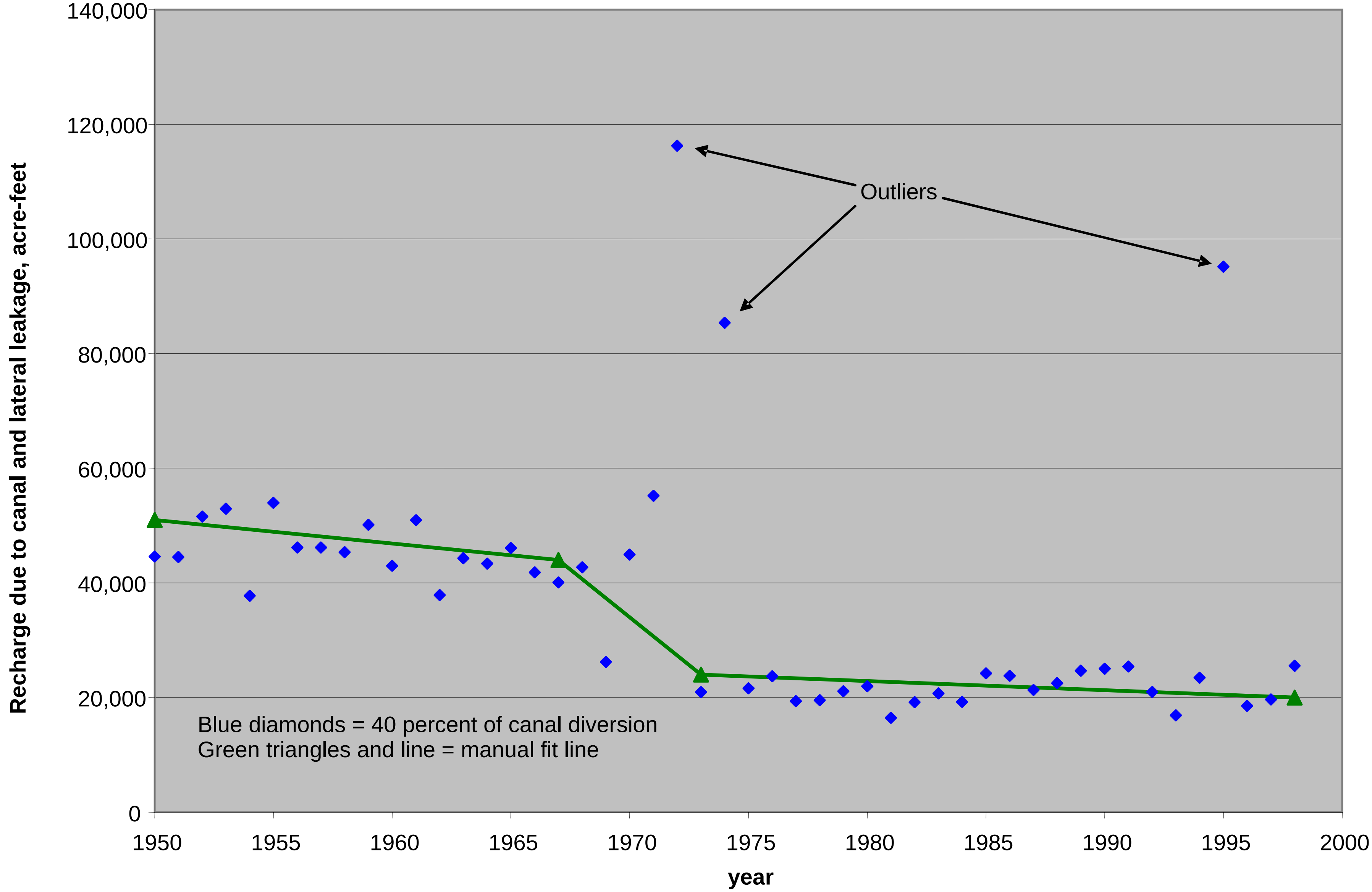


Figure 13. An example of a manual line used to represent historic recharge due to canal and lateral leakage of Gothenburg Canal (after Peterson, 2005).

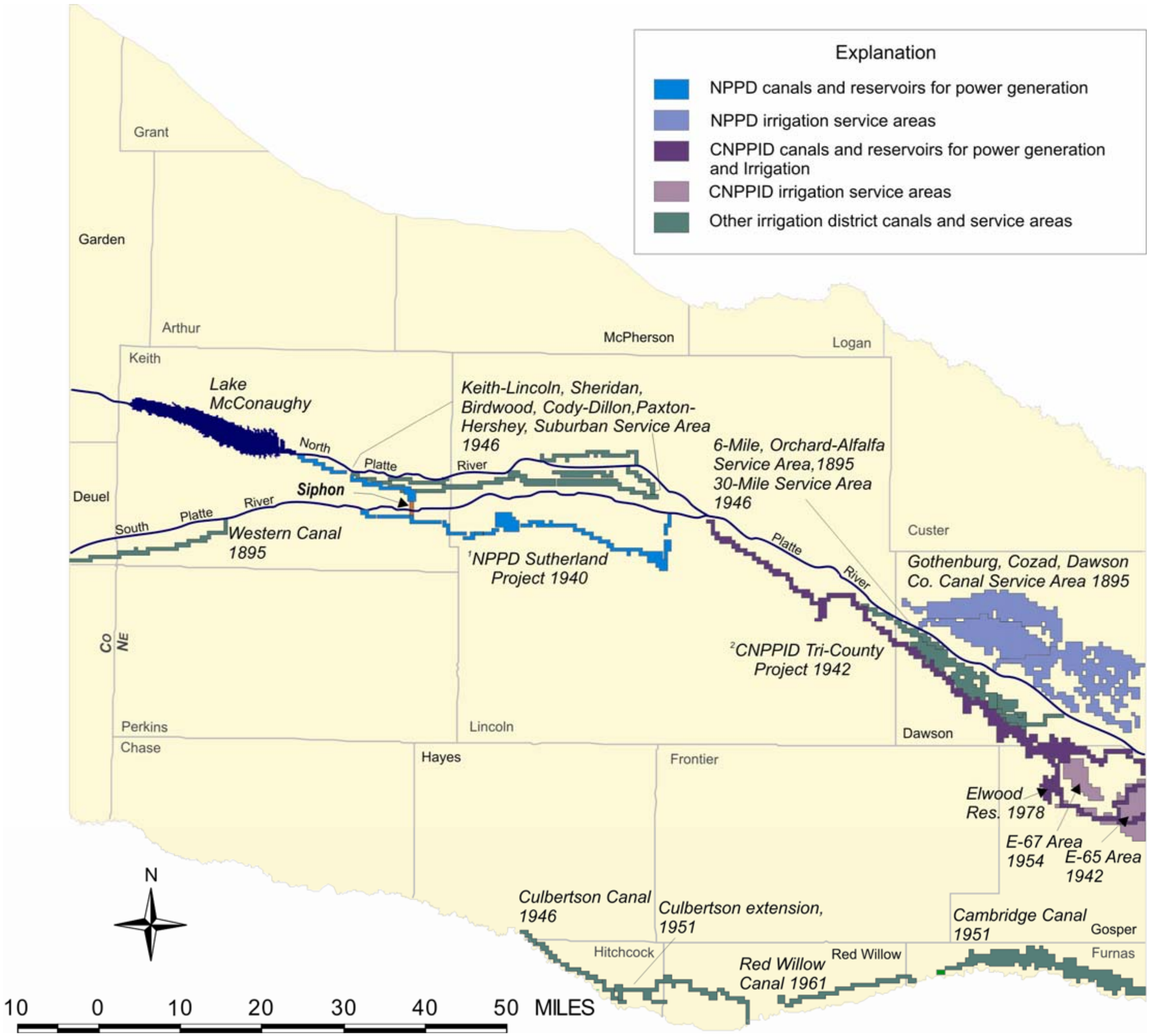


Figure 14. Zones within the Central Model Unit receiving additional groundwater recharge from canal seepage.
Note- Years shown indicate when canals became operational.

[1] Nebraska Public Power District

[2] Central Nebraska Public Power and Irrigation District

Groundwater Pumpage

Pumpage for the groundwater development period is described in the follow two sections. First, the overall methodology for COHYST pumpage development is discussed. The second section describes pumpage dataset development specific to the Central Model Unit.

COHYST Pumpage Development

Pumpage for groundwater-irrigated crops was estimated by COHYST for the calibration period 1950-98 (R.A. Kern, Nebraska DNR, electronic comm., June 6, 2005). 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 were 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 approximately a 5-year recurring basis. Beginning with the 1954 Census, irrigated acres by selected crops were reported. For the 1949 Census, only total irrigated acres were reported and irrigated acres by crop had to be estimated. Not all crops were reported for all years, so dryland and irrigated acres are estimated in some cases. This typically happened with minor crops. As more acres went into production, the Census included these crops. For more information on the processing of acres and pumpage data, see Kern (2004).

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

The location of irrigated cropland, dryland, and rangeland within a county for 1950-98 was estimated based on the 1997 land use map (Dappen and Tooze, 2001), location of surface-water irrigated land, registered irrigation wells (Cooperative Hydrology Study, 2001b), and topographic regions (Conservation and Survey Division, 1998, fig. 2). 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 that were not assumed to change over time. Two minor 1997 land uses, dryland potatoes and dryland sugar beets, were assumed to be irrigated, because these crops are typically irrigated. 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 640-acre 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 cells described in this report. Pumpage was calculated for the 640-acre cells and then was equally distributed to the four 160-acre cells for this model, because information was not available to do otherwise. Each 640-acre cell could potentially contain several land uses, each of which was accounted for in the final aggregated pumpage value for the cell. The 1997 land uses also were aggregated to 10-acre cells and were saved for potential future use in more detailed models.

The process of estimating 1950-97 land use by 640-acre cell started with 1997 land use (Dappen and Tooze, 2001) and worked backwards in time. For example, if total acres for a particular land use in a county were less in 1996 than in 1997, random fields, weighted as described below, were removed from the 1997 data set to develop the 1996 data set. The land use with the largest decrease going back in time was processed first. The fields that were removed were tracked for later re-assignment of land use. After all the land uses in a county that had decreased from 1997 to 1996 were processed, land uses that increased were processed, beginning with the land use that had the largest increase. These land uses were assigned to random fields, also weighted, that had been previously removed. If more area of land uses increased than what had been removed, the additional land uses were added by assuming that rangeland was being converted to the new land use.

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

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

Net Irrigation Requirement

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

The first set of net irrigation requirements were computed from crop consumptive use estimated by Klocke and others (1990, table 1). Crop consumptive use minus effective precipitation is the estimated net irrigation requirement for the crop. This method is called "NebGuide" net irrigation requirement or net pumpage in this report. NebGuide is an informational series for agricultural topics from the University of Nebraska-Lincoln, where the consumptive use estimates are published. The second net irrigation requirements were computed with an unpublished soil-water-balance model developed by Dr. Derrel Martin, University of Nebraska-Lincoln. This model, referred to as CropSim, attempted to deal with the spatial variations of soils, land uses, and the spatial and temporal variations in meteorology. CropSim used daily time steps to account for precipitation, crop evapotranspiration, and remaining available soil moisture. When soil moisture decreases to a specified level in the CropSim model, irrigation water is added. Seasonal net irrigation requirement is equal to the total amount of water added for the season. CropSim is very data intensive since it requires daily inputs for precipitation and parameters to calculate 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.

Daily potential evapotranspiration, the most critical data input to CropSim, was not available for much of the 1950-98 period, and had to be estimated indirectly from meteorological data using the Hargreaves method (Hargreaves, 1994) calibrated to each meteorological station and interpolated to the cells. Potential evapotranspiration changed several inches on an annual basis from one station to the next, probably due to limitations of the applications of the Hargreaves method to the meteorological stations, some of which may be sited in substandard locations for the purpose of estimating potential evapotranspiration. To correct for this, potential evapotranspiration was averaged over the full COHYST area on a daily basis. This calculated value was greater than generally accepted values, so daily potential evapotranspiration values determined by this method were reduced by 10 percent to bring them into the accepted range. Net pumpage was then reduced by 10 percent (based on the recommendation of Dr. Martin) for both NebGuide and CropSim to account for less-than-ideal crops in the real world, because real-world crops are typically less healthy, do not always receive optimal nutrients and water, are stressed by insect and weed pests, and thus consume less water.

Evapotranspiration

The MODFLOW Evapotranspiration Package simulated evapotranspiration in the areas of abundant natural lakes and wetlands in the Sand Hills (figs. 3 and 9) as well as zones ranging from 1 to 6 mi wide along the Platte River system and the South Loup and Republican Rivers were simulated as groundwater evapotranspiration areas to supply water for the riparian woodlands transpiration and open-water and bare-ground evaporation. Evapotranspiration areas were defined using 1997 land use data (Dappen and Tooze, 2001). Evapotranspiration was simulated in a model cell if more than 25 percent of the acres in a cell were 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 is likely to be sub-irrigated by groundwater. Areas outside of the major river valleys, particularly along the major tributaries of these rivers, were also included as areas of evapotranspiration if they met the above criteria.

Model Cell Rewetting

During the 1895-1950 time period, large volumes of water were added to the groundwater system through canal and reservoir seepage. This caused areas in the model with formerly dry cells to become saturated from rising water levels, a process that MODFLOW could not simulate without additional model modification. To alleviate this situation, the model used the MODFLOW Rewetting package (McDonald and others, 1991) to allow rewetting of cells. Cell re-wetting was particularly problematic in the vicinity of Sutherland Reservoir, where very thin dry cells became saturated after 1940 when the reservoir became operational. The Rewetting Package allows for cells that were dry at the beginning of the simulation or that became dry early in a simulation to “re-wet” based on user-defined inputs that control what conditions trigger the rewetting of a cell. The following equation dictates the rewetting of cells that go dry during the simulation (McDonald and others, 1991):

$$H = BOT + WETFCT*THRESH \qquad \text{(Eq. 2)}$$

where:
H = *water level in the cell after rewetting;*
BOT = *Bottom elevation of the dry cell to be re-wetted*
WETFCT = *A user defined coefficient that controls the saturated thickness in the rewetted cell at the next iteration*;
THRESH = *The value to which the water level in cell below must rise above the bottom of the dry cell for rewetting to occur*

A value of 0.05 was used for the wetting factor (WETFCT) and –10.0 ft for the threshold parameter (THRESH). These values allowed for a stable simulation, determined through trial and error, with reasonable results. The negative value of the threshold parameter indicated to MODFLOW that the formerly dry cell can be re-wetted only from the underlying cell as opposed to adjacent neighboring cells. With these parameters, the water level beneath the dry cell would need to rise at least 10 ft above the base of the dry cell before cell rewetting would activate. Upon rewetting, the saturated thickness for the next iteration would be 0.5 ft (WETFCT x THRESH) for the formerly dry cell. Along with the small time steps for each stress period, the Rewetting Package remedied problems related to cells wetting and drying as water levels rose and fell across layers in response to the model stresses.

Numerical Model Calibration

Calibration of a groundwater flow model is an essential step in the modeling process and should be conducted prior to model use for analysis and prediction (Anderson and Woessner, 1992). Calibration is a process of systematically adjusting selected model inputs within reasonable limits while comparing simulated and observed features of the flow system, typically water levels and groundwater discharge to or from streams. The Central Model Unit models were calibrated to observed groundwater levels and groundwater contribution to stream flow for the pre-groundwater development period (pre-1950) and to changes in groundwater levels for the groundwater development period (1950-98). In the pre-groundwater development model, recharge from precipitation, bed conductance, evapotranspiration, and hydraulic conductivity were adjusted. In the groundwater development period model, dryland recharge, irrigated land recharge, and specific yield were adjusted

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

The models described in this report were a refinement of several previously constructed and calibrated models. The initial model started with a coarse grid and simple distributions of parameters and stresses. Over time, the grid was refined with smaller cell sizes and more layers, as well as more detailed parameter distriubutions. 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 (Carney and Peterson, 2001) 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 (Carney and Peterson, 2001).

Observed water levels used in calibration of the pre-groundwater development period model were selected from water levels measured in wells during 1946-55 during a period of relative stability in water levels. Some areas contain numerous observation wells that all reflect the same conditions, so a 4-mi by 4-mi grid was overlain on the COHYST area and the most reliable source of water levels 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 causes of errors in the water level are 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- by 4-mi cells, a few points that appeared to have large errors in location or land-surface elevation were excluded from the calibration data set. The final data set used in the pre-groundwater development calibration consisted of 205 water-level locations.

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 1950-1998, 1950-1961, 1961-1973, 1973-1985, and 1985-1998. To select these points, a 4-mi by 4-mi grid was overlain on the COHYST area and the point with the most water levels in the cell, including ones near the beginning and ending date, was selected. The number of points in the Central Model Unit for each period are shown in Table 4.

Period	Number
1950-98	48
1950-61	54
1961-73	42
1973-85	124
1985-98	227

Table 4. The number of water-level observation points available by sub-period of the groundwater-development period simulation.

Due to the limited number of points in the 1950-1998, 1950-1961, and 1961-1973 periods, some areas had a higher density of observation points than others. In a large area of the Central Model Unit, particularly in the Sand Hills north of the Platte River system valley, observation data are sparse even by 1998. In areas of the Sand Hills, water levels change very little over time, especially in areas of evapotranspiration. Thus, observation points in the Sand Hills contribute very little information to the transient model calibration. Much of the other early observation data exists in the river valleys of the Central Model Unit, where water levels change very little. However, by 1973, abundant observation data existed in areas of large-scale development, particularly in Chase, Perkins, Dawson, Gosper, and Lincoln Counties.

Groundwater model calibration is commonly evaluated by comparing 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:

$$MD = \frac{1}{n}\sum_{1}^{n}(h_s - h_o)_i \qquad \text{(Eq. 3)}$$

where h_o is the measured or observed water levels and h_s is the simulated water level 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:

$$MAD = \frac{1}{n}\sum_{1}^{n}\left|\left(h_s - h_o\right)_i\right| \qquad \text{(Eq. 4)}$$

The mean absolute difference is a good 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 this measure of error. Root mean square (RMS) difference is another commonly used measure of calibration. RMS difference is defined as:

$$RMS = \left[\frac{1}{n}\sum_{1}^{n}\left(h_s - h_o\right)_i^2\right]^{0.5} \qquad \text{(Eq. 5)}$$

RMS is also 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 may be counterintuitive.

Groundwater discharge to streams was estimated using streamflows recorded at gaging stations during the fall (October and November), because this period is less likely to be affected by canal diversions and runoff. The techniques used to estimate groundwater discharge using gaged streamflow data are described by Carney and Peterson (2001). 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 Red Willow Creek, have relatively narrow ranges of observed groundwater discharges, whereas other streams, such as the Platte River, have wide ranges of discharge. Qualitatively, the model calibration was deemed better if the simulated groundwater discharge was close to the mean estimate of the observed range of discharge to that stream.

Pre-Groundwater Development Period Calibration

In the pre-groundwater development period model (1895-1950), rangeland recharge, bed conductance, evapotranspiration, and hydraulic conductivity were adjusted. These parameters were candidates for adjustment due to the likely influence each would have in the calibration as well as the ranges in reasonable values each parameter was likely to have. Other model inputs, such as boundary flows, recharge from canal leakage, and model layer elevations were not adjusted during calibration, as these parameters were assigned with less uncertainty and assumed less influence on the calibration. Following is a description of each parameter added to the pre-groundwater development model.

Hydraulic Conductivity

Hydraulic conductivity, a parameter quantifying the ability of an aquifer to transmit water, was adjusted in a series of model simulations to achieve the best fit between simulated and observed water levels at 1950. Earlier versions of the Central Model Unit model used either a uniform value of hydraulic conductivity or data sets produced from the USGS High Plains aquifer study (Gutentag and others, 1984). However, the delineation of multiple layers within the High Plains aquifer by COHYST allowed for a more detailed representation of hydraulic conductivity across the study area. The Hydrostratigraphic Units described in Cannia and others (2006) focuses on local conditions in three dimensions within the aquifer, unlike the more regionally focused, two-dimensional datasets used in earlier versions of the model. During calibration, a uniform value of hydraulic conductivity was initially applied to each model layer. For example, every cell with some saturated thickness in model layer 1 was assigned identical values of hydraulic conductivity. For model layers 1, 5, and 6, uniform hydraulic conductivity values were retained. For model layers 2, 3, and 4, spatially varying hydraulic conductivity was later applied. Within model layers 2 and 4, mapped hydraulic conductivities were increased or decreased uniformly until the best possible model calibration was achieved. Within model layer 3, mapped hydraulic conductivity was not varied spatially during calibration. Vertical hydraulic conductivity for each cell was assigned as 10 percent of the horizontal hydraulic conductivity.

In some areas of the model where mapped hydraulic conductivities values are sparse, isolated zones were modified independent of the previously defined zones. For example, model layer 4 hydraulic conductivity in north-central Lincoln County east of Birdwood Creek was increased because the model indicated a need for higher hydraulic conductivity in an area where few test holes exist. Based on the west-east orientation of West Birdwood Creek and the presence of the Whitehorse Creek drainage southeast of this zone, it is postulated by the author that former paleo-drainages once existed in this area. Shaded relief maps support the existence of buried channels. A map of former drainage patterns of the Platte River in late Pliocene times (~2.5 million years ago) indicates flow directly through this area (Sounders and others, 1990, fig. 18), increasing the likelihood for the presence of coarse deposits within the paleo-drainages. Table 4 summarizes hydraulic conductivity by layer and figure 15 shows the thickness-weighted hydraulic conductivity distribution used in the calibrated model. Not all model layers are continuous over the entire model domain, but MODFLOW requires that layers be continuous. To accommodate this requirement, missing model layers were simulated as layers 1 ft thick, with the hydraulic conductivity of the cell within the 1-ft layer set as the average hydraulic conductivity of the layer above and below the 1-ft thick cell. In this way, the MODFLOW requirements were met without introducing erroneous hydraulic conductivity values.

Table 5. Hydraulic conductivity values for the calibrated pre-groundwater development period model.

Model Layer	HU	Hydraulic Conductivity (ft/d)		
		Mean	Minimum	Maximum
1	1	23.0	--	
2	2	81.0	16	180
3	3-4	21.0	9	188
4	5	27.5	9	196
5	6	27.5	Uniform values applied	
6	7	27.5	Uniform values applied	

Specific Yield

Specific yield is a dimensionless parameter that represents the amount of water a unit volume of material can release due to influence of gravity. The value applies only to those cells in which the water table exists. Initial values for the pre-1895 and pre-groundwater development simulations used uniform values based on estimates provided by the High Plains aquifer study (Gutentag and others, 1984). The initial values applied to the model were based on average values per each model layer. During calibration of the groundwater development period, specific yield was adjusted for model layers 2 and 4 to better simulate large water-level declines and rises in the CMU. These new specific yield values were then re-applied to the pre-1895 and pre-groundwater development period simulations. The section discussing specific yield calibration in the Groundwater Development Period section of this document describes how the specific yield values were adjusted.

Specific Storage

The specific storage term represents the amount of water an aquifer can receive or release per unit volume of aquifer per unit change in water-level (hydraulic head). This volume is related to the compressibility of water and the expansion of the aquifer material. This value only applies to those cells which are entirely below the water table. For the Central Model Unit model, this value was held constant throughout the simulation with a value of 5.0×10^{-5}, a value commonly associated with Ogallala Group type sediments found in groundwater hydrology publications (Fetter, 1994).

Bed Conductance

Calibration of bed conductance was based on classes of streams and rivers and field data from work done by the U.S. Geological Survey and COHYST in 2000 (Cooperative Hydrology Study, 2001d). Conductance values (fig. 16) were assigned to the stream and river packages of the model based on the following classification of drainages:

1) Major rivers and streams (Platte River system, South Loup River, Republican River, and Frenchman Creek)
2) Northern Platte River system tributaries (those entering the North Platte River or Platte River from the north)
3) Republican River and Frenchman Creek tributaries

These categories are based on streambed core analysis performed in the summer of 2000 (COHYST 2001d), dominant geologic materials within a drainage basin, and proximity to streams of similar size. Initial conductance estimates were obtained from previous versions of the flow model. Drainages in groups 2 and 3 were adjusted on a stream-by-stream basis. Based on simulated river and stream discharges and water levels in the surrounding aquifer, conductances (fig. 16) were adjusted to best match simulated discharges with calculated values in the baseflow analysis (Carney and Peterson, 2001). No adjustments were needed for conductances used on the Group 1 streams in the Platte River system, which remained at 22.5 feet per day per unit length (ft/d/ft). For the upper half of the South Loup River, a conductance of 0.5 ft/d/ft was applied, and for the lower South Loup River, Republican River, and Frenchman Creek a value of 5.0 ft/d/ft was used. The contrast between the Platte River system and the other Group 1 drainages is due to the width and abundant coarse materials in the Platte River system as compared to the more narrow drainages on the Loup River system that typically have streambeds comprised of finer sediments. Group 2 ranged from 0.10 on tributaries to the Platte River in Dawson County to 10.0 ft/d/ft for Birdwood Creek. The range for Group 2 can be attributed to the presence of fine streambed sediments in Whitehorse Creek, whereas coarse sediment comprised the streambeds of

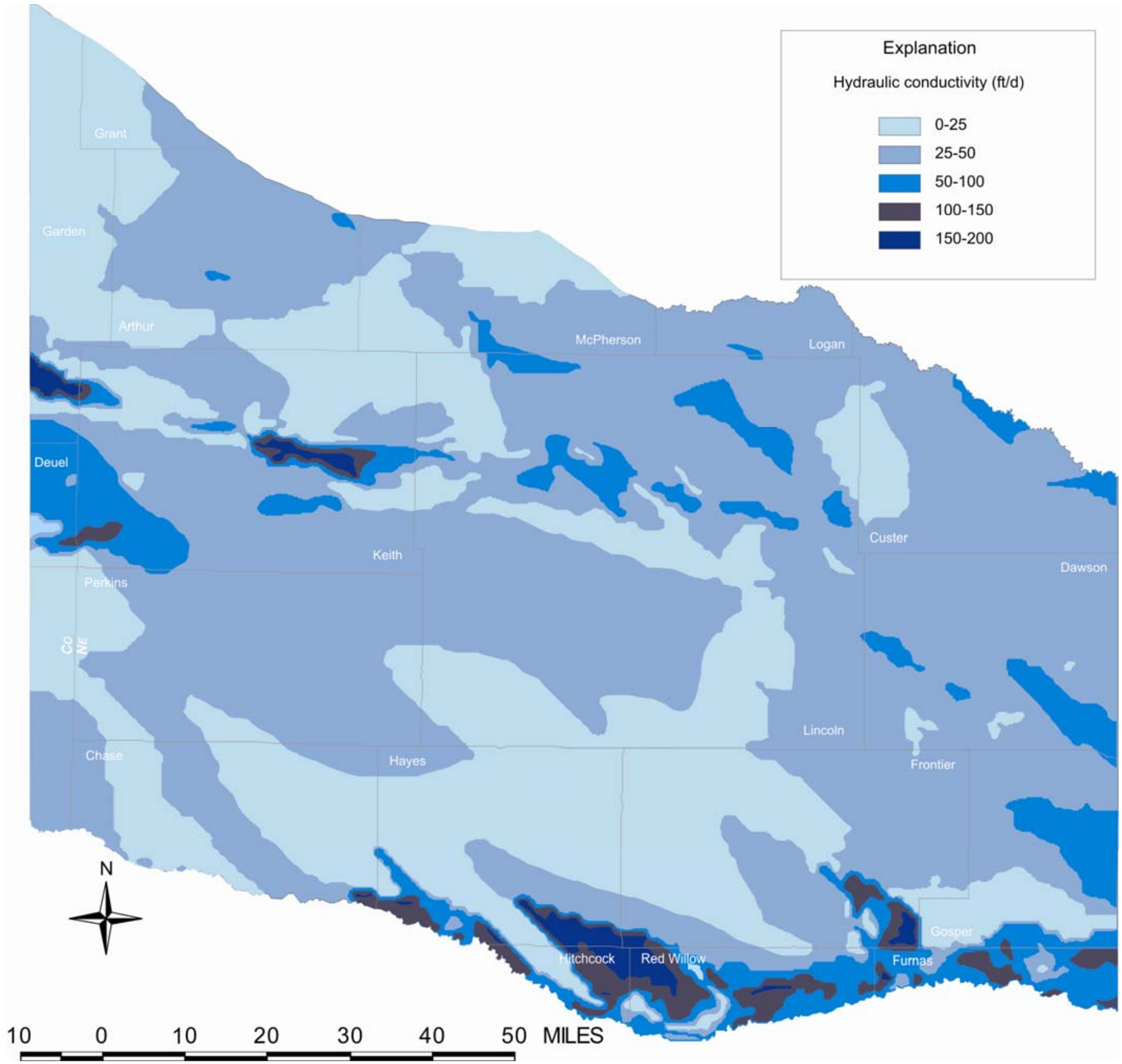


Figure 15. Composite hydraulic conductivity distribution applied to the calibrated model. Values from each layer were weighted by saturated thickness of the layer and averaged to show an effective composite hydraulic conductivity.

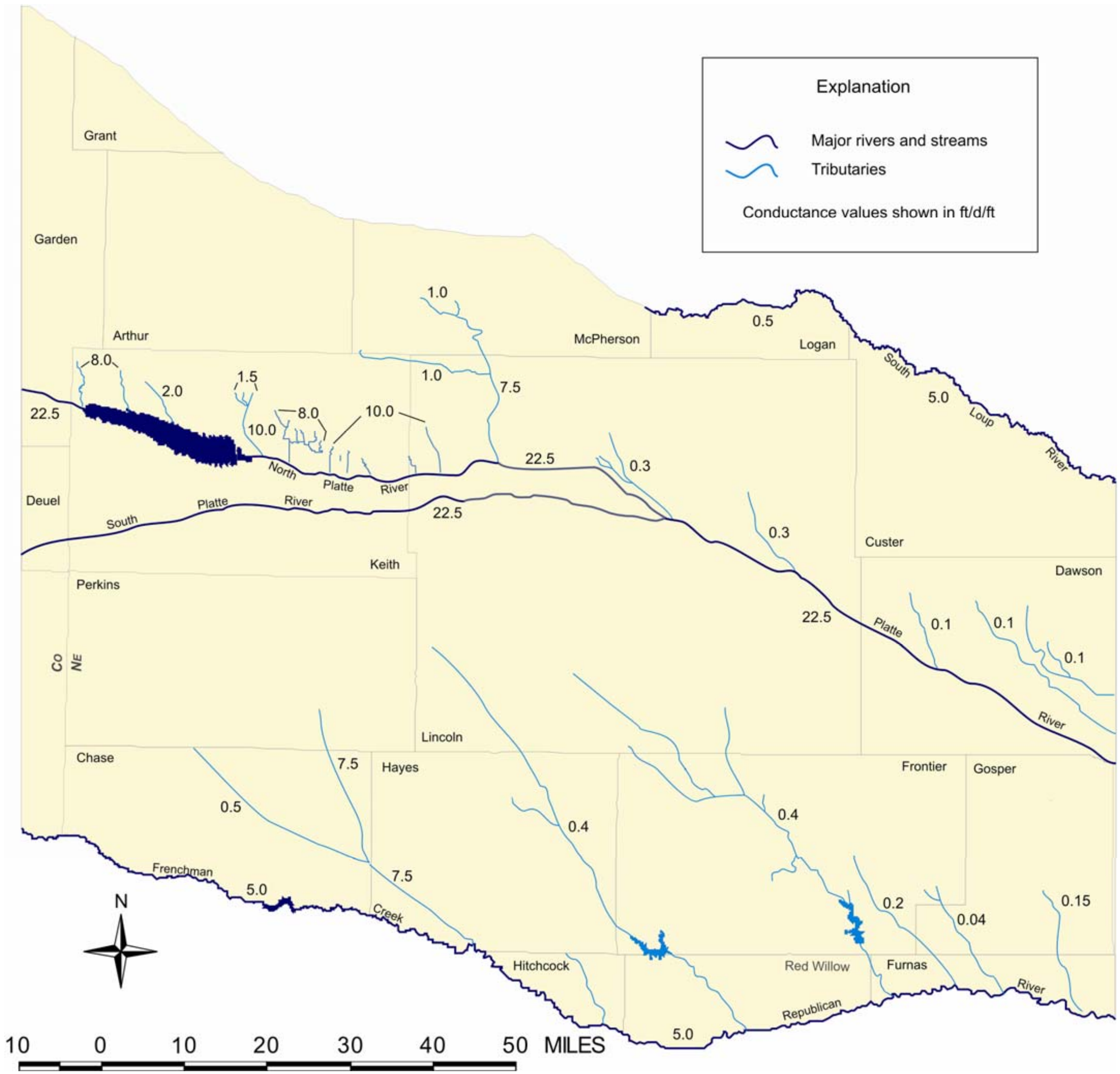


Figure 16. Streambed conductance values applied to the calibrated model.

Otter and Birdwood Creeks (COHYST 2000d). For select drainages in Group 2, such as Birdwood and Whitetail Creeks, upstream reaches were assigned smaller conductances than the downstream reaches. The upper reaches are narrower in comparison to the main reach of the drainage (personal observation by C.P. Carney, 2001-02, USGS 1:24,000 Topographic Maps). Conductances in the upper reaches are 15-20 percent of the values in the lower reach. These values seemed reasonable because stream width is one variable in the MODFLOW method of calculating streambed conductance. Group 3 conductances ranged from 0.04 on Muddy Creek to 7.5 for Stinking Water Creek. For Group 3, a general trend of decreasing conductance from west to east is apparent. Higher values in the west can be attributed to areas of sand hills drained by these streams. Further east, stream cores indicate an abundance of finer sediments, including one core on Muddy Creek indicating nearly 2 ft of clay (COHYST, 2001d).

Drain conductances applied to the Central Model Unit ranged from 0.3 ft/d/ft to 25.0 ft/d/ft. Conductances for drains in the vicinity of Sutherland Reservoir were estimated using discharge values for gaged drains. During calibration, the model was sensitive to these values for these particular drains and the calibrated values were the highest conductances for all drains in the model. Drains that exist mutually in the Central and Eastern Model Unit simulations all have the same conductance of 1.0 ft/d/ft. Conductance values for drains north of the Platte River system ranged from 0.3 to 5.0 ft/d/ft.

Recharge from Precipitation

Groundwater recharge from precipitation during the pre-groundwater development period, or “rangeland” recharge, was based on topographic regions and soil classifications (modified from Cooperative Hydrology Study, 2000b). Topographic regions and associated calibrated recharge rates are shown in figure 17. The rangeland recharge zones were set during model construction and the values applied to the zones were determined during calibration. Areas of greater recharge were in the Sand Hills north of the Platte and North Platte River valleys, which were assigned values ranging from 2.2 to 2.5 in/yr. The lesser values on the eastern extent of the Sand Hills in northeast Lincoln County occur over the linear dunes or thin dune cover when compared to more rounded (barchan or domal) dunes to the west. The barchan or domal dunes typically have a larger surface area, which may allow for greater infiltration rates of precipitation than the narrower, steeper-sloped linear dunes. Figure 18 illustrates the different dune shapes in the eastern zone of the Sand Hills compared to those to the west. Simulated recharge in the Sand Hills north of the Platte River System valley correspond closely with recharge used in other modeling studies (Gutentag and others, 1984, table 7; McLean and others, 1997; Dugan and Zelt, 2000). Sand dunes south of the Platte River System valley tended to require lower recharge rates in the model than those north of the Platte River System valley in order to achieve the best model fit; in some areas the recharge rate south of the Platte River was more than an inch lower than values assigned to the northern Sand Hills. This is likely due to the different landform shape compared to the Sand Hills north of the Platte River system valley (sheet dunes vs. barchan or domal dunes), and a higher percentage of fines (silts and clays) present in the southern sand dunes.

Evapotranspiration

Evapotranspiration of groundwater was simulated in areas of riparian vegetation, wetlands, and numerous Sand Hills lakes in the northwest counties of the Central Model Unit (fig. 10). The maximum groundwater evapotranspiration rate in the Central Model Unit was 17 in/yr in the northwest part of the model in the areas of Sand Hills lakes and was 13 in/yr in all other areas. 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 comm., July, 2004), that accounted for the fact that vegetation evapotranspiration rates are less than open-water rates. The maximum evapotranspiration rate occurred when the simulated water

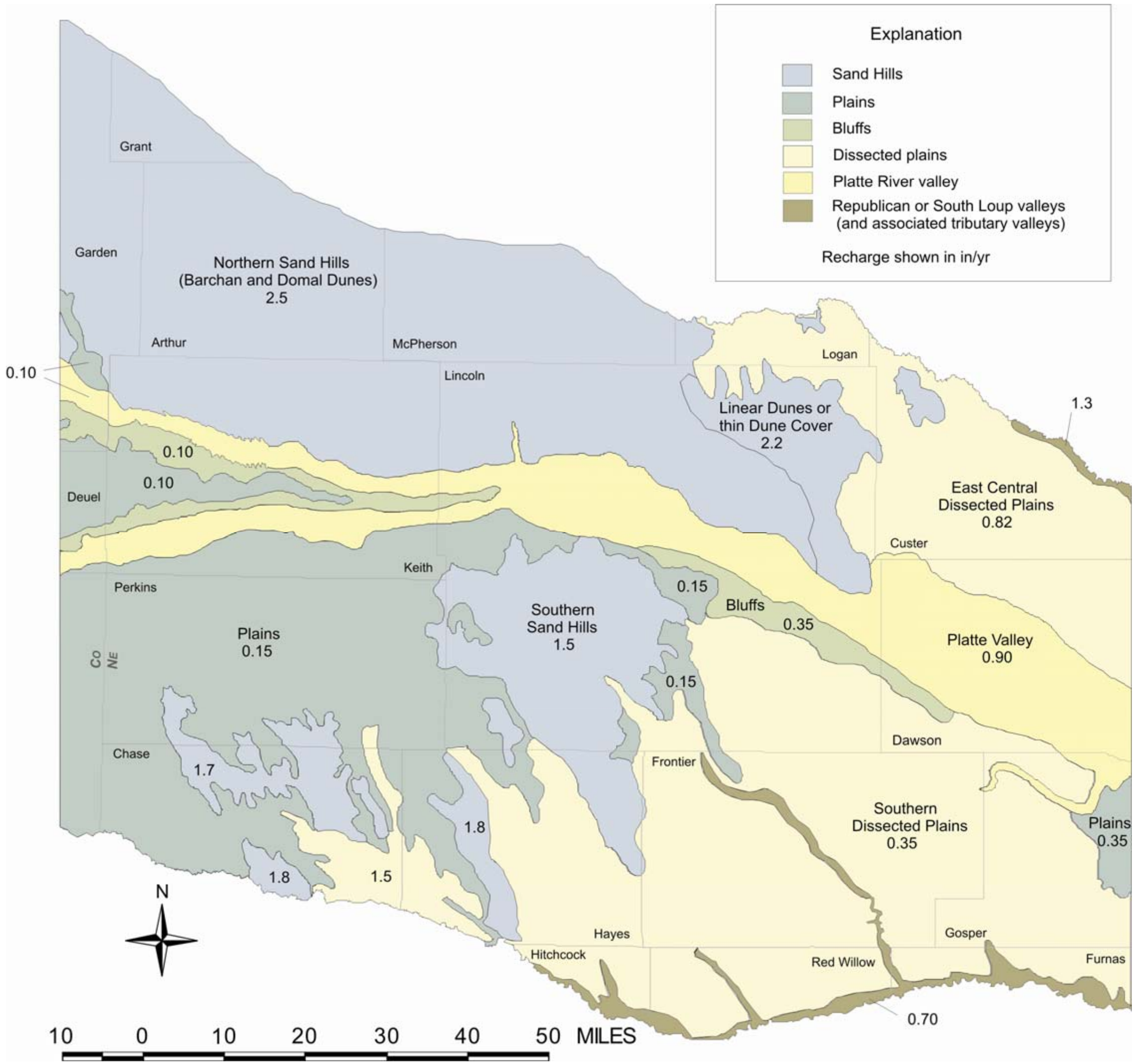


Figure 17. Rangeland recharge distribution applied to the calibrated pre-groundwater development period flow model. Topographic regions are outlined and shown in distinct colors with associated rangeland recharge values.

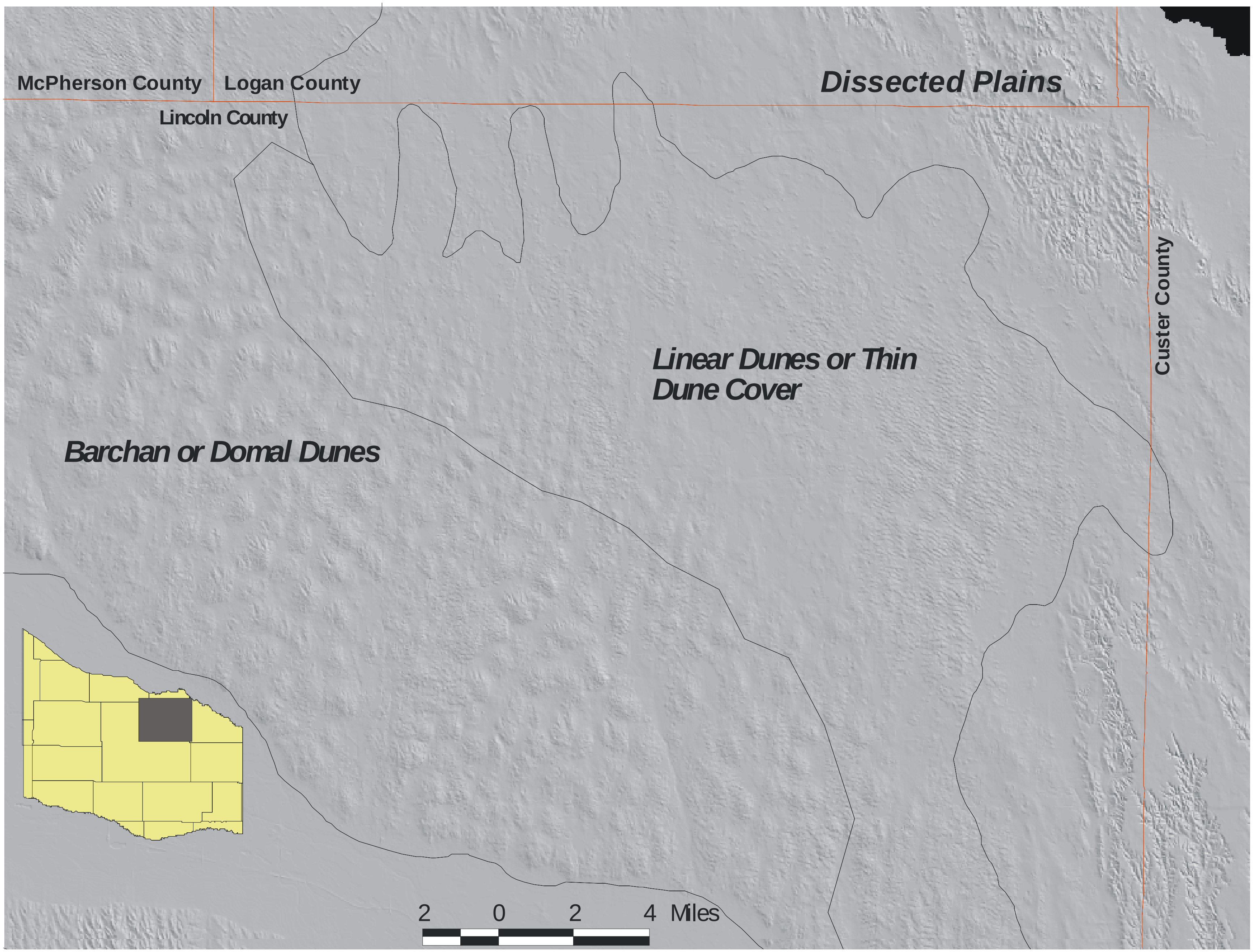


Figure 18. Shaded relief image showing the dune type and spatial distribution in the eastern Sand Hills of the Central Model Unit.

table was at or above the evapotranspiration surface. The evapotranspiration surface was initially estimated as halfway between the mean land surface in the 160-acre model 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 decreased linearly and reached zero when the simulated water table was at the extinction depth below the evapotranspiration surface. In the Sand Hill lakes evapotranspiration areas, the extinction depth was set at 5 feet. The extinction depth was 7 ft in riparian and wetland areas because of deeply rooted cottonwood trees, and 3 ft in locations defined as shallow groundwater evapotranspiration areas, because of shorter rooted grasses and wetland plants.

Simulation Results

The results of both the pre-groundwater development and development period models are discussed in the following sections.

Simulated Groundwater Levels

Figure 19 shows 1950 simulated water levels and comparison of simulated and observed water levels at points within the Central Model Unit. Positive values indicated simulated water levels are above measured water levels, whereas negative values indicated simulated water levels are below measured water levels. Simulated water levels are within ±10 ft for 120 of the 205 (59 percent) measured observation points. A trend of errors within -10 to -30 ft range exists in the southwest portion of the model area (Chase and Perkins Counties) Although not extensive, a band of points straddling the Dawson-Gosper County line in the eastern part of the model are in the +10 to +30 ft range. The largest difference in simulated and observed water levels (41.3 ft) occurs in southwest Perkins County.

Because of a lack of measured observation points in the Central Model Unit at 1950, two additional datasets of interpolated water levels were utilized to calibrate the pre-groundwater development model. Figure 20 shows the comparison between simulated water levels and 1979 water-level contours from the Groundwater Atlas of Nebraska (Conservation and Survey Division, 1998), along with interpolated points based on the published contours. Of the 137 randomly-selected locations from which water levels were interpolated, 57 showed simulated water levels within ±10 ft of the interpolated values (42 percent). The simulated water levels match reasonably well over the model area with a possible error trend in Lincoln and Perkins Counties where simulated values are lower than the interpolated values. The simulated and observed contours match reasonably well with the exception of areas in Perkins and Custer Counties, as well as with the 2,600 ft elevation contour in western Dawson County. This difference is likely due to the Groundwater Atlas map accounting for rises in groundwater levels that occurred into the development period, during which the pre-groundwater model would add more seepage water to the system.

Figure 21 shows a comparison of the simulated water-level contours with the pre-development water-level contours (Cederstrand and Becker, 1999) from the U.S. Geological Survey, along with the same randomly selected interpolated observation points from figure 20. Of the 137 observation locations, 58 (42 percent) show simulated water levels within ±10 ft of the interpolated observation values. Comparison of the contours shown in figure 21 reveal the same trends shown with the Conservation and Survey Division (1998) compared to the simulated water levels, with the exception being in Dawson County where the interpolated values do not show water level rises due to canal seepages from the supply canal (fig. 3) and other local irrigation canals. Point locations from the Conservation and Survey Division (1998) and Cederstrand and Becker (1999) where simulated values are greater than ±30 ft error are not coincident between the two datasets, indicating that the simulated water levels are likely within the range of error inherent in the two sets of contours and points interpolated from the contours. The deviation between simulated and observed water level contours for figures 20 and 21 in parts of Dawson County are attributed to the timeframe differences between the two datasets. The 2,600 foot contour for the observed data replicates the modern-day water level conditions where seepage from the Tri-County Supply Canal

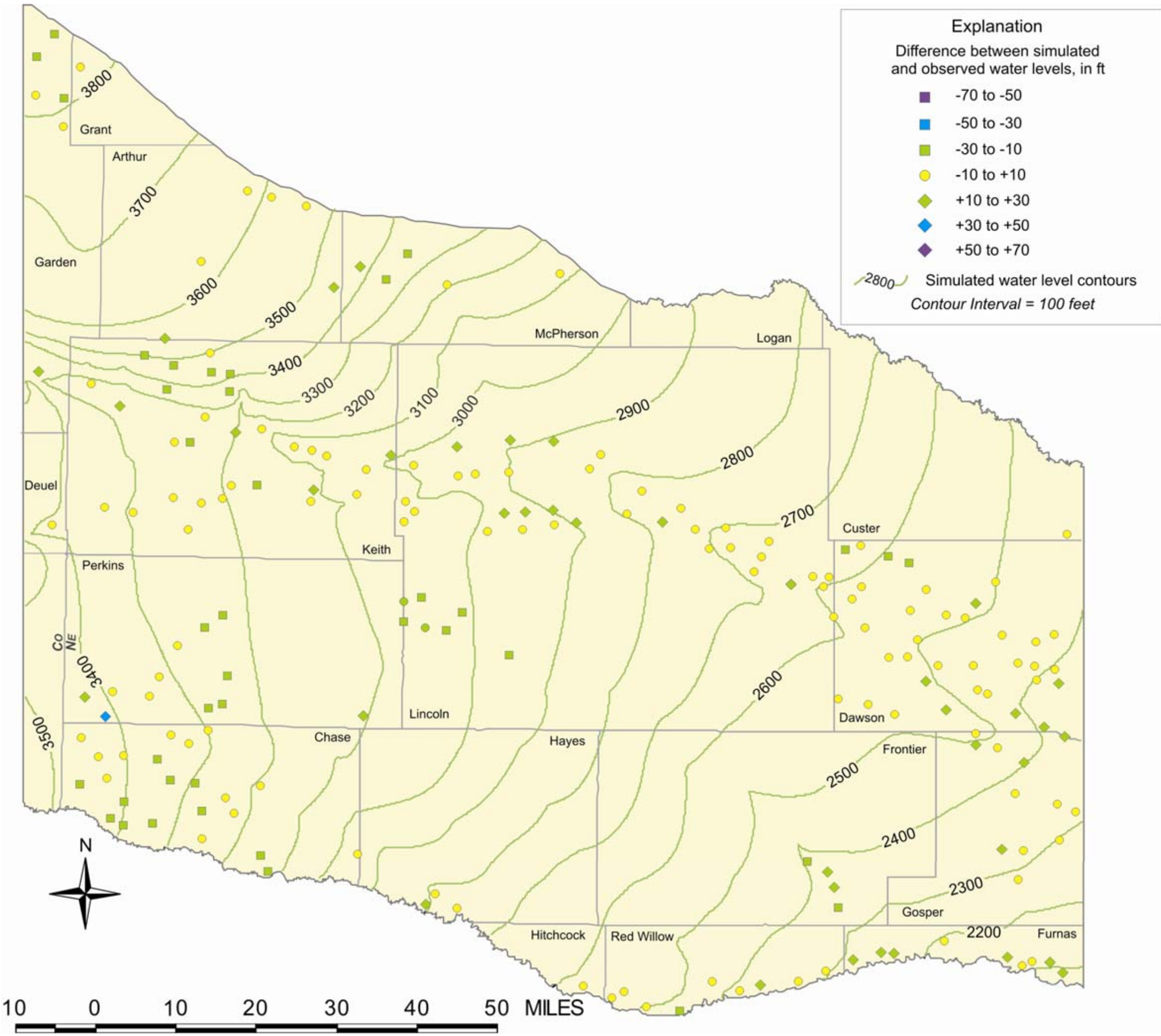


Figure 19. Simulated 1950 water table for the calibrated pre-groundwater development period model and comparison between simulated and observed water levels at observation points in the Central Model Unit. Contour elevations are in feet above mean sea level.

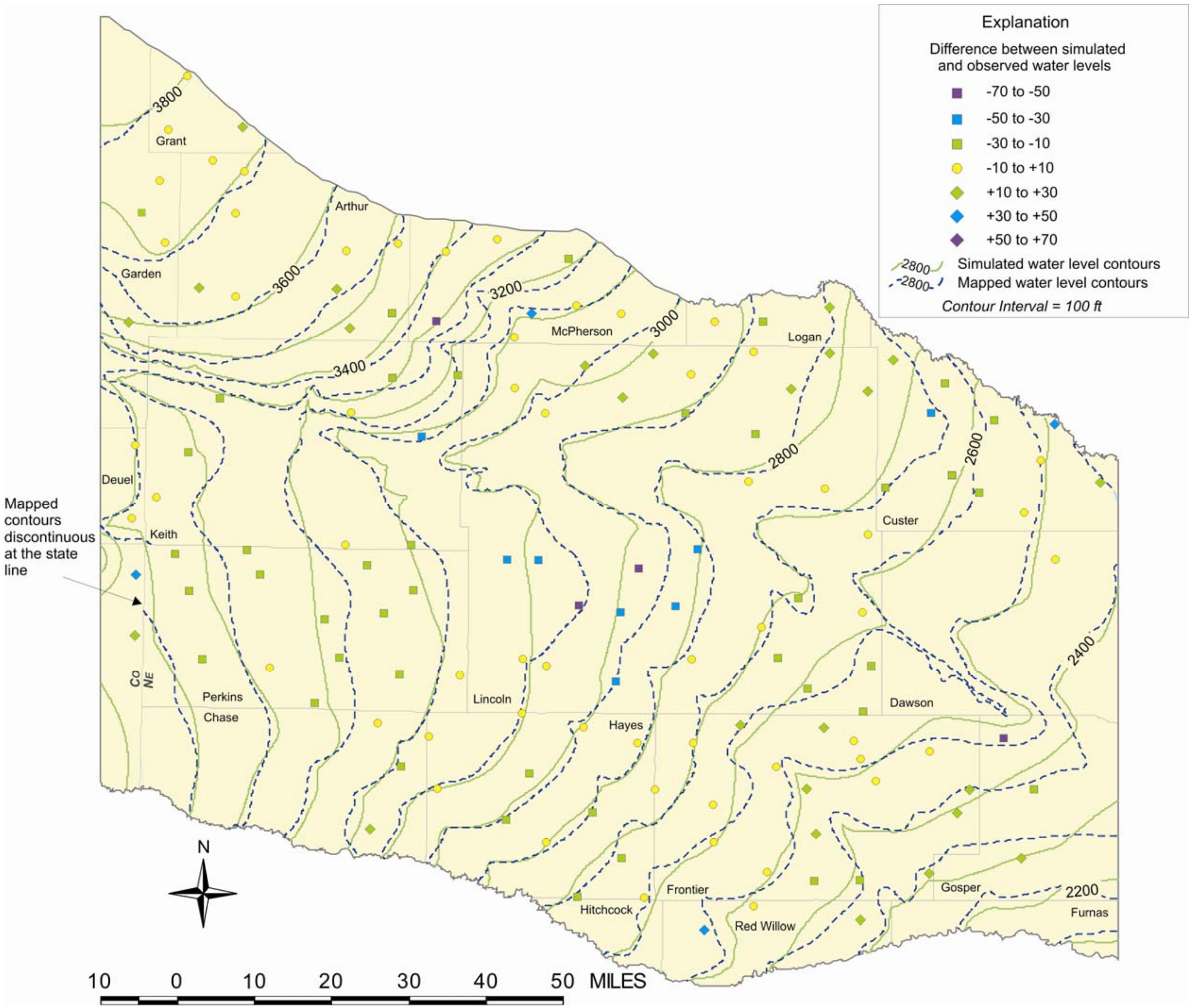


Figure 20. Comparison between simulated 1950 water levels for the calibrated model and pre-groundwater development water-levels from the Groundwater Atlas of Nebraska (Conservation and Survey Division, 1998). Contours published in the Groundwater Atlas were used to generate interpolated observation points, to allow for comparison with simulated water levels in locations where no measured data exist. Contour elevations are in feet above mean sea level.

has significantly altered the water table in the area. In figure 21, the observed contours were created from the earliest data found, and do not account for any seepage from the CNPPID system, whereas by 1950, the simulation indicates some influence of canal seepage as the CNPPID had been in operation for nearly a decade by 1950 (see contours 2,500 and 2,600 in fig. 21).

Figure 22 shows the simulated saturated thickness of the aquifer at 1950. The saturated thickness was greatest (> 800 ft) in Arthur, McPherson, and Grant Counties. Areas where the saturated thickness was least exist in eastern Keith County (just east of Lake McConaughy) and in western Keith County. In these areas, the Ogallala Group is thin to non-existent and saturated aquifer material consists of alluvial material only. In general, the southwest quarter of the Central Model Unit, particularly southern Keith County, Chase County, and Perkins County have less saturated thickness (typically not exceeding 200 ft) than the rest of the study area. This trend in saturated thickness exists over much of the southern portion of the Central Model Unit just north of the Republican River valley, but the remainder of the Central Model Unit is underlain by saturated thicknesses exceeding 300 ft.

Water-Level Calibration Statistics

Calibration statistics for simulated water level versus observed and interpolated values are shown in table 6. The mean difference of 1.59 ft for the observed water-level data set indicates that the simulated water levels averaged somewhat above observed water levels at calibration points. The mean absolute difference was considered to be the most appropriate measure of error for simulated and observed or interpolated water level comparisons. The mean absolute difference between simulated and observed values is 9.38 ft. The root-mean-square difference for the measured data was 11.69 ft.

Simulated Stream Discharges

Table 5 shows Central Model Unit stream baseflows (the contribution of flow from groundwater) at 1950 for the calibrated model. Of the 19 streams or reaches of streams with estimated stream baseflow, 12 were within the target range of groundwater discharge. Of the six remaining streams or reaches of streams with simulated discharges not falling into the ranges of estimated stream flow, two had simulated discharge from the aquifer that deviated substantially from the calculated range. The reach of the North Platte River between Sutherland and North Platte gage showed simulated flows lower than estimated groundwater discharge by 25 ft^3/s. The reach of the South Platte River between Paxton and North Platte show simulated flows lower than estimated flows. This simulated discharge value between Paxton and North Platte combined groundwater discharges to the specified reach of the river as well as to the numerous drains located in the South Platte River valley along this reach since the river gains an appreciable amount of flow from these drains, which were not accounted for in the low-flow analysis that determined the calibration target. The reach from Julesburg to Paxton overestimated inflow from the aquifer by 14 ft^3/s. The remaining three drainages with simulated discharges outside the estimated range were less than 3 ft^3/s in error.

Model Budget

Table 7 shows the water budget for the simulated pre-groundwater development period at 1950. Groundwater recharge from precipitation and canal seepage dwarfed all other components of inflow, comprising 88 percent of inflow to the Central Model Unit. The dominant outflow component of the budget was discharge to rivers and streams, which received 63 percent of all outflow from the Central Model Unit. The second largest component of outflow was evapotranspiration at 29 percent of the budget. All other non-storage components contributed less than 10 percent of inflow or outflow of the model. Storage of water within the aquifer received a net increase of 281 ft^3/s.

The calibrated pre-groundwater development period model for the Central Model Unit was considered a reasonable representation of the groundwater flow system, given the data available and the size of the grid. The calibrated model at 1950 represented the initial conditions for the groundwater development period model (1950-98).

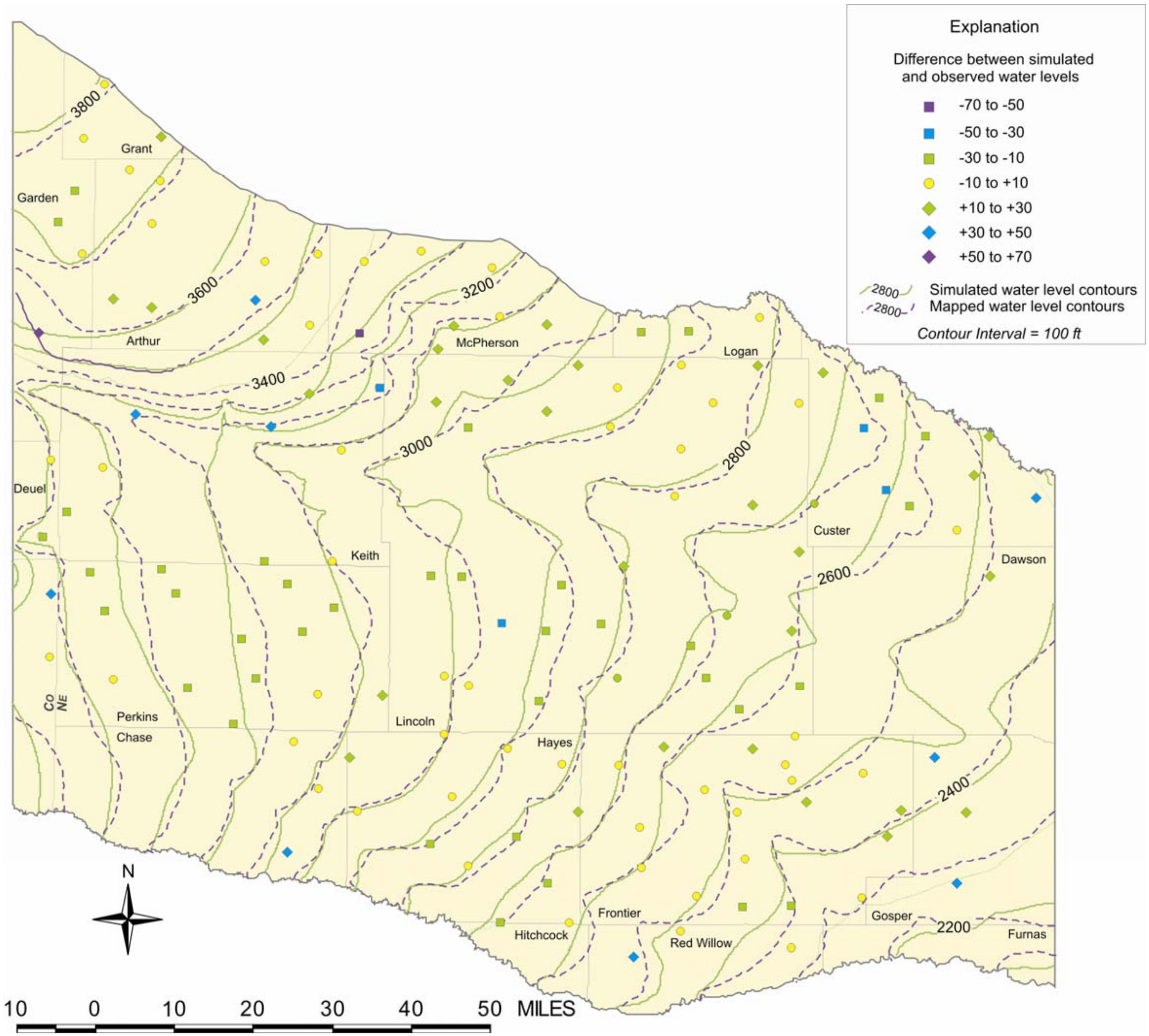


Figure 21. Comparison between simulated 1950 water-levels for the calibrated model and pre-groundwater development water-levels from the U.S. Geological Survey (Cederstrand and Becker, 1999). These contours were used to generate interpolated observation points, to allow for comparison with simulated water levels in locations where no measured data existed. Contour elevations are in feet above mean sea level.

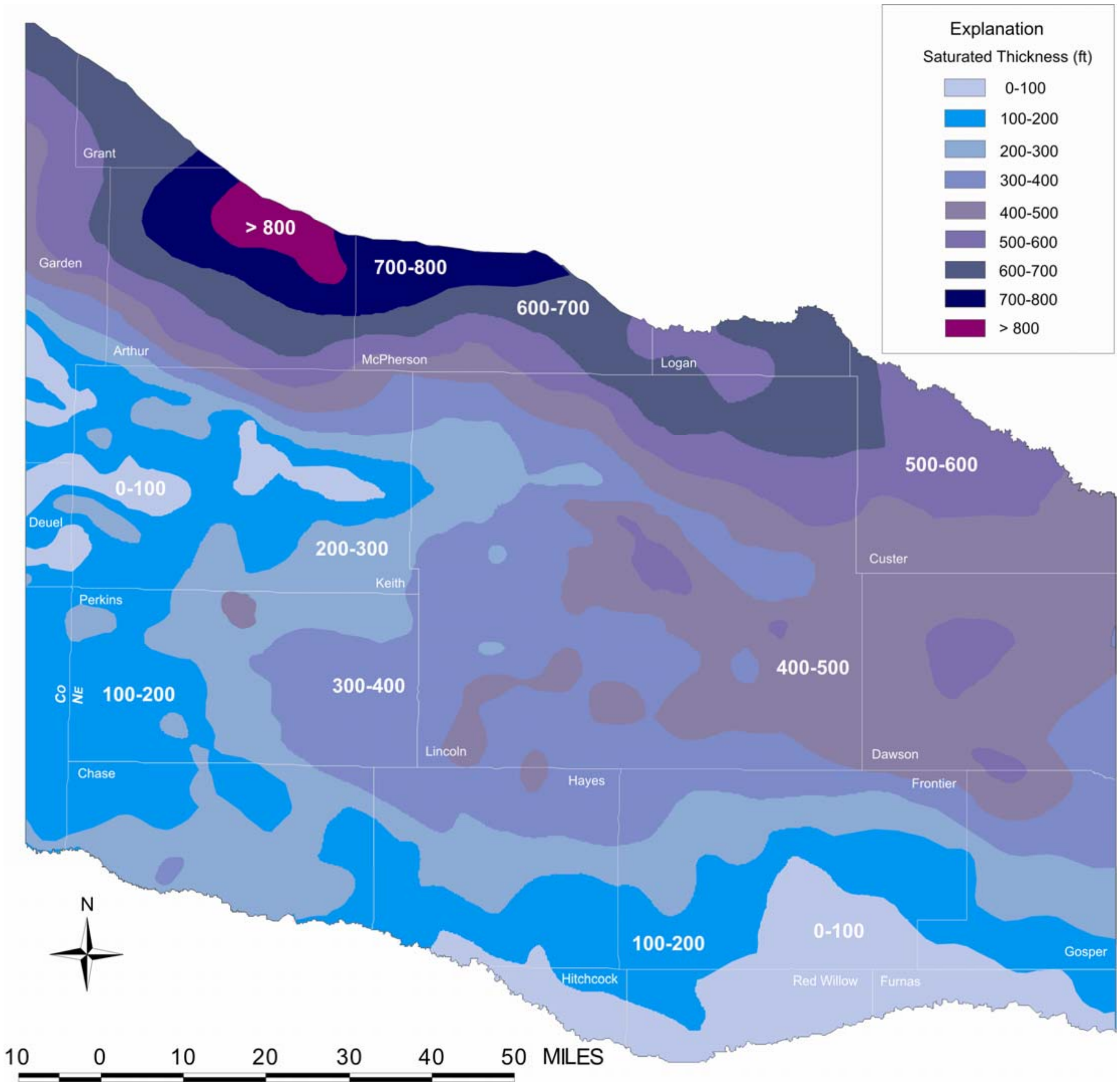


Figure 22. Simulated 1950 saturated thickness of all layers in the Central Model Unit.

Table 6. Simulated and observed discharge to streams for the calibrated pre-groundwater development model at 1950. All flows are in cubic feet per second.

Stream	Reach	Simulated gain	Observed gain (negative is loss)			Remarks
			Minimum	Mean	Maximum	
North Platte River	Sutherland-North Platte	44	69	88	119	Below calibration range
South Platte River	Julesburg- Paxton	28	-42	-10	14	Above calibration range
	Paxton-N. Platte[2]	48	121	128	147	Below calibration range
Platte River	Brady-Cozad	72	55	70	119	Within calibration range
	Cozad-CMU Boundary	33	-133	45	131	Within calibration range
Birdwood Creek	entire	151	138	146	152	Within calibration range
Whitehorse Creek[1]	entire	6	6	8	9	Within calibration range
Whitetail Creek[1]	entire	29	14	29	43	Within calibration range
Pawnee Creek[1]	entire	5	3	6	9	Within calibration range
Otter Creek[1]	entire	11	12	24	36	Below calibration range
Stinking Water Creek	entire	27	23	28	32	Within calibration range
Blackwood Creek	entire	1	0.7	0.9	1.1	Within calibration range
Red Willow Creek	entire	27	22	25	27	Within calibration range
Medicine Creek	entire	44	34	42	51	Within calibration range
Muddy Creek	entire	5.4	3	4	5	Above calibration range
Turkey Creek	entire	2	4	5	6	Below calibration range
Frenchman Creek	entire	18	15	18	27	Within calibration range
Republican River	McCook-Cambridge	4	-48	-38	-2	Above calibration range
	Cambridge-CMU Boundary	5	-13	7	20	Within calibration range
South Loup River	entire	44	Not gaged			

[1] Values not from Low-Flow Analysis (Carney and Peterson, 2001)
[2] Flows include ungaged drains that enter the South Platte between gages.

Table 7. Calibration statistics for the 1950 simulated water levels.

Statistic (all values in ft)	Simulated water levels compared with observed water levels
Mean difference	1.59
Mean absolute difference	9.38
Root-mean squared difference	11.69

Table 8. Simulated 1950 water budget for the calibrated pre-groundwater development period model. The item stream includes both rivers and streams as simulated in MODFLOW. Individual items may not sum to total because of rounding.

Item	ft^3/s	Acre-ft per year (thousands)	Percent of inflow or outflow
Inflow to aquifer			
recharge from precipitation	998	722	56
recharge (canals/irrigation)	568	411	32
external boundaries	154	112	9
from streams	46	33	2.5
from on-stream reservoirs	19	14	1.0
Total	1,785	1,293	100.0
Outflow from aquifer			
streams and drains	948	686	63
evapotranspiration	441	319	29
external boundaries	77	55	5
to on-stream reservoirs	37	27	2.5
Total	1,504	1,089	100.0
Net increase in groundwater storage	281	203	

Groundwater Development Period Calibration

Simulated water levels from the pre-groundwater development period model were used as the starting water levels for the transient groundwater development period model, which simulated the period of May 1, 1950 through April 30, 1998. All of the inputs to the pre-groundwater development period model were retained and other time-varying inputs were added for the 1950-98 period. Groundwater pumpage for agricultural needs, as described in the Numerical Model Construction section, was added to the groundwater development period model and was not changed during calibration. Spatially varying specific yield was added to the model and the values were determined during calibration. Additional time-varying recharge on cultivated land also was added to the model and the values were determined during calibration. These modifications to the model created substantial water-level declines and rises in different areas of the Central Model Unit. The modification of specific yield and time-varying recharge was needed to reach a reasonable calibration of the development period model. The specific storage term, set at 5.0×10^{-5}, was not modified for the groundwater development period simulation.

Model Parameters

Following is a discussion of the process of parameter adjustment during the groundwater development period.

Specific Yield

Calibration of the development period included testing of numerous specific yield values in individual model layers in areas with large water-level changes during the 1950-1998 period. The final values (table 8) applied to the Central Model Unit model were consistent with analysis of specific yield data from testholes in the COHYST well database (Cooperative Hydrology Study, 2001b). Model layer 1 was assigned a uniform specific yield of 0.11 across the model because it consists of fine-grained sediments. Model layer 1 was above the water table across much of the Central Model Unit. Model layer 2 was assigned a variable specific yield across the model, with the variation based on values found in the COHYST well database (Cannia and others, 2006). The mean specific yield in model layer 2 was 0.18, with values ranging from 0.11 to 0.22. Model layers 3-6 were assigned a uniform specific yield of approximately 0.17. The value 0.17 was dominated by values in the COHYST well database for model layer 4 (Hydrostratigraphic Unit

5). Model layer 4 was much thicker and more extensive than model layers 3, 5, or 6. Specific yield is only used by MODFLOW for cells in which the water table occurs. The value was ignored for all cells completely above or below the water table. As a result, only the value of the layer at the simulated water table matters in the model.

Not all model layers are continuous over the entire model domain, but MODFLOW requires that layers be continuous. To accommodate this requirement, missing model layers were simulated as layers 1 ft thick, with the specific yield of the cell within the 1-ft layer set as the average of the cells immediately above and below the 1-ft thick cell. In this way, the MODFLOW requirements were met without introducing erroneous specific yield values.

Table 9. Specific yield values (by model layer) applied to the calibrated model.

Model layer	HU	Simulated specific yield, dimensionless		
		Mean	Minimum	Maximum
1	1	0.11	0.11	0.11
2	2	0.18	0.11	0.22
3-6	3-7	0.17	0.11	0.22

Recharge from Canal Seepage

As with the pre-groundwater development period, groundwater recharge from canal seepage was added to the model via the recharge package in MODFLOW. Changes in seepage values during the development period are listed in table 3 (p. 31).

Land-Use Based Recharge

Additional recharge from precipitation, above the amount in the pre-groundwater period model, was added during the groundwater development period to calibrate the 1950-98 simulation. This recharge was added only to croplands, both dry and irrigated, with more recharge added to irrigated land than to dryland (dryland areas included fallow fields). This recharge varied over time only because the amount of dryland and irrigated crop land varied over time. The justification for adding this extra recharge to dryland is that dryland, when fallow, is managed to capture and maintain soil moisture, and thus soil moisture on dryland regularly exceeds that on rangeland. Therefore, when precipitation falls on dryland, it has a better chance to become recharge than when precipitation falls on uncultivated rangeland. Likewise, on irrigated crop land, soil moisture is maintained by irrigation and precipitation on irrigated land has a better chance of becoming recharge than precipitation on either dryland or rangeland. Extra recharge on irrigated crop land was not the same as deep percolation of applied irrigation water. Deep percolation of applied irrigation water is accounted for by using net pumpage. The amount of additional recharge on dryland and irrigated land was determined during model calibration and was varied over time to account for changes in land-use practices between 1950 and 1998. This additional recharge also varied from west to east, to account for increasing west to east precipitation trends (fig. 5). The need for additional recharge applied in the Central Model Unit during the development period is also supported by work performed by Dugan and Zelt (2000) in which simulations of soil water conditions between 1951-80 showed potential groundwater recharge values similar to those needed for calibration of the development period groundwater model in the Central Model Unit.

Figure 23 shows a sample of the Central Model Unit (Chase and Perkins Counties) which indicates the variability in land use practices that were used to define of additional recharge during the development period. The image was created from satellite imagery provided by Dappen and Tooze (2001) that delineated various crop and land uses based on infrared signatures of plants and soils. The spatial distribution of land use types was based primarily on soil type and areas where the High Plains aquifer yields adequate volumes of water for irrigation. The map exemplifies the influence of topography and soil on what land was used for agriculture and where the aquifer was sufficient to be used to grow irrigated crops in the southwest corner of the Central Model Unit.

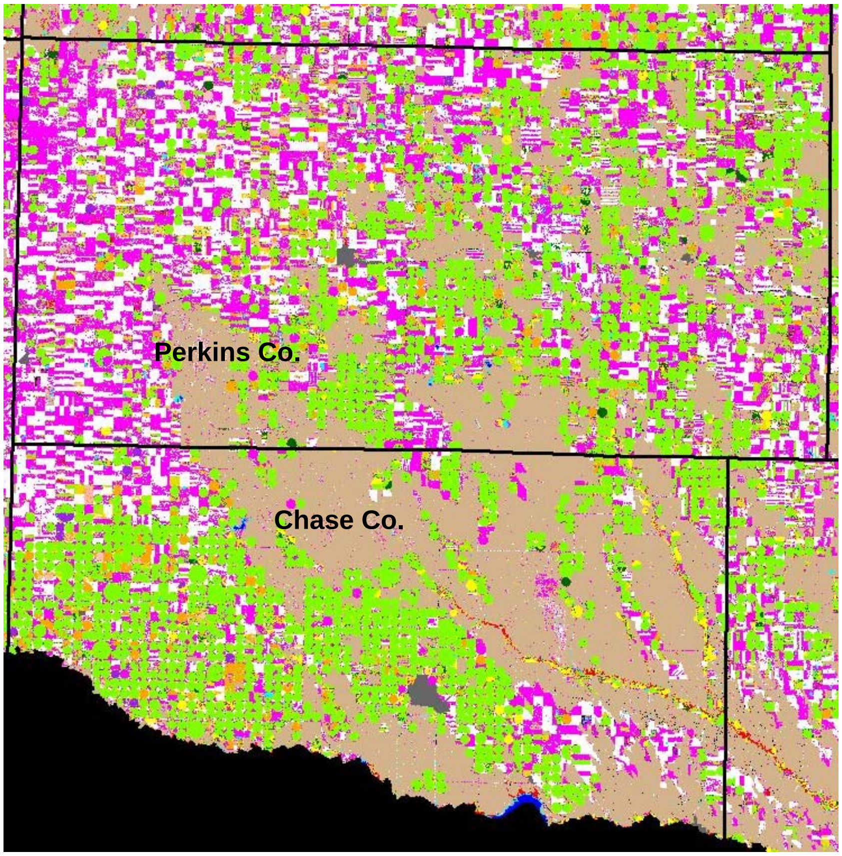


Figure 23. 1997 land-use categories based on satellite imagery (Dappen and Tooze, 2001) exemplifying the variability in dryland (pink and white), irrigated lands (green), and rangeland (brown). Other colors represent other non-agricultural related land types, roads, or cities. Area shown is Perkins and Chase counties.

During the groundwater development period calibration, the Central Model Unit was subdivided into three zones for application of additional recharge based on land use (fig. 24). The 19-inch precipitation contour (fig. 5) roughly separates the western and central recharge zones, and the western boundary of the COHYST Eastern Model Unit (Lincoln-Dawson County line) was set as the boundary between the central and eastern recharge zones. Additional recharge values in the eastern recharge zone were identical to values applied in the Eastern Model Unit simulation to maintain consistent model parameters in the overlap area of the two models. Table 9 shows the additional recharge on dryland and irrigated land increased eastward for both the NebGuide and CropSim pumping scenarios.

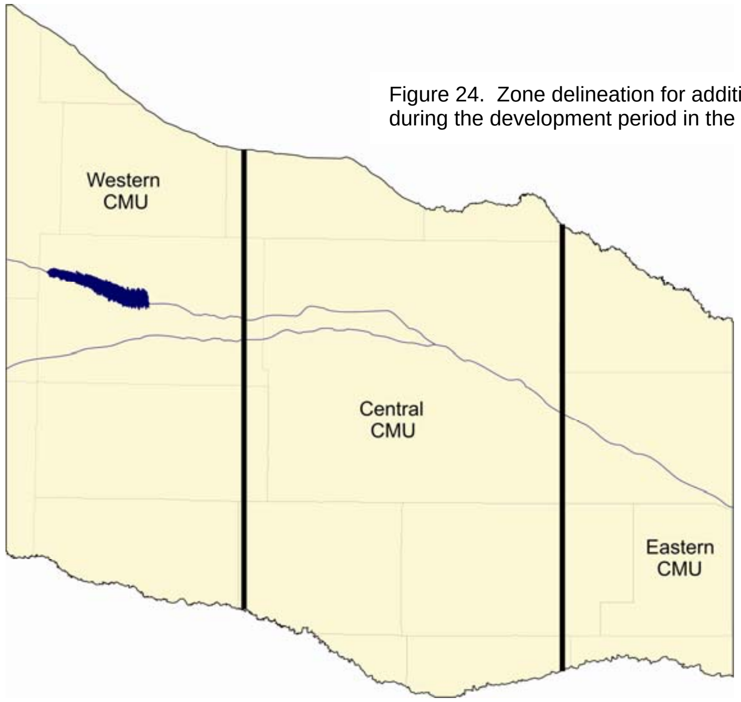


Figure 24. Zone delineation for additional recharge during the development period in the CMU.

Although additional recharge values were consistent within the entire sub-zones shown in fig. 23, Perkins County received 2.35 in/yr (1.25 in/yr less than the overall western recharge sub zone) from 1950-1979 on irrigated lands. The model showed poor calibration in Perkins County for this time period with higher recharge values on irrigated lands. Based on soil moisture capacity maps, Perkins County overall had more area of soils with greater moisture holding capacity, thus reducing the potential for groundwater recharge from precipitation or groundwater-derived irrigation water. Another potential source of reduced irrigated land recharge in Perkins County during this timeframe could be the drought of the mid-1950s causing a reduction in aquifer recharge over the areas of less permeable soils in Perkins County. Although the effects of a reduced recharge may not reach the water table in areas of large unsaturated zones common in Perkins County, the model did not account for unsaturated zone flow timing and recharge was applied instantaneously to the highest saturated or partially saturated layer.

Table 10. Additional annual recharge (inches) applied to the development period model by time frame and land use for both NebGuide and CropSim pumpage simulations. Note Perkins County received 2.35 in/yr from 1950-79 on irrigated lands.

[1] From Dugan and Zelt, 2000, figs. 34 and 36. The first value is the mean annual potential groundwater recharge under non-irrigated conditions, the second value is under irrigated conditions for select crop types.

Time Period	Land Use	Western CMU		Central CMU		Eastern CMU	
		NebGuide	CropSim	NebGuide	CropSim	NebGuide	CropSim
1950-73	Dryland	0.15	0	0.5	0	0.6	0.1
	Irrigated	3.6	4.6	3.5	4.5	3.7	4.7
1973-79	Dryland	0.15	0	0.8	0.3	0.9	0.4
	Irrigated	3.6	4.6	5.5	6.5	5.8	6.8
1979-98	Dryland	0.75	0.25	0.8	0.3	0.9	0.4
	Irrigated	3.96	4.96	5.5	6.5	5.8	6.8
[1] Dugan & Zelt, 1951-1980		2, 2 - 3		1-2, 1.5 – 2		1, 1 – 1.5	

Additional recharge to irrigated and dryland areas changed temporally during the groundwater development period. This period was separated into three segments, 1950-1973, 1973-1979, and 1979-1998. This separation was based on the changes in agricultural practices during the groundwater development period which likely increased groundwater recharge on irrigated and dryland acres (Peterson, in review). These changes included reduction of direct soil evaporation by improvement in row crop planting and soil management. As shown in table 9, irrigated land recharge increased by 2 in/yr or more between the two time periods for the eastern and central sub-zones of the Central Model Unit (fig. 23). However, the time frame for increased recharge in the western zone was offset until 1979 based on model calibration tests and groundwater pumping management practices implemented in the late 1970s in the Upper Republican NRD (fig. 4). Because of rapidly declining water levels resulting from groundwater development for irrigation in the 1970s in Chase and Perkins Counties, the Upper Republican NRD incorporated a groundwater management plan with incentives to irrigators to reduce the volume of groundwater applied to crops annually. These practices took full effect by the end of the 1970s and a decrease in the rate of water-level decline was observed in the 1980s in Chase and Perkins Counties (Goeke, UNL-CSD, personal comm., 2004).

In addition to simulating the groundwater development period with NebGuide (Kern, 2004) based pumpage, the model was also tested with CropSim net pumpage values produced by the University of Nebraska (Martin, UNL, written comm., 1999). Development of these separate datasets is discussed under the Groundwater pumpage section (p. 34). Several combinations of recharge values on irrigated and dryland acres were tested in conjunction with the CropSim pumpage. Ultimately, additional recharge values (table 9) were increased above the calibrated NebGuide recharge values by 1 in/yr on irrigated lands for the entire model area over the time period 1950-1998, and additional recharge was decreased by 0.5 in/yr on dryland acres over the entire model area for the same time period. In areas where there were less than 0.5 in/yr on dryland acres initially, recharge was set to zero for these acres. It remains unclear as to why a decrease in dryland recharge improved the model calibration during this time period, although research in patterns of water movement in the vadose zone may provide further insight into this condition. Although extensive testing of the model was conducted with CropSim pumpage dataset, the final results from the NebGuide-based pumpage simulation are deemed the calibrated model for the Central Model Unit groundwater development period.

Simulation Results

Following is a discussion of simulation results of the groundwater development period simulation. This section describes changes in water levels as opposed to absolute values of water levels as considered in the pre-groundwater development period simulation.

Simulated Groundwater Level Changes

Simulated water-level changes from 1950 to 1998 are shown in figures 25. Within the Central Model Unit, two major areas of water level change occur over the simulation timeframe, with one area in the eastern Central Model Unit south of the Platte River showing significant water-level rises in the first two decades of the groundwater development period, and another area in the southwest portion of the Central Model Unit with substantial water-level declines in the last half of the development period. In the eastern Central Model Unit, groundwater levels began to rise prior to the groundwater development period, and continued through the 1980s. This area of water-level rise is primarily in the vicinity of the Tri-County Supply Canal and irrigation areas (fig. 11). In Lincoln County, substantial water-level rises were occurring at the beginning of the development period as seepage from Sutherland Reservoir and supporting canals caused water levels to rise at least 5 ft as far as 30 mi south of the project area. These two areas of seepage and corresponding water level rises coalesced to form a considerable area of water level rises from the Keith-Lincoln County line to the eastern boundary.

Water-level increases upwards of 25 ft also occurred in the area surrounding Lake McConaughy, as the lake level continued to rise in the early part of the groundwater development period. Slight declines in the water table also occurred in Custer County, where more irrigated land went into production during the 1950-98 timeframe.

In the southwest part of the Central Model Unit, development of the aquifer for irrigated agriculture during the groundwater development period caused extensive water-level declines across Chase and Perkins Counties as well as the segment of Colorado within the model boundary. Declines of a lesser extent were also simulated in parts of Lincoln, Hayes, and Keith Counties. Declines of at least 15 ft occurred in at least half of Perkins County, and declines of at least 25 ft occurred in over half of Chase County. The most severe declines of the entire Central Model Unit were simulated in the southwest corner of Chase County, where the simulated drop in the water table approached 100 ft.

Figures 26 through 29 show the changes in water levels during the 4 sub-periods. The entire timeframe was divided to show in better detail when major changes in the regional water table occurred and because of the greater abundance of observation points available in the individual sub-periods. The first sub-period, 1950 to 1961, showed continued increase in the mounds underlying the Sutherland and Tri-County project canals and reservoirs. The few observation points available in Gosper County indicate the model simulated too large of an increase in water-levels in this area. Most of the increase in the water table adjacent to Lake McConaughy also occurred in this period. In southwest Frontier County, a small area of water-level decrease occurred near where Hugh Butler lake was constructed. The water level decrease was due to the initial stage set in the general head package for the last year of the sub-period causing the surrounding water table to lower.

The sub-period 1961 to 1973 shows continued water-level increases upwards of 15 ft under most of the mound as well as a small area of 25 ft rises in Gosper County. The few observation locations available show the simulated values agreed with observed changes within ±5 ft. Water-levels also continued to rise near Lake McConaughy, although not as much as the previous sub-period. Near Hugh Butler Lake, the water-levels rose upwards of 15 ft. The initial phase of the regional water-level declines in the southwest counties of the Central Model Unit also began in this sub-period as declines of 5 ft were simulated by 1973. By the third sub-period, 1973 to 1985, a much larger abundance of observation points became available for comparison of simulated and observed water level changes. During this timeframe, significant changes occurred in the regional water table in the Central Model Unit. The large mound under the Sutherland and Tri-County projects began to stabilize with the exception of the bulls-eye shaped area of water-level increases in Gosper County. In this area, Elwood Reservoir was completed in 1978 and initial seepage caused major rises in the surrounding water table. The observation points available in this area show that the simulated rise is water-levels is above observed changes, although two points on the periphery of this sub-period rise are within the ±5 ft range. Water level decreases approaching 5 ft in western Custer County are supported by the observed water level changes based on the numerous points within the ±5 ft range. In the southwest counties, declines in water-levels approached 25 ft in Chase County and were at least 5 ft in most of Perkins County. The observed water-level change locations agreed reasonably well in Perkins County with the majority of points within the ±5 ft range. The simulated declines in Chase County were slightly greater than observed changes as three observation locations were in the 5 to 15 ft range of simulated declines greater than observed values.

The final sub-period of the groundwater development period, 1985 to 1998, showed a similar pattern as the previous sub-period, although the rises in Gosper and Dawson Counties under the mound were not as large as from 1973-85. The rises in this area were however more spread out as increases nearly reach the Furnas-Gosper County line. In the area of this sub-period mound, the

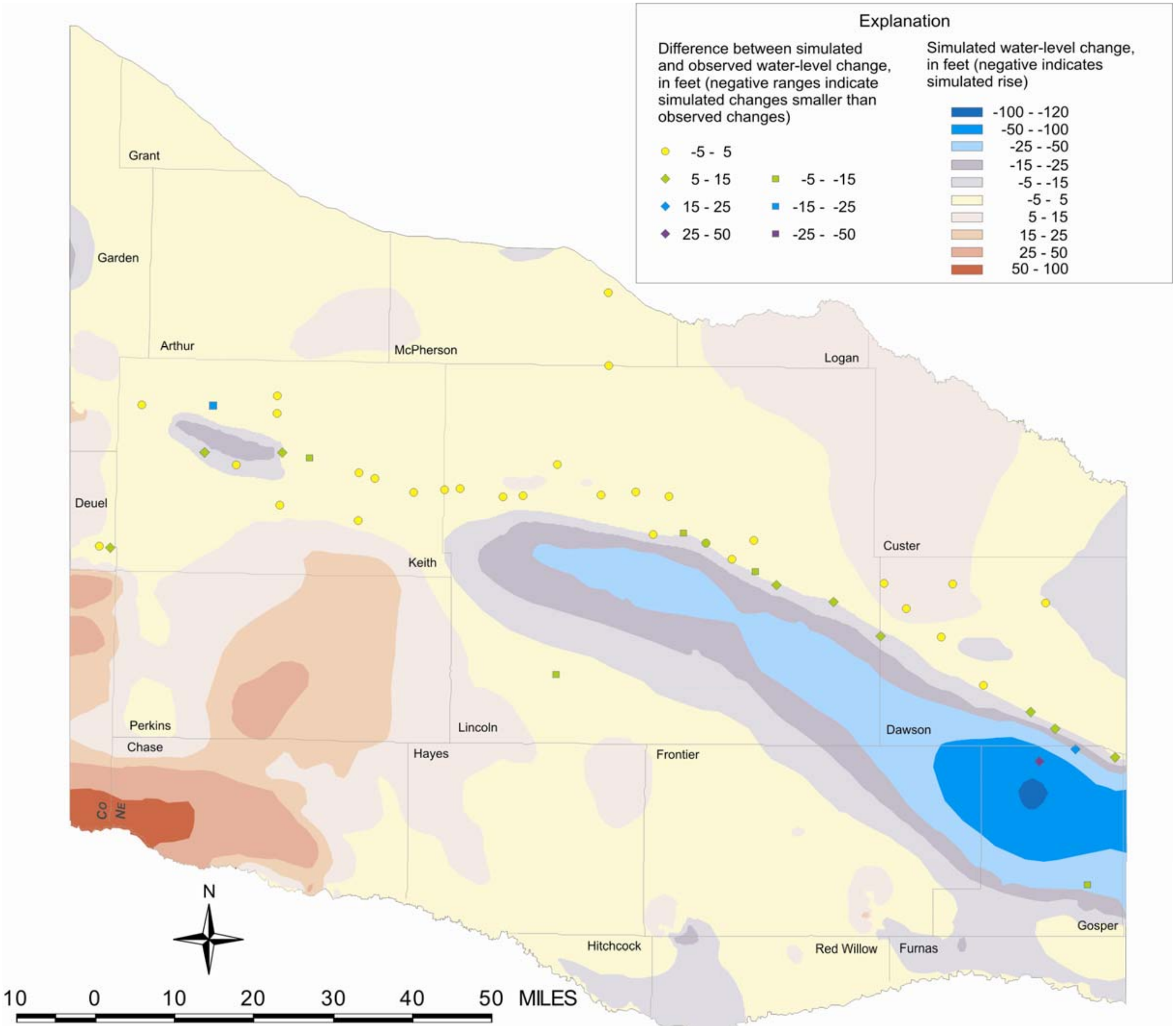


Figure 25. Simulated water-level change for the calibrated groundwater development period model and comparison between simulated and observed water-level change at observation points with records available for the entire model period.

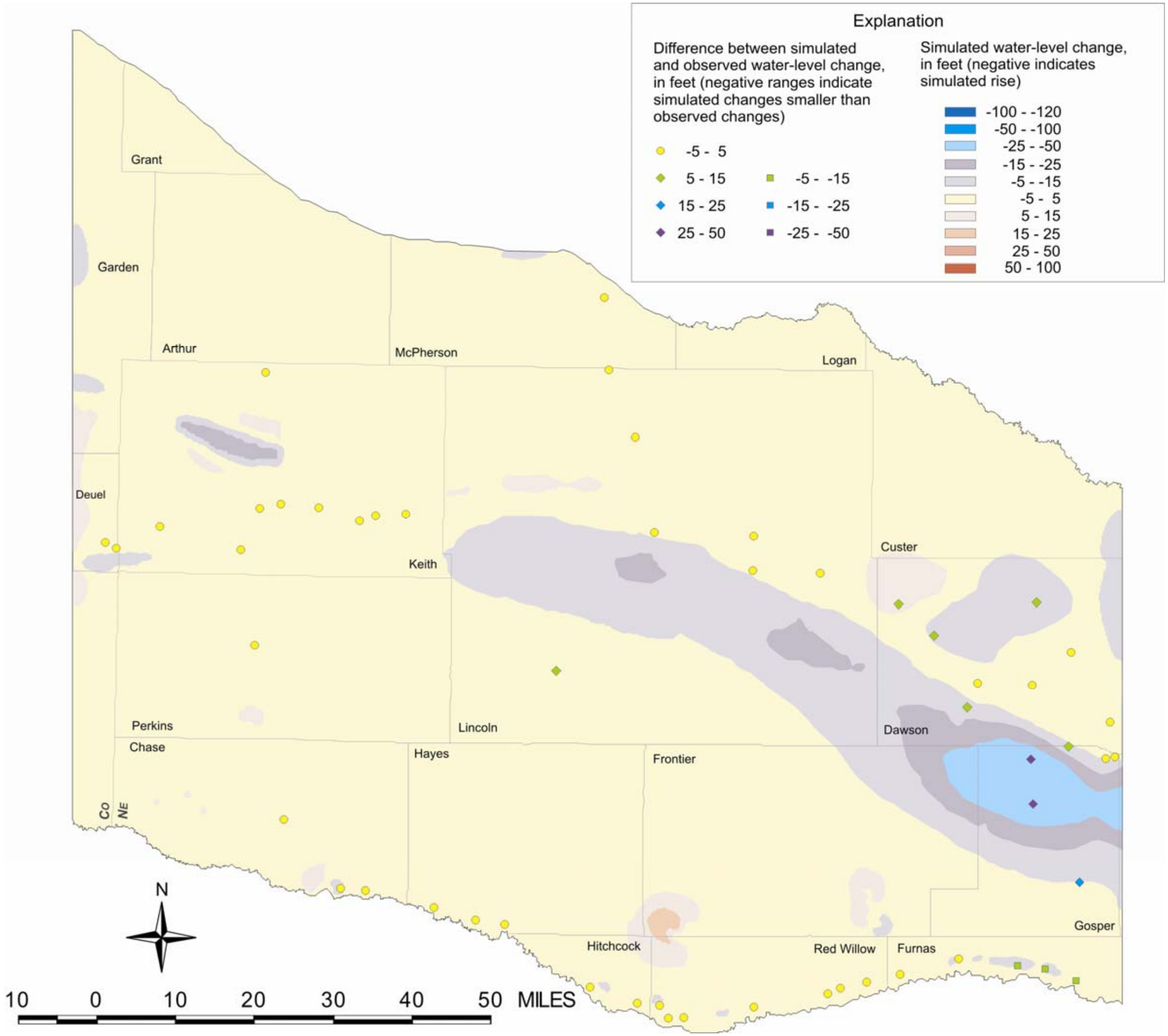


Figure 26. Simulated water-level change for the 1950-61 sub-period of the groundwater development period simulation.

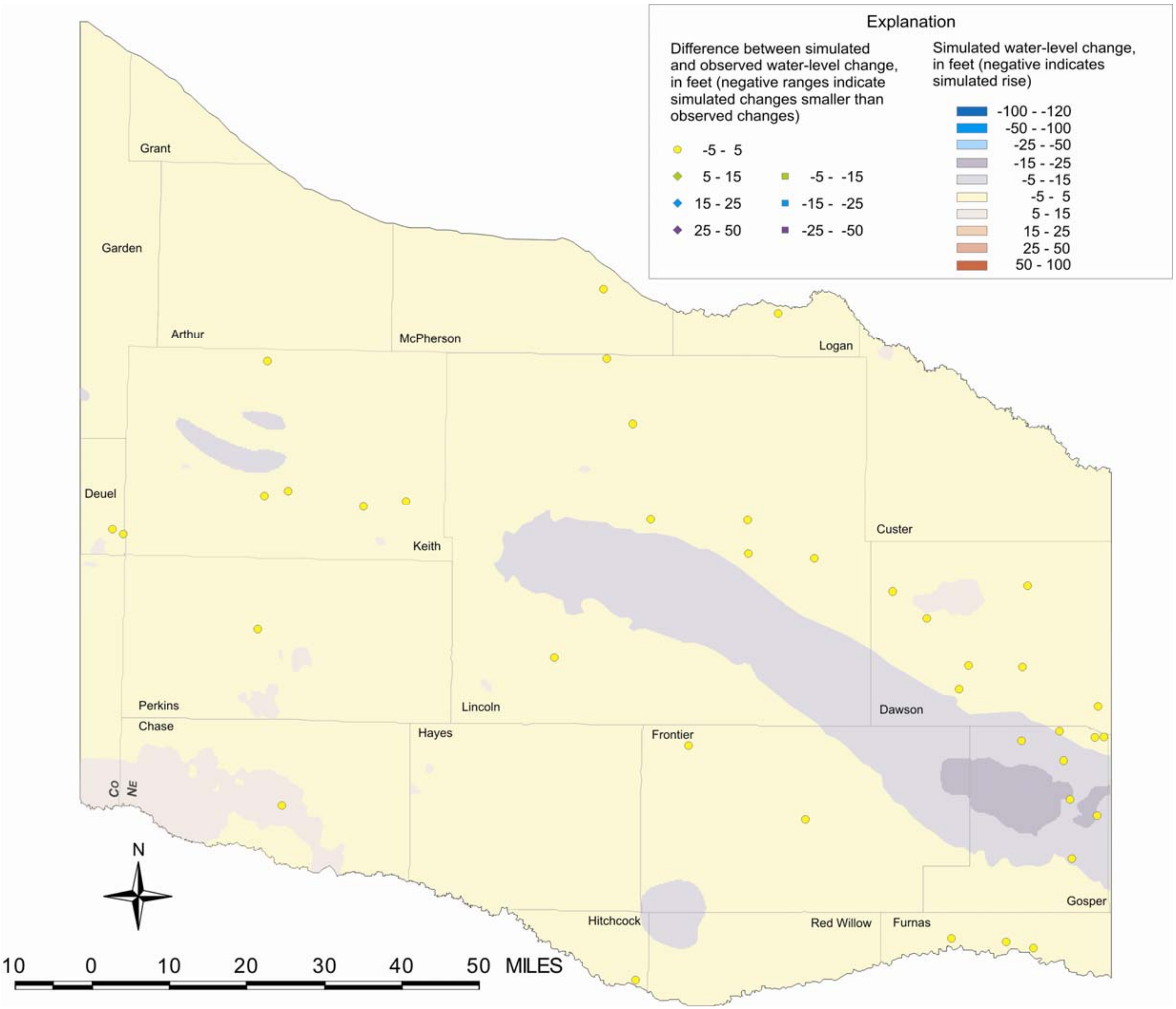


Figure 27. Simulated water-level change for the 1961-73 sub-period of the groundwater development period simulation..

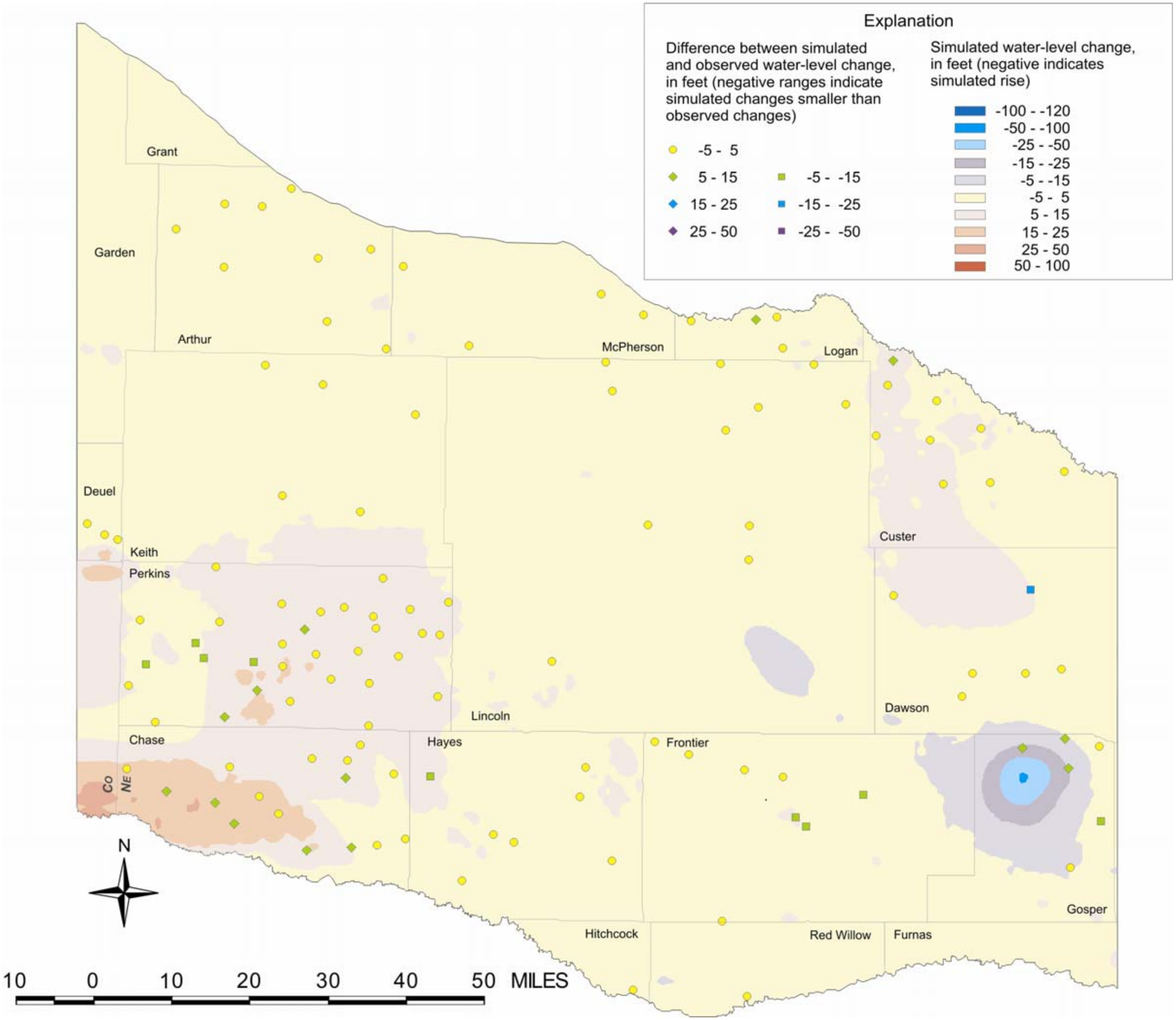


Figure 28. Simulated water-level change for the 1973-85 sub-period of the groundwater development period simulation..

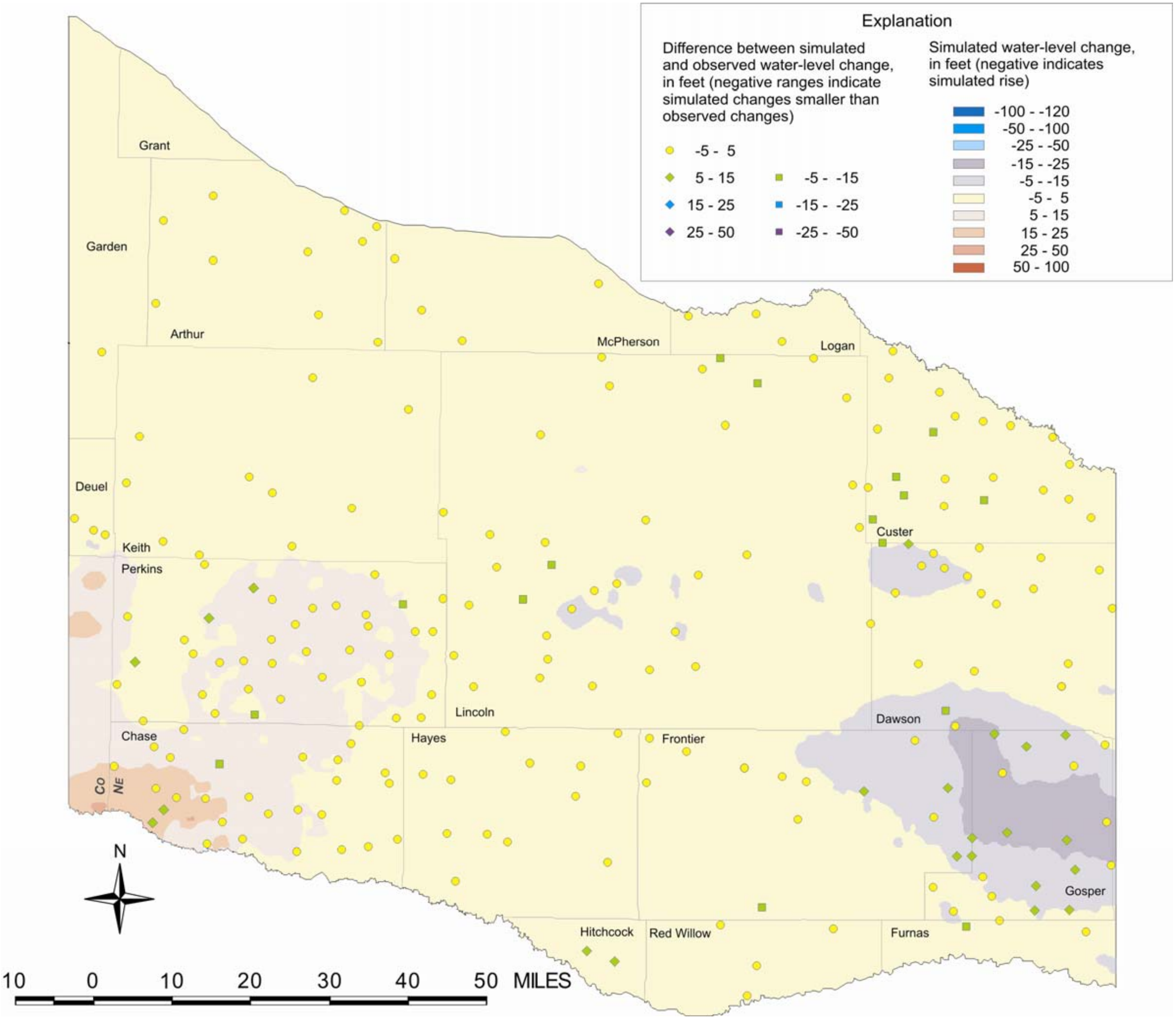


Figure 29. Simulated water-level change for the 1985-98 sub-period of the groundwater development period simulation..

simulated rise in water-levels is higher than observed at 14 locations by at most 25 ft, and is within ±5 ft 10 locations. A small area of water-level increase occurred in northwest Dawson County where more land went into production using groundwater for irrigation and abundant recharge in these areas cause water-levels to increase. This area of rises in the water table was supported by several points within the ±5 ft range. The water-level declines in the southwest counties again showed declines upwards of 25 ft in Perkins County and 50 ft in Chase County. These simulated changes were supported in general by the observed values, although a small number of points in Chase and Perkins Counties indicated simulated values either causing declines or increases greater than the observed values in the 5 to 15 ft range.

The remainder of the model area with simulated water table rises between -5 and 5 ft corresponded to locations of little to no anthropogenic activity that changed the system during this period to cause substantial increases or decreases in the regional water table. Much of the land with little to no change is comprised of the Sand Hills, pastureland, or areas where agricultural practices remained relatively consistent with the period preceding the groundwater development period.

The major areas of observed water-level declines in the Central Model Unit occurred primarily in Chase and Perkins counties with areas of lesser declines simulated in the northeast part of the model area. In Chase and Perkins Counties, water-level declines began in the mid-1960s as irrigation development increased dramatically. By the 1970s, water-level declines over much of Chase County approached 25 ft, and much of Perkins County had declines of at least 15 ft. Declines continued into the 1980s and 90s with Chase County having continued declines of up to 25 ft between 1985 and 1998. Declines of up to 15 ft continued in Perkins County during the1980s and 1990s. Over the entire development period, maximum observed water level declines exceeded 50 ft in both Chase and Perkins Counties (McGuire, 2004).

The simulated net water level decline over the entire development period exceeded 50 ft in a large area of Chase County (fig. 25), and approached nearly 50 ft of decline in south central Perkins County. Fortunately, during the final two sub-periods of the development simulation, abundant observation points were available for calibration in the two counties. Most of the simulated water level changes at the observation points in Chase and Perkins Counties were within ±5 ft water level change, with no points exceeding a 15 ft difference in water level changes. Table 11 summarizes the water level change error statistics for Chase and Perkins Counties only from 1973-85 and 1985-98. Areas of lesser simulated water level declines occurred during the 1970s in Custer County and northern Dawson County. These areas contain a small number of observation points, most of which were within a 5 to 15 ft range in difference between simulated and observed water level changes. Over the entire development period, a large area of simulated water level decline occurred in Logan County, northwest Dawson County, northeast Lincoln County, and southwest Custer County. Unfortunately, no observation points in this area are available over the entire development period to determine the observed water-level changes in these areas.

Calibration Statistics

Calibration statistics for the development period, with both NebGuide and CropSim pumpage are shown in table 10. Note that for the entire 1950-98 period, only 47 observation points with data spanning the entire time period were available for comparison of simulated and observed water-level changes. Most of these points were confined to the Platte River-system valley. Nevertheless, these points were used to examine the match between simulated and observed data over the entire groundwater development period simulation. For the 1950-98 period, the error statistics for both the NebGuide and CropSim pumpage simulations are quite similar. The mean difference for the CropSim data was 1.34 ft more negative than the NebGuide pumpage at the 47 observation points and the mean absolute error for the NebGuide simulation was 0.84 ft less than that for the CropSim simulation. The mean differences with both the NebGuide and CropSim pumpage simulations for the 1950 to 1998 period were negative between simulated and observed water level changes, indicating that at the observation locations in the model, the simulated water level changes tended to be greater than observed changes, particularly with simulated rises being greater than observed rises (since an increase in water levels is indicated as a negative value in MODFLOW drawdown outputs). A negative residual can also occur when comparing simulated and observed water level changes if the simulated decline is less than the observed decline. However, in the case of the CropSim (and to a lesser extent the NebGuide) simulations, the simulated rises being greater than observed rises was the cause for the negative values seen in the mean difference statistics.

Fortunately, for the sub-periods defined for the groundwater development period (fig. 26), a larger number and wider distribution of points were available, especially for the final two sub-periods. The mean-difference for the NebGuide pumpage was 0.88 ft larger than the CropSim pumpage simulation for the 1973-85 timeframe. For the 1985-98 sub-period, the mean differences are closer to zero with the CropSim pumpage simulation having a more negative (-0.40 vs. 0.20) mean error than the NebGuide pumpage. The mean absolute difference for the NebGuide pumpage simulation was over a foot less than the CropSim pumpage simulation for the 1973-85 time period. For the final sub-period, the mean-absolute differences were nearly identical for the NebGuide and CropSim pumpage simulations. The root-mean-square errors for the two datasets were all smaller for the NebGuide pumpage simulation as compared to the CropSim pumpage simulation, with the largest difference being the 1973-85 period (2.72 ft).

Table 11 shows the same statistics as shown in table 10 for Chase and Perkins Counties only with the NebGuide pumpage simulation. These two counties were selected for discussion because of the widespread amount of water-level declines that occurred in the second half of the groundwater development period and the abundant number of observation points that allowed for close comparison of simulated and observed values. For the 1973-85 period, Perkins County had a mean error closest to zero (-0.39 vs. 3.98 ft) as compared to Chase County. The mean absolute difference and root-mean-square error differences were also smaller for Perkins County during this timeframe. For the final sub-period, the mean difference for Chase and Perkins Counties were both less than 1.0 ft, and the mean-absolute difference and root-mean-square difference errors were similar for both counties. The mean-absolute difference in Chase and Perkins Counties for the final sub-period were lower than the overall mean-absolute difference value for the entire model area. The small positive mean-absolute difference values for these two counties during the final two sub-periods indicate that the simulated water-level declines were slightly larger than observed declines.

Table 11. Calibration statistics for the development period simulation showing results using both NebGuide and CropSim pumpage data sets. All values expressed in feet.

Time period	Number of points	NebGuide Pumpage			CropSim Pumpage		
		Mean difference	Mean absolute difference	Root-mean square	Mean difference	Mean absolute difference	Root-mean square
1950-1998	47	-2.5	5.34	8.83	-3.84	6.18	9.98
1950-1961	54	-1.23	3.13	4.18	-1.56	3.28	4.36
1961-1973	42	0.25	1.29	1.73	0.56	1.56	2.07
1973-1985	124	1.09	3.19	4.46	0.21	4.56	7.18
1985-1998	227	-0.20	2.91	3.82	-0.40	2.94	4.21

Table 12. Error statistics of simulated versus observed water level changes for Chase and Perkins counties from 1973-85 and 1985-98 with NebGuide pumpage data. The number of observation points is for each individual county available during the listed time period. All values expressed in feet.

Time period	Chase County				Perkins County			
	Number of points	Mean difference	Mean absolute difference	Root-mean square	Number of points	Mean difference	Mean absolute difference	Root-mean square
1973-1985	16	3.98	4.14	5.07	33	-0.39	3.28	4.26
1985-1998	27	0.94	2.52	3.30	38	0.10	2.83	3.51

Simulated Stream Discharge

The Central Model Unit model calibration to groundwater discharge to streams relied on pre-groundwater development conditions of stream flow to minimize the influence of surface water diversions for the low flow analysis, thus no formal quantitative calibration of aquifer discharge to streams was conducted for the groundwater development period model. A qualitative examination of discharges to stream from the aquifer for this time period did not indicate major changes in flow to streams.

Model Budget

The simulated budget for the development period is shown in table 12. Inflow was dominated by total recharge to the aquifer (72%) and release of water from storage (18%). Inflow to the aquifer from stream leakage (losing reaches), external boundaries, and on-stream reservoirs accounted for the remaining 9% of the inflow to the aquifer. Outflow from the aquifer was predominately to streams and drains (30%), net pumpage (26%), storage (increase in storage) (18%), and evapotranspiration (17%).groundwater development period, with an increase of 509 ft^3/s. This is likely attributed to the large-scale pumping of the aquifer in Chase and Perkins Counties. The amount of water moving into storage during the development period equals that coming out of storage (18%), but occurs in different places. Groundwater flow to streams, and drains decreased as a percentage of the total budget from 52% to 35% between 1950 and 1998. Net pumpage was greater than the additional recharge applied to dryland and irrigated acres (26% vs. 11%), however, recharge from canal seepages, combined with the additional dryland and irrigated land recharge, exceeded net pumpage, resulting in an increase in storage in areas of high canal leakage. The overall budget for the development period is 1.6 times greater than that of the pre-groundwater development period simulation.

Groundwater Mound Volume

As described in the previous section on water-level changes during the 1950-98 period, seepage from canal systems in the central and eastern portion of the model area created appreciable rises in the water table. Due to the lack of observation data during this time, the volume of the coalesced mound of water-level rise in the Central Model Unit was estimated by using an average specific yield and the difference in the 1995 water level map (Conservation and Survey Division, 1998) and the U.S. Geological Survey predevelopment water table (Cederstrand and Becker, 1999). Volumes were determined for the west lobe of the mound in (Sutherland Reservoir and associated canals) and the east lobe (Tri-County canal system) of the mound in 1998.

Table 13. Simulated average budget for the calibrated development period groundwater model using NebGuide net pumpage. Values are averages for the 48-year period. Individual items may not sum to total because of rounding.

Item	ft^3/s	Acre-ft per year (thousands)	Percent of inflow or outflow
Inflow to aquifer			
recharge from precipitation	998	723	35
recharge (canals/irrigation)	740	536	26
recharge (land-use based)	320	232	11
external boundaries	154	38	5
from streams	59	43	2
from on-stream reservoirs	46	35	2
Total	2317	2,054	100
Outflow from aquifer			
streams and drains	970	702	34
net pumpage	736	533	26
evapotranspiration	490	275	17
external boundaries	77	29	3
to on-stream reservoirs	54	38	2
Total	2327	2,054	100
Net decrease in storage	10	7	

The estimated volume of the west lobe is 1,320,000 ac-ft, and the simulated volume for was 1,859,000 ac-ft. The eastern lobe of the mound from Jeffrey Lake eastward to the model boundary was 3,697,000 ac-ft, and the simulated volume is 7,159,000 ac-ft. For the western lobe of the mound, the simulated rises extended further south and southwest than the mapped area used for the estimated volume. The same trend occurred with the eastern lobe of the simulated mound as it expanded further south and southeast than the mapped estimated mound, thus causing a larger overall area for calculation of the simulated mound volume. The difference between simulated and estimated mound volumes for both lobes could be accounted for by errors in estimated canal seepage recharge, groundwater pumping, groundwater discharge to streams, a lack of observed data that the predevelopment water-level maps were based from, or most likely some combination of these factors.

Comparison to Adjacent Models

The Central Model Unit is bordered to the west and east by the Western and Eastern Model Units (fig. 1). Models were created for each of these units using the same protocol as that of the Central Model Unit, and for purposes of continuity between models, the Central Model Unit area overlaps several miles with each of the neighboring study areas.

Central-Eastern Model Unit Comparison

The model representing the Eastern Model Unit contained 5 layers and simulated identical time frames in both the pre-groundwater and development periods. The Central Model Unit overlaps with the Eastern Model Unit by 30 mi from the Lincoln-Dawson County line to the eastern Central Model Unit boundary (fig. 1). 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.

Although each model was calibrated independently by different modelers, the final hydraulic conductivity values were similar for each area. Values applied in the Eastern Model Unit were not adjusted within individual zones of a model layer, whereas certain localized areas of hydraulic conductivity in the Central Model Unit were adjusted within model layers. The mean value for model layer 4, which represents the productive portion of the Ogallala Group, were similar for each model, with 37 ft/d assigned to the Central Model Unit and 33 ft/d assigned to the Eastern Model Unit to achieve the best calibration. Mean values for model layer 2 differed between the two areas, with the Central Model Unit having a mean value of 79 ft/d compared to a mean value of 155 ft/d for the Eastern Model Unit. It should be noted however that model layer 2 was more extensive in the Eastern Model Unit, and is absent in the entire southern half of the Central Model Unit except in the Republican River valley and associated tributary valleys. More observation points were available in the Eastern Model Unit in areas where model layer 2 influences the regional groundwater flow as compared to the Central Model Unit. Thus, it is more likely that the Eastern Model Unit value for layer 2 was better estimated than the value applied in the Central Model Unit.

Similar recharge values were applied to both model areas. Each model 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. The maximum value of recharge on sand hill/dune areas in the overlap area were slightly 0.3 in/yr higher (2.20 vs. 2.50) in the Eastern Model Unit. However, these zones in the Eastern Model Unit were near the western boundary of the eastern model, and the Central Model Unit simulation is likely more sensitive to recharge values on these sandy areas. For the Central Model Unit, the overall mean recharge value was 1.05 in/yr and the median was 0.35 in/yr, contrasted with an overall average mean recharge of 1.35 in/yr and median of 0.78 in/yr for the Eastern Model Unit. This pattern would be expected considering the eastward increase in precipitation on the High Plains.

Areas of groundwater evapotranspiration exist in the area of model overlap, and efforts were made by the two modelers of these areas to ensure that the input parameters of surface elevation, maximum evapotranspiration rate, and extinction depth were identical to maintain consistency between the two models.

Streambed conductance values applied to the Central and Eastern Model Units differed slightly, but are within acceptable ranges and do not result in radically different simulated baseflow discharges. 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 in Dawson County (fig. 3). The South Loup River in the Central Model Unit had a smaller simulated discharge as compared to the same stretch of the river in the Eastern Model Unit. This difference is likely related to the larger values of hydraulic conductivity in model layer 2 of the Eastern Model Unit. The simulated flows for Spring Creek (Dawson County) in the Central Model Unit is higher than the simulated flow to the stream from the aquifer in the Eastern Model Unit. Near Buffalo Creek in both models are West Buffalo Creek and Spring Creek. West Buffalo Creek was not included in the Eastern Model Unit simulation however. Groundwater discharge for these two streams could not be estimated due to a lack of streamflow data, however, personal observations (by C.P. Carney and S.M. Peterson, March, 2001) suggested that discharge to Spring Creek and West Buffalo Creek would unlikely be greater than several cubic feet per second, and simulated baseflow discharge was in that range for both models.

Fig. 28 shows the simulated water levels at 1950 for both the Central and Eastern Model Units in the overlap area. The simulated water levels from the two models were similar in much of the overlap area. Small deviations in limited locations between the 2200-, 2300-, 2400-, and 2500-ft. contours of the water table elevation do exist. These differences are typically less than 2 mi in distance, and the two models were in reasonable agreement. During the development period, water-level changes in both the Central and Eastern Model Units mimicked one another

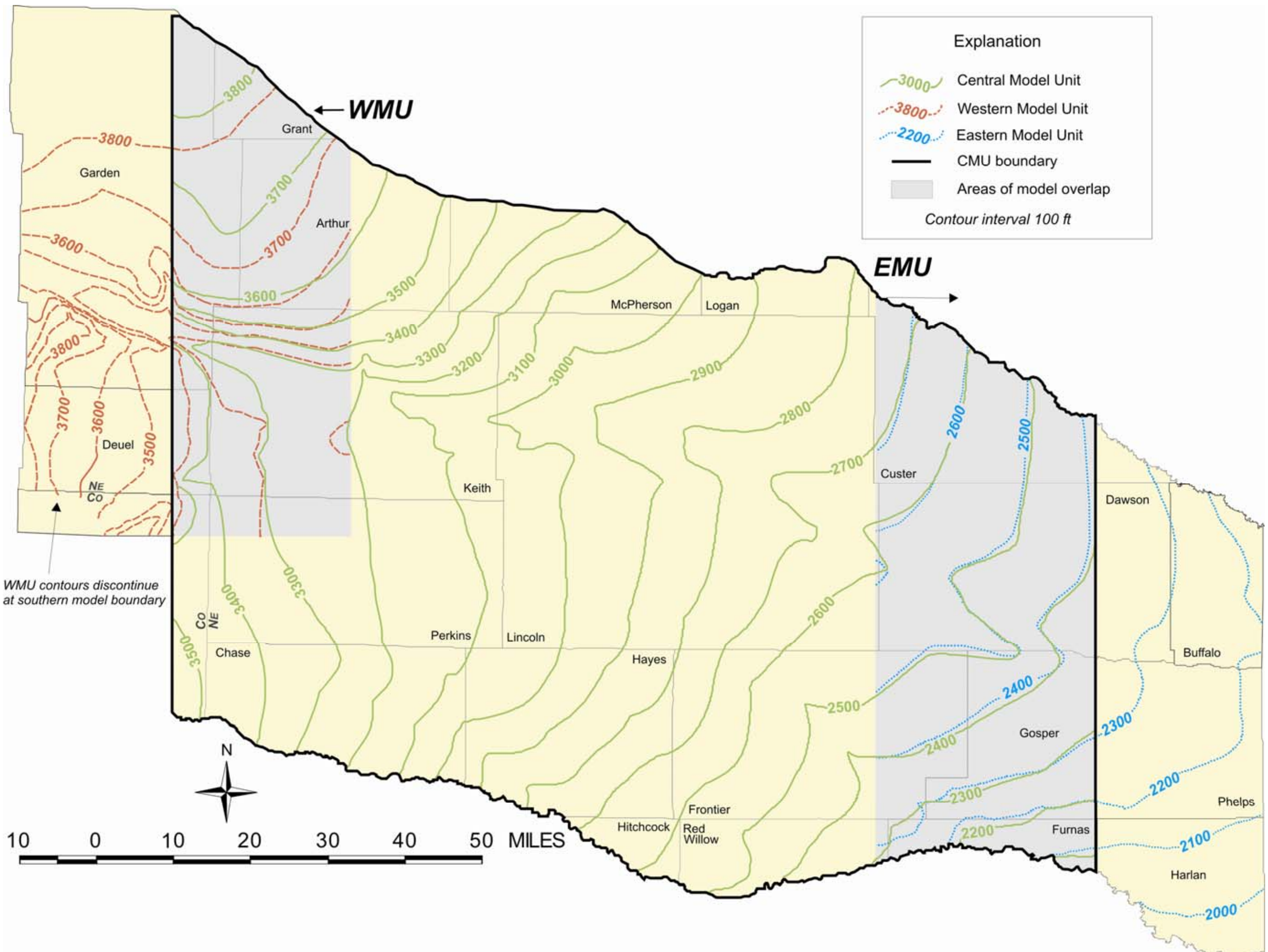


Figure 30. Comparison of simulated water-tables within the overlap area of the Central, Western, and Eastern Model Units.

closely in southern Dawson and Gosper County, and water-level changes at the available observation points in the overlap area within the influence of the CNPPID groundwater mound showed similar trends. This consistency was expected since each simulation used identical canal seepage values calculated by Peterson (2005).

Central-Western Model Unit Comparison

The Western Model Unit (fig. 1) and the Central Model Unit share a 26 mi wide overlap area from Kingsley Dam (Lake McConaughy) westward to the Central Model Unit boundary (fig. 28). The Western Model Unit simulation used one layer to represent the High Plains aquifer. In regards to topography, hydrostratigraphy, and historic changes in the system hydrology, the area within the Western Model Unit is quite dissimilar to either the Central or Eastern Model Units. Topographically, the Western Model Unit contains vast areas of greater topographic relief than either of the two study areas to the east. The Western Model Unit has many areas of abrupt aquifer discontinuity where the Ogallala Group was eroded away during late Tertiary and Quaternary times. In addition to the Ogallala Group, the Arikaree Group is also relied upon as a water source, particularly in the northern half of the Western Model Unit. Historically, the Western Model Unit did not experience widespread water-level rises like those observed in the Central and Eastern Model Units, with the exception of zones of slight water-level rises observed in the southern part of the model area. These rises are likely due to increased recharge from dryland farming (Luckey and Cannia, 2005). One area of major water level decline, on the scale of declines observed in the Central Model Unit's Chase County, occurred in Box Butte County.

Despite the differences between the two model areas and timeframes of model development, the modelers for each area were in frequent communication to ensure similar model construction and parameter inputs. Final calibrated values of hydraulic conductivity were determined using different methods between the two models due to the Western Model Unit single layer grid representation. Hydraulic conductivity for the Western Model Unit in the overlap area was based on subdivisions of geologic units and a conceptual model of deposition as influenced by the Rush Creek Structure, whereas the Central Model Unit was calibrated using hydraulic conductivity values by model layer as described previously. In the area of overlap, the Central Model Unit had values of 0-25 and 25-50 ft/d north of the North Platte Valley, and the Western Model Unit had values of 15 or 35 ft/d for the same area. South of the North Platte River valley, the Central Model Unit used values of 50-100 ft/d, whereas the Western Model Unit had values of 15 or 25 ft/d. Within the South Platte River valley, values ranging from 150-200 ft/d were applied in the Central Model Unit, and the Western Model Unit used 100 ft/d in the same area. The largest relative difference was between the North Platte Valley and the South Platte Valley, where the western model had 15 ft/d and the central model had 50-100 ft/d.

Recharge for both the Central and Western Model Units was based on topographic regions. In the area of overlap, overall calibrated recharge on areas of sand dunes was 2.50 in/yr in the Central Model Unit and 2.30 in/yr in the Western Model Unit. The slightly higher recharge values in the Central Model Unit would be expected based on the eastward increase in precipitation on the High Plains. In much of the remainder of the area of overlap, primarily south of the Sand Hills, recharge was 0.10 to 0.15 in/yr in the Central Model Unit and 0.18 in/yr in the Western Model Unit. The largest relative difference was in the South Platte River valley where the central model had 0.90 in/yr contrasted with the western model having 0.18 in/yr.

Evapotranspiration simulated in the overlap area of the western and central models were identical in spatial distribution of evapotranspiration areas, maximum evapotranspiration rates, and extinction depths below land surface. The modelers for each area mutually defined areas of evapotranspiration in the Sand Hills as described previously in this document. Each model simulated 17 in/yr as a maximum evapotranspiration rate and had an extinction depth of either 7 or 5 ft based on whether the evapotranspiration zones were defined as riparian vegetation or water evapotranspiration from wetlands and lakes, respectively.

Surface water features in the overlap area of the central and western models include the North Platte and South Platte Rivers along with three Sand Hills drainages that feed the North Platte River (Lake McConaughy). The only gaged stream in the overlap area with historic low-flow analysis data was Otter Creek north of Lake McConaughy. The simulated discharge for Otter Creek in the Central Model Unit was 9 ft^3/s, whereas the value simulated in the western model was 4 ft^3/s.

Figure 28 shows a comparison of simulated 1950 water level contours in the overlap area of the Central and Western Model Units. The contours deviated in the Sand Hills north of Lake McConaughy, as well as the 3,200 ft contour just south of the lake. North of Lake McConaughy in western Arthur County, the 3,800 and 3,700 ft contours from the two different models deviated by up to 5 mi, with the Western Model Unit contour further southeast as compared to the Central Model Unit contour. The map of simulated vs. observed water-levels at individual points (fig. 19) provides somewhat inconclusive evidence towards which map shows a better placement of the contours, as 3 of the 6 points near the Central Model Unit 3,800 ft contour show simulated water-levels 10 to 30 ft below the observed water table, while 3 other points within 2 mi of the 3,800 contour indicated the simulated water table was within ±10 ft of the observed water-levels at 1950. Although there are differences in these contours between the two simulations, the gradient of the water table is relatively flat in this area, which would likely result in minor differences in groundwater flux values between the two models. The remainder of the contours match reasonably well in the overlap area.

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, each with different parameter inputs for the separate periods. The sensitivity analysis consisted of uniformly increasing or decreasing a single model parameter by values of ±5, 10, and 20% to determine the influence of the change on observed water-level or water-level-change statistics, as well as simulated groundwater discharge to selected streams. For the pre-groundwater development period, changes in hydraulic conductivity, the ratio of horizontal to vertical hydraulic conductivity, rangeland recharge, evapotranspiration, and bed conductance on all surface water drainages (including engineered drains) were investigated.

For the groundwater development period, changes in specific yield, NebGuide net pumpage, canal seepage recharge (grouped with surface-water irrigation over-application), dryland recharge, and groundwater-irrigated land recharge were investigated. Model input changes in isolated areas or zones, such as rangeland recharge in Custer County, also were not investigated because such changes would generally only affect simulated water levels and groundwater discharge to streams in that particular area.

The pre-groundwater development period model sensitivity was analyzed using 1950 water-level statistics (fig. 29). At calibration (input multiplier equals 1.0); the mean difference between simulated and observed water levels was 1.6 ft. An increase in rangeland recharge of 20% raised the mean difference to 6.3 ft. When rangeland recharge was decreased by 20%, the mean difference dropped to -0.16 ft. This amount of decrease also resulted in the mean difference being closest to 0 for changes in rangeland recharge.

At calibration, the mean absolute difference between simulated and observed water levels was 9.38 ft. Increasing and decreasing the rangeland recharge 20% altered the mean absolute difference to 10.10 and 10.80 ft, respectively. At calibration, the root-mean-square difference between simulated and observed water levels was 11.69 ft. Increasing and decreasing the rangeland recharge 20% altered the root-mean-square difference to 12.6 and 13.6 ft, respectively. Although the differences in simulated and observed water levels aren't strongly sensitive to rangeland recharge, the results suggest that based on the mean absolute difference, a 5-10% increase could reduce the difference slightly. However, this change was not made because it would negatively impact simulated groundwater discharge to some streams, as described below.

The pre-groundwater development period model showed a similar sensitivity to hydraulic conductivity as to rangeland recharge (fig. 29), 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 7.9 ft when hydraulic conductivity was decreased 20%. The mean difference increased as hydraulic conductivity decreased and reached -2.35 ft when hydraulic conductivity was decreased 20%. The mean difference was closest to zero when hydraulic conductivity was increased 10%.

The mean absolute difference was 11.87 ft when hydraulic conductivity was increased 20% and was 11.28 ft when hydraulic conductivity was decreased 20%. The root-mean-square difference was 15.14 ft when hydraulic conductivity was increased 20% and was 15.22 ft when hydraulic conductivity was decreased 20%.

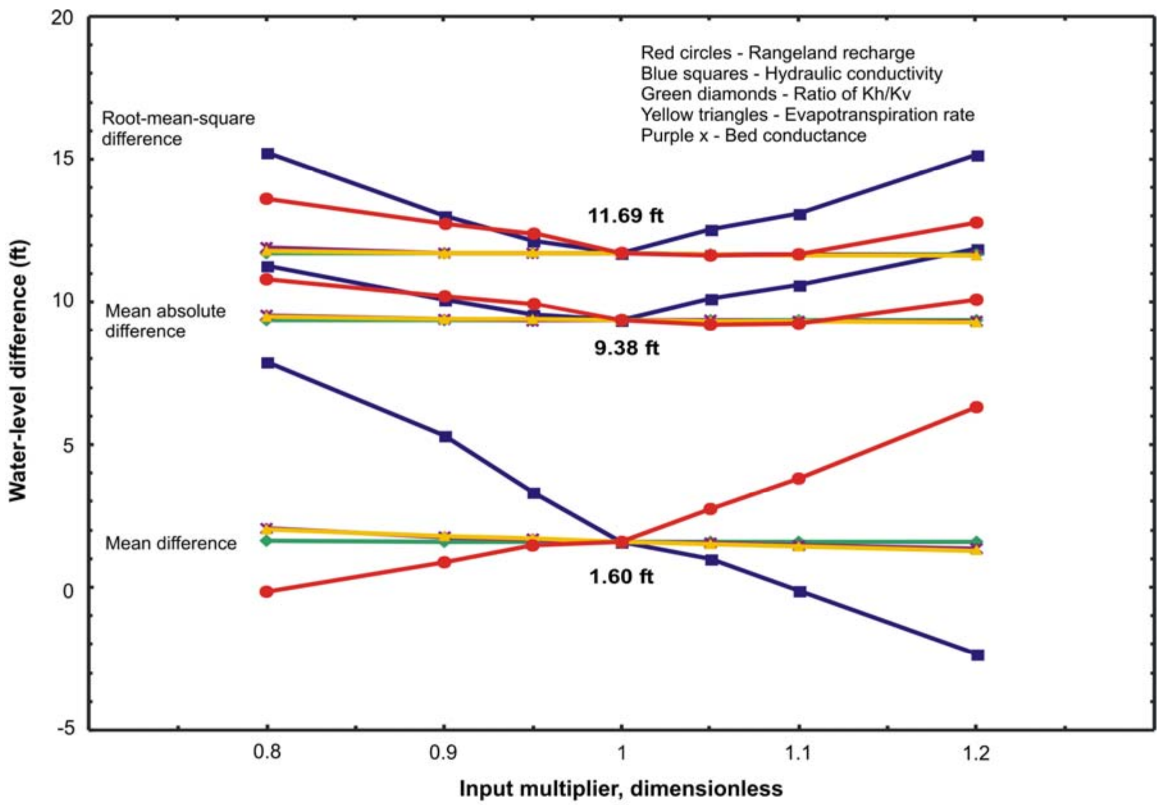


Figure 31. Effects of varying rangeland recharge, hydraulic conductivity, the ratio of horizontal to vertical hydraulic conductivity (Kh/Kv), evapotranspiration, and streambed conductance (drains, rivers, and streams) on simulated 1950 water levels.

The sensitivity analysis of hydraulic conductivity suggests that increasing or decreasing the calibrated values beyond 10% would negatively affect the mean absolute difference and root-mean-square difference, although a slight decrease would not change the statistics significantly. A slight increase would however produce an improved mean difference. This change was not made because it would negatively impact simulated groundwater discharge to some streams.

The pre-groundwater development period model showed very little sensitivity to the ±5, 10, and 20% changes in evapotranspiration, bed conductance, and the ratio of horizontal to vertical hydraulic conductivity. Of these three parameters, the largest change in any statistical category was 0.35 ft for the mean difference when streambed conductance was decreased 20%.

The sensitivity of groundwater discharge to streams from changes in rangeland recharge, hydraulic conductivity, bed conductance, and evapotranspiration rates were also investigated at 1950 (fig. 30). Three tributary streams and one main-stem reach of the North Platte River, each representing areas of different topography or predominant land-use practices. The streams chosen

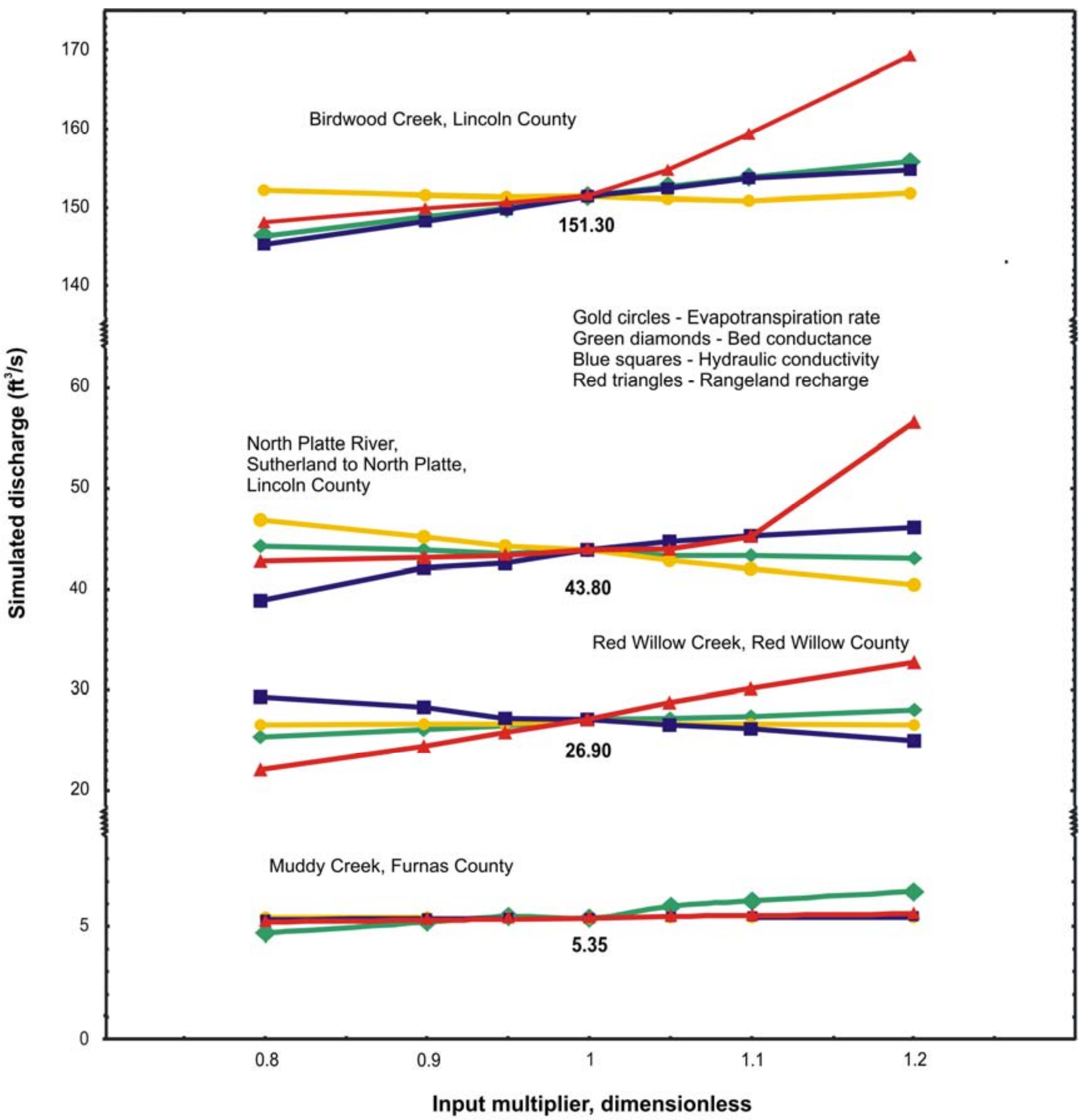


Figure 32. Effects of varying hydraulic conductivity, rangeland recharge, bed conductance, and evapotranspiration on groundwater discharge to Muddy Creek, Red Willow Creek, Birdwood Creek, and the North Platte River between gages at Sutherland, NE and North Platte, NE at 1950.

were Birdwood Creek (fig. 3), a Sand Hills drainage in Lincoln, McPherson, and Keith Counties noted for consistent flows and a large contributor to flow in the North Platte River in the Central Model Unit; Red Willow Creek, a tributary to the Republican River that exists in a zone of lower hydraulic conductivity for the Ogallala Group and zones of variable recharge rates; and Muddy Creek, a small drainage that empties an area of primarily loess hills that also discharges into the Republican River. The North Platte River between gages near Sutherland and North Platte was chosen because this reach was far enough from the east and west model boundaries to likely show minimal effects of boundary conditions and is located in an area with variable recharge and hydraulic conductivity rates.

The simulated baseflow discharge to Birdwood Creek at calibration was 151.3 ft^3/s (fig. 30). When rangeland recharge was increased and decreased 20%, the simulation produced discharges of 169.0 and 148.2 ft^3/s, respectively. When hydraulic conductivity was modified by the same increments, Birdwood Creek discharge was 154.6 ft^3/s when increased 20%, and was 145.2 ft^3/s when decreased 20%. Groundwater discharge to Birdwood Creek was also moderately sensitive to changes in bed conductance. Increasing and decreasing this parameter resulted in simulated discharges of 155.7 and 146.2 ft^3/s, respectively. Changes in discharge of groundwater to Birdwood Creek were not strongly influenced by evapotranspiration, with the largest difference resulting in an increase to flow less than 3 ft^3/s with a 20% decrease in simulated evapotranspiration. Of the 4 parameters tested, rangeland recharge proved to be the parameter with the strongest influence on groundwater flow into Birdwood Creek, especially when the parameter is increased greater than 10%.

At calibration, simulated discharge to Red Willow Creek was 26.9 ft^3/s (fig. 30). As rangeland recharge was increased and decreased 20%, the resulting flows were 32.7 and 21.8 ft^3/s, respectively. As hydraulic conductivity was altered by a 20% increase and decrease, discharge to Red Willow Creek was 24.7 and 29.1 ft^3/s, respectively. Evapo-transpiration and streambed conductance adjustments had little influence on simulated discharge of groundwater to Red Willow Creek, resulting in changes in discharge of less than 2 ft^3/s, with the largest of these changes resulting from a 20% decrease in bed conductance, which reduced flow by 1.8 ft^3/s.

Simulated Muddy Creek discharge at calibration was 5.35 ft^3/s. Although the changes in groundwater inflow to the drainage appeared small since the overall flows were small, changes up to 22% of the total calibrated flow from groundwater to the stream occurred when the parameters were adjusted. The largest change of any adjustment of the four parameters was an increase in groundwater flow to the stream of 1.2 ft^3/s when bed conductance was increased 20%. When streambed conductance was reduced 20%, groundwater outflow to the drainage decreased 0.67 ft^3/s, or 13% of total flow in the stream.

For the reach of the North Platte River in western Lincoln County between the gages at Sutherland and North Platte, the calibrated flow from the aquifer to the river was 43.8 ft^3/s. When rangeland recharge was adjusted by an increase and decrease of 20%, the flow of water from the aquifer to this stretch was 56.8 and 42.7 ft^3/s, respectively. The increase to 56.8 ft^3/s was the largest change of flow (nearly 30% of the calibrated flow) for any reach tested in the sensitivity analysis. This change indicates the importance of further understanding of the impacts recharge on the system has on flow of groundwater to the river. Conceptually, the increased recharge likely increased flow to the river by increasing the hydraulic gradient north of the North Platte River valley. An increase of hydraulic conductivity in the model by 20% increased groundwater contribution to flow to 46.3 ft^3/s, and a decrease by the same amount yielded a groundwater flow to this stretch of 38.7 ft^3/s. Flow of groundwater to this stretch was sensitive to evapotranspiration as well, more so than to the other drainages previously described. Flow from the aquifer to this reach of the river decreased to 41.3 ft^3/s when the evapotranspiration rate was increased by 20%, and increased to 47.9 ft^3/s when the rate of evapotranspiration was decreased by 20%. This reach of the North Platte River showed essentially no sensitivity to changes in bed conductance.

For the groundwater development period, sensitivity analysis was conducted for the entire 1950-1998 period. The simulated 1950-98 water-level changes provide useful insight into model sensitivities, despite the limited number of locations with water-level change data over the entire 1950-1998 period (table 10). The model was most sensitive to canal seepage followed by net pumpage, and least sensitive to dryland recharge and specific yield (fig. 31). The mean difference in simulated versus observed water level changes for the calibrated development period model was -2.50 ft. When canal seepage was adjusted with a 20% increase and decrease, the mean difference changed to -4.32 and 0.11 ft, respectively. This value was closest to zero when net canal seepage was decreased 20%. The mean absolute difference between simulated versus observed water-level changes was 5.34 ft at calibration; 6.86 ft when canal seepage was increased 20 percent and 4.21 ft when reduced 20%. This difference was at a minimum when canal seepage was reduced 20%. The root-mean-square difference for the development period simulation was 8.34 ft. When canal seepage was increased and decreased 20%, the resulting difference changed to 12.43 and 6.30 ft, respectively. Results for canal seepage rate sensitivity indicate that an overall reduction in canal seepages could perhaps improve the calibration statistics. However, the spatial location of where a canal seepage reduction would improve the model was not determined in this analysis. In the Central Model Unit, the density of observation points is greatest in the overlap area with the Eastern Model Unit, where the Central Model Unit uses the same seepage values applied in the Eastern Model Unit simulation. Therefore, to avoid disrupting model continuity between the central and eastern models, no change was made in canal seepages.

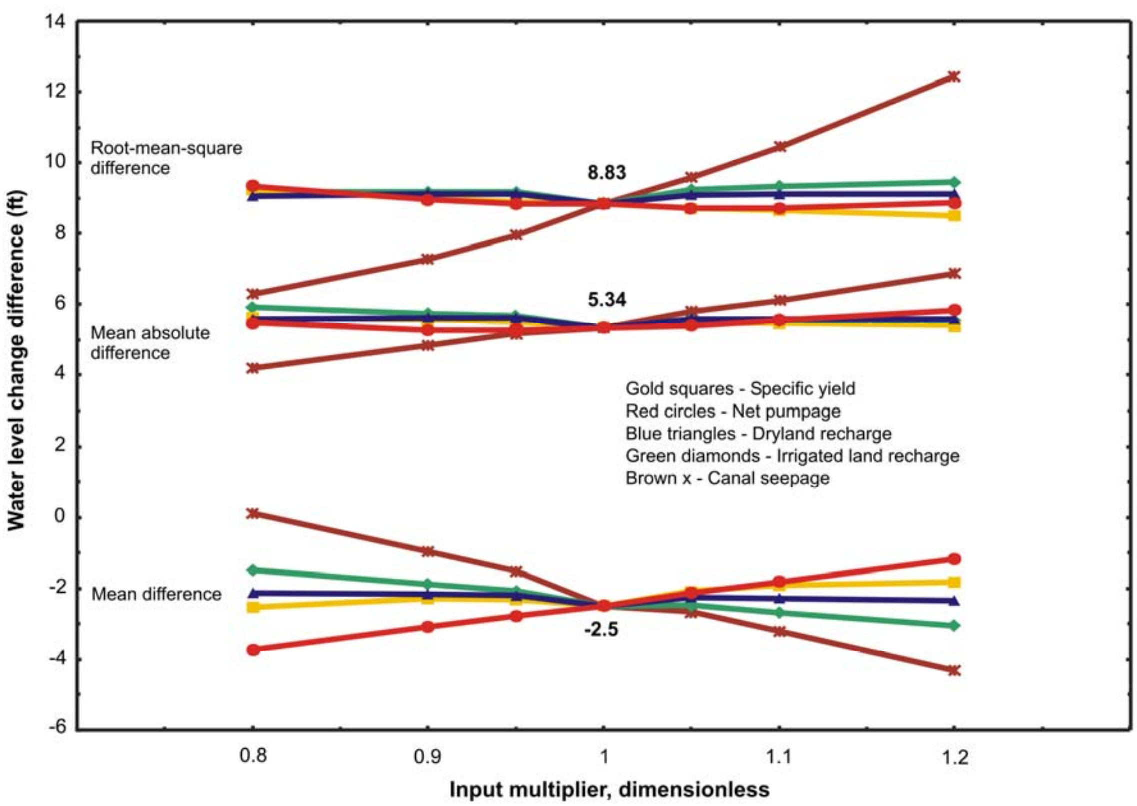


Figure 33. Effects of varying specific yield, net pumpage, dryland recharge, irrigated land recharge, and canal seepage recharge on simulated 1950-1998 water-level changes.

The groundwater-development period model showed a similar but opposite pattern in changes to net pumpage. When net pumpage was increased and decreased 20%, the mean difference changed to -1.19 and -3.72 ft, respectively. For the same increase and decrease in net pumpage, the mean absolute difference changes from 5.83 to 5.49 ft, respectively. The root-mean-square difference showed very small sensitivity, less than 0.5 ft whether net pumpage was increased or decreased 20%.

The development period simulation showed only small sensitivity to changes in specific yield. The largest change to any statistic for modifications to specific yield was an increase in mean difference by 0.68 ft.

The model showed slight sensitivity with changes in dryland and irrigated recharge. For dryland recharge, the largest change for any of the three comparison statistics was a decrease (closer to zero) of 0.37 ft when the parameter was decreased 20%. For irrigated land recharge, the mean difference decreased by 1.01 ft when the parameter was decreased 20%. When irrigated land recharge was increased 20%, the mean increased to -3.06 ft. The largest change in mean absolute difference for changes in irrigated land recharge was an increase of 0.57 ft when the parameter was decreased 20%. The parameter changes by 0.2 ft or less for any increase in the parameter. The largest change in the root-mean-square difference occurred when the irrigated land recharge was increased 20%, with an increase of 0.63 ft.

The sensitivity of simulated 1950-1998 stream discharge with respect to model parameters was not investigated during the sensitivity analysis.

Limitation on Use of this Model

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

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 Central Model Unit of the COHYST study area. Care should be exercised if this model is used beyond the purpose for which it was constructed.

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

This model is better calibrated in regions with greater numbers of water-level or streamflow observations against which to calibrate, and is less precise in regions with limited or no calibration information. The inputs to which the model is more sensitive were considered to be better calibrated than those inputs to which the model is less sensitive.

One particular type of model error, Type IV Error, can limit the usefulness of a model. Type IV Error refers to a model input to which the model calibration is insensitive, but to which the model use is sensitive. Simulated evapotranspiration might fall into this category for some uses of this model. As was shown in the Model Sensitivity section, simulated water levels were relatively insensitive to the evapotranspiration rate, as were simulated tributary streamflows. The simulated discharges to the North and South Platte Rivers were somewhat sensitive to evapotranspiration rates, but the observed discharges to these streams were only known within a fairly broad range (table 6, p. 53). 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.

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

The North Platte River, South Platte River, Platte River, Republican River, and the South Loup River were simulated as river boundaries in the model described in this report. This is appropriate because these streams seldom become dry, and when they do, the period of no flow is short compared to the 48 years of analysis. As a result of how these streams were simulated, this model should not be used to calculated effects of management scenarios that may cause the streams to go dry for months or years. If there is a need to investigate such management scenarios in the future, these rivers should be converted to stream boundaries.

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

Further Work

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

The lack of pumpage data for irrigation wells in the Central Model Unit may be the most significant factor that negatively impacted the quality of calibration for the groundwater development period simulation. Two different pumpage datasets were applied in the Central Model Unit, NebGuide and CropSim, with greater emphasis and effort placed on calibration of the NebGuide pumpage representation during calibration. Improving the accuracy of pumpage data is a task that the Natural Resources Districts in the COHYST study area have identified as a priority. Several years of pumpage data would be needed before an updated version of Central Model Unit model could be re-calibrated. Even when better pumpage data becomes available, it will still be difficult to estimate recharge from deep percolation of pumped or spread irrigation water as well as recharge from precipitation on irrigated fields. These processes also need further research and refinement.

Canal seepage recharge is an important model input for the Central 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 conceptual model of the system. More information and understanding of the amount of delivery to fields and return flow to the river in the Platte River basin are two areas that could improve considerably the estimates of seepage.

Evapotranspiration parameters for areas where the water table is near land surface were defined with large uncertainty in this model. Unfortunately, some of the management scenarios that this model was designed to test may be sensitive to evapotranspiration. The representation of evapotranspiration in the model, as well as evapotranspiration parameters, need further research and refinement.

Much of the northern half of the CMU suffers a lack of observed water-level data, geologic borehole data, and basic meteorological data. This scarcity in data is attributed mostly to the lack of feasible accessibility in much of this area. The lack of observed water level data creates greater uncertainty in the calibration of the water levels in the Sand Hills and dissected plains north of the Platte River system valley. Several geologic test holes were drilled in the Sand Hills during the COHYST study to fill in some of the data gaps. However, areas up to 200 mi^2 of the northern CMU lack geologic borehole data; therefore aquifer geometry and parameters are based on interpolation methods to determine characteristics such as hydraulic conductivity and specific yield.

Distances between some meteorological stations are nearly 40 miles, thus creating the likelihood for unmeasured meteorological events. To help alleviate this problem, COHYST initiated a volunteer weather observation network called NeRain (website located at: http://dnrdata.dnr.ne.gov/NeRain/) in cooperation with the Nebraska DNR to help fill in the large areas between National Weather Service stations. Despite the success of the program at increasing the locations of precipitation measurements, several years of data will be needed to determine climate patterns and trends and observation data is still lacking in rural Sand Hills areas.

Although COHYST defined the groundwater development period beginning in 1950, many irrigation wells were already operating in the Platte River valley prior to this time (Cooperative Hydrology Study, 2004). Within the CMU, over 750 irrigation wells were drilled prior to 1950, most of which were within the Platte River system valleys. These wells were not required to be registered in the mid-20th Century, so the actual number of operating irrigation wells in the CMU was likely ever larger than the registered wells available from the Nebraska Department of Natural Resources. The pre-groundwater development simulation did not simulate the effects of pre-1950 irrigation wells, though it was possible these wells may have influenced the system enough to warrant implementation of these wells in future simulations.

During the 1895-1950 pre-groundwater development period, large areas of land were converted from native grassland/pasture to dryland farming. This modification to the landscape likely altered the regional hydrologic system by creating more potential for more precipitation to enter the subsurface and eventually recharge to the aquifer. However, these changes that occurred over several decades were not included in the pre-groundwater development simulation. These rates may be larger than the rates of recharge on dryland cropping areas during the groundwater development period since improved conservation practices in recent decades likely reduced the amount of water leaving the soil-root zone. It is recommended that this phenomenon is considered for future revisions of the model.

In the realm of technological and computational advances in groundwater modeling, several new applications have become available and could improve system representation, evaluation of model uncertainty, and provide alternative methods of calibration. Recent advances in groundwater modeling software have provided new methods of representing geology (Anderman and Hill, 2000). Recent breakthroughs in regularization techniques and pilot point methods offer additional alternative methods with representation of spatially varying parameters such as hydraulic conductivity or recharge (Doherty, 2003; Doherty and Skahill, 2006). In terms of evapotranspiration, new improvements in MODFLOW Evapotranspiration package (Baird and Maddock, 2005) may lead to improved representations of the riparian and wetland zones in the CMU and help give greater confidence in predictive analyses. Also, recent advances in automated parameter estimation using MODFLOW-2000 (Harbaugh and others, 2000), UCODE_2005 (Poeter and Hill, 1998), and PEST (Doherty, 2004) allow for comprehensive exploration of model uncertainty and sensitivity, and could lead to improvements of the flow system conceptualization.

References Cited

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.

Anderson, M.P., and Woessner, W.W. 1992. Applied Groundwater Modeling. Academic Press, Inc., San Diego, CA.

Aqueveo, 2000. Aqueaveo, Inc., software developers of the Groundwater Modeling System version 3.1. Accessed online at www.aquaveo.com

Baird, K.J. and Maddock, T., 2005. Simulating riparian evapotranspiration: a new methodology and application for groundwater models. Journal of Hydology, vol. 312. p. 176-190.

Bjorklund, L.J., and Brown, R.F., 1957. Geology and ground-water resources of the lower South Platte River valley between Hardin, Colorado and Paxton, Nebraska, with a section on Chemical quality of the ground water, by H.A. Swenson. U.S. Geological Survey Water-Supply Paper 1378. 431 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. 589-712.

Cannia, J.C., Woodward, D.W., and Cast, L., 2006. Cooperative Hydrology Study hydrostratigraphic units and aquifer characterization report. 91 p. Available at http://cohyst.dnr.ne.gov/document/dc012hyrdo_aquifer_022406.pdf

Cardwell, W.D., and Jenkins, E.D. 1963. Ground-water geology and pump irrigation in Frenchman Creek basin above Palisade, Nebraska. U.S. Geological Survey Water-Supply Paper 1577.

Carney, C.P., and Peterson, S.M., 2001. Estimated groundwater discharge to streams from the High Plains aquifer in the Central Model Unit of the COHYST study area for the period prior to major groundwater irrigation. Available at http://cohyst.dnr.ne.gov/adobe/dc012CMU_baseflw_01.pdf

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, 38 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, 1 diskette, available at URL http://water.usgs.gov/lookup/getspatial?ofr99-264_predwlv/.

Condra, G.E., 1907, Geology and water resources of the Republican River valley and adjacent areas, Nebraska: U.S. Geological Survey Water-Supply Paper 216, 71 p.

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.

Cooperative Hydrology Study, 2000a. COHYST Databank – Consumptive Use Data. Accessed March 15, 2000 at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Cooperative Hydrology Study, 2000b. Topographic regions: file g002toporeg_97. Accessed May 15th, 2000, at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Cooperative Hydrology Study, 2001a, Databank – Evaluation of historic land use: Accessed February 1, 2001, at URL http://cohyst.dnr.state.ne.us/dc012HistLU_00.htm .

Cooperative Hydrology Study, 2001b, Databank – Registered wells: Accessed August 31, 2001, at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

Cooperative Hydrology Study, 2001c, Permeameter test sites: Accessed November 23, 2004, at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html.

Cooperative Hydrology Study, 2001d, Streambed coring sites: Accessed November 23, 2004, at URL http://cohyst.dnr.ne.gov/cohyst_preliminarydata.html

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

Cooperative Hydrology Study Technical Committee, 2000. Flow modeling strategy for COHYST: Accessed July 19th, 2003, at URL http://cohyst.dnr.ne.gov/. (NOTE: Report was subsequently removed from the Internet because it was too out of date to be useful.)

Dappen, Patti, and Tooze, Marcus, 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., 1905, Preliminary report on the geology and underground water resources of the central Great Plains: U.S. Geological Survey Professional Paper 32, 433 p.

Diffendal, R.F., Jr., 1999, Deuel County test-hole logs: Nebraska Water Survey Test-Hole Report no. 25, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 93 p.

Diffendal, R.F., Jr., and Goeke, J.W., 2000, Arthur County test-hole logs: Nebraska Water Survey Test-Hole Report no. 3, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 56 p.

Diffendal, R.F., Jr., and Goeke, J.W., 2004, Keith County test-hole logs: Nebraska Water Survey Test-Hole Report no. 51, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 121 p.

Doherty, J.E., 2003. Ground water model calibration using pilot points and regularization. Ground Water, vol. 41, no. 2. p. 170-177.

Doherty, J.E., and Sahill, B.E., 2006. An advanced regularization methodology for use in watershed model calibration. Journal of Hydrology, vol. 327. p. 564-577.

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

Dreezen, V.H., 2000a, Chase County test-hole logs: Nebraska Water Survey Test-Hole Report no. 15, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 75 p.

Dreezen, V.H., 2000b, Perkins County test-hole logs: Nebraska Water Survey Test-Hole Report no. 68, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 112 p.

Dugan, J.T. and Zelt, R.B., 2000. Simulation and analysis of soil-water conditions in the Great Plains and adjacent areas, central United States, 1951-80. U.S. Geological Survey Water Supply Paper 2427, 81 p.

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.

Eversoll, D.A., 2000, Hayes County test-hole logs: Nebraska Water Survey Test-Hole Report no. 43, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 56 p.

Eversoll, D.A., 2003, Red Willow County test-hole logs: Nebraska Water Survey Test-Hole Report no. 73, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 189 p.

Eversoll, D.A., 2004, Hitchcock County test-hole logs: Nebraska Water Survey Test-Hole Report no. 44, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 125 p.

Fetter, C.W. 1994. Applied Hydrogeology, 3rd Edition. MacMillan College Publishing Company.

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: Nebraska Water Survey Paper no. 70, 89 p.

Goeke, J.W., 2004a, Lincoln County test-hole logs: Nebraska Water Survey Test-Hole Report no. 56, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 200 p.

Goeke, J.W., 2004b, McPherson County test-hole logs: Nebraska Water Survey Test-Hole Report no. 60, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 54 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 & 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.

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

Harza Engineering Company, 1993. Water Utilization Study for the Sutherland Project: FERC Project No.1835 – vol. 1. Prepared for the Nebraska Public Power District.

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 Brennan. U.S. Geological Survey Water-Supply Paper 1489. 142 p.

Keasling, R.D., 1975. A digital model of conjunctive-use irrigation in Dawson County, Nebraska. Thesis presented to faculty of the University of Nebraska in partial fulfillment of requirements for M.S. Degree, Lincoln, NE.

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

Klocke, N.L., Hubbard, K.E., Kranz, W.L., and Watts, D.G., 1990, Evapotranspiration (ET) or crop water use: Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln NebGuide G90-992, 4 p.

Lappala, E.G., 1978. Quantitative hydrogeology of the Upper Republican Natural Resources District, southwest Nebraska. U.S. Geological Survey Water-Resources Investigations Report 78-38. 200 p.

Leonard, G.J., and Huntoon, P.W. 1974. Groundwater geology of the Southwest Nebraska Ground Water Conservation District. Nebraska Water Survey Paper no. 37. 37 p.

Luckey, R.R., 1973. Digital model of the hydrologic system, northern High Plains of Colorado- a preliminary report. Colorado Water Conservation Board Water Resources Circular 19. 40 p.

Luckey, R.R., and Hofstra, W.E., 1974. Digital model of the Ogallala aquifer in the northern part of the northern High Plains of Colorado. Colorado Water Conservation Board Water Resources Circular 24. 22 p.

Luckey, R.R., Gutentag, E.D., Heimes, F.J., and Weeks, J.B., 1986. Digital simulation fo 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.

Luckey, R.R., and Cannia, J.C., 2005. Groundwater flow model of the Western Model Unit of the Nebraska Cooperative Hydrology Study (COHYST) area. 59 p. Accessed February 3, 2005 at URL http://cohyst.dnr.ne.gov/cohyst_data.html

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.

Marlette, R.R., and Lewis, G.L., 1974. Digital simulation of conjunctive-use irrigation in Dawson County, Nebraska. Paper presented at the 1974 Fall Annual Meeting of A.G.U., San Francisco, California (abstracted in Dec 1974 EOS).

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., and 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.

McGuire, V.L., 2004. Water-level changes in the High Plains aquifer, predevelopment to 2003 and 2002 to 2003. U.S. Geological Survey Fact Sheet FS 2004-3097, 6 p.

McLean, J.S., Chen, H.H., and Goeke, J.W., 1997. Simulation of groundwater flow in the High Plains aquifer, southern Sandhills area, west-central Nebraska: U.S. Geological Survey Open-File Report 96-206, 16 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.

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

Missouri Basin State Association, 1982a, Technical Paper, Ground Water Depletion, Platte and Kansas River Basins, Colorado-Kansas-Nebraska-Wyoming, Appendix II of Ground Water Depletions Technical Paper; Omaha, Nebr., Missouri River Basin hydrology study, 71 p.

Missouri Basin State Association, 1982b, Transmissivity and stream depletion factor maps; Platte and Kansas River Basins, Colorado-Kansas-Nebraska-Wyoming, Appendix II of Ground Water Depletions Technical Paper; Omaha, Nebr., Missouri River Basin hydrology study, 16 pls.

Nebraska Conservation and Survey Division, 1990. An atlas of the Sand Hills. Institute of Agriculture & Natural Resources, University of Nebraska-Lincoln. Resource Atlas no. 5a, 264 p.

Nebraska Conservation and Survey Division, 1995. Configuration of the water table in 1995. Institute of Agriculture & Natural Resources, University of Nebraska-Lincoln. Online GIS data set at http://csd.unl.edu/general/gis-datasets.asp.

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

Nebraska Department of Environmental Quality, 1981. Title 124, Chapter 18- Lagoons, site location and evaluation; Design. Figure 18.3.

Nebraska Department of Natural Resources, 2000a. Precipitation database. Accessed December 13, 2000 at http://www.dnr.state.ne.us/databank/tab.html

Nebraska Department of Natural Resources, 2000c. Streamflow database. Accessed December 16, 2000 at http://www.dnr.state.ne.us/databank/tab.html

Nebraska Department of Natural Resources NeRain website. Accessible on the world wide web at http://dnrdata.dnr.ne.gov/NeRain/

Nebraska Department of Public Works, 1933-1946. Hydrographic report of Bureau of Irrigation, Water Power and Drainage. Claflin Printing Company.

Nebraska State Historical Society website. Description of Dawson County and the Central Platte valley. Accessed October 19th, 2004 at http://www.nebraskahistory.org/publish/markers/texts/central_platte_valley2.htm

Peckenpaugh, J.M., and Dugan, J.T. 1983. Hydrogeology of parts of the Central Platte and Lower Loup Natural Resources Districts, Nebraska. U.S. Geological Survey Water-Resources Investigations Report 83-4219. 100 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 Survery Water Resources Investigations Report 87-4176.

Peckenpaugh, J.M., Kern, R.A., Dugan, J.T., and Kilpatrick, J.M. 1995. Simulated response of the High Plains aquifer to ground-water withdrawals in the Upper Republican Natural Resources District, Nebraska. U.S. Geological Survey Water-Resources Investigations Report 95-4014. 60 p.

Peterson, S.M., in review. Groundwater flow model of the Eastern Model Unit of the Nebraska Cooperative Hydrology Study Area. Nebraska Platte River Cooperative Hydrology Study Technical Committee Report. 67 p.

Pettijohn, R.A., and Chen, H.H., 1983a, Geohydrology of the High Plains aquifer system in Nebraska: U.S. Geological Survey Water-Resources Investigations Report 82-502, map, scale 1:175,000, 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, scale 1:175,000, 3 sheets.

Poeter, E.P. and M.C. Hill, 1998, Documentation of UCODE: A computer code for universal inverse modeling, U.S. Geological Survey Water-Resources Investigations Report 98-4080, 116 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.

Redell, D.L., 1967, Distribution of ground-water recharge. Ft. Collins, Colorado, Colorado State University, Agricultural Engineering Department technical report. 132 p.

Smith, F.A., 1999, 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., 2003, 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., and Swinehart, J.B., 2000, Garden County test-hole logs: Nebraska Water Survey Test-Hole Report no. 35, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 91 p.

Sounders, V.L., Swinehart, J.B., and Dreezen, V.H.. 1990. Postulated evolution of Platte River and related drainages. University of Nebraska-Lincoln Conservation and Survey Division map.

U.S. Census Bureau. Accessed in 2001 at www.census.gov.

U.S. Department of Agriculture, 1967, Irrigation water requirements: Soil Conservation Service, Engineering Division, Technical Release no. 21, 88 p.

U.S. Department of Agriculture, 1997, Census of Agriculture for Nebraska: National Agricultural Statistical Services, 536 p. plus six appendixes.

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, 2000. United States National Water Inventory Survey database. Accessed August 18, 2000 at http://waterdata.usgs.gov/nwis-w/US/.

Waite, H.A., 1949. Progress report on the geology and ground-water 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., 1946. Groundwater in the Republican River basin, Nebraska, Parts II, III, and IV. University of Nebraska Conservation and Survey Division, Nebraska Water Resources Survey Water Supply Paper 1, 109 p.

Waite, H.A., and others, 1948. Progress report on the ground-water hydrology of the Republican and Frenchman River Valleys, with a section on The chemical quality of the groundwater, by H.A. Swenson. U.S. Geological Survey Circular 19. 83 p.

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. and Waite, H.A. 1941. Ground Water in Keith County, Nebraska. U.S. Geological Survey Water-Supply Paper 848. 68 p.

Wigley, P.B., 2001, Logan County test-hole logs: Nebraska Water Survey Test-Hole Report no. 57, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 17 p.

Worldclimate website. Maximum and minimum temperatures for Arthur and Cambridge, NE. Accessed on December 14, 2000 at www.worldclimate.com