# Hydrogeologic Setting and Ground-Water Flow Simulations of the Eastern High Plains Regional Study Area, Nebraska

By Matthew K. Landon and Michael J. Turco

Section 8 of

**Hydrogeologic Settings and Ground-Water Flow Simulations for Regional Studies of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells—Studies Begun in 2001**

Edited by Suzanne S. Paschke

Professional Paper 1737–A

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

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**U.S. Geological Survey**
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Suggested citation:
Landon, Matthew K., and Turco, Michael J., 2007, Hydrogeologic setting and ground-water flow simulation of the Eastern High Plains Regional Study Area, Nebraska, *section 8 of* Paschke, S.S., ed., Hydrogeologic settings and ground-water flow simulations for regional studies of the transport of anthropogenic and natural contaminants to public-supply wells—studies begun in 2001: Reston, Va., U.S. Geological Survey Professional Paper 1737–A, pp. 8–1 – 8–28.

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## Abstract

The transport of anthropogenic and natural contaminants to public-supply wells was evaluated in a part of the High Plains aquifer near York, Nebraska, as part of the U.S. Geological Survey National Water-Quality Assessment Program. The aquifer in the Eastern High Plains regional study area is composed of Quaternary alluvial deposits typical of the High Plains aquifer in eastern Nebraska and Kansas, is an important water source for agricultural irrigation and public water supply, and is susceptible and vulnerable to contamination. A six-layer, steady-state ground-water flow model of the High Plains aquifer near York, Nebraska, was constructed and calibrated to average conditions for the time period from 1997 to 2001. The calibrated model and advective particle-tracking simulations were used to compute areas contributing recharge and traveltimes from recharge areas to selected public-supply wells. Model results indicate recharge from agricultural irrigation return flow and precipitation (about 89 percent of inflow) provides most of the ground-water inflow, whereas the majority of ground-water discharge is to pumping wells (about 78 percent of outflow). Particle-tracking results indicate areas contributing recharge to public-supply wells extend northwest because of the natural ground-water gradient from the northwest to the southeast across the study area. Particle-tracking simulations indicate most ground-water traveltimes from areas contributing recharge range from 20 to more than 100 years but that some ground water, especially that in the lower confined unit, originates at the upgradient model boundary instead of at the water table in the study area and has traveltimes of thousands of years.

## Introduction

The Eastern High Plains regional study area for the transport of anthropogenic and natural contaminants to public-supply wells (TANC) is within the High Plains Regional Ground Water study unit of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) program near York, Nebraska (fig. 8.1). The study area is in the High Plains aquifer, which is an important water source for agricultural irrigation and drinking-water supply throughout the region and for York, Nebraska.

### Purpose and Scope

The purpose of this Professional Paper Chapter is to present the hydrogeologic setting of the Eastern High Plains regional study area. The chapter also documents the setup and calibration of a steady-state regional ground-water flow model for the study area. Ground-water flow characteristics, pumping-well information, and water-quality data were compiled from existing data to develop a conceptual understanding of ground-water conditions in the study area. A six-layer steady-state ground-water flow model of the High Plains aquifer near York, Nebraska, was developed and calibrated for this study to represent average conditions for the period from 1997 to 2001. The 5-year period 1997–2001 was selected for data compilation and modeling exercises for all TANC regional study areas to facilitate future comparisons between study areas. The calibrated ground-water flow model and associated particle tracking were used to simulate advective ground-water flow paths and to delineate areas contributing recharge to selected public-supply wells. Ground-water traveltimes from recharge to public-supply wells, oxidation-reduction (redox) conditions along flow paths, and presence of potential contaminant sources in areas contributing recharge were tabulated into a relational database as described in Section 1 of this Professional Paper. This section provides the foundation for future ground-water susceptibility and vulnerability analyses of the study area and comparisons among regional aquifer systems.

### Study Area Description

The Eastern High Plains regional study area encompasses 388.5 km$^2$ and is located in east-central Nebraska around the city of York (fig. 8.2). Ground water in the study area is contained within Quaternary alluvial deposits that compose the High Plains aquifer in eastern Nebraska and Kansas. The study area was chosen because the aquifer is used extensively for public water supply, is susceptible and vulnerable

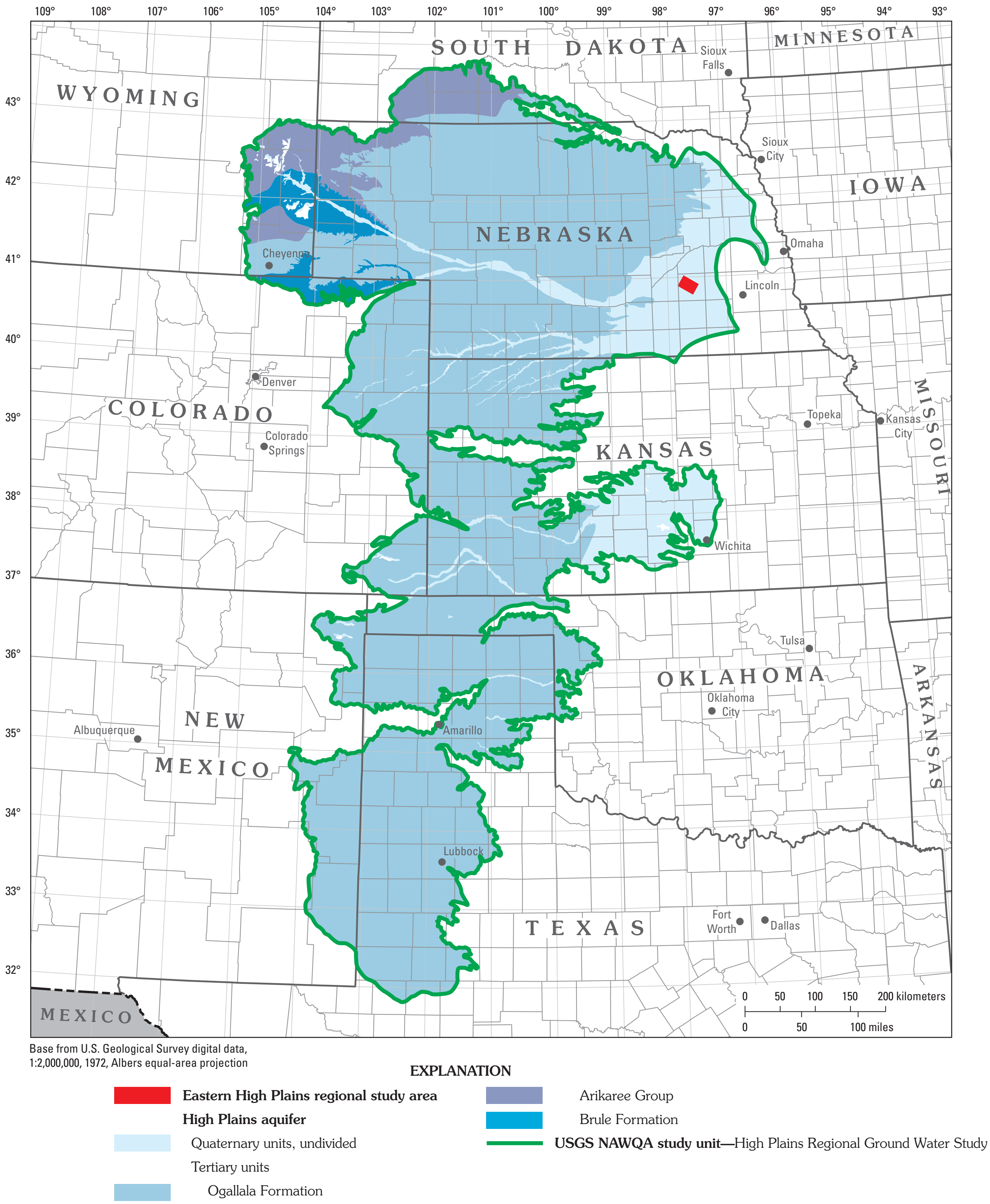



**Figure 8.1.** Location of the Eastern High Plains regional study area within the High Plains aquifer.

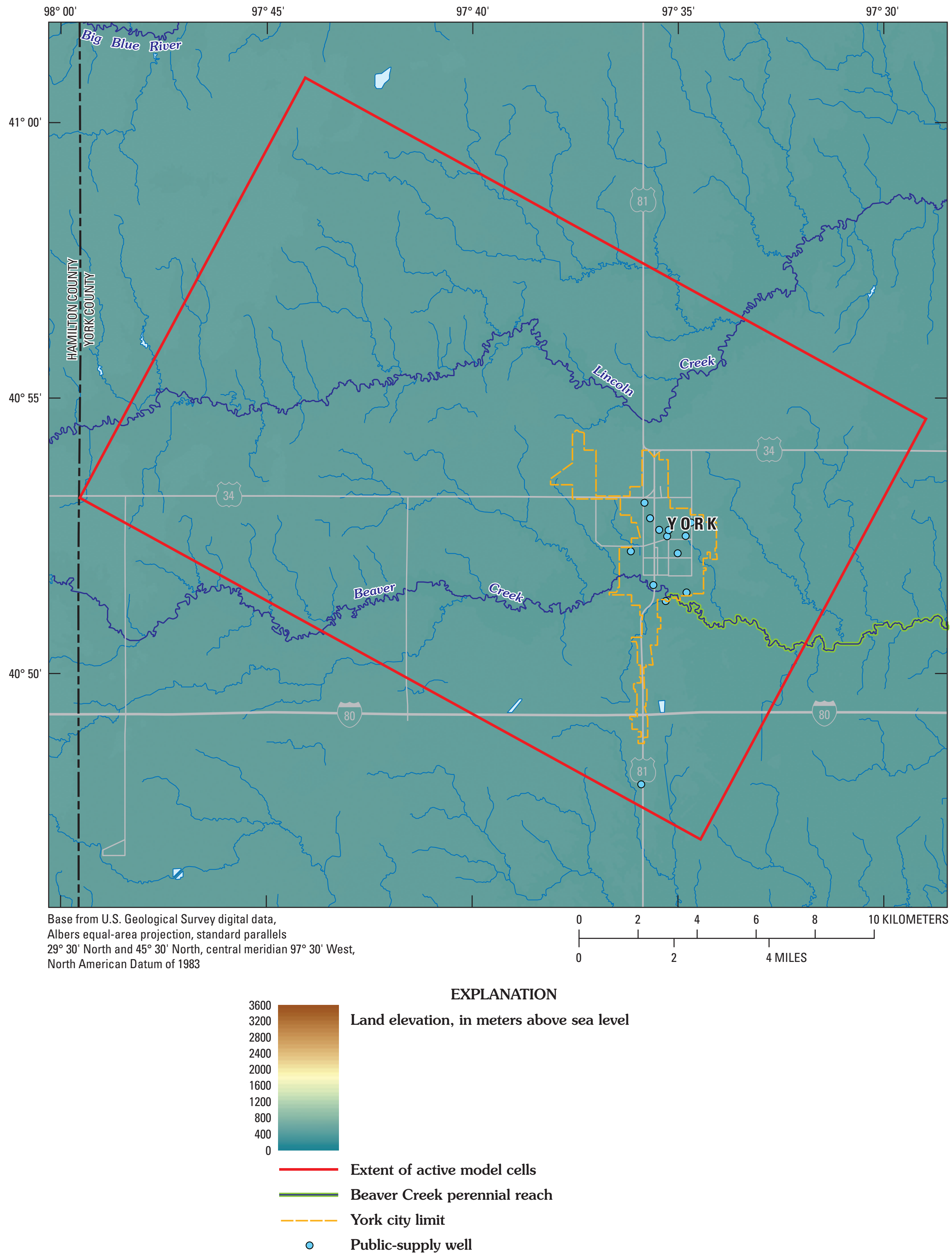



**Figure 8.2.** Topography, hydrologic features, and location of public-supply wells, Eastern High Plains regional study area, Nebraska.

to contamination, and is representative of the High Plains aquifer (table 8.1). The rectangular study area was selected to facilitate ground-water flow modeling of the region upgradient from and around York and coincides with the area between two ground-water flow lines from a regional ground-water flow-model (COHYST, 2001).

## Topography and Climate

The Eastern High Plains regional study area is located within a mostly flat lying region of windblown silt (loess) with relatively little dissection by streams (fig. 8.2, table 8.1). The study area includes portions of the upper Lincoln and Beaver Creek Basins, tributaries to the Big Blue River. The topography is typical of the extensive upland areas of the High Plains with low relief.

Mean annual precipitation at York for 1950–2001 is 71.1 cm/yr (High Plains Regional Climate Center, 2003) with most of the precipitation falling during thunderstorms in the spring and fall (Verstraeten and others, 1998) (table 8.1). The High Plains generally has a middle-latitude dry continental climate with abundant sunshine, moderate precipitation, frequent winds, low humidity, and a relatively high rate of evaporation (Gutentag and others, 1984). Because evaporation rates usually exceed precipitation (table 8.1), there is little water available to recharge the aquifer (Luckey and Becker, 1999). Estimates of recharge rates from precipitation range from 0.1 cm/yr in parts of Texas to 15.2 cm/yr in areas of dune sand in Kansas and Nebraska (Gutentag and others, 1984); average rates are about 1.5 cm/yr based upon regional water budgets (Luckey and others, 1986; Dennehy and others, 2002). The High Plains in eastern Nebraska and central Kansas have a humid continental climate that has slightly greater precipitation and humidity than the dry continental climate of the remainder of the High Plains and is therefore likely to have greater recharge from precipitation (table 8.1) (Dugan and Zelt, 2000).

## Surface-Water Hydrology

The High Plains aquifer is in hydraulic connection with the major river systems crossing the aquifer from west to east (Weeks and others, 1988). During low-flow periods, water in the rivers is almost entirely derived from ground-water discharge. However, the major rivers derive most of their flow from the Rocky Mountains to the west (Dennehy and others, 2002). Because evaporation rates exceed precipitation rates and topographic slopes are relatively flat, little water is available to produce surface-water runoff (Gutentag and others, 1984; Litke, 2001).

There are no naturally perennial streams in the Eastern High Plains regional study area other than the lower reaches of Beaver Creek near the southeastern edge of the study area. Flows in Beaver Creek east of York (fig. 8.2) are maintained by discharges from the York wastewater plant (6,500 $m^3$/d, 1997–2001 average) and York Cold Storage (2,700 $m^3$/d, 1997–2001 average), which pumps ground water for cooling in western York and discharges the water to Beaver Creek. Low-flow streamflow measurements on Beaver Creek near the southeastern edge of the study area reported by Fallon and McChesney (1993) average about 5,600 $m^3$/d. Subtracting the downstream measurement of 5,600 $m^3$/d from the sum of the upstream inflow (9,200$m^3$/d), implies a loss of about 3,600 $m^3$/d from Beaver Creek to the aquifer in the measured stream reach. Seasonally, flow in Beaver Creek may be greatest during the June through August irrigation season owing to irrigation return flows.

## Land Use

Irrigated agriculture is the primary land use in the study area (85 percent of total land in the study area). Predominant crops in the study area, with their percentage of total land area in parentheses, are irrigated corn (50.0 percent); dryland corn (12.8 percent); irrigated soybeans (9.7 percent); dryland soybeans (5.6 percent); irrigated sorghum, alfalfa, and small grains (1.3 percent); and dryland sorghum, alfalfa, and small grains (3.9 percent) (Center for Advanced Land Management Information Technologies, 2000). The study area is within one of the most heavily irrigated parts of the High Plains aquifer (Thelin and Heimes, 1987; Qi and others, 2002). Irrigation well density in the study area is 2.0 wells/$km^2$ compared to an average of about 0.4 well/$km^2$ in the High Plains. Urban land uses, including commercial/industrial/transportation and low intensity, residential areas account for about 2.6 percent of the study area (U.S. Geological Survey, 1999–2000).

The population of the study area is approximately 9,400 (U.S. Census Bureau, 2003) with an average population density of about 24.2 people/$km^2$. The population of York is approximately 8,100 (U.S. Census Bureau, 2003), 86 percent of the total population in the study area. The only other community in the study area is Bradshaw (about 16 km west of York), with a population of approximately 330. Rural households account for about 10 percent of the population.

## Water Use

Ground-water withdrawals for irrigation are the largest outflow from the ground-water system in both the High Plains aquifer and the Eastern High Plains regional study area (table 8.1). Irrigation withdrawals from the High Plains aquifer were about 72 million $m^3$/d in 1995 and accounted for 96 percent of withdrawals from the High Plains aquifer (Dennehy and others, 2002). The average withdrawal rate over the entire irrigated area of the High Plains aquifer (approximately 55,000 $km^2$) was about 39 cm/yr in 1995. In the study area, withdrawal rates for irrigation were estimated at 25.4 cm/yr for 1998 through 2002 on the basis of metered pumping reported to the Upper Big Blue Natural Resources District (NRD) in 50 to 150 wells per year (Rod DeBuhr, Upper Big

Blue Natural Resources District, written commun., April 15, 2003). Withdrawal rates for irrigation have changed through time with gradual decreases in withdrawal rates since the early 1980s because of increased irrigation efficiency, conversion of gravity irrigation systems to center pivot irrigation systems, and wetter climatic conditions than in the 1970s and early 1980s (Orville Davidson, Public Utilities Director, City of York, Nebraska, written comm., February 15, 2002).

Ground-water withdrawals for public-supply and industrial purposes account for less than 6 percent of withdrawals in both the Eastern High Plains regional study area and the High Plains aquifer (table 8.1). Ground water withdrawn from the High Plains aquifer is the source of drinking water for 100 percent of the population in the study area and 82 percent of the people in the area underlain by the High Plains aquifer (Dennehy and others, 2002). Public-supply withdrawals in the study area increased by about 4 percent per year during 1997–2001, and average public-supply withdrawals for 1997–2001 were about 15 percent greater than withdrawals for 1981–1996. Public-supply withdrawals fluctuate seasonally because of outdoor water use during the summer months. Average monthly withdrawals for May through September are about 65 percent greater than those for October through April for 1997–2001.

Withdrawals for commercial/industrial purposes slightly exceed those for public supply. Withdrawals for self-supplied domestic or livestock purposes were not quantified because they are considered negligible compared to other withdrawals (Upper Big Blue Natural Resources District, 1999).

# Conceptual Understanding of the Ground-Water System

The conceptual model of ground-water flow for the Eastern High Plains regional study area was developed on the basis of data and interpretations of previous investigations including test-hole logs and hydrogeologic studies, water-level data, potentiometric maps, hydraulic-property measurements, measurements or estimates of pumping rates and irrigated areas, climatic data, and ground-water quality data. Average ground-water fluxes were estimated for 1997–2001.

## Geology

The Quaternary-age sediments that compose the High Plains aquifer in the study area consist of heterogeneous, mostly fluvial deposits of sand, gravel, silt, and clay that form a layered sequence of unconfined and confined units with intervening confining units. About 70 geologic logs in the study area were assembled from test holes drilled by the Nebraska Conservation and Survey Division and the U.S. Geological Survey (Smith, 2000), wells drilled by the City of York (Orville Davidson, Public Utilities Manager, City of York, Nebraska, written commun., February 15, 2002), and registered wells (Nebraska Department of Natural Resources, 2002) that fully penetrated the High Plains aquifer. Inspection of the logs led to the conceptualization of a 6-layer system (fig. 8.3).

Layer 1 is mostly unsaturated loess (Keech and others, 1967; Swinehart and others, 1994) consisting of silty clay or clayey silt and ranging from 5 to 27 m thick with an average thickness of 16 m. The loess is thinnest in the valleys along Beaver and Lincoln Creeks, where a thin veneer of loess and soil overlies sand and gravel.

Layer 2 is sand and gravel with some discontinuous silt and clay. This layer is 6 to 43 m thick with an average thickness of 21 m and contains the coarsest gravels of all layers in the study area. Ground water in layer 2 is mostly unconfined, and the water table is at or just below the top of this unit. Depth to water ranges from 15 to 30 m below land surface. The sand and gravel deposits are sometimes fining downwards and contain abundant interbedded clays and silts, especially near the bottom of the unit. Layer 2 is continuous across the study area.

Layer 3 is predominantly clayey glacial till but includes silt layers where they directly underlie or overlie the clayey till. Cross sections by Keech and others (1967) indicate that thin silt layers adjacent to the glacial till are common. The glacial till has been interpreted as deposited by continental glaciers that advanced southward into eastern Nebraska; the western extent of these deposits is slightly to the west and south of the study area (Swinehart and others, 1994). Layer 3 is mostly continuous across the study area but is absent in a few locations in the southeastern portion. The thickness ranges from 0 to 35 m with an average thickness of 16 m, and the layer serves as a confining unit for the underlying sand of layer 4.

Layer 4 was assigned as the uppermost sand layer underlying the clayey till/silt. This fine to medium sand contains minor amounts of gravel and is considerably more homogeneous than layer 2. This upper confined sand thins in the northwestern one-half of the study area and is absent in some areas. Nearly all public-supply wells and many irrigation wells are fully screened across the layer 4 sand. The thickness ranges from 0 to 25 m with an average thickness of 11 m.

Layer 5 consists of clay and silt deposits underlying layer 4 but includes minor amounts of interbedded sand. Five public-supply wells are partially screened across layer 5. Layer 5 thins both at the southeast edge and in the northwestern half of the study area, where a bedrock high limits layer thickness. Layer 5 is heterogeneous, and the individual thin lithologic layers within it are probably not continuous over great distances. The thickness ranges from 0 to 32 m with an average thickness of 12 m.

Layer 6 consists of thinly interbedded fine to medium sand and silty clay. Most public-supply wells and some irrigation wells have screens that partially penetrate sand deposits in layer 6. Layer 6 has a spatial distribution of thickness similar

**Table 8.1.** Summary of hydrogeologic and ground-water-quality characteristics for the High Plains aquifer and the Eastern High Plains regional study area, Nebraska.

[m, meters; cm/yr, centimeters per year; %, percent; $m^3/s$, cubic meters per second, $km^2$, square kilometers; m/d, meters per day; mg/L, milligrams per liter; Kh, horizontal hydraulic conductivity; Kz, vertical hydraulic conductivity; NRD, Natural Resources District]

| Characteristic | High Plains aquifer | Eastern High Plains regional study area |
|---|---|---|
| | **Geography** | |
| Topography | Flat to gently rolling with local relief of less than 90 m (Gutentag and others, 1984). | Mostly flat to gently rolling upland with shallow depressions; some stream valleys are incised into the uplands with local relief of less than 20 m. |
| Climate | Semiarid: mean annual precipitation 40 to 72 cm/yr from west to east; pan evaporation 150 to 270 cm/yr from north to south (Gutentag and others, 1984). | Subhumid; mean annual precipitation 68 cm/yr (High Plains Regional Climate Center, 2003); potential evapotranspiration 165 cm/yr (Gutentag and others, 1984). |
| Surface-water hydrology | Relatively low precipitation and slopes produce low runoff (0.1 to 6.1 cm/yr) (Hedman and Engel, 1989; Litke, 2001). | Ephemeral streams with relatively low runoff (3.3–4.5 cm/yr) (Hedman and Engel, 1989; Ma and Spalding, 1997); Beaver Creek is only perennial stream; flows maintained by municipal and commercial discharges. |
| Land use | Rangeland, 56%; agriculture, 41%; wetlands, forest, urban, water, and barren, 3% (U.S. Geological Survey, 1999–2000); irrigated lands, 12% (Qi and others, 2002). | Agriculture, 85%; rangeland, 8%, wetlands, forest, urban, water, and barren, 7% (U.S. Geological Survey, 1999–2000); irrigated lands, 61% (Center for Advanced Land Management Information Technologies, 2000). |
| Water use | Irrigation: 833 $m^3/s$, 39 cm/yr average application on 12% of area, 94% of total;<br>Municipal: 18.5 $m^3/s$, 3% of total;<br>Livestock: 9.7 $m^3/s$, 1% of total;<br>Mining: 9.3 $m^3/s$, 1% of total;<br>Industrial: 6.8 $m^3/s$, 1% of total (values calculated from Dennehy and others, 2002). | Irrigation: about 25 cm/yr withdrawal over 61% of study area, 1.89 $m^3/s$, 94% of total;<br>Industrial: 0.08 $m^3/s$, 4% of total;<br>Municipal: 0.05 $m^3/s$, 2% of total. |
| | **Geology** | |
| Surficial geology | Eolian loess overlying Quaternary alluvial and valley-fill deposits of the High Plains aquifer (Gutentag and others, 1984). | Heterogeneous, layered Quaternary deposits; loess overlying sand and gravel overlying clayey glacial till overlying fine sand overlying layered silt, clay, and sand. |
| Bedrock geology | Semiconsolidated Ogallala Formation (principal unit of High Plains aquifer) with heterogeneous sequences of sand, gravel, clay, and silt;<br>Underlain by consolidated Tertiary, Cretaceous, Jurassic, Triassic, and Permian units (Gutentag and others, 1984). | Consolidated Cretaceous Carlile Shale and Niobrara Formation (Chalky Shale) underlie unconsolidated High Plains aquifer (Keech and others, 1967). |

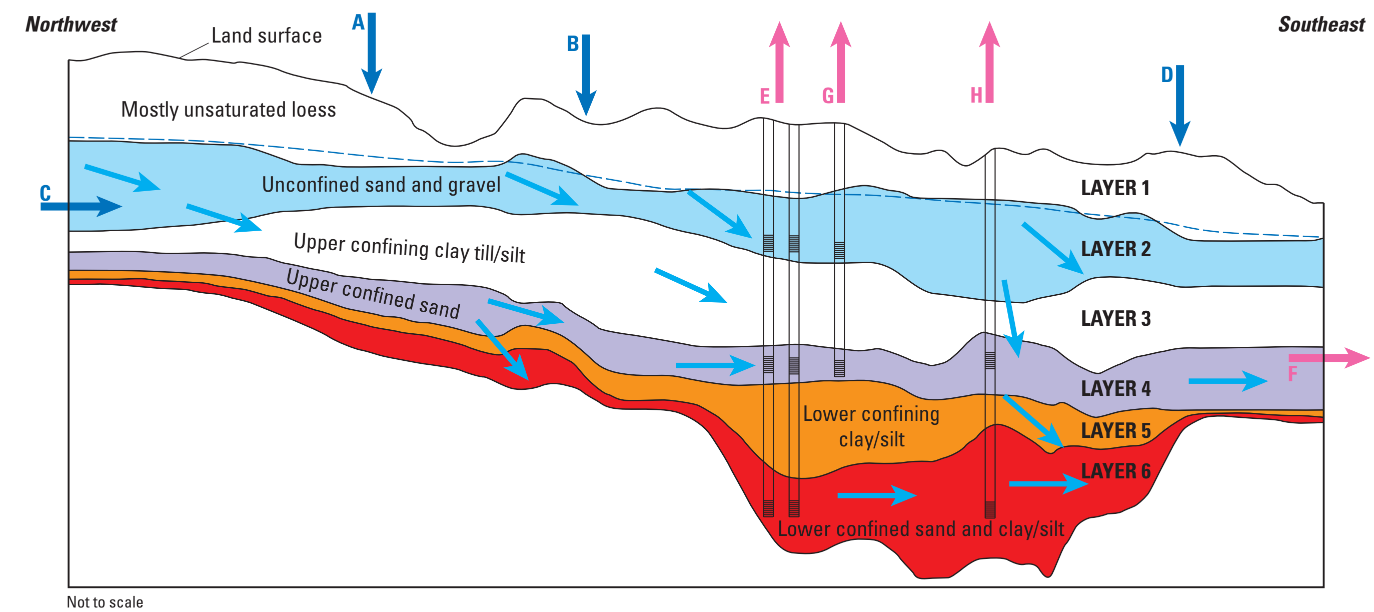
to layer 5. The thickness ranges from 0 to 48 m with an average thickness of 16 m.

The six model layers are underlain by the Carlile Shale of Late Cretaceous age in the southeastern two-thirds of the study area and the Cretaceous Niobrara Formation, consisting of chalky shale and chalk, in the northwestern one-third of the study area (Keech and others, 1967). The Cretaceous rocks are much less permeable than the sands and gravels of the High Plains aquifer and are considered the base of the High Plains aquifer (Gutentag and others, 1984). A bedrock high in the northwestern one-half of the study area results in thinning of the overlying Quaternary deposits to about one-half their thickness compared to similar deposits beneath York.

**Table 8.1.** Summary of hydrogeologic and ground-water-quality characteristics for the High Plains aquifer and the Eastern High Plains regional study area, Nebraska.—Continued

[m, meters; cm/yr, centimeters per year; %, percent; $m^3/s$, cubic meters per second, $km^2$, square kilometers; m/d, meters per day; mg/L, milligrams per liter; Kh, horizontal hydraulic conductivity; Kz, vertical hydraulic conductivity; NRD, Natural Resources District]

| Characteristic | High Plains aquifer | Eastern High Plains regional study area |
|---|---|---|
| | Ground-water hydrology | |
| Aquifer conditions | Extent: 450,660 $km^2$, primarily bounded by erosional contacts; regionally unconfined, locally confined; saturated thickness: average 61 m, ranges 0 to 366 m; in hydraulic connection with major river systems crossing aquifer (Gutentag and others, 1984; Weeks and others, 1988; Dennehy and others, 2002). | Extent: 388.5 $km^2$, bounded laterally by approximate regional ground-water flow lines; unconfined and confined layers in aquifer (Keech and others, 1967);<br>Saturated thickness: average 64 m, range 15 to 106 m; only perennial stream is artificially maintained by municipal and commercial discharges, primarily loses water to aquifer. |
| Hydraulic properties | Kh: average 18.3 m/d, range 0 to 91.4 m/d (Gutentag and others, 1984);<br>Specific yield: average 15.1%, range 5 to 30% (Gutentag and others, 1984). | Kh unconfined: 41.5 m/d;<br>Kh upper confined: 19.8 m/d;<br>Kh lower confined: 4.8 to 6.9 m/d;<br>Storage: Specific yield for unconfined, 0.01–0.3; storage coefficient for confined, $6 \times 10^{-6} - 2 \times 10^{-3}$ (Argonne National Laboratory, 1995; Upper Big Blue NRD, 1999). |
| Ground-water budget | Precipitation recharge: 0.1 to 15.2 cm/yr, average 1.5 cm/yr, 1 to 25% of precipitation (Gutentag and others, 1984; Luckey and others, 1986; Dugan and Zelt, 2000; Dennehy and others, 2002);<br>Irrigation recharge: as much as 30 to 40% of applied (Luckey and others, 1986);<br>Other inflow: canal and reservoir seepage (Luckey and others, 1986);<br>Irrigation pumpage: average 39 cm/yr (Dennehy and others, 2002), consumptive irrigation demand, 20 to 53 cm/yr (Dugan and Zelt, 2000);<br>Other outflow: discharge to streams (Luckey and others, 1986) | Precipitation recharge: 14.2 cm/yr, 20% of precipitation;<br>Irrigation recharge: 6.4 cm/yr, 25% of irrigation pumpage;<br>Stream seepage: 0.04 $m^3/s$;<br>Irrigation pumpage: 25.4 cm/yr, 1.89 $m^3/s$;<br>Industrial pumpage: 0.08 $m^3/s$;<br>Municipal pumpage: 0.05 $m^3/s$. |
| | Ground-water quality | |
| Water chemistry | In areas unaffected by natural or anthropogenic contamination, primarily calcium bicarbonate waters with dissolved solids less than 517 mg/L, pH ranging from 7 to 8, median concentrations of dissolved oxygen greater than 5.4 mg/L; generally oxidizing conditions but some more reducing conditions occur locally (Dennehy and others, 2002). | Calcium bicarbonate waters with dissolved solids of 280 to 474 mg/L;<br>pH ranges from 6.2 to 8.0;<br>Oxygen reducing in unconfined to iron-reducing in lower confined; nitrate-to-iron reducing conditions in confined can locally become more oxidizing as a result of pumping. |
| Contaminants | Natural: salinity, iron, manganese, fluoride, radon, uranium, arsenic;<br>Anthropogenic: nitrate, pesticides, salinity, carbon tetrachloride. | Natural: arsenic and uranium;<br>Anthropogenic: nitrate, chlorinated solvents, carbon tetrachloride, pesticides. |




**EXPLANATION**

**Oxidation-reduction conditions**

- Oxygen reduction
- Nitrate reduction
- Manganese reduction
- Iron reduction

**Generalized ground-water flow direction**

**Water table**

**Withdrawal well with typical screen placement**

**Inflow source and identifier**

A Recharge from precipitation—20 percent of annual precipitation (71.1 cm/yr) equals 14.2 cm/yr, about 151,000 $m^3/d$ across study area, 67 percent of inflows

B Recharge from irrigation—25 percent of irrigation return flow from 25.4 cm/yr application equals 6.4 cm/yr over about 61 percent of study area, about 44,900 $m^3/d$ across study area, 20 percent of inflows

C Regional ground-water inflow from upgradient boundary—Estimated as 24,200 $m^3/d$, 11 percent of inflows

D Seepage from streams—Estimated as 3,460 $m^3/d$, 2 percent of inflows

**Outflow sink and identifier**

E Withdrawals for irrigation—25.4 cm/yr application over about 61 percent of study area, about 163,300 $m^3/d$ across study area, 73 percent of outflows

F Ground-water outflow to downgradient boundary—Estimated as 43,900 $m^3/d$, 22 percent of outflows

G Withdrawals for industrial supply—Estimated as 6,910 $m^3/d$, 3 percent of outflows

H Withdrawals for municipal supply—Estimated as 4,320 $m^3/d$, 2 percent of outflows

**Figure 8.3.** Ground-water flow and geochemical conditions, Eastern High Plains regional study area, Nebraska.

## Ground-Water Occurrence and Flow

Unconfined and confined ground-water conditions occur in the Quaternary sediment layers as defined in the “Geology” section. Ground-water flow in the Eastern High Plains regional study area is predominantly from the northwest to the southeast with an average gradient of about 0.001326 (Johnson and Keech, 1959; Keech and others, 1967; Conservation and Survey Division, 1980; Verstraeten and others, 1998; Dreeszen, 2000). Quaternary sediment thickness, and therefore, aquifer saturated thickness increases near the center of the study area (fig. 8.3). Saturated thickness ranges from a minimum of 15 m in the northwestern part of the study area to a maximum of 106 m in the region near York, with an average of about 64 m. Ground water passing under the study area that is not withdrawn by pumping farther downgradient probably discharges into the West Fork of the Big Blue River about 24 to 32 km to the southeast. Exchanges of water between the High Plains aquifer and underlying Cretaceous units are considered negligible in comparison to other fluxes (Luckey and others, 1986).

Historical water-level data indicate the ground-water system was in a quasi-steady-state condition from 1997 through 2001. Winter water levels in observation wells generally fluctuated by less than 1.2 m from 1997 through 2001 and were similar to winter water levels prior to 1960, before substantial effects from ground-water withdrawals for irrigation occurred. During summer months, hydraulic heads in the confined aquifer decrease by as much as 15 m in response to irrigation withdrawals. After irrigation ceases in August or September, hydraulic heads in the confined aquifer increase sharply and then gradually recover until reaching stable maximum values during the following winter or spring. Thereafter, this annual cycle is repeated when irrigation withdrawals begin again in June. Over periods greater than 1 year, the effect of a single season cycle diminishes, and hydraulic heads in the late winter-early spring reflect climatic and water-use conditions over several preceding years.

Long-term ground-water hydrographs (U.S. Geological Survey Ground Water Site Inventory Data Base; Rod DeBuhr, Upper Big Blue Natural Resources District, written commun., April 15, 2003) indicate winter hydraulic heads around York decreased about 4.6 m from 1957 to 1982, increased about 4.6 to 5.2 m from 1983 to 1995, and were relatively stable from 1995 to 2001. The water-level history probably reflects the effect of agricultural irrigation in the area. Pumping apparently exceeded recharge prior to 1982, but the conversion from gravity to sprinkler irrigation, improved irrigation efficiency, and slightly wetter climatic conditions during the 1980s and early 1990s resulted in smaller irrigation withdrawals, greater recharge, and rising water levels. Winter hydraulic heads in 2002 and 2003 decreased by more than 2 m in response to persistent drought conditions beginning in 2001.

Ground-water withdrawals from the confined sand layers induce large downward vertical gradients and flow (fig. 8.3). Comparison of hydraulic head in well clusters with wells screened in the unconfined and upper confined layers from 1957 to 1970 and from 1990 to 1994 shows heads in the confined layer are a maximum of 12.2 m lower than in the unconfined layer during the summer irrigation season. Heads in the confined layer are 0.3 to 2.7 m lower than in the unconfined layer during the fall, winter, and spring when irrigation withdrawals are absent. Seasonal water-level declines in response to irrigation withdrawals are larger in the confined layers than in the unconfined layer because storage coefficients are much smaller in the confined than in the unconfined layer. Hydrographs from a well cluster in north York showed that heads in the lower confined layer were 0.6 to 2.4 m lower than in the upper confined layer during 1983–2002 (U.S. Geological Survey Ground Water Site Inventory Data Base; Rod DeBuhr, Upper Big Blue Natural Resources District, written commun., April 15, 2003).

Many irrigation and some older public-supply wells are screened across both the unconfined and upper and lower confined layers of the aquifer. Those wells with multiple screened intervals and boreholes penetrating confining layers may provide pathways for water and contaminants to move to deeper parts of the aquifer. Active York public-supply wells are screened only in the confined part of the aquifer. Several wells with screens that partially penetrate the unconfined parts of the system were decommissioned in the last decade because of contamination with nitrate or trichloroethylene (Orville Davidson, Public Utilities Director, City of York, Nebraska, written comm., February 15, 2002).

## Aquifer Hydraulic Properties

Horizontal hydraulic conductivity of the unconfined layer ranges from 41 to 122 m/d (Argonne National Laboratory, 1995). Results of a 5-day aquifer test just west of York indicate a horizontal hydraulic conductivity value of 41.5 m/d for the unconfined layer (Ma, 1996). Results of a 63-hour aquifer test in northern York indicate a range of horizontal hydraulic-conductivity values between 41 and 122 m/d for the unconfined layer (Argonne National Laboratory, 1995). Horizontal hydraulic-conductivity values for the confined layers were determined from one 24-hour aquifer test in the upper confined layer and two 24-hour aquifer tests in the lower confined layer (Layne Geosciences, Valley, Nebraska,, written commun., 1997). The horizontal hydraulic-conductivity value of the upper confined layer was 19.8 m/d, and horizontal hydraulic-conductivity values for the lower confined layer were 4.8 and 6.9 m/d. Thickness-weighted horizontal hydraulic conductivity for the entire thickness of the High Plains aquifer in the study area used in previous regional ground-water flow models was about 15 m/d (Luckey and others, 1986; COHYST, 2001). Horizontal hydraulic- conductivity values from the aquifer tests were used as initial estimates in the Eastern High Plains regional ground-water flow model.

Storage properties of the unconfined and confined layers were determined from aquifer tests in and around York and generally span a considerable range and have high uncertainties (table 8.1). Thickness-weighted average values of specific yield determined from interpretations of lithologic-log analysis reported by Gutentag and others (1984) indicate that specific yield in most of the study area is in the range of 10 to 20 percent.

Systematic estimates of vertical hydraulic conductivity, ratios of horizontal to vertical hydraulic conductivity, and porosity have not been made across the High Plains aquifer or in the study area. Chen and Yin (1999) summarize results from several aquifer tests in Quaternary or younger alluvial deposits along the Platte and Republican Rivers in Nebraska (north and south, respectively, of the study area), as having ratios of horizontal to vertical hydraulic conductivity ranging between 15 and 70. Values in this range were used as initial estimates for the Eastern High Plains regional ground-water flow model. Estimates of porosity for the various lithologic materials ranged from 0.2 to 0.4 based on specific-yield values presented by Gutentag and others (1984) and typical values reported by Zheng and Bennett (2002).

## Water Budget

A conceptual water budget for the study area was developed and provided initial estimates of boundary fluxes for the ground-water flow model (fig. 8.3, table 8.1). Estimates of ground-water withdrawals and seepage from streams were reasonably well constrained. Withdrawals for irrigation per unit area are estimated as 25.4 cm/yr (see “Water Use”) over the irrigated part of the study area (61 percent) resulting in an estimated volumetric flux of 163,300 $m^3$/d. Withdrawals for industrial and public-supply purposes were known or estimated from historical records and were 6,910 $m^3$/d and 4,320 $m^3$/d, respectively. Seepage from streams to ground water (see “Surface-Water Hydrology”) was estimated as 3,460 $m^3$/d by subtracting measured low-flow stream discharge in Beaver Creek near the southeast end of the study area from commercial and wastewater discharges to Beaver Creek in York.

Ground-water inflows through the northeastern model boundary and outflows through the southwestern model boundary were estimated from Darcy’s equation (Freeze and Cherry, 1979). The Darcy’s equation calculation used a horizontal hydraulic-conductivity value of 61 m/d for the unconfined sand and gravel and 23 m/d for the confined sand, an average regional hydraulic gradient of 0.001326 (Keech and others, 1967), and saturated-thickness values representative of the boundary. Hydraulic-conductivity values in the upper range of possible values were selected so the calculated boundary fluxes would be near the upper limits of any boundary-flux estimates. On the basis of data from nearby test holes, a saturated thickness of 19 m was assigned for the unconfined sand and gravel on the upgradient boundary, and saturated thicknesses of 33 m and 13 m were assigned for the unconfined sand and gravel and confined sand, respectively, on the downgradient boundary. The resulting calculated inflow on the upgradient boundary was 24,200 $m^3$/d, and the calculated outflow on the downgradient boundary was 49,300 $m^3$/d.

Areal recharge is the primary source of inflow to the ground-water system and typically has greater uncertainty associated with its estimation than other budget terms. Recharge estimates were constrained by the need to balance the inflow and outflows of the water budget. The assumption of a balanced water budget is justified by the quasi-steady-state condition of winter water levels during 1995–2001 and the similarity of these water levels to those prior to the late 1950s. Total recharge across the study area is about 196,000 $m^3$/d, assuming a balanced water budget. Recharge from irrigation return flows was assumed as 25 percent of withdrawals (25.4 cm/yr) or 6.4 cm/yr over the irrigated area for a volumetric flux of about 44,900 $m^3$/d. The assumed proportion of irrigation return flow is less than some historical estimates in the High Plains of 30 to 40 percent (Luckey and others, 1986) but reflect that irrigation efficiency has improved in the last 2 decades and that there has been considerable conversion of gravity irrigation to more efficient center-pivot irrigation in the study area. To balance the water budget, recharge from precipitation was assumed as 20 percent of annual precipitation or 14.2 cm/yr. Applied over the entire study area, this assumed recharge rate results in a flux of 151,000 $m^3$/d. The assumption of precipitation recharge as 20 percent of annual average precipitation is slightly higher than a previous recharge estimate of 15 percent of precipitation for the study area, based upon soil-water balance simulations (Dugan and Zelt, 2000), but is similar to values used in a previous local ground-water modeling study (Upper Big Blue Natural Resources District, 1999).

In the conceptual water budget (fig. 8.3), recharge accounts for about 87 percent of inflows, and withdrawals account for about 78 percent of outflows. Boundary inflows (11 percent of total) and outflows (22 percent of total) are lesser but important terms in the water budget. Conceptually, the dominance of recharge and withdrawals in the water balance indicates there should be considerable vertical and horizontal flow in the system between recharge areas and withdrawal wells, considering the relatively small size of the study area.

## Ground-Water Quality

Sources of ground-water quality information in the study area include (1) samples collected as part of compliance monitoring of public-supply wells from the Nebraska Department of Health and Human Services (Ann Pamperl, Nebraska Department of Health and Human Services, Lincoln, Nebraska, written comm., January 15, 2002); (2) data from test wells drilled by the City of York (Orville Davidson, Public Utilities Director, City of York, Nebraska, written comm., February 15, 2002); (3) ground-water contamination investigations (Argonne National Laboratory, 1995); (4) regional ground-water quality investigations (Verstraeten and others, 1998); (5) data bases with compilations of historical data collected in the area (U.S. Geological Survey National Water Information System; University of Nebraska–Lincoln, 2000); and (6) samples collected from eight York public-supply wells for the NAWQA Source Water Quality Assessment (SWQA) program in October through December 2002. Of these sources, there are relatively few analyses with complete data with which to classify the oxidation-reduction (redox) state of the water. Moreover, many samples have been collected from wells with long screened intervals and large withdrawal rates such as irrigation or public-supply wells that may cause mixing of waters with different redox characteristics or have incomplete well-construction information so that the screened interval is not known. These factors limit the number of analyses useful for characterization of redox conditions.

The major-ion chemical data from City of York test wells, Argonne National Laboratory (1995), Verstraeten and others (1998), and SWQA data indicate ground water in the study area is of calcium-bicarbonate type water with dissolved-solids concentrations ranging from 280 to 474 mg/L with an average of about 364 mg/L (35 analyses). Values of pH are neutral ranging from 6.2 to 8.0 with an average of about 7.1 (151 analyses). Consistent spatial patterns of pH are not apparent from the available data.

Of the 124 sample results with sufficient data for redox classification, 98 of the samples were collected from the unconfined sand and gravel. Only one of the 98 samples had a dissolved-oxygen analysis (7.4 mg/L). All 98 samples had concentrations of nitrate-nitrogen greater than 0.5 mg/L, indicating the waters are likely in the range of oxygen- to nitrate-reducing waters.

Twenty-six samples with sufficient data for redox classification were collected from wells screened in the confined parts of the aquifer. Of these, 23 samples were collected from wells with unique locations: 10 were from public-supply wells, 12 were from test wells temporarily installed during exploratory drilling for public-supply wells by the City of York, and one was from a monitoring well. The spatial distribution of these samples is limited to areas in or near York (fig. 8.4). The four oxygen-reducing samples were all collected from public-supply wells. Most of the samples from test or monitoring wells (7 of 12) were consistent with manganese- or iron-reducing conditions. At four of the locations with redox data in the confined aquifer, data were available from different depths. At all four locations, the water generally became more reduced with depth, becoming either iron or manganese reduced in the lowermost sample. Generally, the redox data indicate the unconfined parts of the aquifer are oxidized and the confined parts of the aquifer are reduced with some mixtures and oxidized waters. The occurrence of more mixed and oxidized waters from public-supply wells than in test or monitoring wells is consistent with the redox chemistry being affected by withdrawals from the wells.

Direct evidence of changes in redox status as a result of pumping is demonstrated by water-chemistry data from York public-supply well 97-1A, screened in the upper confined layer, and wells 97-1 and 97-2, screened in the lower confined layer (fig. 8.5). Samples collected in 1996 (prior to public-supply well operation) from nearby test wells with screen lengths similar to those of the public-supply wells indicated ground water in 97-1A was manganese reducing and water in the lower confined sand was iron reducing at 97-1 and manganese reducing at 97-2. No nitrate-nitrogen was detected in any of the three samples. After withdrawals from the three public-supply wells began in 1997, nitrate-nitrogen was detected in all three wells, and concentrations of iron, manganese, and arsenic decreased in wells 97-1 and 97-2. Sampling results in 2001-2002 indicate oxygen-reducing conditions at well 97-1A, manganese-reducing conditions at well 97-1, and oxygen- or nitrate-reducing conditions at well 97-2.

The changes in the public-supply wells to more oxidized conditions has two implications: (1) the redox data in large-capacity wells can be affected by the withdrawals and may not be representative of ambient chemistry in most of the confined aquifer, and (2) the reducing conditions in the confined aquifer are weakly poised and subject to change to more oxidized conditions in places in the aquifer. The persistence of iron-reducing conditions in two public-supply wells and manganese-reducing conditions in three public-supply wells indicates that redox conditions are not as changeable in response to withdrawals in all locations as in 97-1, 97-1A, and 97-2. The variability of redox conditions in public-supply wells may indicate spatial variations in the mineralogy, hydrogeology, and distribution of redox-sensitive dissolved constituents that influence the redox condition.

The time-series chemistry data from wells 97-1, 97-1A, and 97-2 indicate ambient redox conditions in the confined layers are primarily manganese or iron reducing, conditions become more reducing with depth, and redox conditions can change in response to withdrawals. The time-series data and the preponderance of evidence from other sites in the confined layers (fig. 8.4) indicate ground water in the confined layers is predominantly manganese or iron reduced and leads to the conceptual model shown in fig. 8.3.

# Ground-Water Flow Simulations

A MODFLOW-2000 (Harbaugh and others, 2000) model was constructed to simulate ground-water flow in a 388.5-km$^2$ area of the High Plains aquifer near York, Nebraska. The model created for this study is discretized into rows, columns, and layers to represent the various hydrogeologic materials in the area, to simulate ground-water flow, and to delineate the areas contributing recharge to York public-supply wells. The flow model assumes steady-state conditions and represents average conditions for 1997–2001. Historical water-level data indicate the ground-water system was in a quasi-steady-state condition during 1997–2001 (see “Ground-Water Occurrence and Flow”). Most of the hydraulic-head data used to calibrate the model were collected in April 2001, and the values reflect average winter conditions for 1997–2001.

## Modeled Area and Spatial Discretization

A previous regional ground-water flow model (COHYST, 2001) of a 26,936-km$^2$ area was used to select the model boundaries for this study. The Eastern High Plains regional ground-water flow model was aligned northwest to southeast at an azimuth of 117 degrees (fig. 8.6), which approximately corresponds to the regional flow direction on potentiometric maps from before 1953 (Johnson and Keech, 1959), 1964 (Keech and others, 1967), 1979 (Conservation and Survey Division, 1980), 1995 (Dreeszen, 2000), and 1996 (Verstraeten and others, 1998). The southeast model boundary is located closer to York than the northwest model boundary because ground-water flow is from the northwest, and areas contributing recharge to wells will likely extend toward the northwest. The northeastern and southwestern boundaries, approximately corresponding to lateral no-flow boundaries of two ground-water flow lines in the regional flow model, were selected far enough from York so as not to affect simulated flow paths to York public-supply wells.

Horizontal and vertical discretization was specified to yield representative simulation of ground-water flow and areas contributing recharge to public-supply wells while maintaining simplicity in model geometry. The flow model consists of 200 rows and 300 columns of square cells with dimensions of 82.57 m on each side. There are six model layers corresponding to the loess-unconfined, unconfined, upper confining, upper confined, lower confining, and lower confined units, as shown in the conceptual model (fig. 8.3).

Layer thicknesses are not uniform except for layer 1, which has a uniform thickness of 4.57 m. Layer 1 was specified with a relatively thin uniform thickness to better represent the interaction between Beaver Creek, which is simulated exclusively in layer 1, and the unconfined aquifer. The loess areas in layer 1 outside of the Beaver Creek alluvial valley go dry during the simulation. The remaining model layer thicknesses were interpolated from 71 driller’s logs in the study area, after assigning lithologies in the logs to the layers of

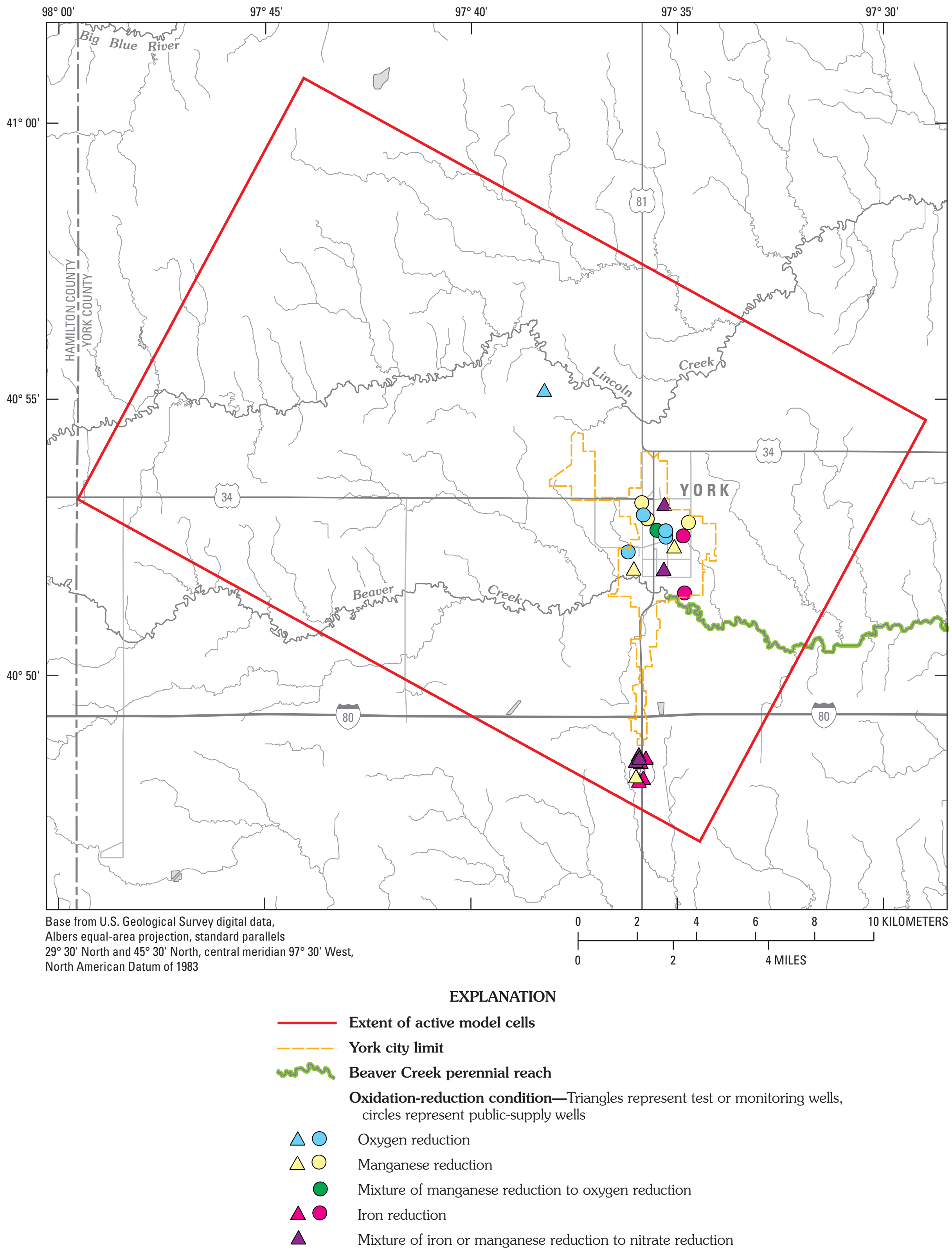



**Figure 8.4.** Oxidation-reduction conditions in wells screened in the confined part of the High Plains aquifer, Eastern High Plains regional study area, Nebraska.

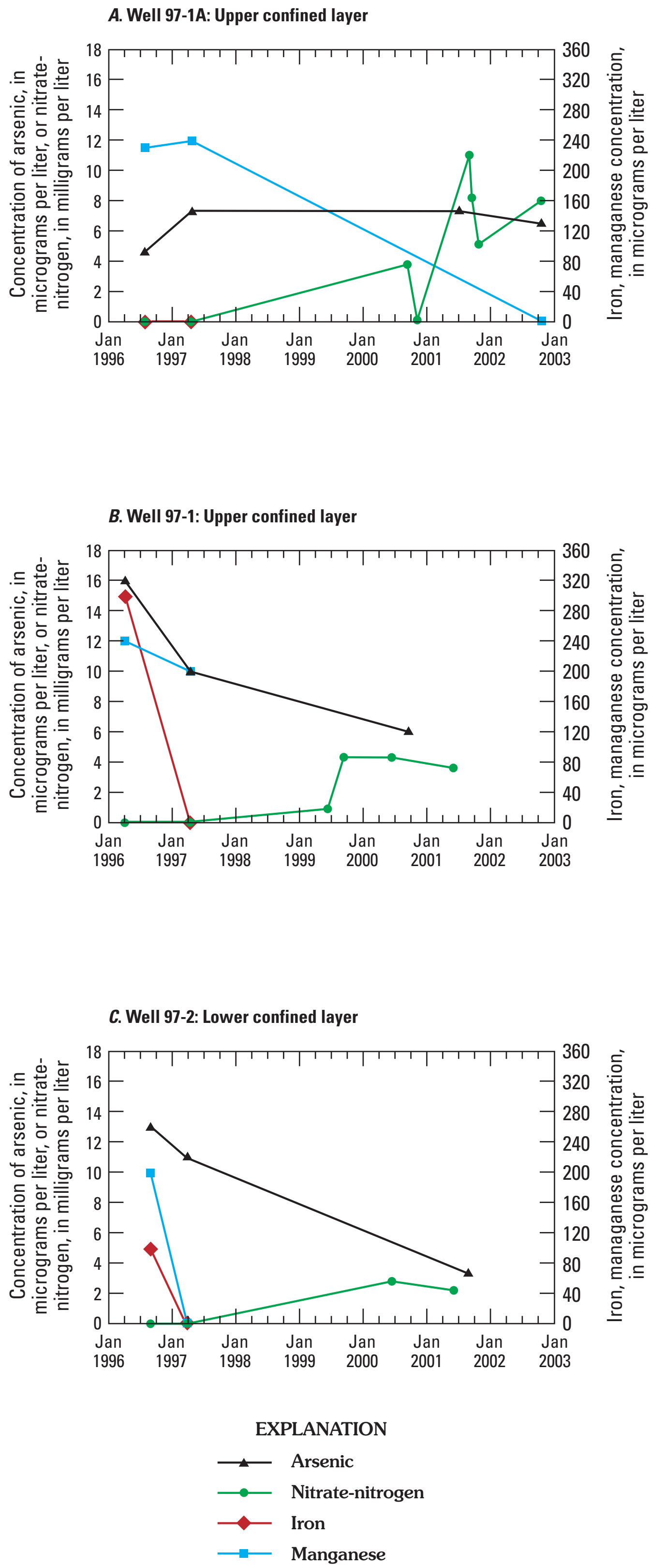



**Figure 8.5.** Changes in concentration of oxidation-reduction sensitive species in three York public-supply wells from 1996, prior to withdrawals for public water supply, and for 1997–2002, when municipal withdrawals occurred.

the conceptual model. Interpolations between geologic logs to develop hydrogeologic sections and three-dimensional stratigraphic models were done using the Department of Defense Groundwater Modeling System (GMS), version 4.0, developed by the Engineering Computer Graphics Laboratory at Brigham Young University. A minimum thickness of 0.3 m was assigned to model layers where layers were absent, which was primarily an issue for layers 4, 5, and 6. In general, the overall model thickness is smaller in the northwestern one-half of the modeled area than in the southeastern one-half to reflect changes in the bedrock topography (fig. 8.3).

## Boundary Conditions and Model Stresses

The northeastern and southwestern model boundaries were specified as no-flow boundaries because they correspond to ground-water flow lines from the regional ground-water flow model. The northwestern (upgradient) and southeastern (downgradient) boundaries were initially specified-head boundaries by using heads telescoped to the model from the regional model and following the methods of Leake and Claar (1999). Following initial model simulations, the upgradient and downgradient model boundaries were changed from specified-head to specified-flux boundaries to more realistically represent ground-water underflow in the aquifer. Specifying flux rather than head along the boundaries allows head along the boundary to change with varying stress, which eliminates the artificial constraint of specified head.

Flux boundaries were specified for each of the primary water-bearing units on the upgradient and downgradient boundaries of the flow model. Flux boundaries were simulated using wells in each cell on the boundary for the unconfined, upper confined, and lower confined units, corresponding to layers 2, 4, and 6 (fig. 8.7). It is assumed that lateral inflow or outflow in the two confining layers is negligible. The flux boundaries are uniform along the boundary and unique for each water-bearing unit at the upgradient and downgradient boundaries. Initial boundary-flux estimates were based on conceptual-model estimates.

Anthropogenic stresses on the ground-water system include withdrawal for agricultural, industrial, and municipal needs. The MODFLOW Well package was used to simulate withdrawals from the aquifer. The locations of registered irrigation and industrial wells and data on potential irrigated area per well were available from a State of Nebraska data base (Nebraska Department of Natural Resources, 2002). The locations of public-supply wells were determined with a Global Positioning System and verified on street and topographic maps. Available well-screen elevations were used to assign withdrawal values to corresponding model layers. Withdrawal from wells without well-screen information was assigned to model layers considering nearby well-screen elevations and water use. For wells screened in multiple layers, the proportion of the total withdrawal assigned to each layer was determined from the ratio of an individual layer's transmissivity to the

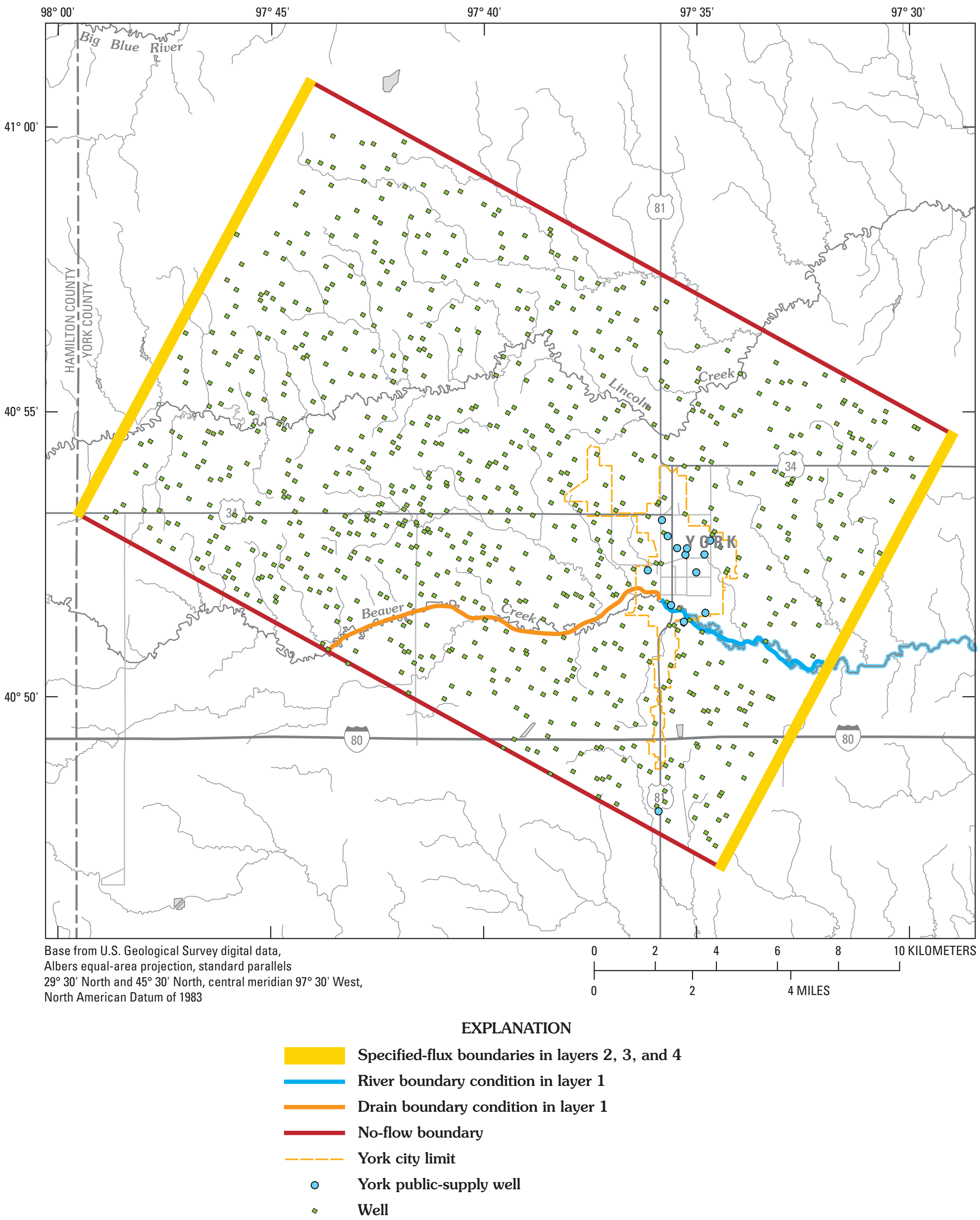



**Figure 8.6.** Ground-water flow model grid boundary and selected boundary conditions in different model layers, Eastern High Plains regional study area, Nebraska.

overall transmissivity. For example, the proportion of flow from layer 1 would be calculated as:

$$\frac{K_1 b_1}{\sum_{i=1}^{n} K_i B_i}$$

Where $K_1$ is the hydraulic conductivity of layer 1, $b_1$ is the saturated thickness of layer 1, $K_i$ is the hydraulic conductivity of individual layer *i*, $b_i$ is the saturated thickness of that layer, and *n* is the total number of layers.

A constant withdrawal rate of 25.4 cm/yr (see "Water Use") was multiplied by the estimated irrigated area to calculate the 1997–2001 average volumetric withdrawal rate for each irrigation well. For the 794 registered irrigation wells in the study area, the sum of the irrigated areas associated with each well record was considerably larger than the irrigated area in the study area indicated by a map of 1997 land use (Center for Advanced Land Management Information Technologies, 2000), a year with relatively normal climatic conditions. The irrigated areas listed in the well registration overestimate actual irrigated area because not all farmers irrigate all of the irrigable land each year. Consequently, the actual irrigated area per well was estimated by multiplying the potential irrigated area for each well by the ratio of the 1997 irrigated area from the 1997 land-use map to the sum of the irrigated areas from the well registration for the study area.

There were 14 public-supply wells active in York for all or most of 1997–2001 (table 8.2). Several public-supply wells have multiple screens that typically fully penetrate the upper confined sand (layer 4) and fully or partially penetrate the lower confined sand (layer 6). Six wells have screens in sand lenses that partially penetrate layer 5, the lower confining clay/silt. Three wells have screens that partially penetrate the unconfined sand and gravel, layer 2; two of these wells were shut down due to nitrate-nitrogen concentrations in excess of the EPA MCL of 10 mg/L during 2000–2001. Average 1997–2001 withdrawal rates were assigned for the steady-state simulations.

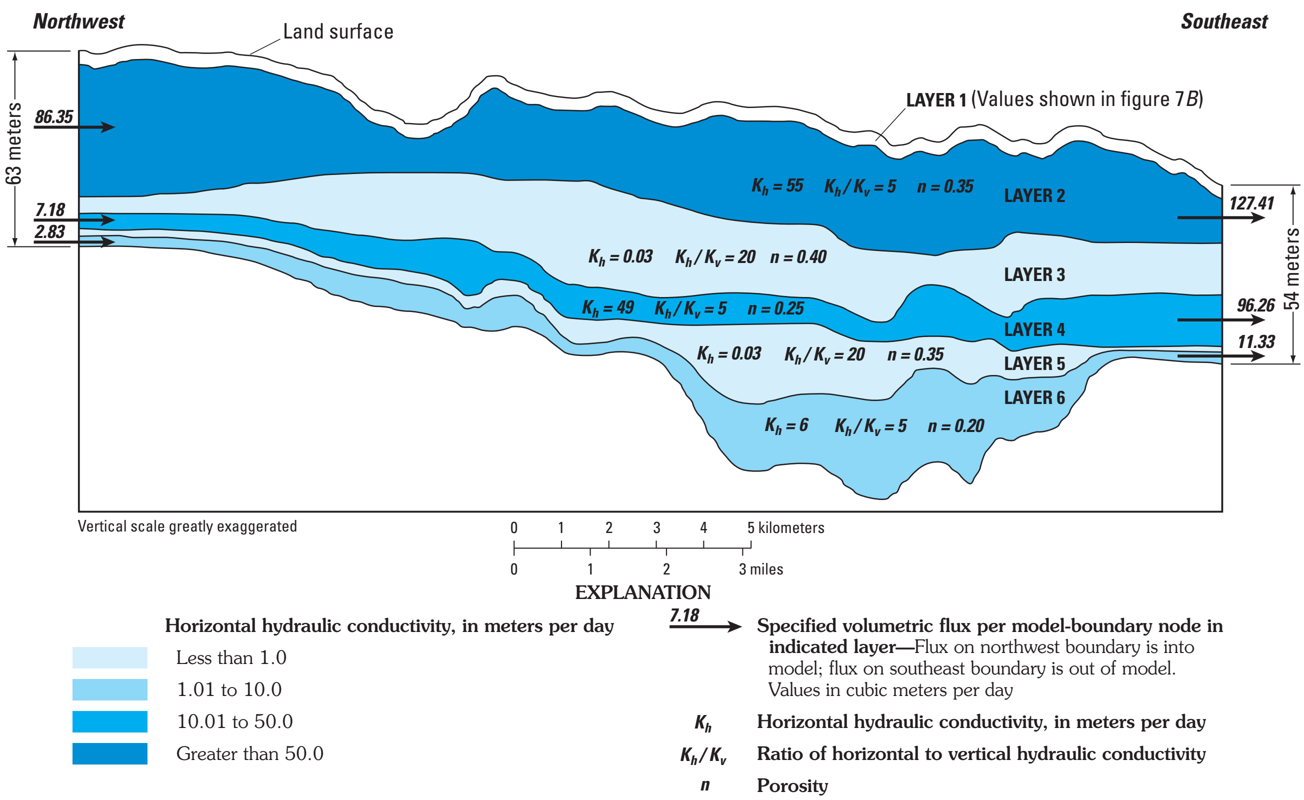
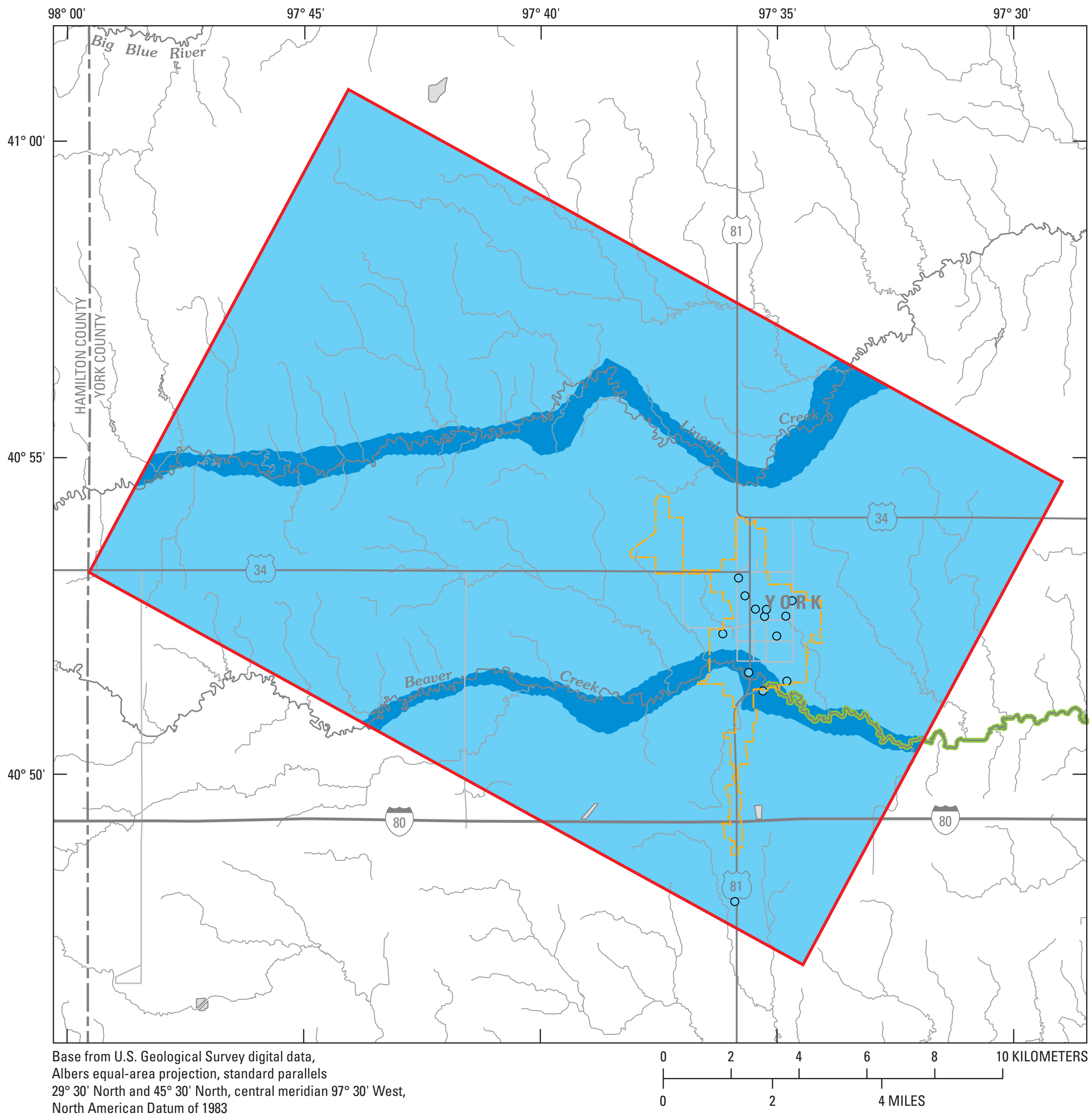



**Figure 8.7*A*.** Hydrogeologic section showing hydraulic-conductivity zones and flux-boundary values for layers of calibrated ground-water flow model.




**EXPLANATION**

**Horizontal hydraulic conductivity, in meters per day**

Less than 1.00—$K_h$ = 0.03; $K_h/K_v$ = 20; $n$ = 0.40

Greater than 50.01—$K_h$ = 55; $K_h/K_v$ = 5; $n$ = 0.35

**Extent of active model cells**

**York city limit**

**Beaver Creek perennial reach**

**York public-supply well**

[$K_h$, horizontal hydraulic conductivity, in meters per day; $K_h/K_v$, ratio of horizontal to vertical conductivity; $n$, porosity]

**Figure 8.7*B*.** Hydraulic-conductivity and active-cell zones in layer 1 of calibrated ground-water flow model, Eastern High Plains regional study area, Nebraska

There were 10 commercial/industrial wells active in the study area, and most of the withdrawals were from 4 of the 10 wells. Withdrawal rates for commercial wells were estimated using values from the Upper Big Blue NRD (1999), or from the City of York, or by contacting commercial water users. The commercial/industrial wells were screened in layers 2, 4, and(or) 6.

Beaver Creek is the only continuously flowing stream in the modeled area (see "Surface Water Hydrology"), and flow in the creek results from municipal wastewater and commercial discharges in York. Downstream (southeast) from York, surface water in Beaver Creek seeps into the ground-water system, contributing about 3,630 $m^3/d$. Beaver Creek is simulated as a MODFLOW drain upstream from the York Cold Storage facility discharge (fig. 8.6). This part of the creek is dry except after rainstorms. Outflow to the drain is assumed to be zero during the steady-state simulation. The streambed-conductance factor is the product of the streambed hydraulic conductivity and the streambed width divided by the thickness of the streambed material. A 0.3048-m streambed thickness, a 3.048-m-wide stream channel, and a streambed hydraulic conductivity of 0.1 m/d were assumed, yielding a streambed-conductance factor of 1.0 $m^2/d$. The conductance factor was multiplied by the length of the stream reach in each drain cell to calculate the conductance (in $m^3/d$). Drain elevation was set as the estimated elevation of land surface. Four flow observations of zero were intermittently specified along the drain reach. The drain was included in the model as an aid in calibration rather than for its role in the water budget.

MODFLOW river cells represent Beaver Creek downstream from the York Cold Storage discharge to the southeastern model boundary to represent ground-water/surface-

**Table 8.2.** Average ground-water pumping rates for public-supply wells, 1997–2001, Eastern High Plains regional study area, Nebraska (Orville Davidson, Public Utilities Director, City of York, Nebraska, written commun., Feb. 15, 2002).

[m, meters; $m^3/d$, cubic meters per day]

| Well name | Elevation of land surface (m) | Year of construction | Average withdrawal 1997–2001 ($m^3/d$) | Total length of well screens (m) | Well status | Actual screen placmement |
|---|---|---|---|---|---|---|
| 48–1 | 501.40 | 1948 | 0.43 | 10.67 | Shut down 2000* | 2 screens partially penetrate layer 2 |
| 62–1 | 485.24 | 1962 | 9.53 | 35.66 | Active | 2 screens partially penetrate layer 2 and fully penetrate layer 4 |
| 68–1 | 499.87 | 1968 | 1,315.62 | 57.61 | Active | 2 screens fully penetrate layers 4 and 6 |
| 73–1 | 503.53 | 1973 | 535.68 | 71.63 | Active | 7 screens fully penetrate layer 4, partially layers 5 and 6 |
| 76–1 | 485.55 | 1976 | 123.98 | 21.34 | Active | 1 screen in layer 4 |
| 77–1 | 502.31 | 1977 | 239.84 | 60.96 | Active | 3 screens fully penetrate layer 4, partially layers 5 and 6 |
| 77–3 | 492.25 | 1977 | 276.63 | 43.28 | Active | 2 screens fully penetrate layers 4 and 6 |
| 77–4 | 489.20 | 1977 | 350.38 | 34.14 | Active | 2 screens fully penetrate layer 4 and partially penetrate 5 or 6 |
| 82–1 | 502.62 | 1982 | 465.93 | 59.44 | Active | 2 screens fully penetrate layer 4 and partially penetrate 5 and 6 |
| 82–2 | 502.92 | 1982 | 381.65 | 51.82 | Active | 3 screens fully penetrate layer 4 and partially penetrate 5 or 6 |
| 88–1 | 501.70 | 1988 | 1,646.23 | 44.20 | Shut down 2001* | 3 screen partially penetrate layers 2 and 5, fully penetrate 4 |
| 97–1 | 503.22 | 1997 | 278.25 | 25.73 | Active | 1 screen partially penetrates layer 6 |
| 97–1A | 502.62 | 1997 | 230.55 | 20.12 | Active | 1 screen fully penetrates layer 4 |
| 97–2 | 502.92 | 1997 | 340.38 | 32.89 | Active | 2 screens partially penetrate layer 6 |

* Wells shut down because of nitrate contamination.

water interaction (figs. 8.6 and 8.7). The MODFLOW River package allows surface water to flow into the ground-water system where river leakage occurs and allows ground water to discharge to surface water near the southeastern edge of the study area where the stream becomes perennial. River conductance was calculated similar to drain conductance. A 0.3048-m streambed thickness, a 3.048-m-wide stream channel, and a streambed hydraulic conductivity of 0.8 m/d were assumed, yielding a streambed-conductance factor of 8.0 $m^2$/d. Stage was specified as 0.3048 m above the land surface. About one-half of the Beaver Creek leakage to the ground-water system is assumed to occur along the river reach within York where downward head gradients between the river and the aquifer are relatively large.

The upper model boundary consists of a water-table surface allowing inflow from recharge throughout the uppermost active model layer. A specified-flux boundary was used to simulate recharge to the ground-water flow system. Recharge was specified for the entire modeled area and was categorized as predominantly nonirrigated, gravity-irrigated, or sprinkler-irrigated agricultural land, urban land, or surface water. A recharge rate was specified for each of the following recharge zones, with percentage of total land area in parentheses: nonirrigated land 17.1 cm/yr (33 percent), gravity-irrigated agricultural land 22.8 cm/yr (33 percent), and sprinkler-irrigated agricultural land 20.6 cm/yr (28 percent), urban land 1.5 cm/yr (4 percent), and surface water 0 cm/yr (1 percent) (fig. 8.8). Initial estimates were values described in the conceptual model (see “Water Budget”). Urban recharge was assumed principally derived from leakage from the water-distribution system, and urban recharge from precipitation was considered negligible because of the large proportion of impervious area. For 1997–2001, the unaccounted water, the difference between water pumped and the water delivered, was 27,600 $m^3$/d (Orville Davidson, Public Utilities Director, City of York, Nebraska, written commun., June 6, 2003) or 12 percent of the annual pumping. Areal recharge in urban areas was therefore assumed equal to 27,600 $m^3$/d uniformly distributed across the urban area. Infiltration of surface water, with the exception of Beaver Creek, was considered insignificant; therefore, cells designated as “surface water” were given a value of zero recharge**.** The surface of the Carlile Shale and Niobrara Formation, underlying the High Plains aquifer in the study area, is represented as a no-flow boundary beneath the model.

## Aquifer Hydraulic Properties

Aquifer hydraulic properties were assigned to model layers on the basis of lithology of the six layers of the conceptual model (figs. 8.3 and 8.7, table 8.1). Horizontal hydraulic- conductivity and vertical-anisotropy parameter values were incorporated into the model by using the Layer Property Flow Package (Harbaugh and others, 2000). Layer 1 of the flow model contains parameter zones representing the unconfined sand and gravel in the Beaver and Lincoln Creeks alluvial valleys and the more widespread silt and clay of the loess elsewhere (fig. 8.7*B*). Layers 2 through 6 were each assigned homogeneous values for hydraulic conductivity, vertical anisotropy, and porosity consistent with the predominant lithology based on the conceptual model. Final hydraulic-conductivity values were determined from model calibration.

## Model Calibration and Sensitivity

Model calibration is the process by which model parameter values are adjusted within reasonable limits to minimize the difference between model-computed and measured heads and fluxes. Ground-water levels in 31 wells, mostly measured during the spring of 2001, and estimated fluxes from Beaver Creek into the aquifer were used as the basis of calibration. Every parameter used in the simulation was adjusted within reasonable limits until the differences between the model-computed and measured hydraulic heads were reduced to about 5.0 percent of the total head change across the study area. The final model was compared to measured hydraulic heads and estimated discharges in Beaver Creek to evaluate the calibration process.

The overall goodness of fit of the model to the observation data was evaluated using summary measures and graphical analyses. The root-mean-squared error (RMSE), the range of head and residuals, the mean residual, the standard deviation, and the standard-mean error of the residuals (SME), were used to evaluate the model calibration. The RMSE is a measure of the variance of the residuals and was calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (h_{meas} - h_{sim})i^2}{N}}$$

where $h_{meas}$ is the measured hydraulic head, $h_{sim}$ is the model-computed (simulated) hydraulic head, ($h_{meas} - h_{sim}$) is the head residual, and N is the number of wells used in the computation. If the ratio of the RMSE to the total head change in the modeled area is small, then the error in the head calculations is a small part of the overall model response (Anderson and Woessner, 1992).

The mean residual ($R_{mean}$) is computed as:

$$R_{mean} = \frac{\sum_{i=1}^{n} (h_{meas} - h_{sim})i}{N}$$

and its positive or negative sign indicates whether model-computed hydraulic heads were higher or lower than measured hydraulic heads, respectively.

The SME was calculated as:

$$SME = \frac{\sigma(h_{meas} - h_{sim})}{\sqrt{N}}$$

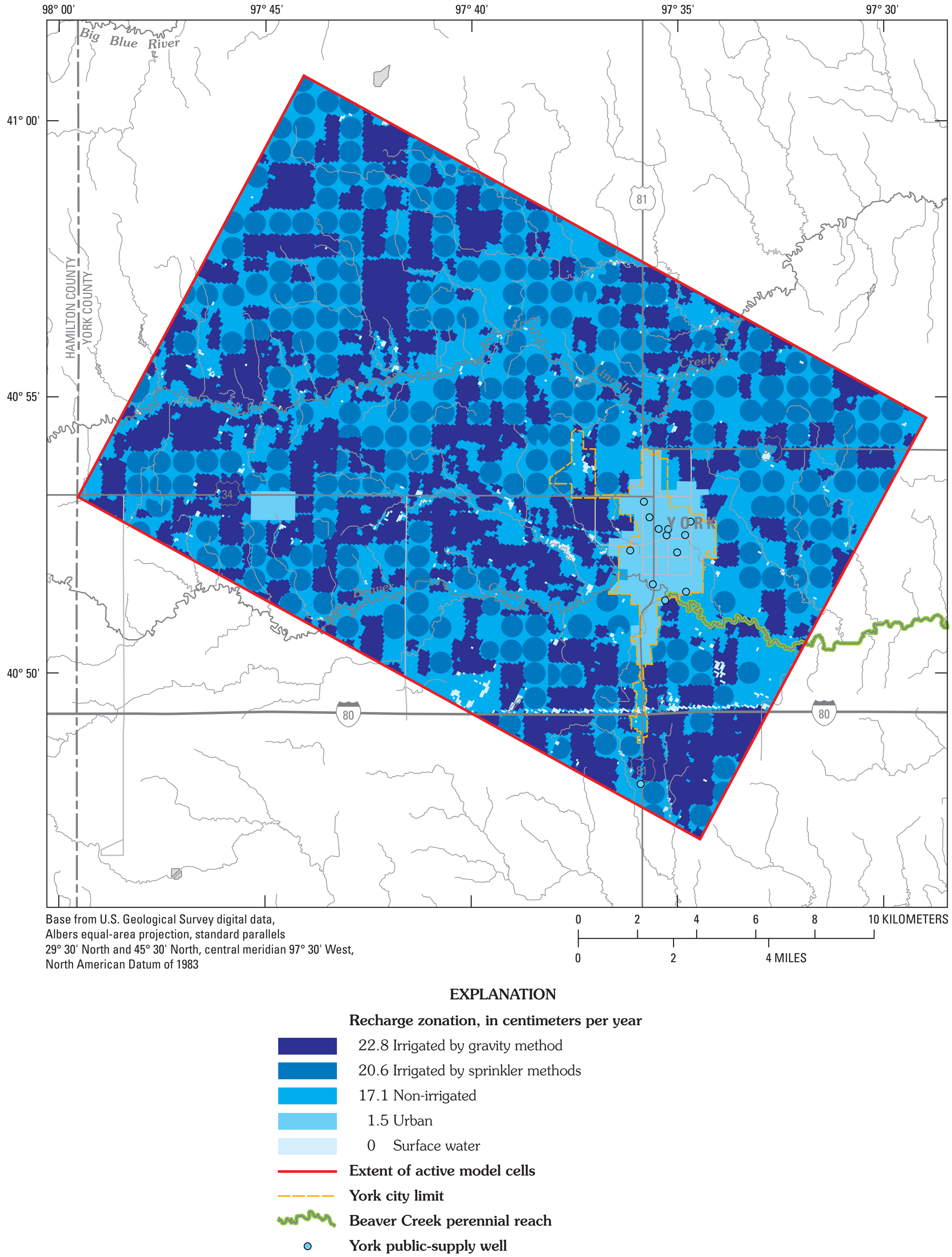



**Figure 8.8.** Distribution of recharge estimates used as ground-water flow model input, Eastern High Plains regional study area, Nebraska.

where $\sigma(h_{meas} - h_{sim})$ is the standard deviation of the residuals.

Model calibration continued until the mean residual and RMSE of the residuals for all model layers were minimized. The flow model was considered calibrated when the following criteria were satisfied:

1. Incremental changes in model parameters did not substantially reduce the RMSE (Hill and others, 2000) or other calibration statistics.
2. The RMSE of the entire model was less than approximately 5 percent of the total head change in the study area.
3. The simulated vertical gradients in two sets of nested wells were similar to the measured vertical gradients.
4. Simulated seepage to the High Plains aquifer from Beaver Creek was within one order of magnitude of the conceptual discharge of about 3,630 $m^3/d$.

The calibrated model is a simplified representation of a complex hydrogeologic system and inherently sensitive to some model parameters. The model is influenced by the uncertainty in the value of these parameters and in the dynamics of the boundary conditions. A sensitivity analysis characterizes the effect of model-parameter change on the model results. The model is considered sensitive to a model parameter when changes in the model parameter produce substantial changes in the model results. This type of analysis can be used to identify areas where additional hydrogeologic information is needed.

Sensitivity analysis was performed using MODFLOW-2000 and the sensitivity process (Hill and others, 2000). The calibrated steady-state model is nearly four orders of magnitude more sensitive to recharge than to any other type of parameter. The model also is sensitive to the hydraulic conductivity of layers 2 and 4 and the specified-flux boundaries. The model is relatively insensitive to the vertical anisotropy and the conductance factor of Beaver Creek.

Parameter values were changed within acceptable limits from initial estimated values to the final values during the calibration process. Most of the parameter changes before the change from specified-head to specified-flux boundaries were limited to the hydraulic conductivity of layers 2, 4, and 6; values in layer 2 yielding the best model fit at one point reached a value of about 150 m/d, about 3 times greater than values estimated from pumping tests. After the switch to the specified-flux boundary, hydraulic-conductivity values in all layers were changed to previously estimated values (see “Aquifer Hydraulic Properties”) resulting in a lower sum of square residuals and better vertical head distribution. Recharge values in the five zones were specified such that the total amount of recharge applied to the study area agreed with the conceptual model. Adjustments to the recharge distribution among the five recharge zones assumed gravity irrigation provided more recharge than sprinkler irrigation (Mustick and Stewart, 1992), irrigated land provided more recharge than nonirrigated land, urban land provided less recharge than agricultural lands, and surface-water areas provided no recharge (fig. 8.8). Although individual initial recharge parameters may have changed during the calibration process, the total recharge applied to the model remained essentially the same. After about 200 model runs, adjustments were made only to the most sensitive model parameters with most of the final adjustments occurring at the specified-flux boundaries.

## Model-Computed Hydraulic Heads

The model-computed hydraulic heads in all model layers were in good agreement with ground-water flow directions and gradients indicated by previous regional investigations. A simple method of assessing model fit is to plot the model-computed hydraulic head values against the measured observations. For a perfect fit, all points should fall on the 1:1 diagonal line. Figure 8.9 presents a graph of the model-computed hydraulic heads plotted against measured hydraulic heads for the Eastern High Plains regional study area and indicates reasonable model fit. The mean residual for the entire model is -0.7 m, and residuals range from -3.6 m to 3.5 m (range of 7.1 m). The RMSE for the entire model is 1.66 m, which is about 5.4 percent of the 31-m range of head observations in the model, and the head residuals appear to be randomly distributed across the study area (fig. 8.10) at all values of measured head (fig. 8.11). The standard deviation of the residuals is 1.53 m, and the SME is 0.28 m. Individual layer calibration statistics vary, which is likely because most of the water-level measurements are located in layers 2 and 4, with only two water-level measurements in layer 6. Mean error and RMSE for layers 2, 4, and 6 are 0.53 m and 1.56 m, 0.15 m and 0.94 m, and 1.87 and 2.69, respectively. The sum

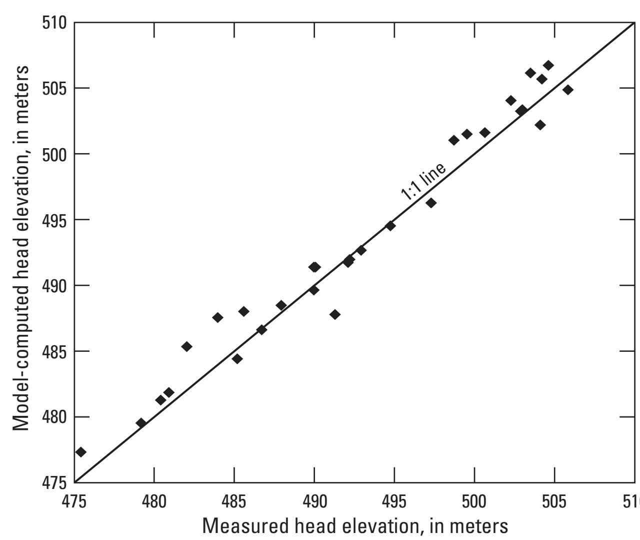
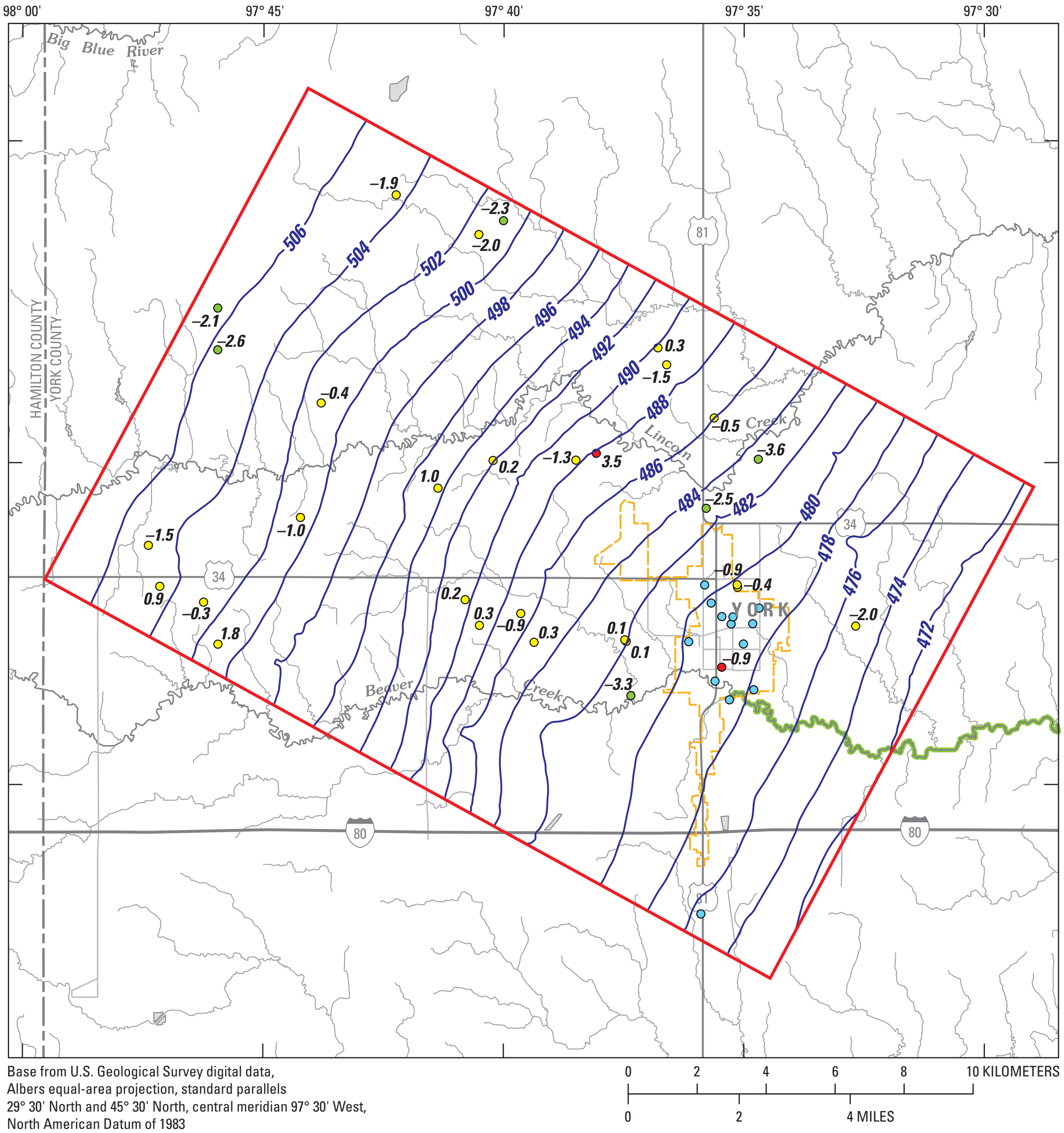



**Figure 8.9.** Relation between model-computed and measured hydraulic head, Eastern High Plains regional study area, Nebraska.




**EXPLANATION**

—490— Elevation contour of model-computed potentiometric surface in model layer 4, in meters above sea level. Contour interal 2 meters

Observation well and residual head values (measured minus modeled), values in meters

- 3.5 Greater than 2
- –0.3 2 to –2
- –3.3 Less than –2

York public-supply well

Extent of active model cells

York city limit

Beaver Creek perennial reach

**Figure 8.10.** Model-computed potentiometric surface in layer 4 and observation points and residuals in all layers, Eastern High Plains regional study area, Nebraska.

of squared-weighted residuals for all heads in the model is 74.17 m, whereas the sum of squared-weighted residuals for all observations, including estimated Beaver Creek discharge, is 97.61 m. The reported correlation between the weighted residuals and normal order statistics is 0.950 (which is greater than the 5-percent significance level of 0.946), indicating the hypothesis that the weighted residuals are independent and normally distributed at the 5-percent significance level is valid (Hill, 1998).

The calibrated steady-state ground-water flow model calculates water levels and internal fluxes for each model cell. The simulated potentiometric surface in the upper confined unit (layer 4) and the simulated vertical distribution of head along row 100 in the model are shown in figs. 8.10 and 8.12, respectively. Simulation results indicate the direction of flow is predominantly from the northwest to the southeast, as expected from the conceptual model. The potentiometric surface of layer 2 in the area near Beaver Creek, indicates leakage from the reach of the creek downstream from York.

The magnitude and horizontal extent of vertical ground-water flow between model layers is greatest between the unconfined and upper confined layers (layers 2 and 4) (fig. 8.12, table 8.3). Although there are localized areas of vertical downward gradients between the upper confined and lower confined aquifers (layers 4 and 6) comparable to the gradients between layers 2 and 4, the typical head difference is about 1 m. The largest area of vertical downward movement is in and around the city of York between layers 2 and 4. The magnitude of the largest difference in simulated head between layers 2 and 4 is about 5 m.

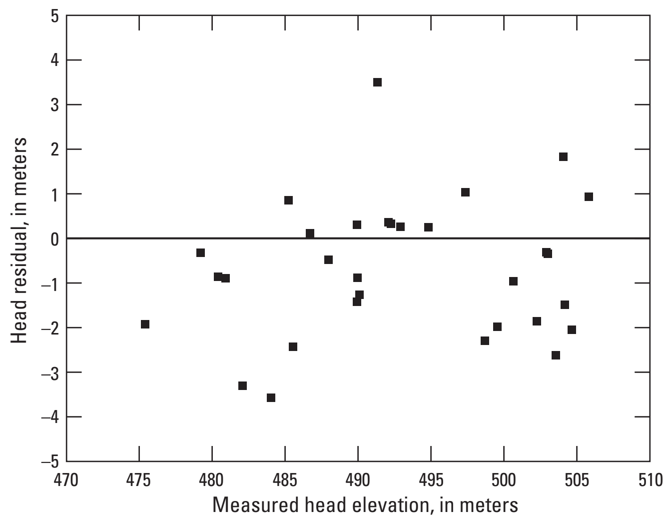



**Figure 8.11.** Relation between head residuals and measured hydraulic head, Eastern High Plains regional study area, Nebraska.

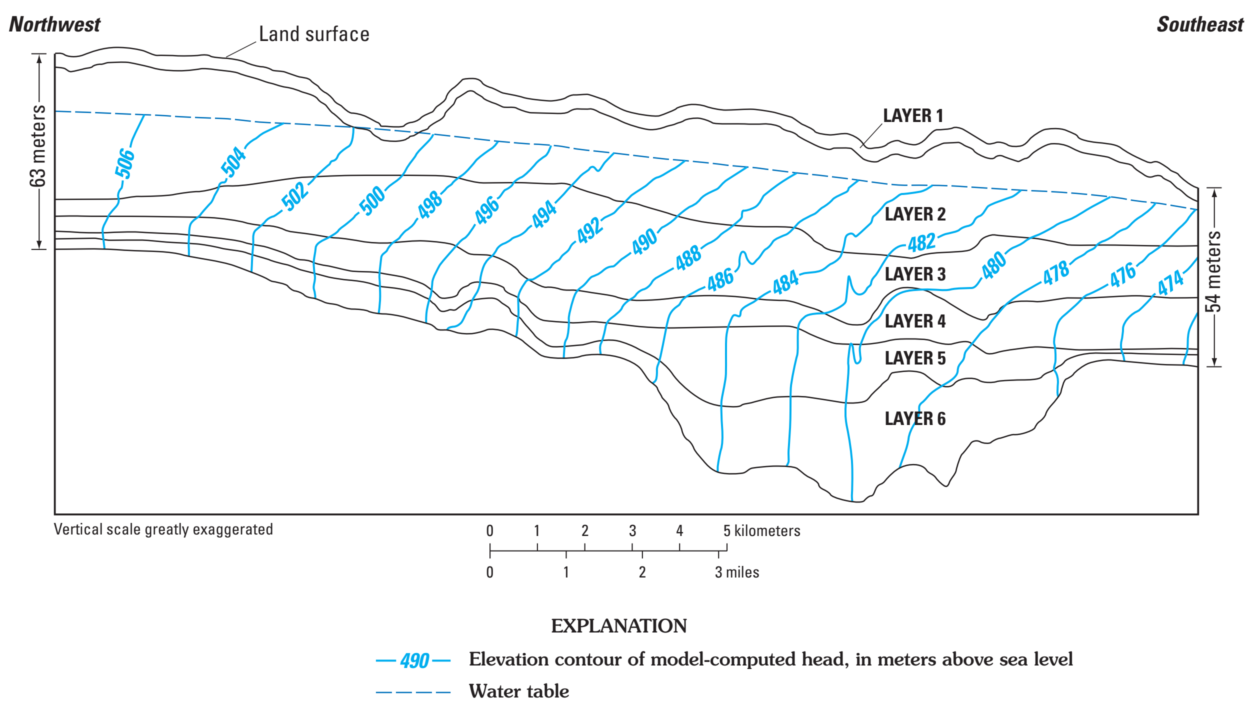



**Figure 8.12.** Hydrogeologic section showing model-computed hydraulic heads through row 100 of calibrated ground-water flow model, Eastern High Plains regional study area, Nebraska.

**Table 8.3.** Model-computed water budget for 1997–2001 average conditions, Eastern High Plains regional study area, Nebraska.

[m³/d, cubic meters per day; %, percent; <, less than; —-, not computed]

| Water-budget component | Layer | | | | | | Total | Percentage of inflow or outflow |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | | |
| **Model inflow (m³/d)** | | | | | | | | |
| Upgradient constant-flux boundary | — | 13,875 | — | 1,416 | — | 566 | 15,857 | 6.9 |
| Recharge | 14,431 | 189,932 | — | — | — | — | 204,363 | 89.3 |
| Beaver Creek—downstream from York | 8,780 | — | — | — | — | — | 8,780 | 3.8 |
| Beaver Creek—upstream from York | — | — | — | — | — | — | — | — |
| Wells | — | — | — | — | — | — | — | — |
| Downgradient constant-flux boundary | — | — | — | — | — | — | — | — |
| **SUBTOTAL** (boundary fluxes) | 23,211 | 203,807 | — | 1,416 | — | 566 | 229,000 | 100 |
| INTERNAL FLUXES From: | — | — | — | — | — | — | — | — |
| Layer 1 | — | 25,436 | — | — | — | — | 25,436 | 9.4 |
| Layer 2 | 2,206 | | 103,509 | — | — | — | 105,715 | 39.1 |
| Layer 3 | — | 287 | — | 95,385 | — | — | 95,672 | 35.3 |
| Layer 4 | — | — | 4,350 | — | 19,428 | — | 23,778 | 8.8 |
| Layer 5 | — | — | — | 995 | — | 16,255 | 17,250 | 6.4 |
| Layer 6 | — | — | — | — | 2,667 | — | 2,667 | 1.0 |
| **SUBTOTAL** (internal fluxes) | 2,206 | 25,723 | 107,859 | 96,380 | 22,095 | 16,255 | 270,518 | 100 |
| **TOTAL** (boundary + internal fluxes): | 25,417 | 229,530 | 107,859 | 97,796 | 22,095 | 16,821 | 499,518 | |
| **Model outflow (m³/d)** | | | | | | | | |
| Upgradient constant flux boundary | — | — | — | — | — | — | — | — |
| Recharge | — | — | — | — | — | — | — | — |
| Beaver Creek—downstream from York | 27.2 | — | — | — | — | — | 27.2 | 0.01 |
| Beaver Creek—upstream from York | 5.7 | — | — | — | — | — | 5.7 | 0.0 |
| Wells | — | 95,838 | 12,186 | 54,617 | 4,844 | 11,828 | 179,313 | 78.3 |
| Downgradient constant-flux boundary | — | 27,895 | — | 19,402 | — | 2,326 | 49,623 | 21.7 |
| **SUBTOTAL** (boundary fluxes): | 32.9 | 123,733 | 12,186 | 74,019 | 4,844 | 14,154 | 228,969 | 100 |
| INTERNAL FLUXES To: | — | — | — | — | — | — | — | |
| Layer 1 | — | 2,206 | — | — | — | — | 2,206 | 0.8 |
| Layer 2 | 25,436 | — | 287 | — | — | — | 25,723 | 9.5 |
| Layer 3 | — | 103,509 | — | 4,350 | — | — | 107,859 | 39.9 |
| Layer 4 | — | — | 95,385 | — | 995 | — | 96,380 | 35.6 |
| Layer 5 | — | — | — | 19,428 | — | 2,667 | 22,095 | 8.2 |
| Layer 6 | — | — | — | — | 16,255 | — | 16,255 | 6.0 |
| **SUBTOTAL** (internal fluxes): | 25,436 | 105,715 | 95,672 | 23,778 | 17,250 | 2,667 | 270,518 | 100 |
| **TOTAL** (boundary + internal fluxes): | 25,469 | 229,448 | 107,858 | 97,797 | 22,094 | 16,821 | 499,487 | |
| **INFLOW-OUTFLOW** | -52 | 82 | 1.0 | <-1.0 | <1.0 | 0.0 | 31 | |
| Percent discrepancy | -0.2% | 0.04% | 0.00% | 0.00% | 0.00% | 0.00% | 0.01% | |

## Model-Computed Water Budget

The calibrated model produces a detailed distribution of ground-water fluxes across cell faces and boundary conditions. The model-computed water budget indicates areal recharge from irrigation return flow and precipitation provides about 89 percent (14,431 $m^3$/d) of the total water flow into the modeled area (table 8.3). Inflow from the upgradient specified-flux boundary and ground-water seepage from Beaver Creek accounts for about 6.9 and 3.8 percent of model inflow, respectively. Simulated inflow from Beaver Creek in and below the city of York is 8,780 $m^3$/d. The model-computed water budget indicates that about 78 percent (179,314 $m^3$/d) of the model outflow is to wells, with the downgradient specified-flux boundary accounting for about 22 percent of the total outflow (49,623 $m^3$/d). A small outflow (0.01 percent) occurs along Beaver Creek near the southeastern boundary and at a topographic low near the middle of the simulated reach.

The simulated internal flux distribution indicates most of the water flows downward from the overlying layers to layer 4 with decreasing downward flow from layer 4 to layer 5 and from layer 5 to layer 6. Based on model results, a downward flux is persistent throughout the area. Overall, the difference between inflows and outflows throughout the entire modeled area was about 0.01 percent.

## Simulation of Areas Contributing Recharge to Public-Supply Wells

The calibrated steady-state model was used to estimate the areas contributing recharge to selected public-supply wells in the city of York by using the MODPATH (Pollock, 1994) particle-tracking post processor. Output from the steady-state model is used in the MODPATH simulation to calculate the path of imaginary particles moving through the simulated ground-water system (Pollock, 1994). As MODPATH tracks the path of each particle, it also tracks the time required for the particle to travel along the path, yielding results both in direction and time, which is useful information when delineating areas contributing recharge to wells (Pollock, 1994). The model-computed areas contributing recharge represent advective ground-water flow and do not account for mechanical dispersion. Advection-dispersion transport simulations would likely yield larger areas contributing recharge than advective particle-tracking simulations because the effects of dispersion caused by aquifer heterogeneity would be included.

Along with output from the calibrated steady-state MODFLOW model, the MODPATH simulation requires specified porosity values to calculate ground-water flow velocities. Porosity values were assumed uniform within each layer (fig. 8.7) based on layer lithology, specific-yield values presented by Gutentag and others (1984), and typical porosity values listed in Zheng and Bennett (2002).

Results from the MODPATH simulations were used to delineate areas contributing recharge and zones of contribution to York public-supply wells (fig. 8.13). Because of the natural horizontal gradient from the northwest to the southeast across the study area, the areas contributing recharge extend northwest from the public-supply wells of York. Additional pumping upgradient from the public-supply wells affects the locations and orientations of the areas contributing recharge, as indicated by their occasionally irregular shapes. Traveltimes from the areas contributing recharge to wells range from 20 to more than 100 years. Based on particle-tracking results, some particles, especially those reaching screens in the lower confined unit, do not originate at the water table in the study area but track to the northwestern specified-flux boundary. These particles have estimated traveltimes of thousands of years. The zones of contribution to public-supply wells typically broaden until the area contributing recharge at the water table is reached then narrow as only a few deeper pathlines delineating the zones of contribution continue upgradient.

## Limitations and Appropriate Use of the Model

The ground-water flow model for the Eastern High Plains regional study area was designed to delineate contributing areas to public-supply wells, to help guide data collection, and to support future local modeling efforts. Limitations of the ground-water flow model, assumptions made during model development, and results of model calibration and sensitivity analysis all are factors that constrain the appropriate use of the model and highlight potential future improvements.

The Eastern High Plains regional ground-water flow model simulates flow in the High Plains aquifer, assuming steady-state conditions. Although hydrologic conditions for the nonirrigation season from 1997 to 2001 appeared in a quasi-steady-state condition, hydrologic conditions during the late 1950s through the mid-1990s were not steady state. The effects of these deviations from steady-state conditions compared to the simulated ground-water fluxes and areas contributing recharge are difficult to predict without developing a transient model of the last several decades, which was beyond the scope of this study. Results of this steady-state model may not be representative of instances when hydrologic conditions are dissimilar to the assumed steady-state conditions. Seasonally transient stresses and vertical gradients of large magnitude that occur in the ground-water system during the irrigation season are not represented in the steady-state model. Public-supply withdrawals for 1997–2001 were greater than during earlier times, so the simulated areas contributing recharge and zones of contribution to public-supply wells using 1997–2001 average pumping in a steady-state model are likely larger than those that would be calculated for previous time frames. The 1997–2001 average areas contributing recharge and zones of contribution are therefore considered conservative (maximum) estimates of potential source areas for water reaching public-supply wells.

Recharge was estimated and its areal distribution was assigned on the basis of 1997 land use (U.S. Geological Sur-

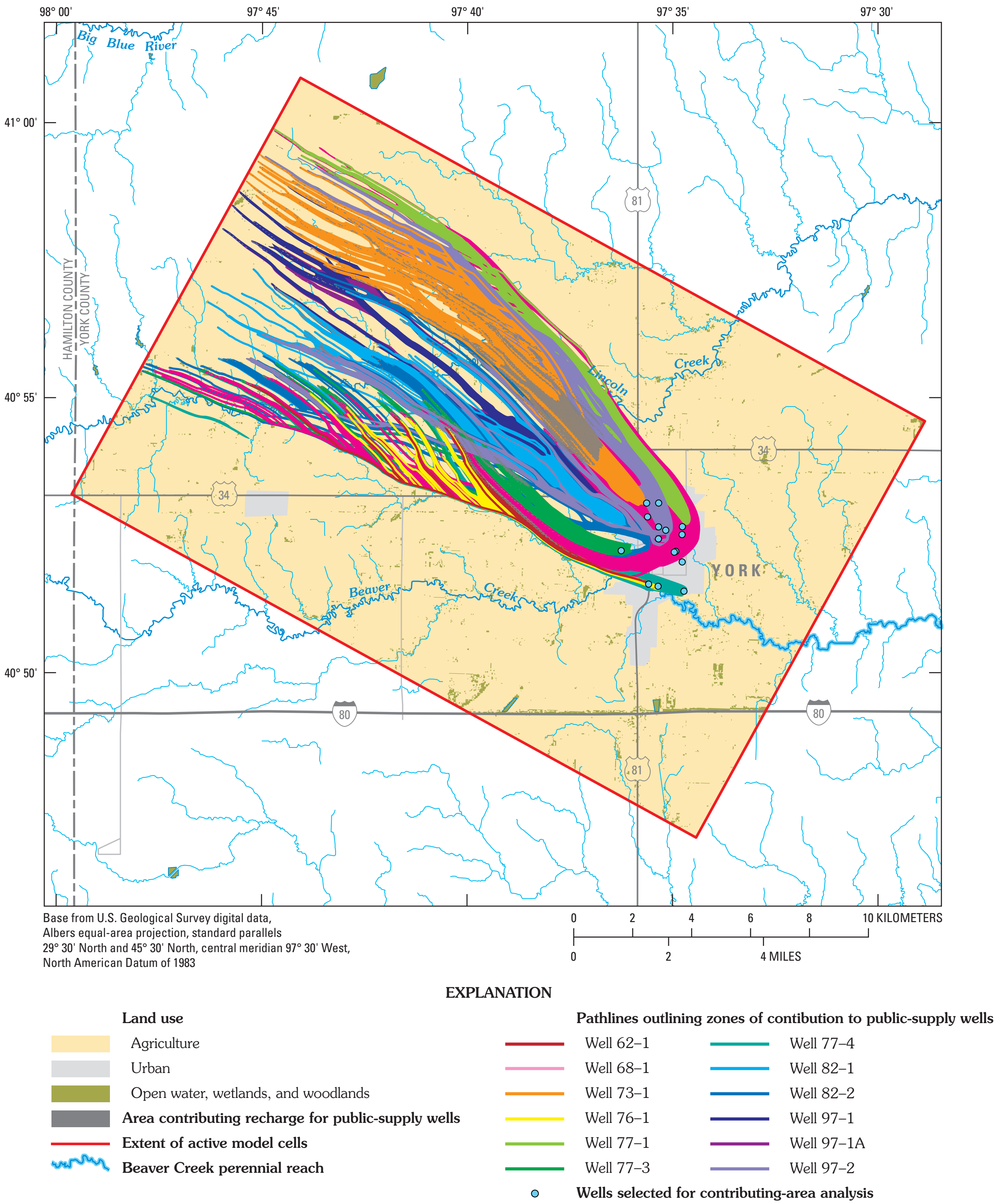



**Figure 8.13.** Model-computed areas contributing recharge and zones of contribution for 12 public-supply wells, Eastern High Plains regional study area, Nebraska.

vey, 1999–2000). Considering the significant sensitivity of the model to recharge values, the recharge distribution could be a significant, but presently unknown, source of error.

The ground-water flow model does not account for the heterogeneous nature of the High Plains aquifer but rather approximates all lithologies as being uniform throughout each layer. Heterogeneous aquifer complexity is beyond the scope of this study, but detailed mapping of aquifer lithology and layering would be appropriate for more site-specific modeling studies.

Computed areas contributing recharge and traveltimes through zones of contribution are based on a calibrated model and estimated effective porosity values. In a steady-state model, changes to input porosity values do not change the area contributing recharge to a given well. Changes to input porosity values will change computed traveltimes from recharge to discharge areas in direct proportion to changes of effective porosity because there is an inverse linear relation between ground-water flow velocity and effective porosity and a direct linear relation between traveltime and effective porosity. For example, a one-percent decrease in porosity will result in a one-percent increase in velocity and a one-percent decrease in particle traveltime. A detailed sensitivity analysis of porosity distributions was beyond the scope of this study, although future work could compare simulated ground-water traveltimes to ground-water ages to more thoroughly evaluate effective porosity values.

The Eastern High Plains regional ground-water flow model uses justifiable aquifer properties and boundary conditions and provides a reasonable representation of ground-water flow conditions in the study area for 1997–2001. The model can be used to better understand regional water budgets and ground-water flow paths in the study area for the time period of interest but may not be suitable for long-term predictive simulations. The model also proved helpful for understanding the vertical movement of water between various layers of the High Plains aquifer. This model provides a useful tool to evaluate aquifer vulnerability at a regional scale, to facilitate comparisons of ground-water traveltime between regional aquifer systems, and to guide future detailed investigations in the study area.

# References Cited


Anderson, M.P., and Woessner, W.W., 1992, Applied groundwater modeling: Academic Press, Inc., New York, 381 p.

Argonne National Laboratory, 1995, Final phase II report—Expedited site characterization, York, Nebraska: Prepared for Community Credit Corporation, United States Department of Agriculture, April 1995.

Center for Advanced Land Management Information Technologies, 2000, Delineation of 1997 land use patterns for the Cooperative Hydrology Study in the Central Platte River Basin: University of Nebraska, Lincoln, Center for Advanced Land Management Information Technoligies.

Chen, X., and Yin, Y., 1999, Evaluation of streamflow depletion for vertical anisotropic aquifers: Journal of Environmental Systems, v. 27, no. 1, p. 55–70.

COHYST, 2001, Pre-groundwater development 1-mile groundwater flow model for the Eastern Model Unit: COoperative HYdrology STudy Technical Committee, May 2, 2001, 46 p., accessed June 26, 2006, at *http://cohyst.dnr.ne.gov/*

Conservation and Survey Division, 1980, Configuration of the water table 1979, 1:250,000 Lincoln and Nebraska City quadrangle, Nebraska: Conservation and Survey Division, Lincoln University of Nebraska, accessed June 26, 2006, at *http://csd.unl.edu/general/gis-datasets.asp*

Dennehy, K.F., Litke, D.W., and McMahon, P.B., 2002, The High Plains aquifer, USA—Groundwater development and sustainability, *in* Hiscock, K.M., Rivett, M.O., and Davison, R.M., eds., Sustainable groundwater development: Geological Society, London, Special Publication, 193, p. 99–119.

Dreezen, V. H., 2000, Configuration of the water table 1995, 1:250,000 Lincoln and Nebraska City quadrangle, Nebraska: Conservation and Survey Division, Lincoln University of Nebraska, accessed June 26, 2006, at *http://csd.unl.edu/general/gis-datasets.asp*

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.

Fallon, J.D., and McChesney, J.A., 1993, Surface-water-quality assessment of the lower Kansas River Basin, Kansas and Nebraska—project data, November 1986 through April 1990: U.S. Geological Survey Open-File Report 93–51, 593 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall Inc., 604 p.

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

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

Hedman, E.R., and Engel, G.B., 1989, Flow characteristics for selected streams in the Great Plains subregion of the Central Midwest Regional Aquifer System and selected adjacent areas—Kansas and Nebraska, and parts of Colorado, Iowa, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–708, 3 sheets.

High Plains Regional Climate Center, 2003, National Weather Service surface observations and automated weather data network: accessed March 11, 2003 at *http://www.hprcc.unl.edu/data.htm*

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water flow model—User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00–184, 209 p.

Hill, M.C., 1998, Methods and guidelines for effective model calibration: U.S. Geological Survey Water-Resources Investigations Report 98–4005, 90 p.

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

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

Leake, S.A., and Claar, D.V., 1999, Procedures and computer programs for telescopic mesh refinement using MODFLOW: U.S. Geological Survey Open-File Report 99–238, 53 p.

Litke, D.W., 2001, Historical water-quality data for the High Plains Regional Ground-Water study area in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, 1930-98: U.S. Geological Survey Water-ResourcesInvestigations Report 00–4254, 65 p.

Luckey, R.R., Gutentag, E.D., Heimes, F.J., and Weeks, J.B., 1986, Digital simulation of ground-water flow in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–D, 63 p.

Luckey, R.R., and Becker, M.F., 1999, Hydrogeology, water use, and simulation of flow in the High Plains aquifer in northwestern Oklahoma, southeastern Colorado, southwestern Kansas, northeastern New Mexico, and northwestern Texas: U.S. Geological Survey Water-Resources Investigations Report 99–4104, 35 p.

Ma, Li, 1996, Impact of artificial groundwater recharge at two Nebraska sites: Lincoln University of Nebraska, Ph.D. dissertation, 209 p.

Ma, Li, and Spalding, R.F., 1997, Herbicide persistence and mobility in a recharge lake watershed in York, Nebraska: Journal of Environmental Quality, v. 26, no. 1, p. 115–125.

Mustik, J.T., and Stewart, B.A., 1992, Irrigation technologies, *in* Kromm, D.E., and White, S.E., eds., Groundwater exploitation in the High Plains: Lawrence, University Press of Kansas, p. 110–144.

Nebraska Department of Natural Resources, 2002, Registered groundwater wells data base: accessed January–July 2002, at *http://nrcnt3.dnr.state.ne.us/wellssql/wellsindex.asp*

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, Version 3—A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94–464, accessed Feb. 6, 2007, at *http://water.usgs.gov/nrp/gwsoftware/modpath41/modpath41.html*

Qi, S.L., Konduris, Alexandria, Litke, D.W., and Dupree, Jean, 2002, Classification of irrigated land using satellite imagery, the High Plains aquifer, nominal date 1992: U.S. Geological Survey Water-Resources Investigations Report, 02–4236, 35 p.

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

Swinehart, J.B., Dreeszen, V.H., Richmond, G.M., Tipton, M.J., Bretz, R., Steece, F.V., Hallberg, G.R., and Goebel, J.E., 1994, Quaternary geologic map of the Platte River 4° X 6° quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series Map I–1420 (NK-14), 1 plate.

Thelin, G.P., and Heimes, F.J., 1987, Mapping irrigated cropland from Landsat data for determination of water use from 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–C, 38 p., 1 plate.

University of Nebraska–Lincoln, 2000, Quality-assessed agrichemical contaminant database for Nebraska ground water: A cooperative project of the Nebraska Departments of Agriculture, Environmental Quality, and Natural Resources and the University of Nebraska – Lincoln: accessed May 15, 2002 at *http://nrcnt3.dnr.state.ne.us/clearinghouse/index.asp*

Upper Big Blue Natural Resources District, 1999, A study of ground-water pumping for existing uses and proposed industrial development of the Heartland Fibers Processing Plant, York County, Nebraska: York, Nebraska, Upper Big Blue Natural Resources District, August 3, 1999, 32 p.

U.S. Census Bureau, 2003, 2000 Census of population and housing—population and housing unit counts: Washington, D.C., PHC–3–29, Nebraska,

U.S. Geological Survey, 1999-2000, National land cover data base: accessed June 26, 2006, at *http://edcwww.cr.usgs.gov/products/landcover.html*

Verstraeten, I.M., McGuire, V.L., and Heckman, K.L., 1998, Hydrogeology and subsurface nitrate in the Upper Big Blue Natural Resources District, Central Nebraska, July 1995 through September 1997: U.S. Geological Survey Water-Resources Investigations Report 98–4207, 81 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.

Zheng, Chunmiao, and Bennett, G.D., 2002, Applied contaminant transport modeling (2nd ed.): New York, Wiley and Sons, 621 p.