HYDROGEOLOGY IN THE VICINITY OF THE NEBRASKA MANAGEMENT SYSTEMS EVALUATION AREA SITE, CENTRAL NEBRASKA

By VIRGINIA L. MCGUIRE *and* JOHN M. KILPATRICK

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 97-4266

Lincoln, Nebraska
1998

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
THOMAS J. CASADEVALL, Acting Director

For additional information write to:

District Chief
U.S. Geological Survey
Room 406, Federal Building
100 Centennial Mall North
Lincoln, NE 68508

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
gallon per minute (gal/min)	0.06309	liter per second
inch per hour (in/h)	0.0254	meter per hour

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

$$°F = (1.8 \times °C) + 32$$

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

$$°C = (°F - 32) / 1.8$$

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

Altitude, as used in this report, refers to distance above or below sea level.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

HYDROGEOLOGY IN THE VICINITY OF THE NEBRASKA MANAGEMENT SYSTEMS EVALUATION AREA SITE, CENTRAL NEBRASKA

By Virginia L. McGuire *and* John M. Kilpatrick

ABSTRACT

From 1991 to 1992, the U.S. Geological Survey participated with the U.S. Department of Agriculture and the University of Nebraska-Lincoln in research activities at the Nebraska Management Systems Evaluation Area (MSEA) site near Shelton, Nebraska. The purpose of the U.S. Geological Survey study was to define the hydrogeologic system in the vicinity of the Nebraska MSEA site to aid the interpretation of ground-water sampling results by other researchers. The primary aquifer in the study area is the High Plains aquifer, which consists of an unconfined part, the shallow aquifer; a silt and clay unit that acts as a confining layer; and a confined part, the Ogallala aquifer. The shallow aquifer is the focus of this study. To determine aquifer properties for the shallow aquifer, two constant-discharge aquifer tests and about 450 straddle-packer slug tests were conducted. The test results indicate horizontal hydraulic conductivity values for the shallow aquifer ranged from 340 to 390 feet per day, and horizontal hydraulic conductivity values for 1.6-foot vertical intervals in the aquifer ranged from 92 to more than 620 feet per day.

A ground-water flow model of the shallow aquifer in the study area was developed using historical data and the hydrologic data collected for this study. The model quantified the water budget for the shallow aquifer in the study area. Aquifer properties were estimated for each cell, based on analysis of drillers' logs from irrigation wells and test holes and the results of constant-discharge aquifer tests and straddle-packer slug tests. Recharge and pumpage were estimated using a soil-moisture budget model.

Water budgets calculated by the model indicated that in 1931, the shallow aquifer discharged 25 percent of its outflow to the main channel of the Platte River and, in 1991, the main channel of the Platte River supplied more than 12 percent of the total inflow to the aquifer. In 1991, the largest sources of water to the system were recharge from precipitation (42 percent) and ground-water inflow from the western boundary of the model area (31 percent) and the losses were due to pumpage (81 percent) and ground-water outflow through the eastern boundary of the model (19 percent).

The study indicates that water collected from wells screened near the bottom or middle of the shallow aquifer at the MSEA site likely entered the system far upgradient of the site and that a vertical gradient is not measurable in the shallow aquifer except possibly in the immediate vicinity of a pumping irrigation well. Therefore, concentrations of agricultural chemicals in ground water collected from wells screened only at the top of the shallow aquifer probably are influenced by the effects of farming practices at the site.

INTRODUCTION

From 1991 to 1992, the U.S. Geological Survey (USGS) joined the U.S. Department of Agriculture (USDA) and University of Nebraska-Lincoln (UNL) in research activities at the Nebraska Management Systems Evaluation Area (MSEA) site near Shelton, Nebraska. The goals of the MSEA researchers at this site are to (1) assess the effects of common farming practices and proposed best-management practices (BMPs) on ground-water quality, (2) develop new technologies or management methods to reduce ground-water contamination, and (3) evaluate the socioeconomic effects of these new technologies and management methods. USGS studies at the site are related to the assessment of the effects of common farming practices and BMPs on ground-water quality.

The Nebraska MSEA site is located in southeastern Buffalo County, about a mile southwest of Shelton, Nebraska. This area is characterized by widespread and historic ground-water contamination with nitrate (Exner and Spalding, 1976). Because the concentrations of agricultural chemicals in the ground water represent a composite result of past and present agricultural practices, an accurate and detailed description of the hydrogeologic framework and a good understanding of the manner in which ground water moves through the aquifer at the site are required so that researchers can evaluate the effectiveness of different BMPs on reducing ground-water contamination. Because available hydrogeologic information in the vicinity of the site was insufficient for this purpose, the USGS began a study to provide additional hydrologic data and to characterize ground-water flow, direction, and velocity in the unconfined part of the High Plains aquifer, called the shallow aquifer in this report.

Purpose and Scope

The purpose of this report is to describe the hydrogeology of the High Plains aquifer in the 50-mi^2 (square mile) area around the MSEA site (fig. 1), particularly in the shallow aquifer, to aid the interpretation of ground-water sampling results by other researchers. This hydrogeologic description is based on data from previous studies, additional hydrologic data that was collected during this study, and the results of digital simulations. The shallow aquifer was simulated using a soil-moisture budget model and a ground-water flow model. The soil-moisture budget model was used to estimate 1931 and 1991 pumpage and recharge using existing hydrologic, soil, vegetation, topographic, and 1931 to 1991 climatic data. The ground-water flow model estimated the aquifer's inflows and outflows, based on a conceptual model of the aquifer; the flow model was calibrated using 1931 and 1991 water-level data. The report presents (1) two geologic sections, (2) a map of the base of the Quaternary-age sand and gravel deposits, which is the base of the shallow aquifer, (3) a map of the altitude of the water table in the study area, June 1991, and (4) a description of ground-water flow, including the water budget, for the shallow aquifer in 1931 and 1991.

Location and Description of the Study Area

The study area covers about 50 mi^2 of Buffalo and Hall Counties and is bounded on the north by Wood River and on the south by the Platte River (fig. 1). The MSEA research site encompasses about 560 acres and is near the center of this 50-mi^2 area. The study area is intensely cropped, with more than 90 percent of the land under cultivation. More than 75 percent of the cultivated land is used for continuous production of irrigated corn and about 10 percent is used for continuous production of irrigated soybeans.

The study area lies in the High Plains section of the Great Plains physiographic province (Fenneman, 1931), on flood plain and terrace deposits. The land surface altitude in the study area ranges from about 2,085 ft (feet) in the west to about 1,990 ft in the east, which is a slope of about 7.3 ft/mi (feet per mile) in an easterly direction.

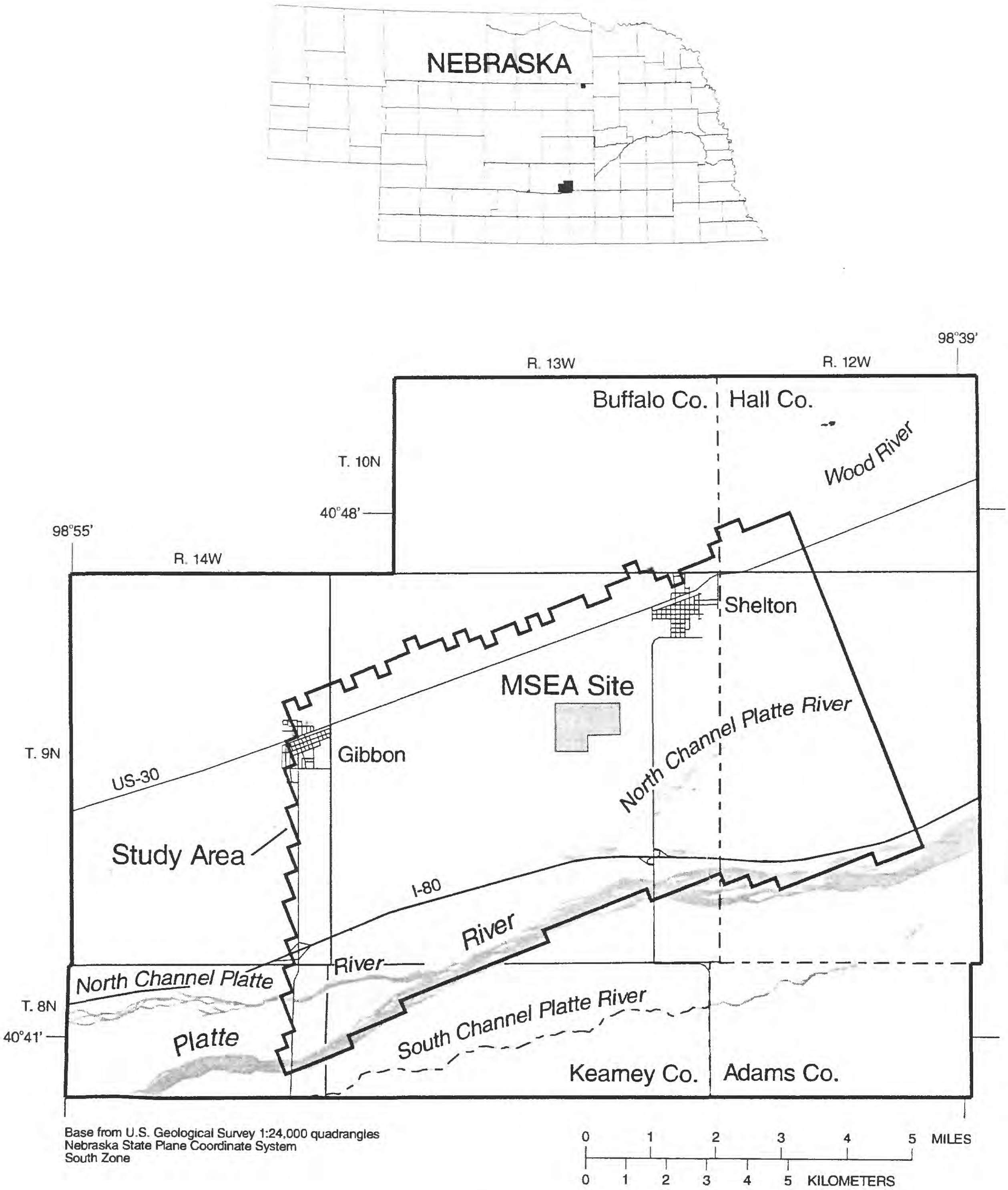


Figure 1. Location of study area and Management Systems Evaluation Area (MSEA) site.

The climate in the study area is continental and temperate, with large seasonal variations in temperature and precipitation. From 1951 through 1980, the Kearney weather station, which is about 15 miles west-southwest of the MSEA site, recorded a mean annual temperature of 49.6 °F (degrees Fahrenheit) and mean annual precipitation of 24.53 in. (inches). The mean monthly temperature from 1951 to 1980 varied from 21.1 °F in January to 76.2 °F in July; the mean monthly precipitation varied from 0.49 in. in January to 4.03 in. in May. Typically, most precipitation occurs between April and September (National Oceanic and Atmospheric Administration, 1982).

The soils in the study area are classified into 15 soil series with permeabilities ranging from 0.06 to 0.20 in/h (inch per hour) of water to more than 20 in/h of water (Buller and others, 1974; Yost, 1962). The soil series formed on stream terraces are Blendon, Cozad, Hall, Hord, Median, O'Neill, and Wood River; the soil series formed on wind-reworked loamy and sandy material are Orthello and Thurman. These soils are all generally thick and well drained. The soil series formed on bottomlands are Cass, LeShara, Platte, Silver Creek, and Wann; the soil series formed on silty alluvium on bottomlands or low stream terraces is Gibbon. These soils are all generally thick and somewhat poorly drained.

Acknowledgments

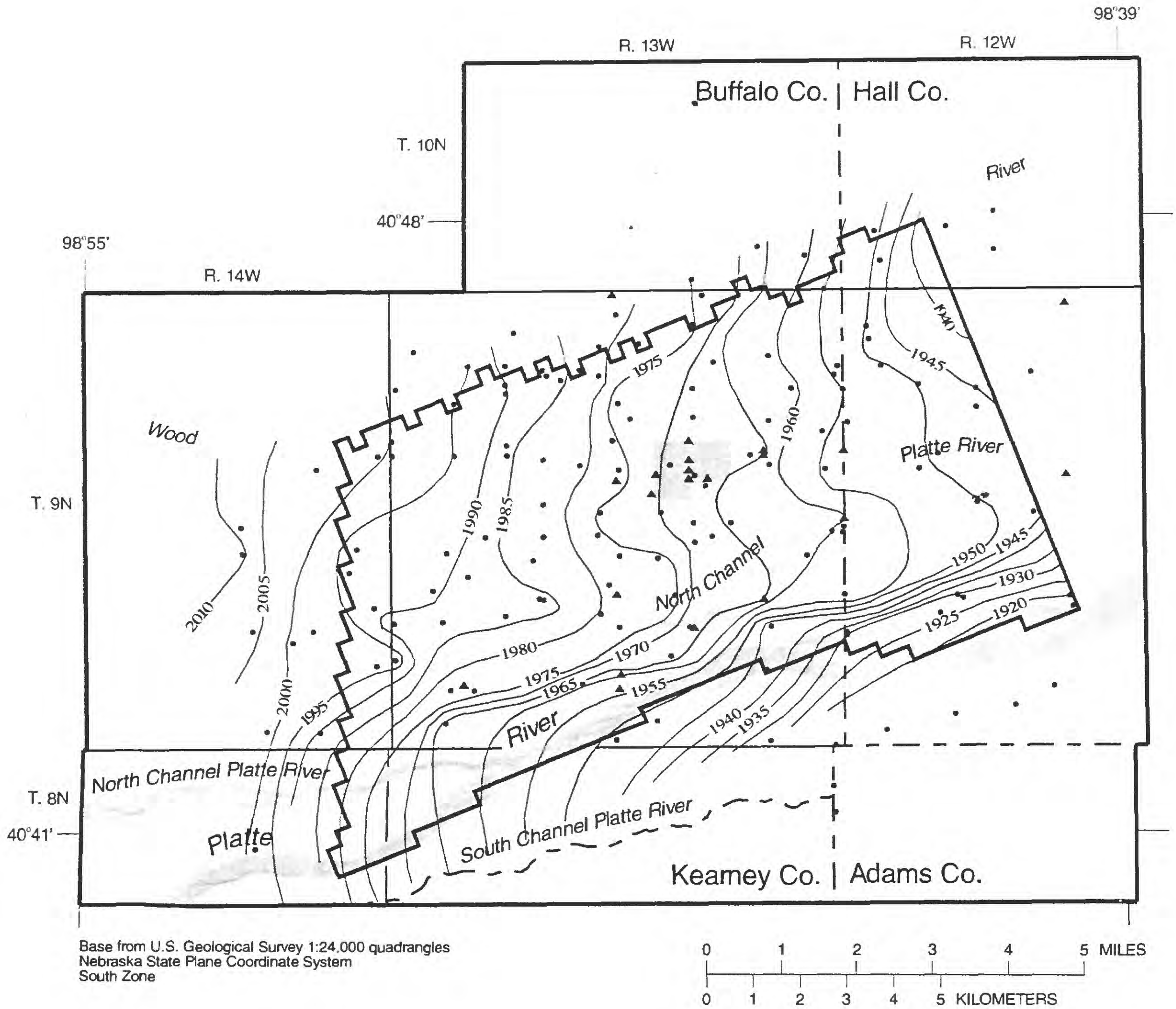
The authors thank Vitaly Zlotnik, UNL Department of Geology, for assistance in organizing and performing the first constant-discharge aquifer test and for providing the straddle-packer slug-test results. The authors also thank Loren Niemack, the property owner, for allowing access to the site and for providing equipment used in the constant-discharge aquifer tests.

HYDROGEOLOGY

The geologic units in the study area are defined by Gutentag and others (1984), Keech and Dreeszen (1964), and Schreurs (1956); the units overlying the Pierre Shale are summarized in table 1. About 160 test-hole lithologic logs and irrigation-well drillers' logs were analyzed to determine the altitude and thickness of each unit in the study area. The logs were also used to map the altitude of the base of the Quaternary age sand and gravel deposits (fig. 2). The logs from test holes and irrigation wells located along traces shown in figure 3 were used to construct two geologic sections of the study area. These geologic sections are presented in figures 4 and 5.

Table 1. Summary of geologic units in the vicinity of the Nebraska Management Systems Evaluation Area (MSEA) site

Era	System	Geologic unit	Lithology	Thickness (feet)
Cenozoic	Quaternary	Undifferentiated Holocene and Pleistocene deposits	Sand and gravel deposits with interbedded silt and clay in some areas	45-100
	Quaternary (?)	Unnamed	Silt and clay	10-64
	Tertiary	Ogallala Formation	Greenish-tinted sands and gravels, with siliceous root fragments: generally unconsolidated but may be cemented by calcium carbonate or secondary accumulations of silica	10-145
Mesozoic	Cretaceous	Pierre Shale	Gray to black shale	not determined



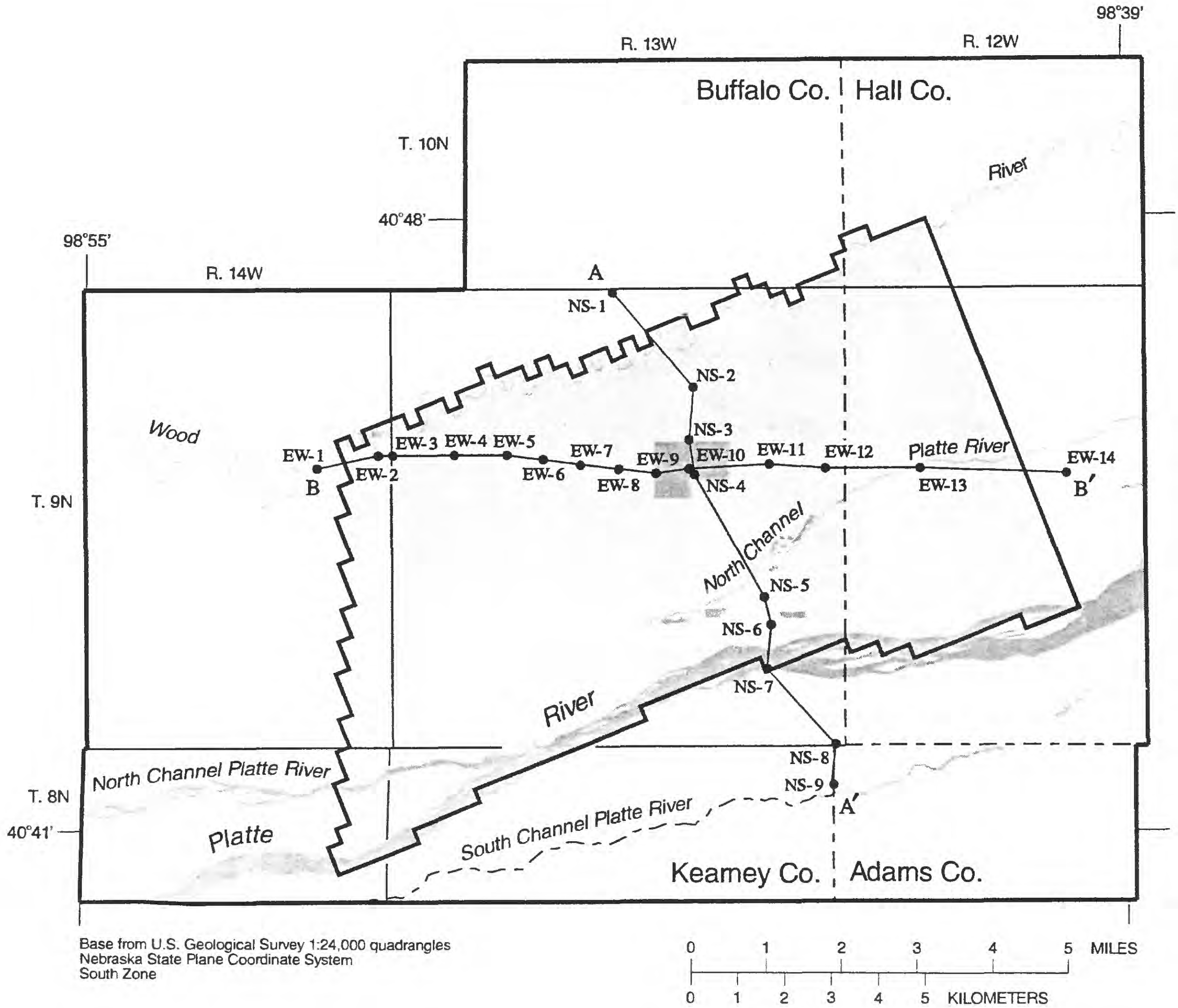
EXPLANATION

—2000— Base-of-Aquifer Contour--Shows altitude of the base of the Quaternary-age sand and gravel deposits. Contour interval 5 feet. Datum is sea level

• Irrigation well used for control

▲ Test hole used for control

Figure 2. Altitude of the base of the Quaternary-age sand and gravel deposits.



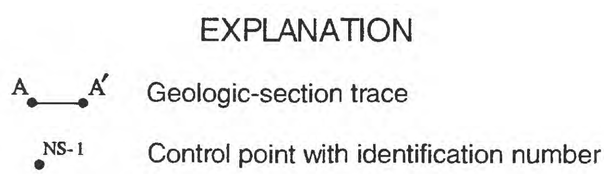


Figure 3. Trace of geologic sections A-A′ and B-B′.

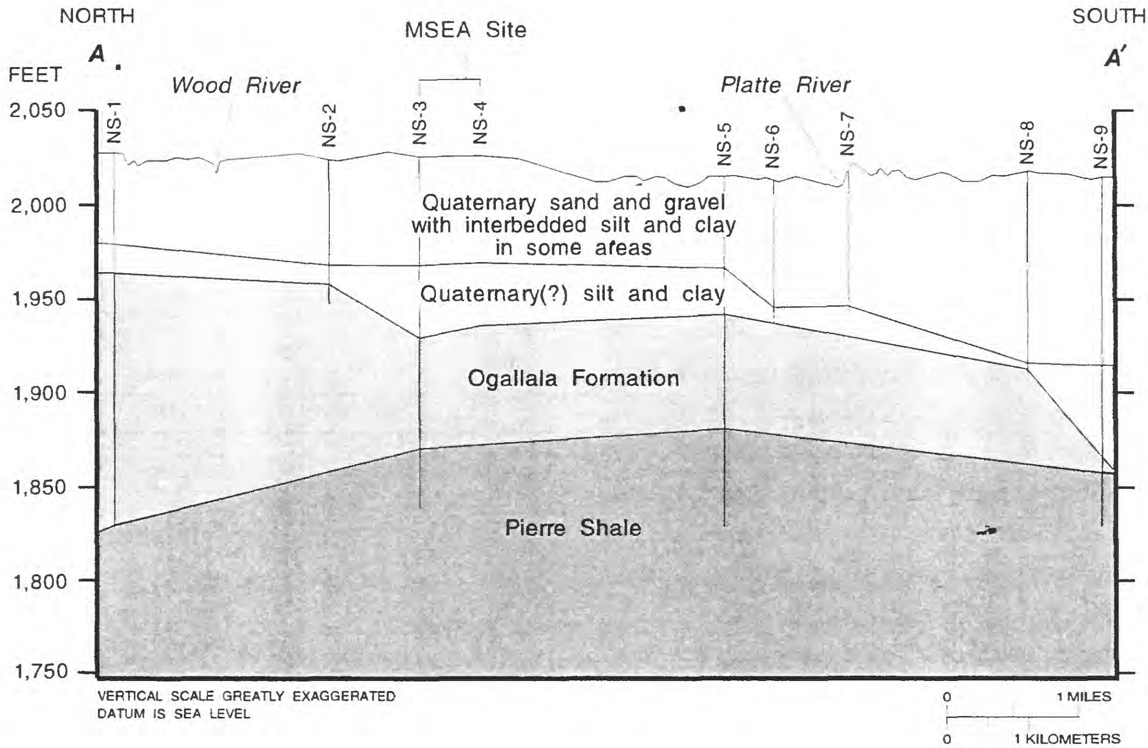


Figure 4. Geologic section A-A′.

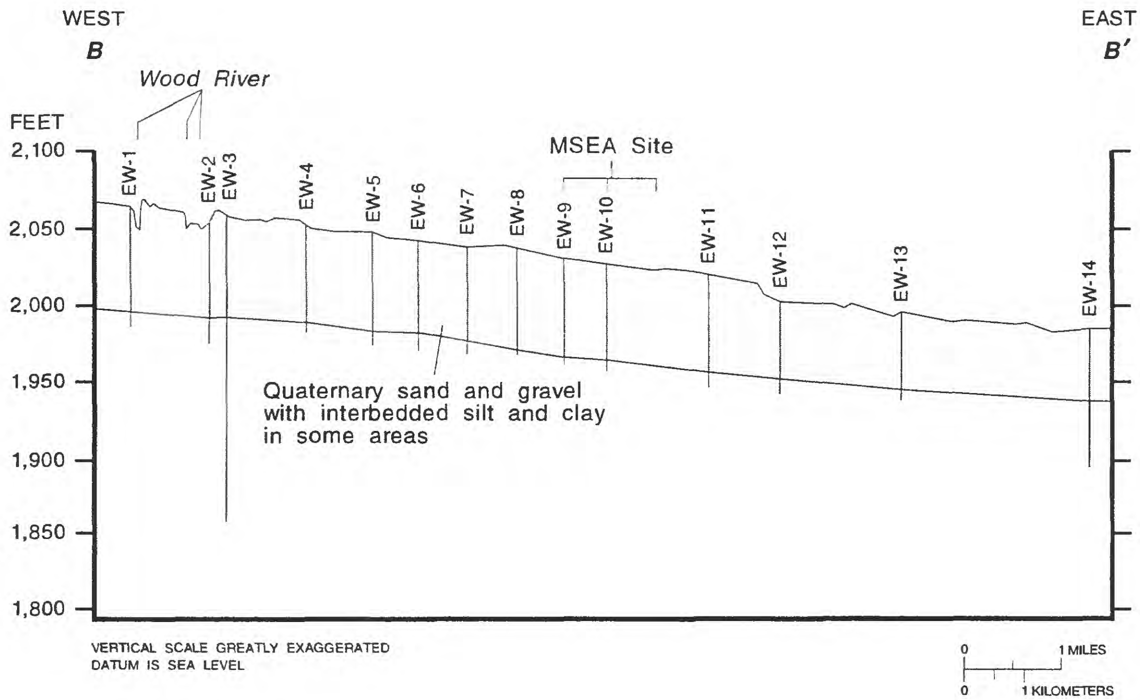


Figure 5. Geologic section B-B′.

The primary aquifer in the study area is the High Plains aquifer, which consists of the shallow aquifer; a silt and clay unit that is thought to act as a confining layer; and a part of the aquifer in the Ogallala Formation, called the Ogallala aquifer in this report. The High Plains aquifer is underlain by the Pierre Shale, which is not considered to yield water in the study area.

The shallow aquifer is the source of water for most irrigation wells in the study area, including more than 275 high-yield (up to 2,000 gal/min (gallons per minute)) irrigation wells; the Ogallala aquifer is the source of water for most domestic and stock wells. The shallow aquifer generally is not used for domestic and stock wells in the area because the nitrate concentrations in water from wells screened in the shallow aquifer can be greater than 20 mg/L (milligrams per liter). The nitrate concentrations in water from wells screened in the Ogallala aquifer are less than 1.0 mg/L (Exner and Spalding, 1990).

Hydrologic Data

Hydrologic data that were collected for the study include (1) precipitation data from May to July 1991, (2) river stages and ground-water levels during May and July 1991, and (3) results of constant-discharge aquifer tests and straddle-packer slug tests that were conducted during 1991 to 1993.

Landowners or lessees collected precipitation data from May to July 1991 at 17 sites in the study area (fig. 6). These data indicate that mean monthly precipitation in the study area was 4.5 in. in May 1991, 2.2 in. in June 1991, and 0.9 in. in July 1991 (table 2); however, rainfall amounts were highly variable over the area.

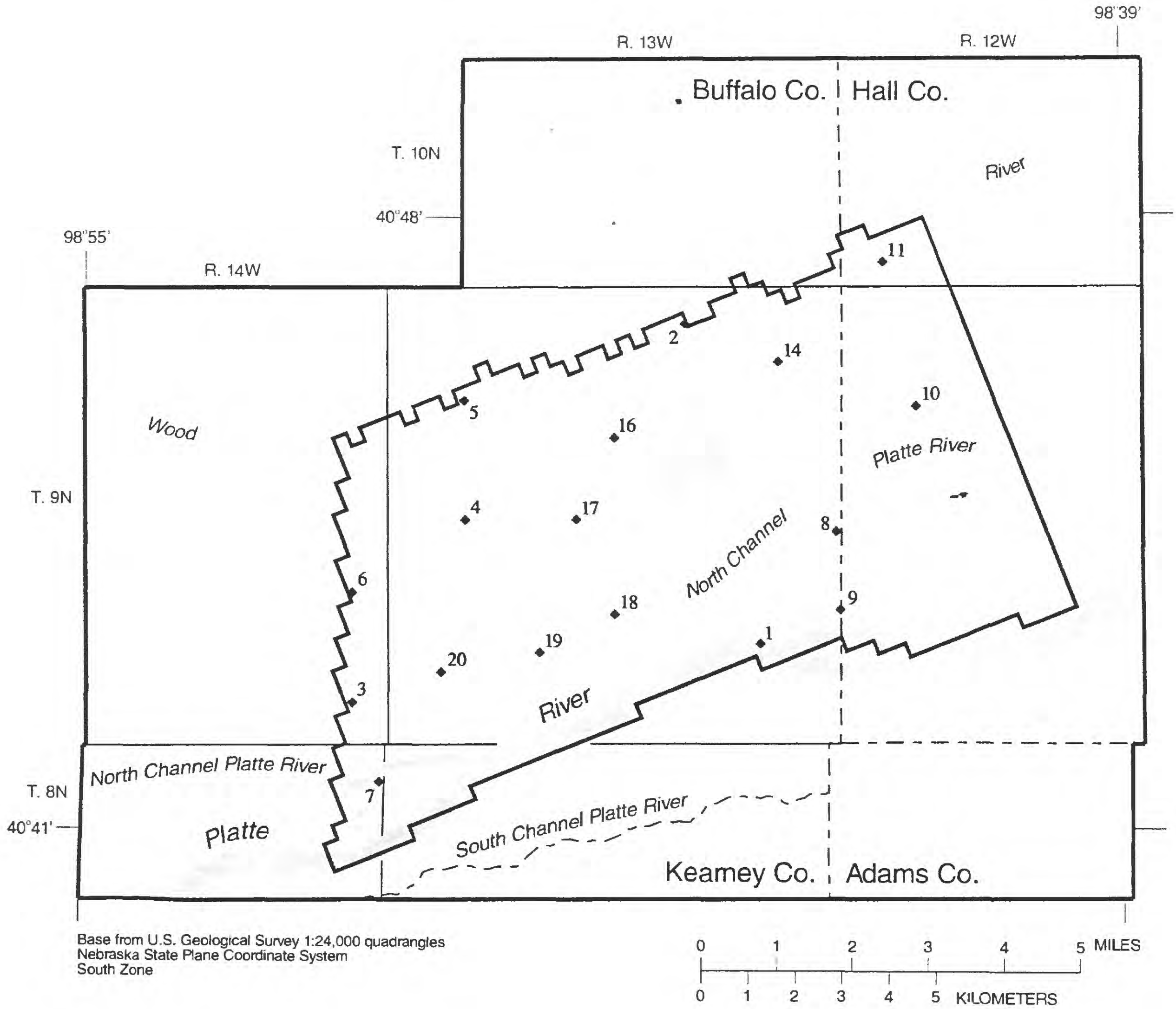
From April to September 1991, river stages were measured at 12 locations on three to four occasions along the Wood River, the main channel of the Platte River, and the North Channel Platte River. The stage measurement sites are shown in figure 7 and the stage values in June and September 1991 are listed in table 3. During the same period, ground-water levels were measured in about 130 observation wells that are screened in the shallow aquifer; the location of these wells is shown in figure 8.

Table 2. Total monthly precipitation for May, June, and July 1991

[--, not reported]

Site number	Total monthly precipitation (inches)		
	May 1991	June 1991	July 1991
1	2.80	3.37	0.69
2	6.05	--	--
3	3.98	2.14	1.12
4	5.59	3.30	.50
5	6.30	1.37	2.08
6	3.75	1.85	--
7	2.82	.86	.54
8	4.12	3.12	.50
9	4.07	2.60	--
10	3.98	2.89	.88
11	5.52	.90	--
14	5.93	2.74	1.60
16	4.10	1.93	1.21
17	4.60	.85	.41
18	4.04	2.32	.41
19	4.14	2.47	.74
20	4.12	2.45	.94

The river stage and ground-water levels indicate that the shallow aquifer is not connected with Wood River and that the main channel of the Platte River does not have a large effect on the water-table configuration in the study area. The water level and relevant river-stage values for June 1991 are contoured in figure 8 and show that, in the shallow aquifer, the average hydraulic gradient is 7.5 ft/mi and that ground-water flows to the east-northeast (Kilpatrick, 1996).



EXPLANATION

◆1 Precipitation measurement site and site number (17 total)

Figure 6. Location of precipitation measurement sites.

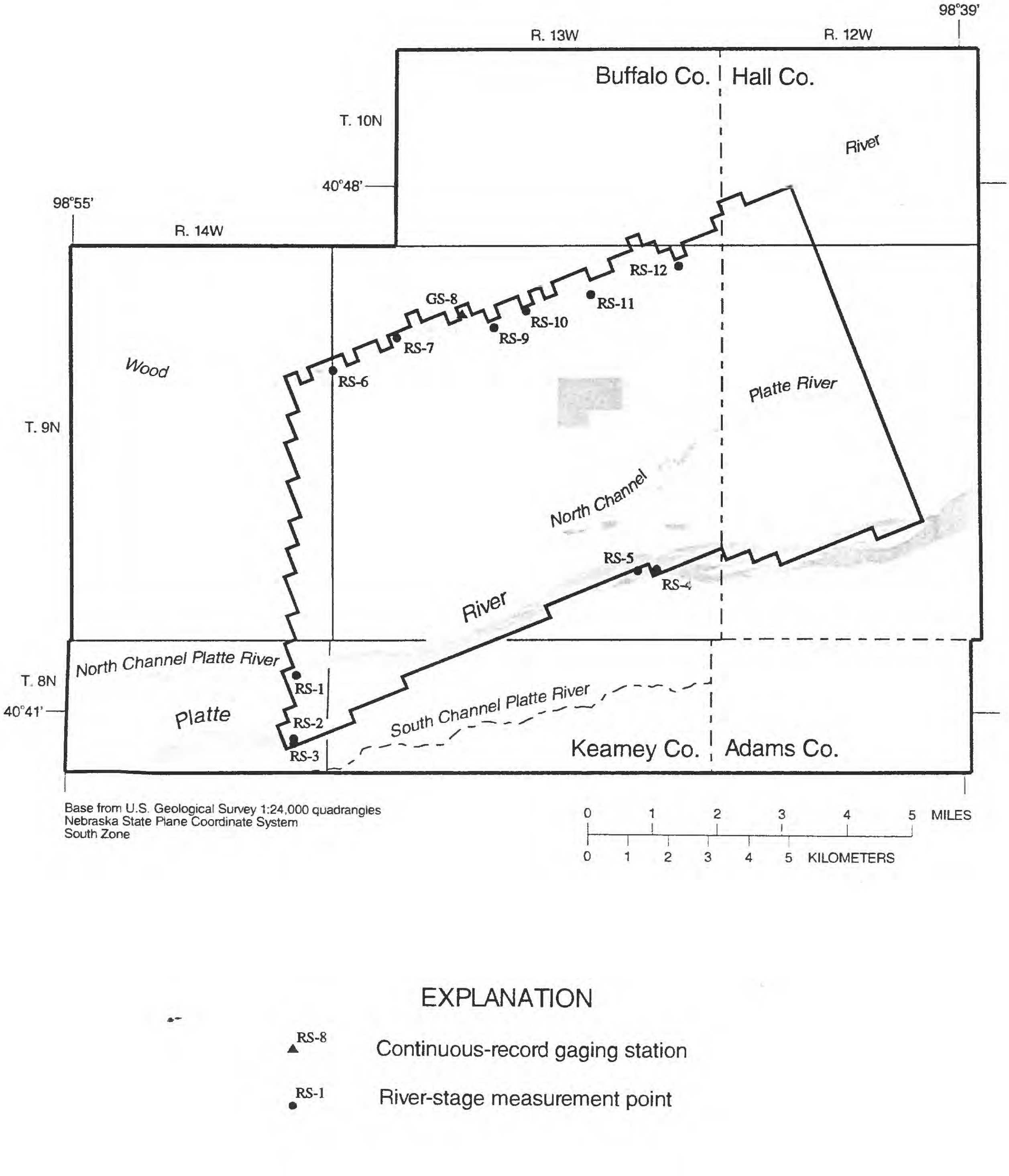
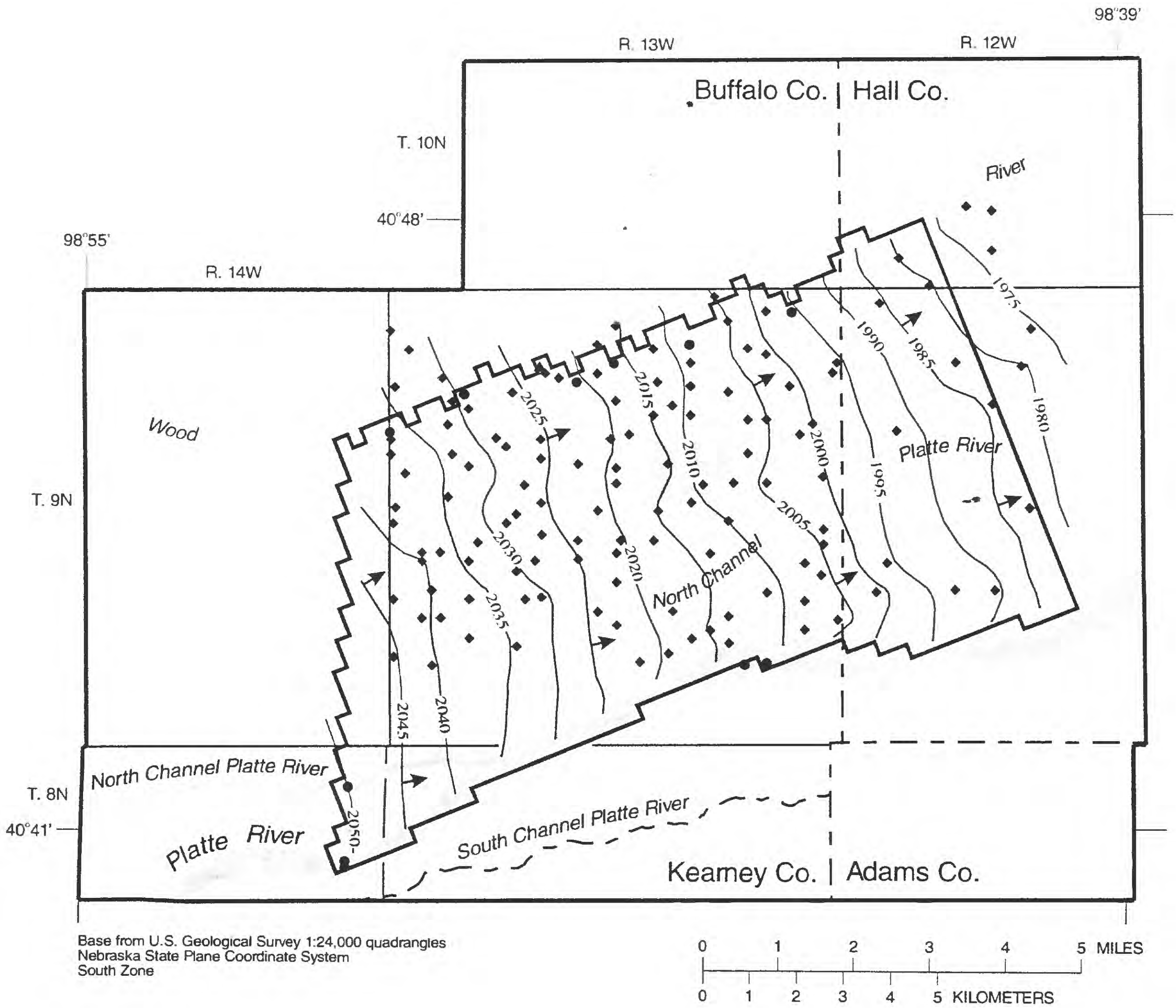


Figure 7. Location of gaging stations and river-stage measurement sites.



EXPLANATION

—2000— Water-Table Contour--Shows altitude of water-table. Contour interval 5 feet. Datum is sea level

→ Ground-Water Flow Direction

▲ Continuous-record gaging station

● River-stage measurement site used for control

◆ Observation well used for control

Figure 8. Water table in study area, June 1991 (modified from Kilpatrick, 1996).

Table 3. River-stage data, Platte and Wood Rivers near the Nebraska Management Systems Evaluation Area (MSEA) site

Stage measurement site number (fig. 7) and description	Date	Stage (feet above sea level)
RS-1: Platte River near Gibbon, north of north channel 45 feet	06/12/91	2,050.26
	09/12/91	2,049.73
RS-2: Platte River near Gibbon, north of mid-channel 200 feet	06/12/91	2,050.74
	09/12/91	2,050.61
RS-3: Platte River near Gibbon, south of mid-channel north wing wall	06/12/91	2,051.25
	09/12/91	2,050.79
RS-4: Platte River near Shelton, north of mid-channel	06/12/91	2,012.59
	09/12/91	2,012.38
RS-5: Platte River near Shelton, south of mid-channel	06/12/91	2,012.81
	09/12/91	2,012.40
RS-6: Wood River, east edge of Gibbon	06/12/91	2,043.91
	09/12/91	2,044.63
RS-7: Wood River, 1.9 miles northeast of Gibbon	06/12/91	2,038.23
	09/12/91	2,038.88
GS-8: Wood River at Gibbon Gage	06/12/91	2,027.21
	09/12/91	2,027.88
RS-9: Wood River, 0.5 mile east-southeast of Gibbon Gage	06/12/91	2,029.06
	09/12/91	2,029.46
RS-10: Wood River, 1 mile east of Gibbon Gage	06/12/91	2,017.91
	09/12/91	2,017.33
RS-11: Wood River, 1 mile west of Shelton	06/12/91	2,014.20
	09/12/91	2,014.00
RS-12: Wood River, north edge of Shelton	06/12/91	2,009.04
	09/12/91	2,009.02

The water-level measurements also show water levels in many wells are between 2 and 10 ft lower in September 1991 than in June 1991. Comparison of 1931 water levels (Lugn and Wenzel, 1938) and spring 1991 water levels in the shallow aquifer indicates these water levels have not changed significantly over the 61-year period (Kilpatrick, 1996).

Two constant-discharge aquifer tests were conducted—the first by UNL and USGS in November 1991, the second by USGS in May 1992—in the southeastern part of the MSEA site (fig. 9) to estimate the hydraulic properties of the shallow aquifer in the study area. The constant-discharge aquifer tests were conducted to determine transmissivity (T); specific yield (S_y); horizontal hydraulic conductivity (K_r) at a large scale; and anisotropy, the ratio of vertical hydraulic conductivity (K_z) to K_r

The well array for the first aquifer test is shown in figure 9. Water levels and temperature were monitored for more than 2 days prior to the first aquifer test in a well screened in the shallow aquifer (well 1) and in a well screened in the underlying Ogallala aquifer (well O) to determine water-level trends in each aquifer. During this time, natural water-level fluctuations in the shallow aquifer did not match the natural water-level fluctuations in the underlying Ogallala aquifer, and water temperature in the shallow aquifer was greater that the water temperature in the Ogallala aquifer. These results indicate that the two aquifers probably are not effectively connected.

The first aquifer test started on November 19, 1991. The water level in the shallow aquifer at this location averaged about 16.2 ft below land surface before the start of the test, giving an initial saturated thickness of 42.8 ft. The aquifer test procedure consisted of pumping the discharge well (irrigation well 1) for 53 hours at about 1,083 gal/min. The pumping response was monitored in five fully penetrating wells (wells 1, 6, UNL-2, UNL-3, and UNL-4) and two partially penetrating wells (wells 3 and 5) screened in the shallow aquifer, a well screened in the confining layer (well S), and two partially penetrating wells screened in the Ogallala aquifer (wells O and UNL-1). After pumping ceased, recovery response was monitored for 90 hours in two fully penetrating wells (wells 1 and 6) and two partially penetrating wells (wells 3 and 5) screened in the shallow aquifer.

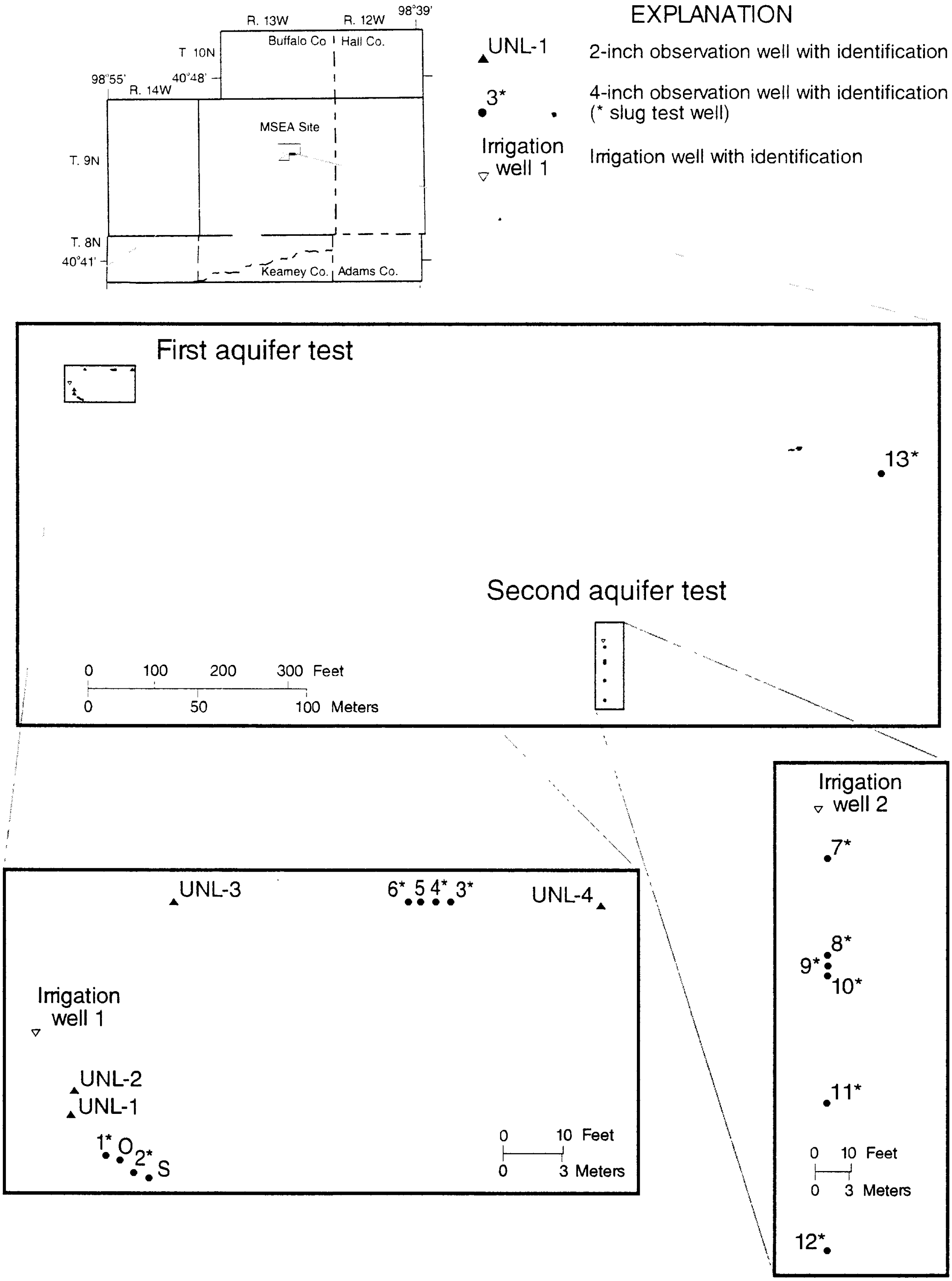


Figure 9. Site of first and second constant-discharge aquifer tests and straddle-packer slug tests.

During the first aquifer test, the water level in the well screened in the confining layer decreased; however, drawdown was not as great as in wells screened in the shallow aquifer. The water level in the wells screened in the Ogallala aquifer did not change. The response in the confining layer indicates the well screened in the confining layer may be hydraulically connected with the shallow aquifer, possibly through the material intended to provide a seal around the well. The lack of response in the Ogallala aquifer indicates that the Ogallala aquifer is effectively separated from the shallow aquifer in this area.

The response to pumping in the first aquifer test was analyzed using the Neuman method (Neuman, 1972, 1974, 1975; Moench, 1993, 1994); the analysis results are: T=14,000 ft^2/d (feet squared per day), K_r=340 ft/d, S_y=0.09, and K_z/K_r=0.11. The recovery response in wells 1, 3, 5, and 6 was analyzed using the Theis method (Theis, 1935); the K_r values from this analysis were within 6 percent of the K_r value obtained from the Neuman method.

The well array for the second aquifer test also is shown in figure 9. The discharge well for the second aquifer test (irrigation well 2) is located approximately 900 ft southeast of the discharge well for the first aquifer test (irrigation well 1). The water level in the shallow aquifer in the vicinity of the second aquifer test was an average of about 18 ft below land surface before the start of the test, giving an initial saturated thickness of 39 ft. The aquifer test procedure consisted of pumping the discharge well at an approximate rate of 625 gal/min for 50 hours and monitoring the response in three fully penetrating wells screened in the shallow aquifer (wells 8, 11, and 12) and two partially penetrating wells screened in the shallow aquifer (wells 9 and 10). After pumping ceased, recovery was monitored for 74 hours in the same wells.

The response to pumping in the second aquifer test was analyzed using the Neuman method (Neuman, 1972, 1974, 1975; Moench, 1993, 1994); the analysis results are: T = 15,000 ft^2/d, K_r = 390 ft/d, S_y = 0.09, and K_r/K_z = 0.05. The recovery responses in wells 8, 9, 10, and 11 were analyzed using the Theis method (1935); the K_r values from this analysis were within 3 to 20 percent of the K_r value obtained using the Neuman method.

In November 1993, UNL Geology Department conducted about 450 straddle-packer slug tests at eleven wells shown in figure 9. The staddle-packer apparatus isolated a 2-ft vertical section of the well; the slug tests were performed every 1.6 ft over the screened portion of the well, starting below the static water table. Analysis of straddle-packer-slug-test responses indicated the K_r values for each 1.6 vertical interval ranged from 92 to more than 620 ft/d (McGuire, 1994). In the first aquifer test area, K_r near the top of the aquifer ranged from 98 to 210 ft/d. For the remaining thickness of the aquifer, K_r ranged from 210 to 390 ft/d. In the second aquifer test area, K_r near the top of the aquifer ranged from 260 to 390 ft/d; and in the rest of the aquifer, there were 3 to 4 zones of higher K_r (260 to more than 620 ft/d) between zones of lower K_r (110 to 300 ft/d). At well 13, K_r in the upper and middle part of the aquifer ranged from 82 to 160 ft/d and K_r in the lower part of the aquifer ranged from 160 to 430 ft/d.

Model Development

One tool commonly used to visualize groundwater flow through an aquifer is a conceptual model. Such a model qualitatively describes the movement of water particles in an aquifer from entry at a recharge area to exit at a discharge area. A digital model then can be developed, based on the conceptual model, to describe quantitatively ground-water flow and provide estimated water budgets.

Conceptual Model

From the hydrologic and geologic data that was collected and analyzed as part of this study, a conceptual model of the shallow ground-water-flow system was developed. Analysis of changes in water levels over time has indicated that the system appears to be in a state of dynamic equilibrium, despite relatively heavy pumping during the growing season (Kilpatrick, 1996). Analysis of water-level and stage data along the main channel of the Platte River indicates that the main channel of the Platte River does not have a large effect on the water-table configuration in the study area. The available hydrologic data indicates that there is little or no interaction between the shallow aquifer and the Ogallala aquifer below it. The largest sources of water for the shallow aquifer in the study area are flow across the western boundary of the study area and recharge from precipitation. Pumping from irrigation and flow across the eastern boundary are likely the largest losses for the shallow aquifer in the study area.

Digital Model

From the conceptual model, a digital ground-water flow model was developed for the study area. A large study area was selected to reduce boundary effects of the model at the MSEA research site. This model was used to simulate ground-water flow at two different times representing two different steady-state conditions. The first time was 1931, when the aquifer was only sparsely developed and there was little pumpage (Lugn and Wenzel, 1938). This is the earliest time for which sufficient, reliable water-level data are available, and is assumed to be representative of early development equilibrium (steady-state) conditions. The second time was 1991, when the aquifer was heavily developed and assumed to have reached long-term, dynamic equilibrium (steady-state) conditions. The water budgets for these two times were compared to better understand the effects of increased pumpage on ground-water flow in the system.

Model Description

The shallow ground-water system in the study area was simulated using a two-layer, regularly spaced grid with 31 rows and 55 columns (fig. 10) and the modular, three-dimensional, finite-difference, ground-water flow computer model MODFLOW (McDonald and Harbaugh, 1988). Each row and column represented a 1,000-ft-wide strip of the aquifer so that each cell represented an area of about 23 acres. Of the 1,705 cells per layer, 1,279 in each layer were active. The shallow aquifer was simulated using two layers to evaluate the significance of vertical hydraulic gradients, because initial study indicated that most wells were screened in the lower half of the aquifer. For this purpose, the aquifer was arbitrarily divided in half, with layer 1 representing the upper half and layer 2 representing the lower half. A more comprehensive survey of irrigation wells in the study area later indicated that most wells were screened in both the upper and lower halves of the aquifer. The active model area coincides with the study area boundary. The grid was oriented so that rows extended from west-southwest to east-northeast, parallel to the direction of ground-water flow.

Boundary Conditions

The boundary conditions for the ground-water flow model were chosen to reasonably represent hydrologic conditions along the study-area boundaries. Because only a small part of a much more extensive aquifer system was simulated, it was not possible to extend the model to natural boundaries at all margins. The upper boundary of the model is the water table in the shallow aquifer. The lower boundary of the model is the base of the shallow aquifer, which is assumed to be impermeable. The northern boundary of the model is the Wood River (fig. 10) and was simulated as a general-head boundary, so that flow across the boundary is proportional to and in the same direction as the hydraulic gradient across the boundary. The Wood River was not simulated as a constant-head boundary because it was not indicated to be hydraulically connected to the shallow aquifer. Because ground water enters the model area along the western boundary and leaves the area along the eastern boundary, the eastern and western boundaries also were simulated as general-head boundaries. Initial estimates of conductances used for these general-head boundaries were based on the initial hydraulic conductivity values used in the model. Conductance is a combination of several parameters used in Darcy's Law. It is equal to the hydraulic conductivity along the flow path multiplied by cross-sectional area

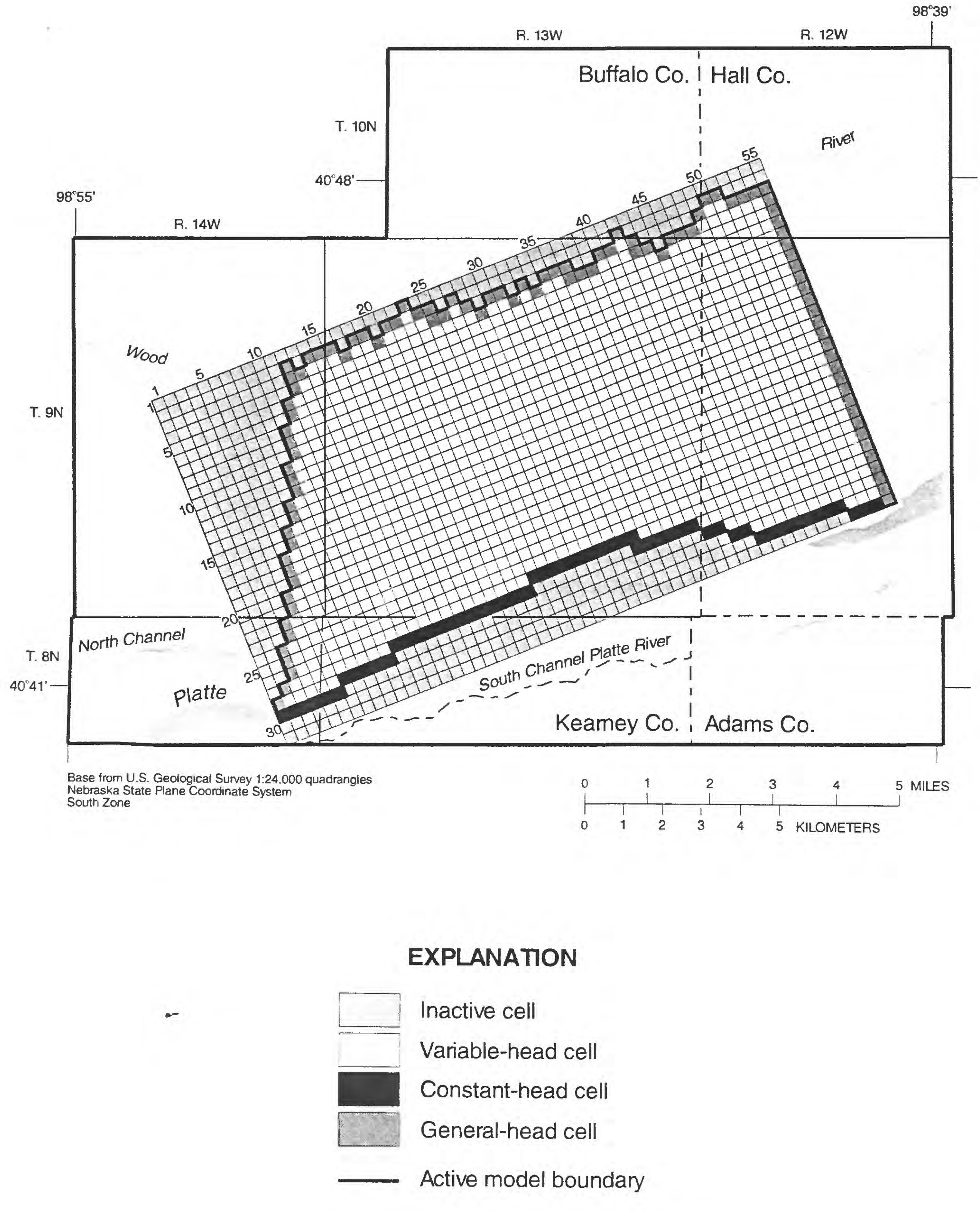


Figure 10. Finite-difference grid and boundary conditions used in modeling ground-water flow in the study area.

perpendicular to flow divided by the length of the flow path (McDonald and Harbaugh, 1988). The boundary heads for simulating 1931 and 1991 conditions were estimated for the general-head nodes based on water levels measured in 1931 and the spring of 1991, respectively. The southern boundary of the model is the main channel of the Platte River, because it is hydraulically connected to the shallow aquifer. The main channel of the Platte River was simulated as a constant-head boundary, and cells south of the main channel of the Platte River were made inactive. The boundary conditions were the same for both layers.

Aquifer Properties

The saturated thickness and hydraulic conductivity of the aquifer in the study area were estimated from analysis of the drillers' and lithologic logs of about 160 irrigation wells and test holes and the results of the aquifer tests and straddle-packer slug tests that were discussed previously. The logs were used to estimate the aquifer thickness, and the aquifer thickness value varied areally. The assigned thickness value for a cell in layer 1 or 2 is equal to one-half of the estimated actual aquifer thickness representative of that cell.

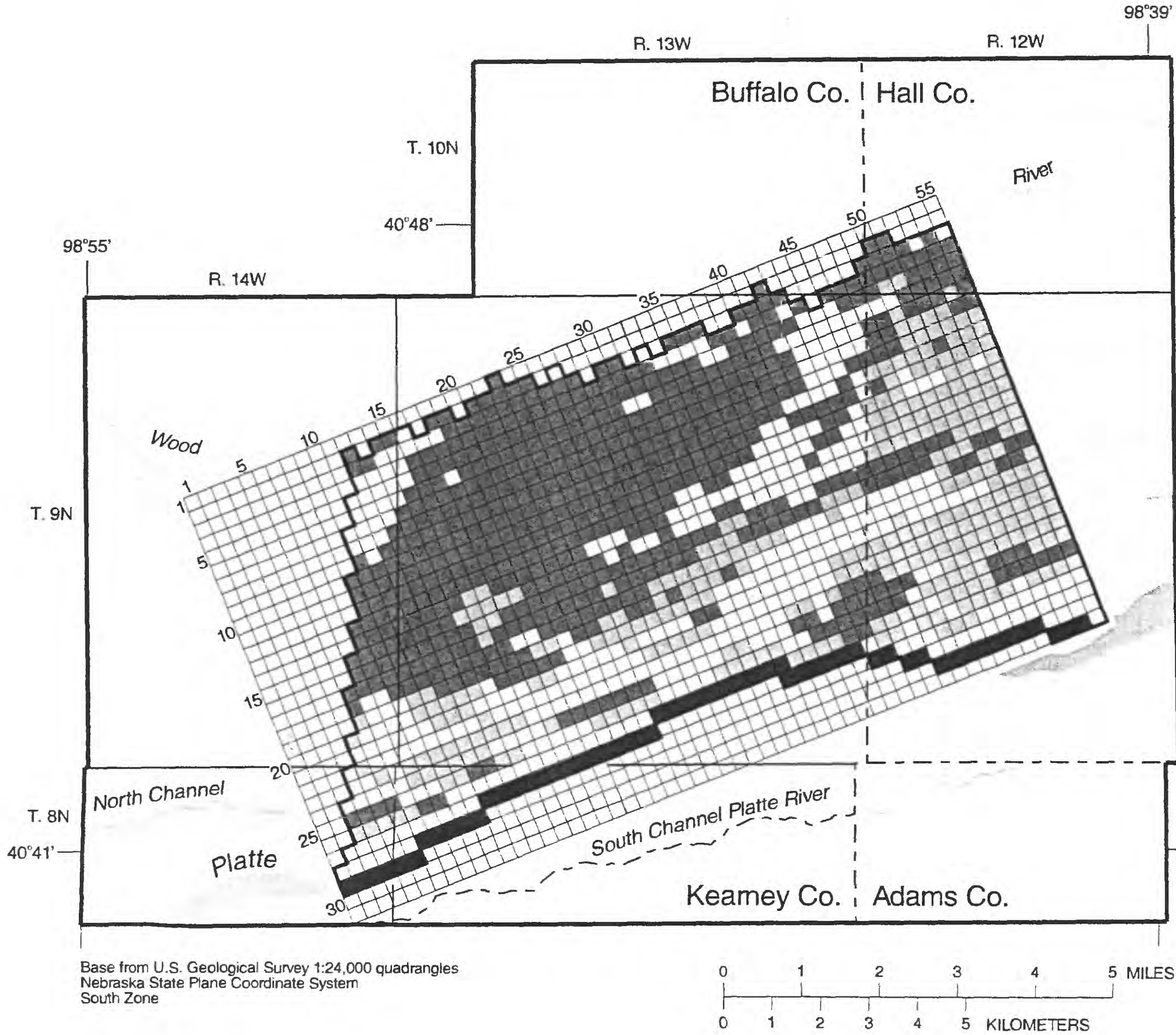
The logs, aquifer tests, and straddle-packer slug tests were used to estimate the hydraulic conductivity of the aquifer. The same initial hydraulic conductivity value (350 ft/d) was assigned to all cells in both layers because of the limited hydraulic conductivity data available outside of the aquifer test areas at the MSEA site. This hydraulic conductivity value was assumed to represent an average based on available lithologic data from logs in other parts of the study area. These data indicated lithologies similar to that found at the aquifer test area.

Stresses on the Aquifer System

Recharge from the percolation of precipitation and pumpage from irrigation wells are the only large stresses on the aquifer system. The initial estimates of recharge for the study area were calculated using a soil-moisture budget model that has been extensively used and documented in past studies (Cady and Peckenpaugh, 1985; Peckenpaugh and others, 1987; Peckenpaugh and others, 1995; Dugan and Zelt, in press).

The soil-moisture budget model uses climatic, hydrologic, soil, vegetation, and topographic data to estimate the amount of precipitation that percolates to the water table, recharging the shallow aquifer. The soil-moisture budget model accounts for evapotranspiration, which results in reduced recharge, and for additional soil-water from irrigation, which may result in increased recharge. For 1931 (early-development) conditions, recharge for each cell was assigned assuming dryland (nonirrigation) farming as calculated by the soil-moisture program using 1931 climatic data (1931 was near average, climatically, and is assumed representative of predevelopment conditions). For later development conditions (considered represented by 1991), the recharge for each cell was assigned assuming irrigated farming and 1990 crop types as calculated by the soil-moisture program using average climatic data for the period 1931 to 1991. All recharge for both 1931 and 1991 was applied to layer 1.

The soil-moisture budget model can also estimate the amount of water needed by crops to thrive. This is an estimate of net pumpage, because any excess pumpage is assumed to percolate back through the sandy soil to the water table. Pumpage rates for 1931 conditions were assigned to each cell containing an irrigation well based on the average effective pumping rate calculated by the soil-moisture program and assuming each well irrigated an average of 38 acres for this period (Lugn and Wenzel, 1938). This method was used for 1931 conditions because detailed crop-type information was not available, but locations of most irrigation wells that existed in 1931 were known. Pumpage rates for development conditions in 1991 were assigned to each cell (fig. 11) on the basis of the net pumpage rate calculated by the soil-moisture model using average climatic data for the period 1931 to 1991 and crop types found in the study area in 1990. Pumpage for both 1931 and 1991 conditions was equally divided between layer 1 and layer 2.



EXPLANATION

Pumpage, in cubic feet per day

- No pumpage
- 1,801 to 2,000
- 2,001 to 2,200
- 2,201 to 2,400
- Constant-head cell
- Active model boundary

Figure 11. Pumpage assigned for development conditions, 1991.

Model Calibration

The model was calibrated under two different steady-state conditions to determine whether the final model reasonably simulates steady-state ground-water flow in the aquifer under different stresses. In general, the calibration consisted of minor adjustments to aquifer hydraulic conductivity, general-head boundary conductances, and recharge rates to obtain the best possible match between observed and simulated water levels for both 1931 and 1991 (September 1991 water levels were used because they are slightly more reflective of conditions that include pumpage). Recharge values for development conditions in 1991, which were used in the calibrated model, are shown in figure 12. The hydraulic conductivity value in the calibrated model was 403 ft/d, slightly higher than the initial estimate but within a reasonable range of values. The best simulation was obtained with general-head boundary conductances along the northern boundary set much lower than initial estimates, probably because the hydraulic conductivity of the aquifer is lower to the north than in much of the rest of the aquifer.

Observed water-table configurations for 1931 and 1991 were discretized and the root mean square error (RMSE) was calculated for the entire area to assess how closely the observed and simulated water levels for each cell matched for each simulation. In general, the simulated and observed water tables were very similar for both 1931 (fig. 13) and 1991 (fig. 14). The simulated water levels for layer 1 and layer 2 were the same for both 1931 and 1991. The RMSE for 1931 was 1.16 ft and for 1991 was 0.98 ft. The maximum absolute error for 1931 was 4.5 ft and for 1991 was 5.4 ft. These numbers indicate that the simulated and actual water-level measurements match within the measurement error for the actual water levels, 2.5 ft, because many of the land surface elevations for the observation wells were picked from topographic maps with contour intervals of 5 ft.

Sensitivity Analysis

The sensitivity of the model (under 1991 conditions) to 20-percent changes in the aquifer hydraulic conductivity, recharge from precipitation, pumpage, and general-head boundary conductance is shown in table 4, expressed as the RMSE in ft. The model is most sensitive to changes in pumpage.

Table 4. Sensitivity of the 1991 steady-state model

Variable	Root mean square error (feet)		
	Initial value	Decrease of 20 percent in variable value	Increase of 20 percent in variable value
Hydraulic conductivity	0.98	1.03	1.02
Recharge from precipitation	.98	1.03	1.02
Pumpage	.98	1.14	1.16
General-head boundary conductance	.98	1.01	.99

Model Limitations

The model was intended to simulate ground-water flow in the immediate vicinity of the Nebraska MSEA site. Simulated ground-water flow near the boundaries may be affected by boundary conditions used in the model and therefore may not be representative of natural ground-water flow. The model simulated steady-state flow conditions in the shallow aquifer for two times: 1931 and 1991. It was not intended to simulate transient flow conditions in the shallow aquifer resulting from pumpage or other stresses that vary substantially over time.

Water Budget

Comparison of the water budgets (table 5) simulated by the model for 1931 and 1991 conditions generally confirms the conceptual model described earlier. The results of the model indicate the much increased pumpage in 1991 caused the main channel of the Platte River to supply 12 percent of the total inflow to the

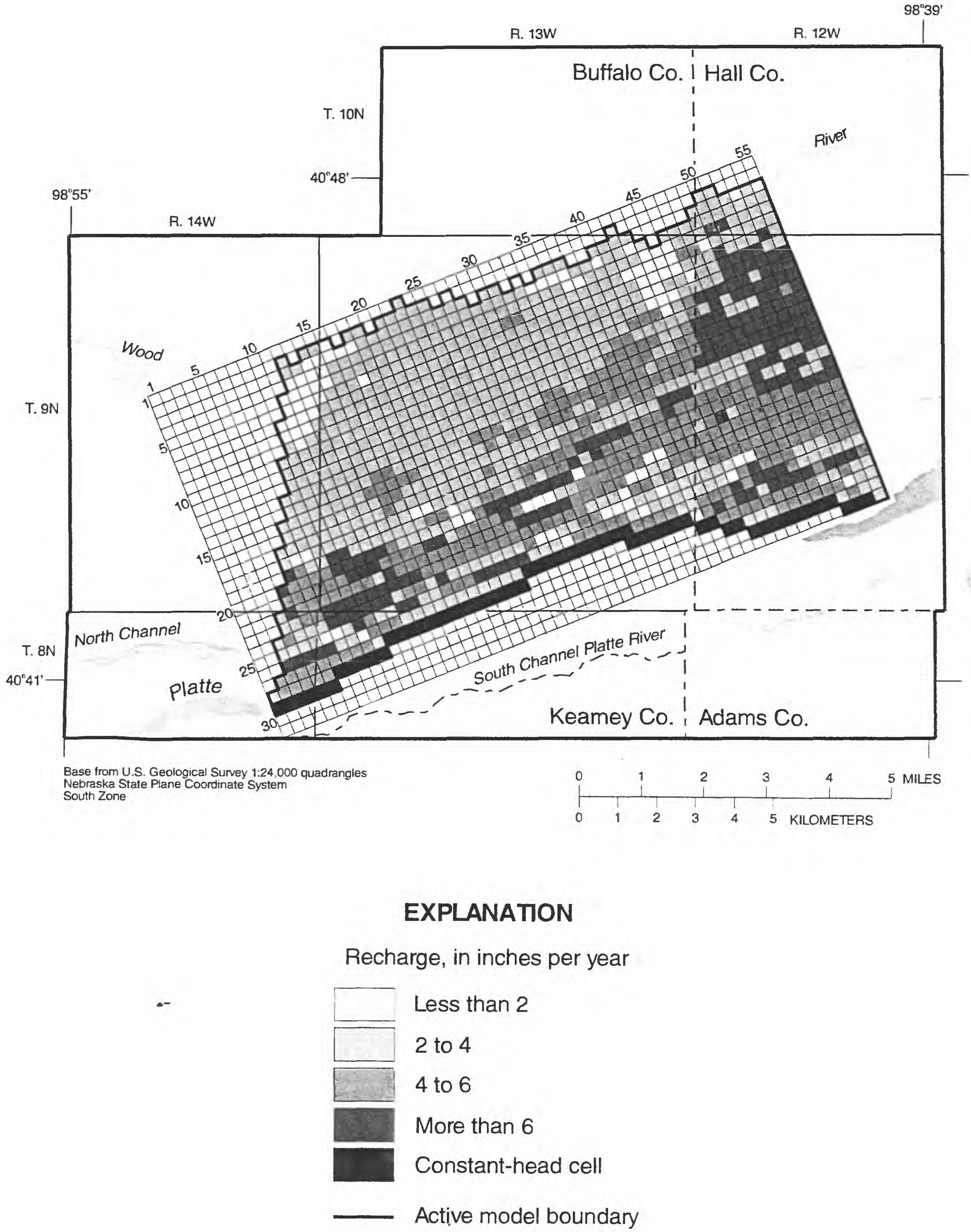
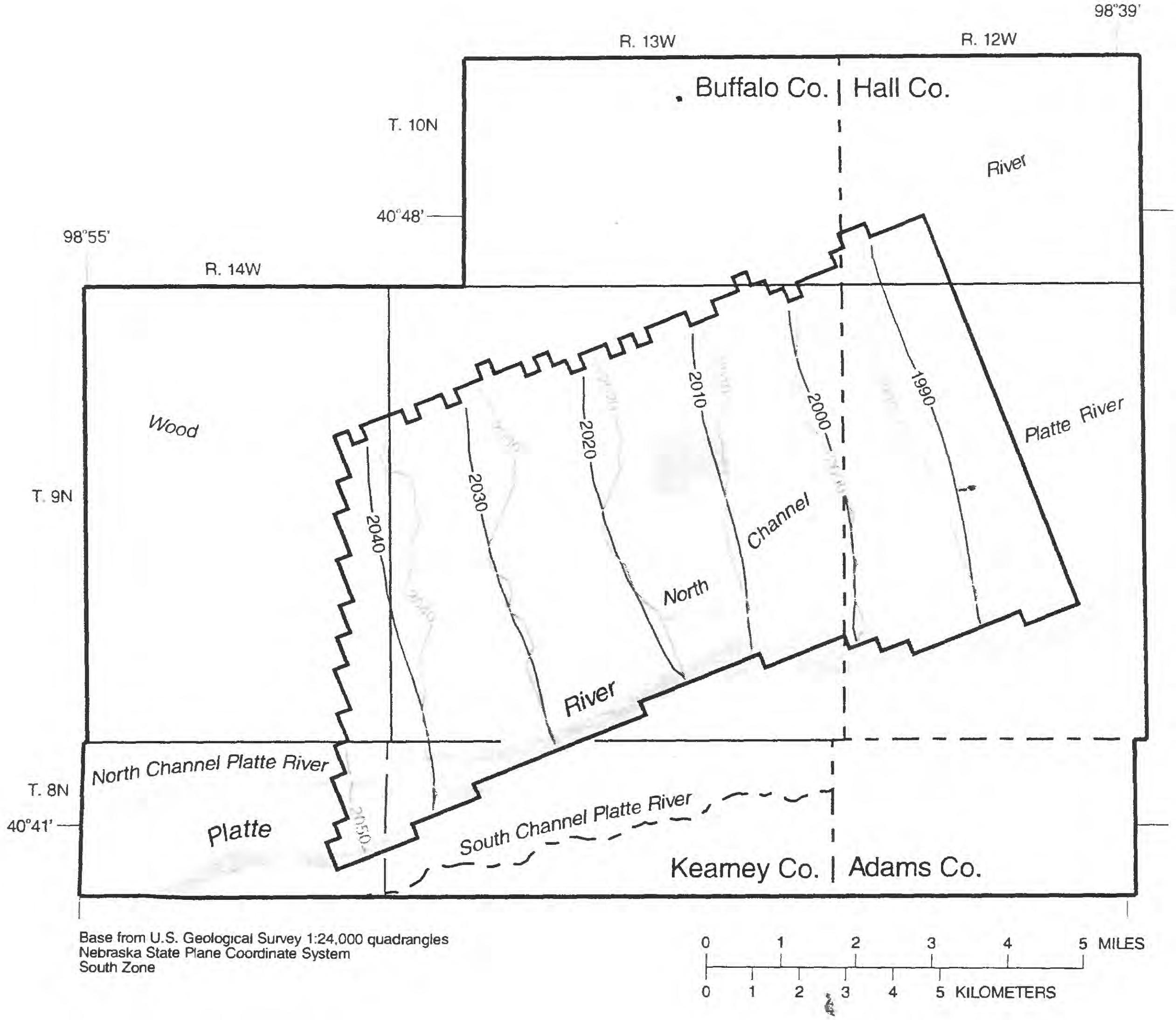


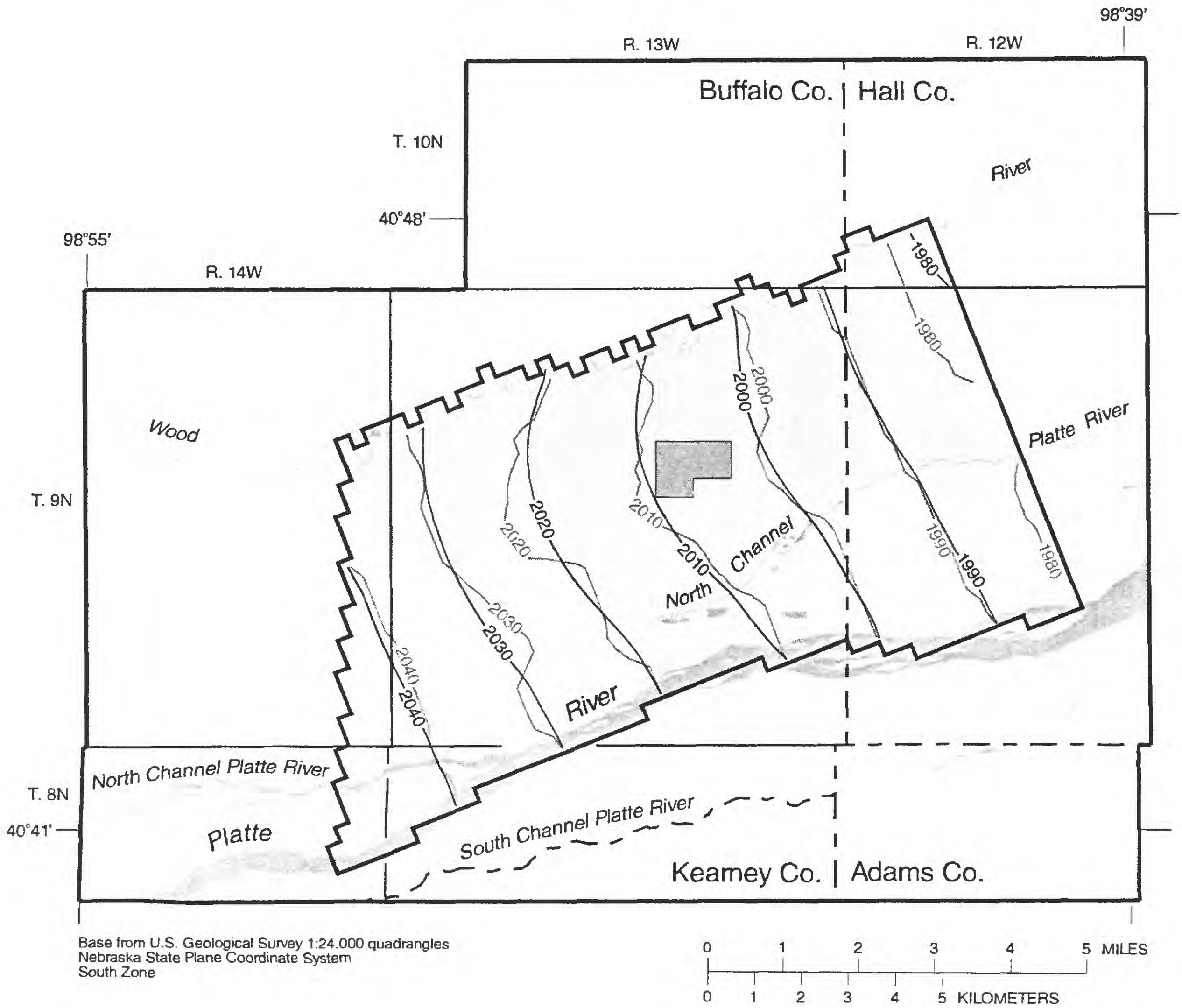
Figure 12. Simulated recharge for development conditions, 1991.



EXPLANATION

—2000—	Simulated Water-Table Contour-- Shows simulated altitude of water table, 1931. Contour interval 10 feet. Datum is sea level
—2000—	Observed Water-Table Contour-- Shows altitude of water table. Contour interval 10 feet. Datum is sea level
———	Active model boundary

Figure 13. Simulated and observed water tables in the study area, 1931. Observed water table modified from Lugn and Wenzel (1938).



EXPLANATION

—2000— Simulated Water-Table Contour-- Shows simulated altitude of water table, 1991. Contour interval 10 feet. Datum is sea level

Observed Water-Table Contour-- Shows altitude of water table, September 1991. Contour interval 10 feet. Datum is sea level

Active model boundary

Figure 14. Simulated and observed water tables in the study area, 1991. Observed water table modified from Kilpatrick (1996).

aquifer, whereas in 1931 the main channel of the Platte River received 25 percent of the total outflow from the aquifer. The increased pumpage in 1991 also induced almost 50 percent more flow across the northern boundary of the model area and reduced flow out of the model area across the eastern boundary by about 31 percent. Climatic differences as well as changed crop-types that affect the downward percolation of precipitation caused an increase in recharge. For 1991 conditions, the largest sources of water for the model area were recharge from precipitation (42 percent) and lateral flow across the western boundary (31 percent). The largest losses of water from the model area for 1991 conditions were through pumpage (81 percent) and flow across the eastern boundary of the model area (19 percent). These water budgets did not include any change in storage because of the steady-state assumption.

Table 5. Simulated water budget, 1931 and 1991

Source or sink	Net inflow (+) and outflow (-) (thousands of cubic feet per day)			
	1931	Percent	1991	Percent
Flow across western boundary	709	45	738	31
Flow across northern boundary	238	15	351	15
Flow across eastern boundary	-665	42	-458	19
Recharge from precipitation	619	40	1,000	42
Pumpage	-510	33	-1,924	81
Main channel of Platte River	-391	25	293	12

Ground-Water Flow

The data collected and the steady-state ground-water flow model results indicate ground water primarily flows horizontally through the study area from the western boundary to the eastern boundary with little vertical movement. Horizontal flow velocity (v) was calculated to be between about 0.3 and 3.5 ft/d using a hydraulic gradient (i) of 7.5 ft/mi, a hydraulic conductivity (K) between 92 and 620 ft/d, a porosity (n) of 0.25 to 0.50 (Freeze and Cherry, 1979), and the following equation:

$$v = \frac{Ki}{n}$$

The anisotropy ratio determined from the aquifer tests suggests vertical flow velocities are likely to be much lower than horizontal flow velocities. Under non-pumping conditions, there is no measurable vertical gradient between wells screened near the top of the aquifer and those screened near the bottom, based on the 1991 water-level measurements. There is also no evidence to suggest that pumping irrigation wells would substantially increase vertical flow velocity, because most wells are fully screened and therefore would not induce much vertical gradient, except perhaps in the immediate vicinity of the pumping well.

Therefore, most of the ground water collected from wells screened near the bottom or middle of the shallow aquifer at the MSEA site likely entered the system far upgradient of the site. Thus, concentrations of agricultural chemicals in ground water collected in these wells probably are not a result of farming practices at the site; however, concentrations in ground-water samples collected from wells screened at the top of the shallow aquifer probably are influenced by farming practices at the site.

SUMMARY

From 1991 to 1992, the USGS participated with the USDA and UNL in research activities at the Nebraska MSEA site. The purpose of the USGS study was to define the hydrogeologic system in the vicinity of the Nebraska MSEA site to aid in the interpretation of ground-water sampling results by other researchers. The primary aquifer in the study area is the High Plains aquifer, which consists of an unconfined part, the shallow aquifer; a silt and clay unit that acts as a confining layer; and a confined part, the Ogallala aquifer. The shallow aquifer is the source of water for more than

275 irrigation wells in the study area and is the focus of this study.

Three types of hydraulic data were collected for the study. First, precipitation was measured at 17 sites in the study area from May through July 1991; these measurements show the variability of rainfall during the growing season. Second, water levels and river stage were measured at about 142 locations on three to four occasions in 1991. These measurements indicate that the Wood River is apparently not hydraulically connected to the shallow aquifer and that the main channel of the Platte River does not have a large effect on the water-table configuration in the study area. Third, two constant-discharge aquifer tests and about 450 straddle-packer slug tests were conducted to determine aquifer properties for the shallow aquifer. The test results indicate horizontal hydraulic conductivity values for the shallow aquifer ranged from 340 to 390 ft/d, and horizontal hydraulic conductivity values for any single 1.6-ft vertical interval of the aquifer ranged from 92 to more than 620 ft/d.

A ground-water flow model of the shallow aquifer in the study area was developed using historical data and the hydrologic data collected for this study. The model was intended to provide a quantitative analysis of ground-water flow and of the water budget for the shallow aquifer in the study area. Aquifer properties were estimated for each cell based on analysis of drillers' and lithologic logs from irrigation wells and test holes and the results of constant-discharge aquifer tests and straddle-packer slug tests at the site. Recharge and pumpage were estimated using a soil-moisture budget model. The ground-water flow model was used to simulate ground-water flow at two different times (1931 and 1991), representing two different steady-state conditions (early development and later development). The model was calibrated using minor adjustments to aquifer hydraulic conductivity, general-head boundary conductances, and recharge rates until simulated and measured water levels matched. A RMSE of about 1 ft was achieved for both steady-state conditions. The model was found to be most sensitive to changes in pumpage.

The calibrated model was used to calculate the water budgets for each steady-state condition. The sources of water to the system in 1931 were flow across the western boundary of the model area (45 percent), recharge from precipitation (40 percent), and flow across the northern boundary of the model area (15 percent). The losses in 1931 were flow across the eastern boundary of the model (42 percent), pumpage (33 percent), and flow into the Platte River (25 percent). The sources of water to the system in 1991 were recharge from precipitation (42 percent), flow across the western boundary of the model area (31 percent), flow across the northern boundary of the model area (15 percent), and flow from the Platte River (12 percent). The losses in 1991 were pumpage (81 percent) and flow across the eastern boundary of the model (19 percent). A comparison of the 1931 and 1991 water budgets indicated that the much higher pumpage in 1991 was supplied by increased flow into the model area along the northern model boundaries and from the main channel of the Platte River and decreased flow out of the model area along the eastern boundary.

Under nonpumping conditions there is no measurable vertical gradient between wells screened at the top of the aquifer and those screened near the bottom, based on the 1991 water-level measurements. In addition, because most irrigation wells are fully or almost fully screened, there is no evidence to suggest that pumping irrigation wells would induce a substantial vertical gradient, except perhaps in the immediate vicinity of the well. These results indicate most of the ground water collected from wells screened near the bottom or middle of the shallow aquifer at the MSEA site likely entered the system far upgradient of the site. Thus, concentrations of agricultural chemicals in ground water collected in these wells probably are not a result of farming practices at the site; however, concentrations in ground-water samples collected from wells screened at the top of the shallow aquifer probably are influenced by farming practices at the site.

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