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Scientific Investigations Report 2004-5130

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

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Conversion Factors and Datum

Multiply	By	To obtain
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter
inch (in.)	2.54	centimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Elevation as used in this report refers to distance above or below NAVD 88. NAVD 88 can be converted to National Geodetic Vertical Datum of 1929 (NGVD 29) by using the National Geodetic Survey conversion utility available at URL http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Simulation of Ground-Water Flow in the Cedar River Alluvial Aquifer Flow System, Cedar Rapids, Iowa

By Michael J. Turco and Robert C. Buchmiller

Abstract

The Cedar River alluvial aquifer is the primary source of municipal water in the Cedar Rapids, Iowa, area. Since 1992, the U.S. Geological Survey, in cooperation with the City of Cedar Rapids, has investigated the hydrogeology and water quality of the Cedar River alluvial aquifer. This report describes a detailed analysis of the ground-water flow system in the alluvial aquifer, particularly near well field areas.

The ground-water flow system in the Cedar Rapids area consists of two main components, the unconsolidated Quaternary deposits and the underlying carbonate bedrock that has a variable fracture density. Quaternary deposits consist of eolian sand, loess, alluvium, and glacial till. Devonian and Silurian bedrock aquifers overlie the Maquoketa Shale (Formation) of Ordovician age, a regional confining unit.

Ground-water and surface-water data were collected during the study to better define the hydrogeology of the Cedar River alluvial aquifer and Devonian and Silurian aquifers. Stream stage and discharge, ground-water levels, and estimates of aquifer hydraulic properties were used to develop a conceptual ground-water flow model and to construct and calibrate a model of the flow system. This model was used to quantify the movement of water between the various components of the alluvial aquifer flow system and provide an improved understanding of the hydrology of the alluvial aquifer.

Ground-water flow was simulated for the Cedar River alluvial aquifer and the Devonian and Silurian aquifers using the three-dimensional finite-difference ground-water flow model MODFLOW. The model was discretized into 223 rows and 354 columns of cells. Areal cell sizes range from about 50 feet on a side near the Cedar River and the Cedar Rapids municipal wells to 1,500 feet on a side near the model boundaries and farthest away from the Cedar Rapids municipal well fields. The model is separated into five layers to account for the various hydrogeologic units in the model area.

Model results indicate that the primary sources of inflow to the modeled area are infiltration from the Cedar River (53.0 percent) and regional flow in the glacial and bedrock materials (34.1 percent). The primary sources of outflow from the modeled area are discharge to the Cedar River (45.4 percent) and pumpage (44.8 percent). Current steady-state pumping rates have increased the flow of water from the Cedar River to the alluvial aquifer by 43.8 cubic feet per second. Steady-state and transient hypothetical pumpage scenarios were used to show the relation between changes in pumpage and changes in infiltration of water from the Cedar River. Results indicate that more than 99 percent of the water discharging from municipal wells infiltrates from the Cedar River, that the time required for induced river recharge to equilibrate with municipal pumpage may be 150 days or more, and that ground-water availability in the Cedar Rapids area will not be significantly affected by doubling current pumpage as long as there is sufficient flow in the Cedar River to provide recharge.

Introduction

The Cedar River alluvial aquifer is a primary source of municipal water in the Cedar Rapids, Iowa, area. The City of Cedar Rapids withdraws water for municipal needs from the alluvial aquifer adjacent to the Cedar River in Linn County, in east-central Iowa (fig. 1). Fifty-three vertical and two horizontal collector municipal wells are located along a reach of the Cedar River that extends from near Palo, Iowa, south to Cedar Rapids. The Cedar River alluvial aquifer is the only unconsolidated aquifer in the area capable of supplying large quantities of water for public and industrial use.

Since 1992, the U.S. Geological Survey (USGS), in cooperation with the City of Cedar Rapids, has investigated the hydrogeology and water quality of the Cedar River alluvial aquifer. The studies have expanded the knowledge of surface-water and ground-water interactions in the Cedar River valley and their effects on the quality of the ground-water withdrawn for municipal supply.

In 1994, the nature of this interaction was evaluated by sampling the adjacent alluvial aquifer for biogenic material that infiltrates from the Cedar River and monitoring for selected water-quality constituents to determine the effectiveness of the alluvial aquifer to filter river-borne biogenic material (Schulmeyer, 1995). Travel times of water from the Cedar River to municipal wells were estimated to range from 7 to 10 days based on changes in water-quality indicators.

A regional ground-water flow model was constructed in the mid-1990's to simulate ground-water flow in the Cedar River alluvial aquifer, the Devonian aquifer, and Silurian

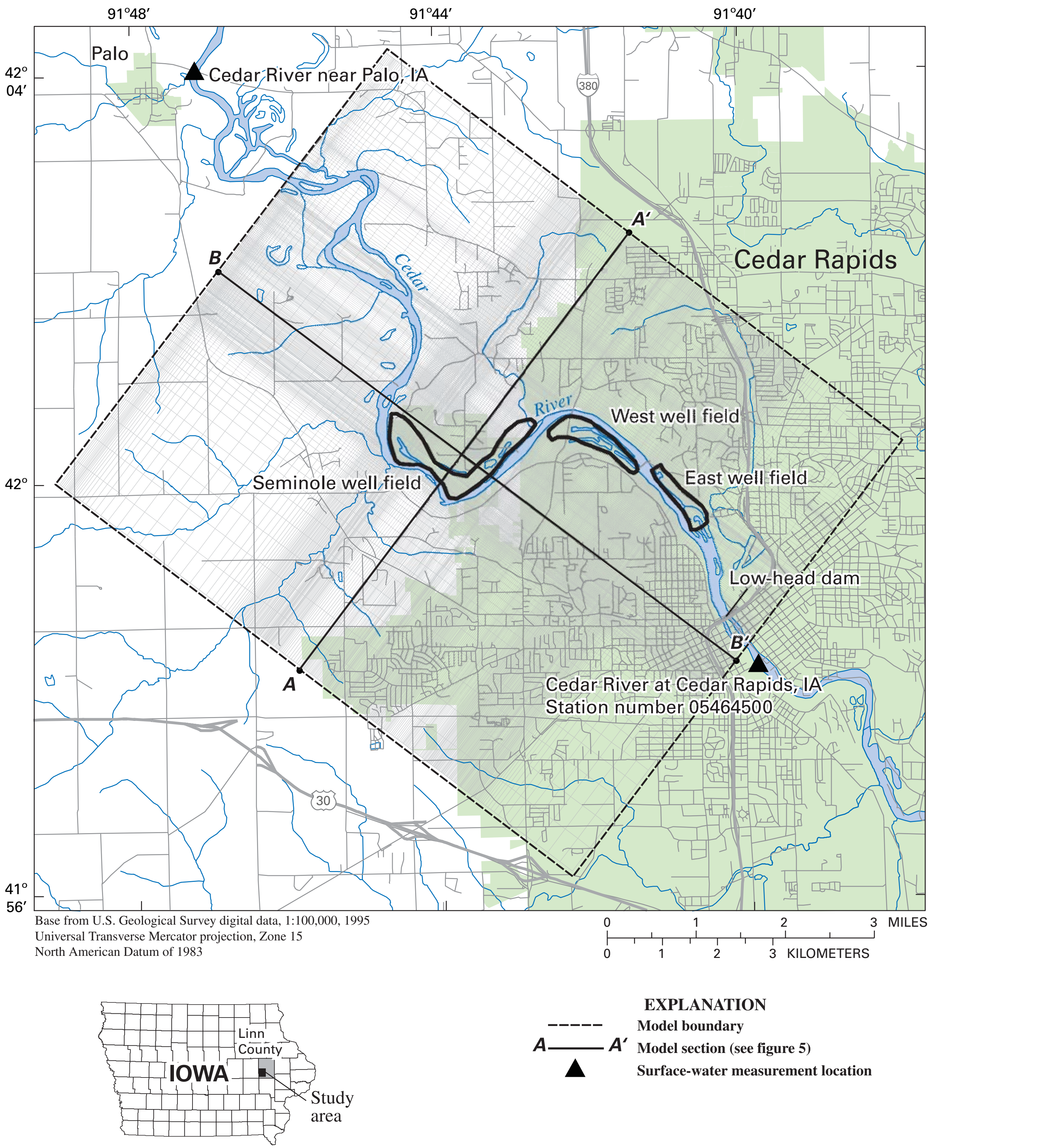


Figure 1. Location of study area and surface-water data-collection sites, extent of digital model, and location of generalized sections through the modeled area near Cedar Rapids, Iowa.

aquifer over a 231-mi^2 area in Benton and Linn Counties near Cedar Rapids (Schulmeyer and Schnoebelen, 1998). The primary sources of inflow to the regional model included infiltration of precipitation and water from the Cedar River to the alluvial aquifer (Schulmeyer and Schnoebelen, 1998). Municipal pumpage accounted for most of the outflow (Schulmeyer and Schnoebelen, 1998). Simulation results, assuming hypothetical climate and water-use conditions, indicated that the interaction of the Cedar River and the adjacent alluvium was more dependent on the total amount of pumpage from the system than the amount of infiltration of precipitation. Since 1999, efforts have been underway to refine the analysis of the interaction between the alluvial aquifer and the Cedar River and to focus specifically on the three Cedar Rapids well field areas.

Purpose and Scope

This report presents the results of a simulation of ground-water flow in the Cedar River alluvial aquifer and underlying bedrock aquifers in the area where municipal water withdrawals occur (alluvial aquifer flow system). The report details the construction of a three-dimensional steady-state and transient ground-water flow model to provide quantitative estimates of the interaction between the alluvial aquifer and the Cedar River and provides an analysis of simulated hypothetical pumping scenarios and the resulting effect on the amount and timing of water infiltrating from the Cedar River. The results can be used to describe the potential range in temporal and spatial variations of surface-water and ground-water interaction in the Cedar River alluvium where municipal pumping causes induced recharge to the aquifer.

Description of Study Area

The study area is located in east-central Iowa and encompasses an area of about 45 mi^2 from about Palo, southeast to Cedar Rapids, and includes about a 20-mi reach of the Cedar River and adjacent unconsolidated deposits (fig. 1). The study area consists of a relatively flat alluvial valley bounded by upland areas. Upland areas in the southeastern half of the study area include steep bluffs with bedrock exposures and incised tributary streams near the Cedar River. The bluffs rise to about 200 ft above the river floodplain. Upland areas in the northwest half of the area consist of lower relief topography. The alluvial valley consists primarily of fluvial and glaciofluvial sand and gravel deposits, whereas the upland areas consist primarily of loess and glacial till. Alluvial deposits, about 100 ft thick, consist primarily of sand and gravel on the inside of river channel bends.

The Cedar River flows predominately from northwest to southeast through the alluvial valley in the central part of the study area. A low-head dam located beneath the Interstate 380 bridge in Cedar Rapids (fig. 1) maintains river stages in the reach adjacent to the most downstream municipal wells during periods of low streamflow. Former river-channel meanders, sloughs, and oxbow lakes are present as wetland areas, particularly in the upper half of the study area. The Cedar River is in direct hydraulic connection with the Cedar River alluvial aquifer. Most pumpage from the Cedar River alluvial aquifer near Cedar Rapids occurs along about 6 mi of alluvium upstream from the low-head dam at depths ranging from about 40 to 72 ft.

The three Cedar Rapids municipal well fields are located primarily north and east of the Cedar River (fig. 2). The Seminole well field (fig. 2) consists of 23 production wells in the floodplain. The West well field, located just downstream from the Seminole well field, consists of 11 production wells. The East well field, located just downstream from the West well field, includes 19 production wells. Two horizontal collector wells (RANEY1, RANEY2) are located southwest across the Cedar River from the Seminole well field (fig. 2).

Land use in much of the northwestern part of the study area is agricultural, mostly corn and soybeans (U.S. Department of Agriculture, 1976). Land use becomes increasingly urban towards the southeastern part of the study area. Riparian areas throughout the study area, as well as areas of steeper topography in the southeastern part of the study area, are forested.

Annual precipitation for 1961-90, at the Eastern Iowa airport (not shown in fig. 1) about 8 mi southwest of the well fields, averages about 36.39 in/yr (National Oceanic and Atmospheric Administration, 1999). Average annual temperature at Cedar Rapids is 49.1ºF.

Acknowledgments

The authors would like to thank the personnel of the Cedar Rapids Water Department for their assistance in data collection and construction of observation wells, G. Ludvigson of the Iowa Department of Natural Resources, Iowa Geological Survey, for the use of geological maps of Linn County, and the numerous USGS field personnel that collected surface-water and ground-water data throughout this study. The authors also thank Mark Savoca and Dan Christiansen, USGS, for their help in converting the conceptual flow model to the digital model and preparing data visualizations.

Methods of Investigation

Surface-water and ground-water data were collected during this study to better define the hydrogeology of the Cedar River alluvial aquifer and Devonian and Silurian aquifers, and to assist in construction of the ground-water flow model. Data were collected at three surface-water sites along the Cedar River and 23 drilled observation wells screened in the Cedar River alluvium. Wells used for this study were selected on the basis of their location and aquifer completion, with an emphasis on a spatial distribution that would adequately represent the ground-water flow system at varying distances from the Cedar River in the Cedar River alluvial aquifer near the municipal well fields.

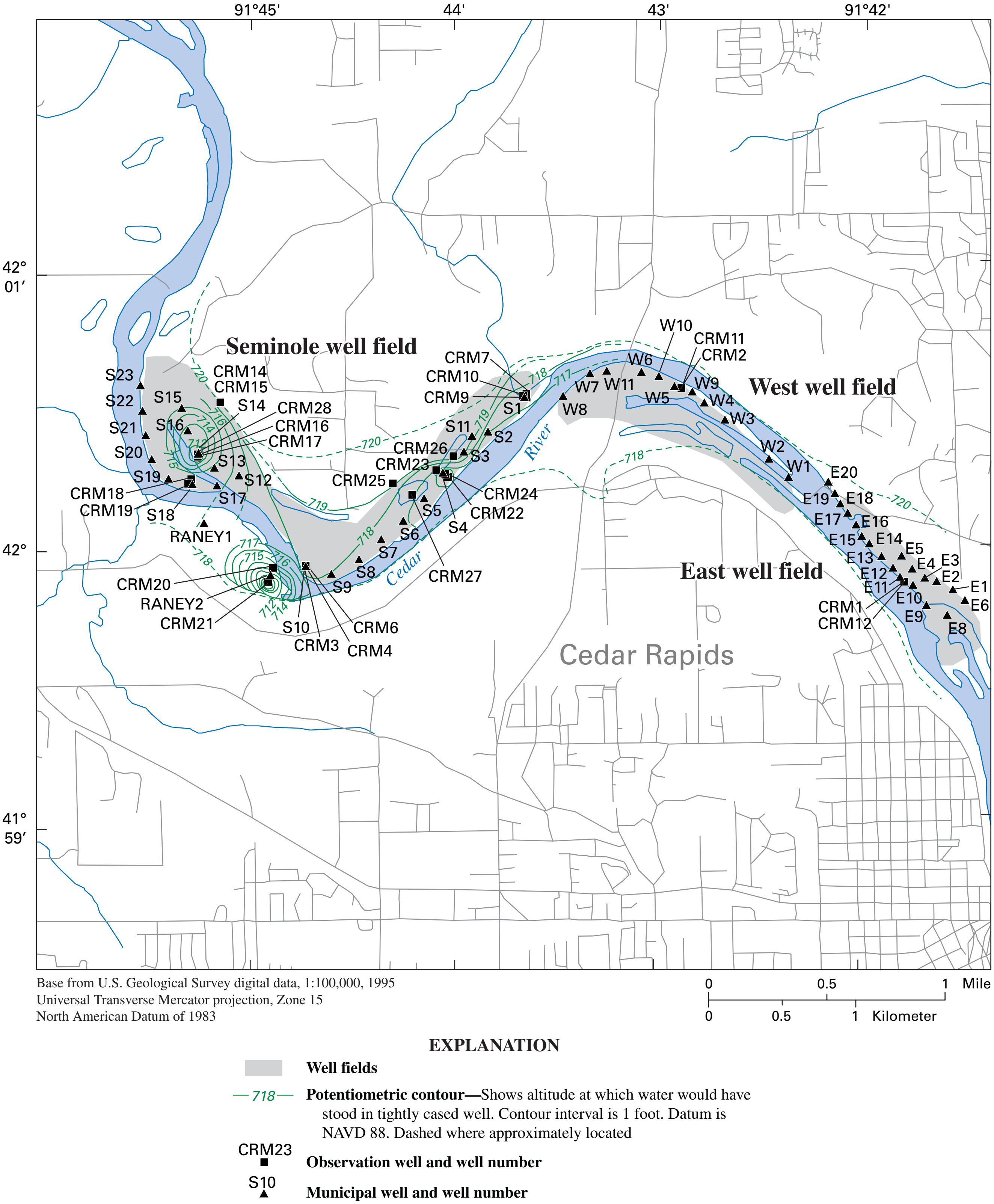


Figure 2. Location of wells used in the modeled area and potentiometric surface of the Cedar River alluvial aquifer near Cedar Rapids, Iowa, December 21, 1998 (area shown in figure 1).

Ground-water flow in the study area was simulated using the USGS three-dimensional finite-difference ground-water flow model MODFLOW (Harbaugh and McDonald, 1996). Model parameters interpolated into the finite-difference grid and simulation results were processed using the U.S. Department of Defense's Groundwater Modeling System (GMS) (Brigham Young University, 1998). The model was used to obtain a better understanding of ground-water flow in the Cedar River alluvial aquifer, to provide a quantitative estimate of the water budget in the study area, and to evaluate the effect of several hypothetical pumping scenarios on the variability of surface-water and ground-water interaction in the study area.

Surface-Water Measurements

Streamflow and stage data have been collected periodically from 1902 to 2003 at the USGS streamflow-gaging station Cedar River at Cedar Rapids (05464500) (fig. 1) as part of the USGS streamflow network in Iowa (Nalley and others, 2003). Synoptic surface-water discharge measurements for this study were made at two additional selected sites along the Cedar River near the town of Palo and from the U.S. Highway 30 bridge (not shown) southeast of Cedar Rapids in November 2000 during base-flow conditions and in May 2001 during high-flow conditions. The synoptic discharge measurements were used to identify and evaluate losing or gaining reaches along the Cedar River in the study area. Measured streamflow and stage data were utilized in the construction and calibration of the ground-water flow model.

Well Construction and Nomenclature

Twenty-three observation wells used for this study were installed during previous investigations of the Cedar River and the Cedar River alluvial aquifer (Schulmeyer, 1995; Schulmeyer and Schnoebelen, 1998). Observation wells were developed by pumping three or four casing volumes of water to assure a representative water level was obtainable (Schulmeyer and Schnoebelen, 1998). All observation and municipal wells were surveyed for vertical control and referenced to North American Vertical Datum of 1988 and location with a combination of Global Positioning System (GPS) and conventional surveying techniques (Schulmeyer and Schnoebelen, 1998). Observation wells were identified by a local site name containing CRM (Cedar Rapids Municipal) as a prefix followed by a unique number (for example, CRM7). Further information on these wells and the methods of their construction is available in Schulmeyer and Schnoebelen (1998).

Ground-Water Measurements

Measured ground-water levels (table 1) were used to evaluate the local flow directions in the study area, to evaluate the seasonal variation in horizontal and vertical ground-water flow, to aid in the development and validation of the conceptual ground-water flow model, and to aid in the calibration of the steady-state and transient numerical model simulations. Automatic water-level recorders measured water levels every 5 minutes in all 23 observation wells. Periodic ground-water levels were manually measured to calibrate and verify automatically collected data. Manual ground-water levels were measured from 1993 to 2002 using a chalked, graduated steel-tape.

Aquifer Properties

Specific-capacity data provided by the City of Cedar Rapids for municipal wells (table 2) and hydraulic conductivities reported in Schulmeyer and Schnoebelen (1998) were used as initial estimates of the hydraulic conductivity of the geologic materials in the study area. In this report, hydraulic conductivity refers to horizontal hydraulic conductivity unless specifically referred to as vertical hydraulic conductivity.

Hydrogeology

Hydrogeologic units in the study area and their water-bearing characteristics are summarized in table 3. Additional hydrogeologic information relevant to the description of the conceptual ground-water flow system and the construction of the ground-water flow model has been presented in previous publications (Schulmeyer, 1995; Schulmeyer and Schnoebelen, 1998). For a more detailed geologic description of the bedrock units in the study area the reader is referred to Horick (1984) and Olcott (1992).

Geology and Water-Bearing Characteristics

A variety of unconsolidated materials and bedrock units are in direct hydraulic connection in various stratigraphic combinations throughout the study area. Deposits of Quaternary age, ranging in thickness from about 10 to 300 ft in the study area, compose a complex surficial-aquifer system. Quaternary deposits include: the Cedar River alluvium, tributary stream alluvium, eolian sand and loess, buried-channel sand and gravel, and fractured and unfractured glacial till. All of these lithologies have variable permeability, both vertically and horizontally. Limestone of Devonian age forms the uppermost bedrock in some parts of the study area, but is not present throughout the study area. The Otis and Bertram Formations of Devonian age form a local confining unit, separating the Devonian and Silurian bedrock units in most of the study area. Dolomite of Silurian age underlies the entire study area. The Maquoketa Shale (Formation) of Ordovician age, a regional confining unit, underlies the Silurian dolomite.

Aquifers in the study area include the Cedar River alluvial aquifer, tributary stream alluvial aquifers, a buried-channel aquifer, the Devonian aquifer, and the Silurian aquifer.

Table 1. Statistical summary of measured water levels in observation wells near Cedar Rapids, Iowa, 1997-99.

[NAVD 88, North American Vertical Datum of 1988]

Observation well number (fig. 2)	Land-surface elevation (feet above NAVD 88)	Minimum measured water level (feet above NAVD 88)	Date of minimum water level	Maximum measured water-level elevation (feet above NAVD 88)	Date of maximum water level	Assumed steady-state water-level elevation (feet above NAVD 88)	Date of steady-state water-level measurement
CRM1	721.26	695.84	11/14/97	720.95	08/10/98	718.85	12/21/98
CRM2	719.52	708.90	03/03/98	717.15	06/12/98	714.78	12/21/98
CRM3	726.71	710.84	02/13/97	723.81	06/22/98	718.29	12/21/98
CRM4	726.45	710.58	02/13/97	724.47	06/22/98	716.08	12/21/98
CRM7	720.38	716.29	10/29/98	721.25	03/17/97	717.58	12/21/98
CRM9	720.55	717.11	08/14/97	721.24	03/17/97	717.60	12/21/98
CRM10	720.65	717.88	12/21/98	718.00	12/04/98	717.88	12/21/98
CRM11	719.24	710.07	03/04/98	718.56	04/06/98	716.01	12/21/98
CRM12	721.99	695.58	01/26/98	721.30	08/10/98	719.24	12/21/98
CRM14	730.00	717.39	12/21/98	720.03	10/29/98	717.39	12/21/98
CRM15	730.00	715.43	02/13/97	728.44	10/07/98	717.46	12/21/98
CRM16	725.00	704.98	02/13/97	723.09	04/03/98	711.59	12/21/98
CRM17	725.00	708.61	02/21/98	722.80	04/03/98	711.29	12/21/98
CRM18	723.00	703.08	02/14/97	725.27	03/17/97	715.66	12/21/98
CRM19	723.00	701.54	02/14/97	724.03	03/17/97	715.40	12/21/98
CRM21	720.00	710.66	10/29/98	710.66	10/29/98	710.66	10/29/98
CRM22	720.00	716.26	12/21/98	723.00	06/23/98	716.26	12/21/98
CRM23	722.00	718.24	12/04/98	726.50	06/22/98	720.98	12/21/98
CRM24	720.00	714.54	12/21/98	724.42	06/23/98	714.54	12/21/98
CRM25	725.00	719.17	12/21/98	724.76	04/06/98	719.17	12/21/98
CRM26	722.00	718.81	09/28/98	720.28	10/29/98	719.24	12/21/98
CRM27	722.00	717.37	12/21/98	720.78	04/29/98	717.37	12/21/98
CRM28	725.00	706.63	05/18/98	723.00	04/06/98	706.81	12/21/98

Table 2. Construction information and estimated hydrologic properties for municipal water wells near Cedar Rapids, Iowa.

[ft, feet; in., inches; (gal/min)/ft, gallons per minute per foot; ft^2/d, feet squared per day; ft/d, feet per day; NAVD 88, North American Vertical Datum of 1988; NR, no record; specific-capacity, transmissivity, and hydraulic-conductivity data from Schulmeyer and Schnoebelen (1998)]

Municipal well number (fig. 2)	Land-surface elevation (ft above NAVD 88)	Well depth (ft)	Diameter of casing (in.)	Depth to top of well screen (ft)	Length of well screen (ft)	Distance to surface water[1] (ft)	Specific capacity [(gal/min)/ft]	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)
East well field									
E1	728	70.0	30	50.0	20.0	63	21.10	2,706	38.70
E2	728	72.0	30	52.0	20.0	126	23.70	3,153	43.80
E3	728	72.0	30	52.0	20.0	400	42.90	6,156	85.50
E4	728	72.0	30	52.0	20.0	400	51.30	7,362	102.30
E5	728	71.6	30	51.6	20.0	67	45.70	6,558	91.70
E6	726	70.0	30	50.0	20.0	80	29.40	4,006	57.20
E8	724	69.6	30	NR	20.0	80	14.20	1,738	25.00
E9	725	67.0	30	54.0	13.0	80	28.50	3,884	58.00
E10	726	67.0	30	52.0	15.0	86	26.10	3,472	51.80
E11	726	56.5	30	36.5	20.0	36	29.20	3,979	70.40
E12	724	61.0	30	41.0	20.0	43	50.90	7,304	119.70
E13	724	61.0	30	41.0	20.0	48	39.10	5,439	89.20
E14	724	65.0	30	44.5	20.0	53	32.20	4,388	67.50
E15	724	67.0	30	47.0	20.0	32	75.00	11,467	171.10
E16	724	69.0	30	49.0	20.0	49	74.20	11,345	164.40
E17	721	59.0	30	39.0	20.0	62	100.00	15,770	267.30
E18	721	59.0	30	39.0	20.0	57	96.50	14,754	250.10
E19	721	57.0	30	37.0	20.0	56	62.20	9,148	160.50
E20	721	56.0	30	36.0	20.0	52	97.00	17,650	315.20
West well field									
W1	724	64.0	30	34.0	10.0	33	75.00	11,467	179.20
W2	723	72.2	30	62.2	10.0	68	25.00	3,326	46.10
W3	723	72.4	30	62.4	10.0	31	12.60	1,543	21.30
W4	724	69.0	30	54.0	15.0	90	17.80	2,283	33.10
W5	723	68.0	30	53.0	15.0	132	NR	NR	NR
W6	723	70.9	30	NR	NR	93	39.50	5,597	78.90
W7	724	51.5	30	36.5	15.0	30	31.30	4,354	84.50
W8	724	61.8	30	51.8	10.0	30	24.10	3,206	51.90
W9	724	63.0	30	48.0	15.0	38	122.00	19,240	305.40

Table 2. Construction information and estimated hydrologic properties for municipal water wells near Cedar Rapids, Iowa.—Continued

[ft, feet; in., inches; (gal/min)/ft, gallons per minute per foot; ft^2/d, feet squared per day; ft/d, feet per day; NAVD 88, North American Vertical Datum of 1988; NR, no record; specific-capacity, transmissivity, and hydraulic-conductivity data from Schulmeyer and Schnoebelen (1998)]

Municipal well number (fig. 2)	Land-surface elevation (ft above NAVD 88)	Well depth (ft)	Diameter of casing (in.)	Depth to top of well screen (ft)	Length of well screen (ft)	Distance to surface water[1] (ft)	Specific capacity [(gal/min)/ft]	Transmis-sivity (ft^2/d)	Hydraulic conductivity (ft/d)
West well field—Continued									
W10	724	67.0	30	52.0	15.0	64	63.60	9,354	139.60
W11	724	66.0	30	21.0	15.0	67	67.00	10,244	155.20
Seminole well field									
S1	720	64.0	30	53.8	10.2	62	17.80	2,793	43.70
S2	720	53.9	30	43.9	10.0	38	60.00	10,537	195.50
S3	720	62.9	30	52.6	10.2	100	68.60	12,482	198.40
S4	720	54.9	30	34.7	10.2	210	53.10	9,325	169.90
S5	720	64.0	30	34.7	10.2	42	83.30	15,157	236.80
S6	721	61.1	30	50.9	10.2	41	62.20	10,923	178.80
S7	721	63.1	30	52.9	10.2	60	84.20	15,320	242.80
S8	722	57.3	30	47.1	10.2	116	39.90	6,877	120.00
S9	724	57.5	30	47.2	10.2	115	60.00	10,537	183.30
S10	725	68.6	30	58.4	10.2	48	61.70	10,836	158.00
S11	722	62.0	30	47.0	15.0	235	42.00	6,027	97.20
S12	724	58.0	30	43.0	15.0	500	31.20	4,251	73.30
S13	724	61.0	30	46.0	15.0	500	53.80	7,913	129.70
S14	725	59.0	30	44.0	15.0	800	25.40	3,374	57.20
S15	727	62.0	30	47.0	15.0	800	43.50	6,242	100.70
S16	726	65.0	30	50.0	15.0	900	24.80	3,296	50.70
S17	724	58.0	30	34.0	20.0	63	73.10	11,177	192.70
S18	724	52.0	30	32.0	20.0	81	NR	NR	NR
S19	724	40.0	30	28.0	12.0	75	NR	NR	NR
S20	719	43.0	30	28.0	15.0	52	NR	NR	NR
S21	716	51.7	30	36.7	15.0	78	NR	NR	NR
S22	721	57.0	30	42.0	15.0	86	NR	NR	NR
S23	724	57.0	30	40.0	17.0	70	NR	NR	NR

[1]Lateral distance to surface-water source was measured March 22, 1994.

Table 3. Hydrogeologic units in the study area, water-bearing characteristics, and lithology.

[gal/min, gallons per minute; <, less than; >, more than]

System[1]	Estimated thickness[2] (feet)	Hydrogeologic unit[2]	Potential well yield[2]	Lithology[2]
Quaternary	5-95	Cedar River alluvial aquifer	A major source of water in the Cedar Rapids area, well yields can be greater than 1,000 gal/min.	Fining upward sequence of gravel and sand with minor amounts of silt and clay (Schulmeyer and Schnoebelen, 1998).
	<50	Tributary stream alluvial aquifers	Not a major source of ground water.	Occurs along streambeds of tributaries of the Cedar River and is composed of gravel, sand, silt, and clay (Schulmeyer and Schnoebelen, 1998).
	10-300	Buried-channel aquifer	Not a major source of water to the City of Cedar Rapids but may yield a large volume of water.	Silt, fine- to coarse-grained sand, and coarse-grained angular gravel (Schulmeyer and Schnoebelen, 1998).
	1->300	Other Quaternary deposits (glacial till, loess, eolian sand)	Not a major source of water.	Glacial material predominately consists of clay (till), silt (loess) and sand (eolian sand) (Schulmeyer and Schnoebelen, 1998).
Devonian	<1-145	Devonian aquifer	In areas where the aquifer is highly fractured, the substantial increases in secondary permeability may yield more than 2,000 gal/min with little drawdown.	Fractured limestone that is deeply weathered where exposed (Schulmeyer and Schnoebelen, 1998).
	<1-150	Otis and Bertram Formations (local confining unit)	Not a major source of water.	Limestone, dolomite and interbedded shale (Schulmeyer and Schnoebelen, 1998).
Silurian	150-350	Silurian aquifer	Well yields can be as low as 10 percent of those from the Devonian aquifer.	Dolomite with some chert (Schulmeyer and Schnoebelen, 1998).
Ordovician	150-350	Maquoketa Formation[3] (local confining unit)	Not a major source of water.	Green dolomitic shale and medium- to coarse-grained dolomite and limestone (Schulmeyer and Schnoebelen, 1998).

[1]System for unconsolidated deposits and formations defined by the Iowa Department of Natural Resources, Iowa Geological Survey.

[2]Modified from Horick (1984) and Olcott (1992).

[3]Also defined as the "Maquoketa Shale."

The Cedar River alluvial aquifer consists of Cedar River alluvium and varies in thickness from about 5 to 95 ft (Hansen, 1970). The thickness of the alluvium decreases as distance to the Cedar River increases; the thinnest alluvium is adjacent to the valley walls. The Cedar River alluvium is composed of gravel and sand, with minor amounts of silt and clay. Hansen (1970) calculated the approximate transmissivity of the alluvial aquifer to be about 20,000 ft^2/d. Subsequent investigations by Schulmeyer (1995) suggest transmissivity ranges from about 1,500 to about 19,000 ft^2/d using the modified Theis equation (Heath, 1987).

Aquifers associated with tributary stream alluvium and localized deposits of loess and eolian sand overlie glacial till and are of little importance in the study area and thus will not be described in detail. Hydraulic conductivity for the loess and eolian-sand deposits is estimated to be approximately 1.2×10^{-3} ft/d and 2 ft/d, respectively, by Hallberg (1980), or a transmissivity of about 2.4×10^{-2} ft/d and 40 ft/d, respectively, assuming a 20-ft thickness. Tributary stream alluvial aquifers are present along small streams tributary to the Cedar River. An estimated hydraulic conductivity of about 28 ft/d for the tributary stream alluvial aquifers is presented in Kunkle

(1965), or a transmissivity of about 1,400 ft^2/d assuming a thickness of 50 ft for this deposit.

A buried-channel aquifer is located along the northwestern border of the model area and is in proximity to the city of Palo (figs. 3 and 4). The thickness of the buried-channel aquifer ranges from about 10 ft to almost 300 ft. This aquifer is in direct hydraulic connection with all three major underlying bedrock units and underlies the Cedar River alluvium and glacial-till deposits. The aquifer consists primarily of silt, fine- to coarse-grained sand, and coarse gravel. Hansen (1970) reports a yield of about 67,000 ft^3/d from a well completed in the buried-channel aquifer.

The unconsolidated material in the upland areas adjacent to the alluvial aquifers in the study area is composed predominately of glacial till of Pre-Illinoian age. The till consists primarily of clay with discontinuous lenses of silt, sand, and gravel with occasional pebbles and boulders (Schulmeyer and Schnoebelen, 1998). Thickness of the deposits ranges from about 1 ft to more than 300 ft (Hansen, 1970). The hydrogeologic properties of the glacial deposits in the study area are described in more detail in Schulmeyer and Schnoebelen (1998). The upper part of the till is mostly oxidized and fractured whereas the deeper unweathered till is unoxidized and unfractured. Hydraulic conductivities of about 8.5 x 10^{-3} ft/d for the fractured till and 5.7 x 10^{-5} ft/d for the unfractured till have been reported (W. Simpkins, Iowa State University, oral commun., 1994 *from* Schulmeyer and Schnoebelen, 1998).

The Devonian aquifer is composed of bedrock of Devonian age that uncomformably underlies the Quaternary deposits and can be exposed at land surface or at depths of up to about 100 ft. The topography of the bedrock surface indicates that substantial weathering has occurred in the study area because much of the Devonian rocks have been removed by erosion near the Cedar River alluvial and buried-channel aquifer. The thickness of the remaining Devonian bedrock in the study area can range from less than 1 ft to about 145 ft. The hydraulic conductivity of the Devonian aquifer varies greatly depending on the degree of fracturing, dissolution, and other weathering processes. Hydraulic-conductivity values for the Devonian aquifer range from 4 to 294 ft/d (Libra and Hallberg, 1985).

The Otis and Bertram Formations of Devonian age form a local confining unit that restricts the vertical flow of water between the Devonian and underlying Silurian bedrock. The formations consist primarily of limestone, dolomite, and a basal shale. Similar to the overlying Devonian bedrock, the Otis and Bertram Formations also have been removed in parts of the study area. The thickness of the formations can range from less than 1 ft to about 150 ft in the study area. Where the Otis or Bertram Formation is the uppermost bedrock unit and is weathered, the unit can have the same hydrogeologic properties as the overlying Devonian bedrock (Schulmeyer and Schnoebelen, 1998).

The Silurian aquifer is composed of bedrock of Silurian age and consists of dolomite and is continuous throughout the study area (Horick, 1984). The topography of the Silurian bedrock indicates little weathering in the study area, with the exception of the areas beneath the Cedar River valley and the northern part of the buried-channel aquifer (figs. 3 and 4) where the Silurian bedrock is the uppermost unit. The thickness of the unit in the study area ranges from about 150 to 350 ft. A transmissivity of about 1,349 ft^2/d and a hydraulic conductivity of about 6.1 ft/d for a well completed in the Silurian aquifer was estimated from a pumping test (Hansen, 1970).

The Maquoketa Shale (Formation) of Ordovician age is the lowermost unit in the conceptual model of the flow system and is a regional confining unit. This formation consists predominately of shale, limestone, and dolomite. This low-permeability unit restricts the vertical flow of water and is not known to yield substantial quantities of water to wells (Hansen, 1970).

Surface Water

The major surface-water body in the study area is the Cedar River. The river has its headwaters in southern Minnesota and flows southeasterly to its confluence with the Iowa River in southeast Iowa. The Cedar River acts as the regional hydrologic control for discharge of the surficial ground-water systems in the absence of anthropogenic stresses. In the study area, the Cedar River has eroded through and removed all of the glacial deposits, the Devonian age bedrock, and most of the Otis and Bertram Formations in the vicinity of Cedar Rapids. The annual mean daily flow for 1903-99 is 3,760 ft^3/s; the highest daily flow of 71,500 ft^3/s occurred on March 31, 1961. Historically, March and April have greater daily mean flows than other months of the year (Nalley and others, 2003). Flow at the Cedar River at Cedar Rapids streamflow-gaging station exceeds 680 ft^3/s 90 percent of the time.

Synoptic surface-water-discharge measurements were made at two sites along the Cedar River in the study area on November 16, 2000, and May 29, 2001. The November measurements showed a loss of streamflow from Palo to the Cedar River at Cedar Rapids gage of about 130 ft^3/s, and a gain of about 300 ft^3/s for the reach from the gage to U.S. Highway 30. The May measurements were made during a period of high flow and all reaches were gaining reaches, likely due more to tributary stream contributions to the Cedar River rather than additional ground-water discharge.

Other surface-water features in the study area include oxbow lakes and abandoned channels in the Cedar Rapids well field areas created by the historical meandering of the Cedar River. The oxbow lakes predominately have fine-grained bed material that limits or reduces infiltration into the alluvial aquifer. During periods of Cedar River base flow, fine-grained material may be deposited on the riverbed upstream from the low-head dam, reducing the conductance of the riverbed and decreasing the movement of water between the river and the alluvial aquifer.

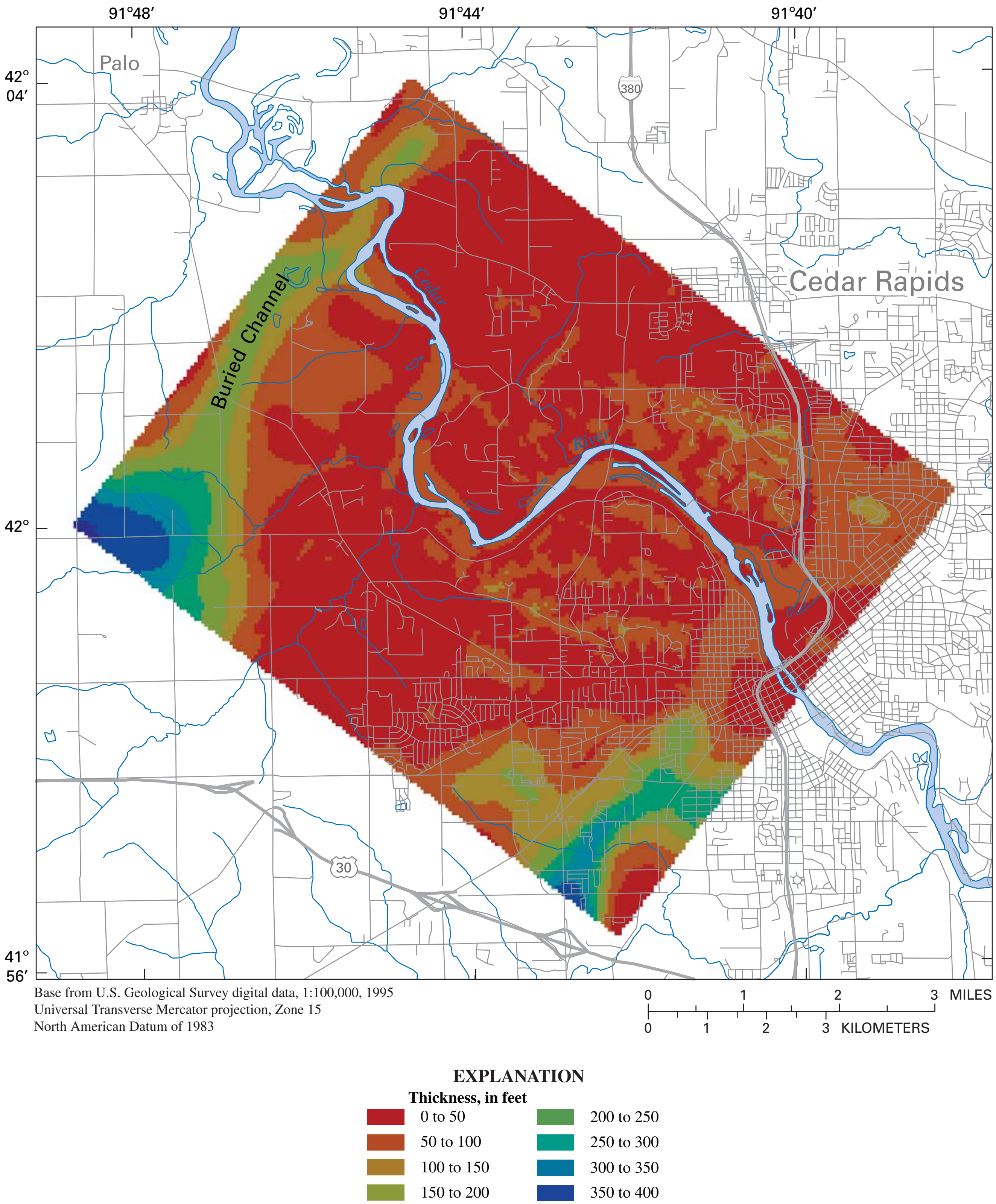


Figure 3. Thickness of the Cedar River alluvium and adjacent Quaternary deposits in the modeled area near Cedar Rapids, Iowa.

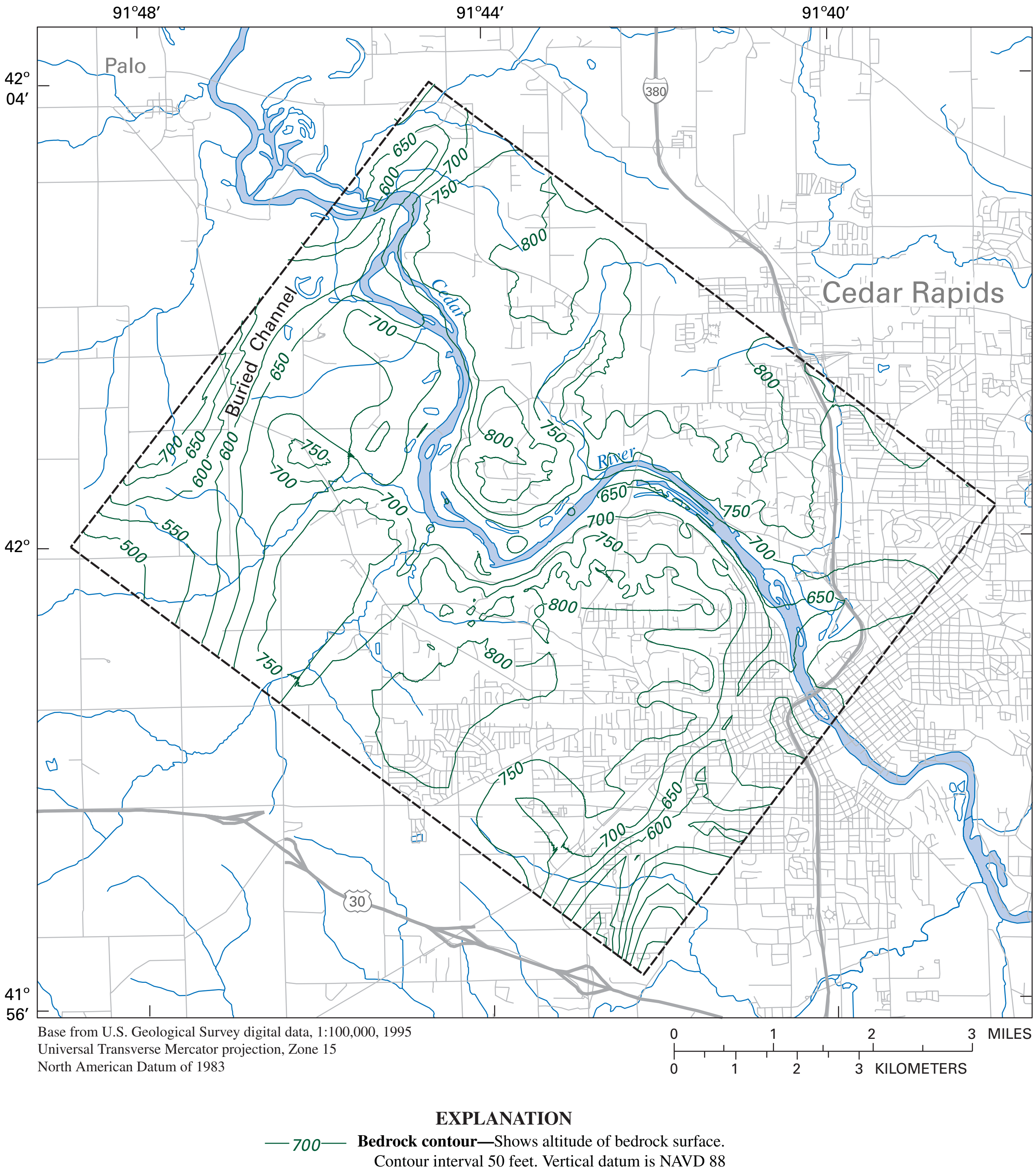


Figure 4. Altitude and configuration of the bedrock surface in the modeled area near Cedar Rapids, Iowa.

Ground Water

The ground-water flow system in the Cedar Rapids area is composed of two main components, the unconsolidated Quaternary deposits and the underlying bedrock that has a variable fracture density. These two components are in direct hydraulic connection throughout the study area and have variable thicknesses and water-bearing characteristics (table 3). The flow system is composed of both local and regional flow systems, all of which would discharge to the Cedar River under predevelopment conditions.

In the absence of pumpage from the Cedar River alluvial aquifer, ground-water flow is typically towards the Cedar River and down the Cedar River valley. During periods of rapid stage increase in the Cedar River, ground-water flow gradients can be temporarily reversed and water flows from the river to the alluvial aquifer. Pumping, as currently occurs in the study area, also can reverse the normal direction of ground-water flow in the vicinity of the municipal well(s) and induce infiltration from the Cedar River to the alluvial aquifer. Drawdown cones surrounding several of the Cedar Rapids municipal wells caused by pumpage on December 21, 1998, are shown in figure 2.

Recharge to the alluvial aquifer is from infiltration of precipitation and runoff from the upland areas adjacent to the alluvial aquifer, infiltration of Cedar River water in areas of municipal pumpage, and regional flow from underlying bedrock units. Discharge from the alluvial aquifer is primarily to the Cedar River and municipal pumpage.

Ground-water flow in the Devonian and Silurian aquifers is primarily regional and is not significantly influenced by local conditions. Historically, the two aquifers were considered to be hydrogeologically similar and were referred to as the Silurian-Devonian aquifer (Horick, 1984). However, recent investigations have shown that the two aquifers have significantly different hydrogeologic properties in many areas. The Devonian aquifer, when present as the uppermost bedrock unit, can have hydraulic conductivities an order of magnitude larger than the Silurian aquifer due to increased secondary permeability, primarily fractures enhanced by dissolution (Turco, 2002). Recharge to the bedrock aquifers occurs regionally where the bedrock is exposed at land surface outside of the study area or through vertical flow from overlying Quaternary deposits. The Devonian and Silurian aquifers are physically separated in most parts of the study area by the confining unit composed of the Otis and Bertram Formations. The primary flow direction for the two bedrock aquifer systems is towards the Cedar River and down the Cedar River valley, much like the overlying Cedar River alluvial aquifer. The primary area of discharge for the Devonian and Silurian aquifers is the Cedar River alluvial aquifer, though there is a regional flow component to the southeast of the study area. The bedrock aquifers are described in greater detail in Schulmeyer and Schnoebelen (1998).

Simulation of Ground-Water Flow

Ground-water flow was simulated for the Cedar River alluvial aquifer and the Devonian and Silurian aquifers using the three-dimensional finite-difference ground-water flow model MODFLOW (Harbaugh and McDonald, 1996). MODFLOW can simulate ground-water flow in a three-dimensional heterogeneous and anisotropic medium, using a partial differential equation where the partial derivatives represent the movement of water, provided that the principle axes of hydraulic conductivity are aligned with the coordinate system (Harbaugh and McDonald, 1996). The flow equation was solved using the preconditioned conjugate-gradient (PCG2) procedure (Hill, 1990), a method that allows for both linear and non-linear flow conditions.

The flow model was constructed to simulate both steady-state and transient conditions. Steady-state conditions occur when the volumetric rate of water entering a system equals the volumetric rate of water flowing out of the system. Steady-state conditions represent a ground-water flow system that is at equilibrium with a set of constant, specified stresses. Ground-water levels measured in December 1998 in the Cedar River alluvial aquifer and the Devonian aquifer were considered to be an acceptable estimate of steady-state conditions. Ground-water levels and streamflow during this time show little variation. No water-level measurements were available for the Silurian aquifer; however, there are no known significant or varying stresses on this aquifer in the study area. The stage of the Cedar River was simulated assuming base-flow conditions. Recharge, used to account for infiltration of precipitation and evapotranspiration, was assumed to be the average daily recharge to the system.

The transient model was used to simulate changes that occur in the ground-water flow system with respect to time, as opposed to the steady-state model, which does not specify the amount of time required to reach equilibrium. The transient model was calibrated using a rise in river stage that occurred during the months of February-March 1998. This increase in river stage was caused by an increase in air temperature and resultant snowmelt. The transient simulations used hypothetical pumping scenarios to evaluate the time-dependant effects of pumping rates on the movement of water infiltrating the alluvial aquifer from the Cedar River.

Model Description and Boundary Conditions

The MODFLOW model grid covers an area of 45 mi^2 and simulates ground-water flow through all hydrogeologic units described in the “Geology and water-bearing characteristics” section. The modeled area is variably discretized into 223 rows and 354 columns, with a finer mesh grid near the Cedar Rapids municipal wells and larger cell sizes near the outer edges of the model (fig. 1). Cells range from about 50 ft to about 1,500 ft on a side. The model was constructed using bedrock topology developed by the Iowa Department of Natural Resources-Iowa Geological Survey.

Five model layers were used to represent the major hydrogeologic units in the model area (table 4). Hydrogeologic units are assigned to specific model layers, based on unconsolidated and bedrock lithology, which simplifies the conceptualization of the model. Layers 1 and 2 represent the unconsolidated deposits. Layer 1 represents the upper 15 ft of the unconsolidated material, which includes loess, eolian sand, fractured glacial till, and the uppermost portions of the Cedar River alluvial and buried-channel aquifers. Layer 2 represents the remainder of the fractured and unfractured glacial till in the upland areas and includes the lower, coarser grained parts of the Cedar River alluvial and buried-channel aquifer. Municipal water withdrawals are made from layer 2. The Devonian aquifer, Otis and Bertram confining unit, and Silurian aquifer are represented in the model as layers 3, 4, and 5, respectively. The approximate thickness of the five layers is shown in two generalized sections through the modeled area in figure 5. Model layers were simulated as unconfined (layer 1), convertible (layers 2, 3, 4), and confined (layer 5). Simulated hydrologic conditions can change from unconfined to confined in convertible layers depending on the simulated water-table surface.

The model area is limited in size compared to the lateral extent of the unconsolidated and bedrock aquifers being investigated. To represent this limitation, model boundary conditions are used to account for conceptualized flow from areas beyond the extent of the modeled area.

The top of layer 1 is simulated as a “free surface” allowing water to enter the system by way of recharge and leave the system by way of evapotranspiration. The perimeter of the model is bounded by a combination of variable-flux boundaries, termed general-head boundaries, and no-flow boundaries. Layers 1 and 2 of the model are simulated using no-flow boundaries on the northeastern and southwestern margins to simulate conceptualized ground-water flow divides associated with surface-water basin boundaries, and on the northwestern and southeastern margins to simulate conceptualized flow parallel to ground-water flow paths towards the Cedar River. The boundaries of the bedrock units, layers 3, 4, and 5, are simulated with general-head boundaries along the northeastern and southwestern margins and with no-flow boundaries along the northwestern and southeastern margins. The general-head boundaries are based on relative head differences between the model cells and the regional potentiometric surface. A constant head source is placed 1 mi from the closest active model cell, and the hydraulic conductivity of the laterally adjacent unit is used in the computation of ground-water flux across the boundary. The ground-water level at the boundary was derived from simulated heads in the regional model (Schulmeyer and Schnoebelen, 1998). The bottom of layer 5, the lowest simulated hydrogeologic unit, is simulated as a no-flow boundary associated with the Maquoketa Shale regional-confining unit.

Table 4. Values of hydraulic conductivity and storage used for the various hydrogeologic units in the study area.

[ft/d, feet per day; --, not applicable]

System[1]	Hydrogeologic unit	Generalized lithology	Model layer	Horizontal hydraulic conductivity (ft/d)	Vertical hydraulic conductivity (ft/d)	Specific yield (dimensionless)	Specific storage (per foot)
Quaternary deposits	Loess, eolian sand	Silt, clay	1	10.00	1.00	0.40-0.42	--
	Glacial till	Fractured, oxidized clay	1, 2	40.00	4.00	0.10	0.0005
	Glacial till	Unfractured, unoxidized clay	2	4.00	1.00	0.05	0.002
	Cedar River alluvial aquifer	Silty, fine-grained sand	1	4-100	1-10	0.25	0.0002
		Fine- to medium-grained sand	1, 2	170-432	17-43	0.30-0.40	0.00005
		Medium- to coarse-grained sand	1, 2	170-600	17-60	0.45	0.00005
	Buried channel aquifer	Medium- to coarse-grained sand	2	40-500	4-50	0.45	0.00001
Devonian	Devonian aquifer	Limestone and dolomite	3	0.1-350	0.001-1.0	0.1-0.15	0.00001
	Otis-Bertram[2] confining unit	Limestone, dolomite, and shale	4	0.1-350	0.001-.01	0.01-.05	0.00001
Silurian	Silurian aquifer	Dolomite	5	0.1-10.0	0.001-1.0	0.1-0.15	0.00001

[1]System for unconsolidated deposits and formations defined by the Iowa Department of Natural Resources, Iowa Geological Survey.

[2]For convenience, the Otis Formation and Bertram Formation are combined to form a local confining unit.

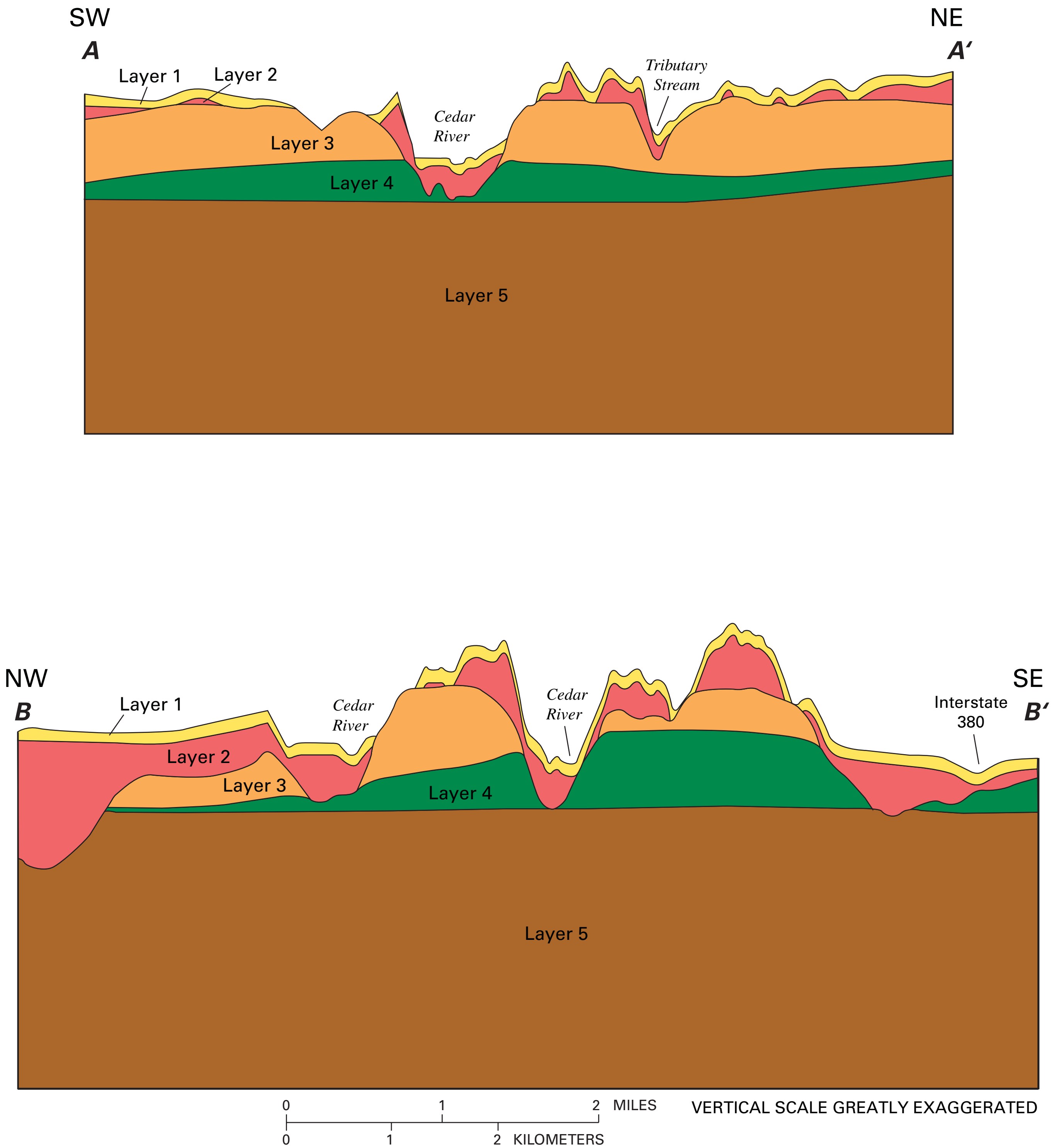


Figure 5. Generalized model sections A-A′ and B-B′ based on ground-water flow model layer construction. Traces of sections shown in figure 1.

Model Parameters

The ground-water flow model includes large arrays of numerical values used to represent the various geometric, hydrogeologic, and climatic variables in the model grid. These arrays are referred to as parameters, which can be assigned to represent rivers, drains, wells, various hydraulic properties, and geologic topology. Parameters are assigned to the centroid of each model cell and are assumed to be the average value throughout the cell. Individual model cells identified as having boundary conditions, river, drain, or well parameters assigned to them are not shown because of the scale of the model grid for this study.

The model was constructed using elevations interpolated from available topographic and geologic maps. The elevation of land surface was interpolated using a kriging technique from a USGS 30-meter digital-elevation model. Relevant geologic contacts in the study area were interpolated to the model grid using the GMS software by the inverse-distance-weighted (IDW) method (Brigham Young University, 1998).

Modeled area orientation and hydraulic-conductivity zones for each model layer are shown in figures 6-10. Initial hydraulic-conductivity values for the various geologic materials were obtained from estimates in Schulmeyer and Schnoebelen (1998), which were then modified within appropriate ranges during model calibration to produce the best-fit model. Horizontal hydraulic conductivities in the Quaternary deposits simulated in layers 1 and 2 ranged from about 4 to 600 ft/d (table 4). Horizontal hydraulic conductivity in layers 3, 4, and 5 included the estimated increase in conductivity due to secondary permeability near the Cedar River valley. Hydraulic conductivities in the Devonian and Silurian bedrock ranged from 0.1 to about 350 ft/d (table 4).

Vertical hydraulic conductivity for the entire model is simulated as a constant factor of one-tenth of the horizontal hydraulic conductivity at each grid cell. Vertical leakance is required by the model to control the rate of ground-water flow between layers. Vertical leakance between two adjacent layers is calculated from the thickness of each layer between its node and the common layer contact and the vertical hydraulic conductivity of each layer (McDonald and Harbaugh, 1988). Vertical leakance between two model layers with an intervening confining unit is calculated from the above properties and the vertical hydraulic conductivity and thickness of the confining unit (McDonald and Harbaugh, 1988).

Natural stresses on the aquifer system include precipitation, evapotranspiration, changes in streamflow of the Cedar River, and drainage from tributary streams in the study area. Recharge, in the form of infiltration of precipitation, was simulated in the steady-state and transient ground-water flow model using values of approximately 6.0 to 7.8 in/yr as previously published by Schulmeyer and Schnoebelen (1998). The rate varied depending on the surficial lithology, with larger values in the alluvium to reflect an increased capacity for infiltration and smaller values in the glacial deposits.

The effects of vegetation on the ground-water flow system through evapotranspiration were simulated as a constant value throughout the model area. The value of evapotranspiration was established during the calibration process to be 0.0095 ft/d for the transient simulation. The extinction depth was estimated to be 5 ft, which was assumed to be the approximate maximum depth of most tree roots in the area, and the surface was the top of layer 1. Field measurements of evapotranspiration were not recorded during this study because evapotranspiration was not assumed to be a significant portion of the total discharge from the alluvial aquifer.

The Cedar River in the study area was simulated using river cells in the MODFLOW model to allow water to flow into and out of the adjacent alluvial aquifer. Flow across a river cell in the model occurs through a riverbed conductance term, which is a function of the area of the river channel, the vertical hydraulic conductivity of the riverbed material, and the thickness of the riverbed (McDonald and Harbaugh, 1988). An estimated river stage was assigned to each model cell using the stage of the Cedar River at Cedar Rapids gaging station and available topographic data upstream from the low-head dam. River stage from the dam upstream to the northern end of the Seminole well field near S23 (fig. 2) was held constant at 718 ft to account for the pool created by the dam. Upstream from S23, the river stage was interpolated along the river reach using topographic elevation data. The riverbed conductance was gradually increased from about 5 ft/d near the dam to about 1,000 ft/d near S23 to simulate the effects of riverbed siltation behind the dam. The stage of the river was adjusted during the transient simulation by applying a daily stage increase or decrease to the river cells for each stress period (fig. 11) based on streamflow records from the Cedar River at Cedar Rapids streamflow-gaging station.

Tributary streams in the model area are simulated as drain cells. Drain cells allow water to move out of the ground-water flow system across the drain boundary if the head in the adjacent model cell is higher than the specified drain elevation (McDonald and Harbaugh, 1988). Drain elevations were estimated from topographic data and elevations were set at about 5 ft below land surface. Conductance of the drain-bed material was estimated to be about 2 ft/d. All drains in the steady-state and transient simulations were assigned the same bed-material conductance value and were held constant during the transient simulation.

Municipal wells in the study area are simulated using the WELL package (Harbaugh and McDonald, 1996). The design of the model grid ensures that each municipal well is located at the centroid of a cell in layer 2. The lateral collector wells, RANEY1 and RANEY2 (fig. 2), are simulated as numerous individual wells, 16 and 19 wells, respectively. The total collector well pumpage was evenly distributed to each of the individually simulated wells. During the steady-state simulation, 19 of the 53 vertical wells pump at a historical average pumping rate of about 1.5 ft^3/s to 2.2 ft^3/s, and each collector well pumps at about 9.0 ft^3/s for a total withdrawal rate of 50.6 ft^3/s. However, during the transient calibration simulation, wells were turned “off” and “on” over time and have a variable pumping rate associated with recorded withdrawal amounts.

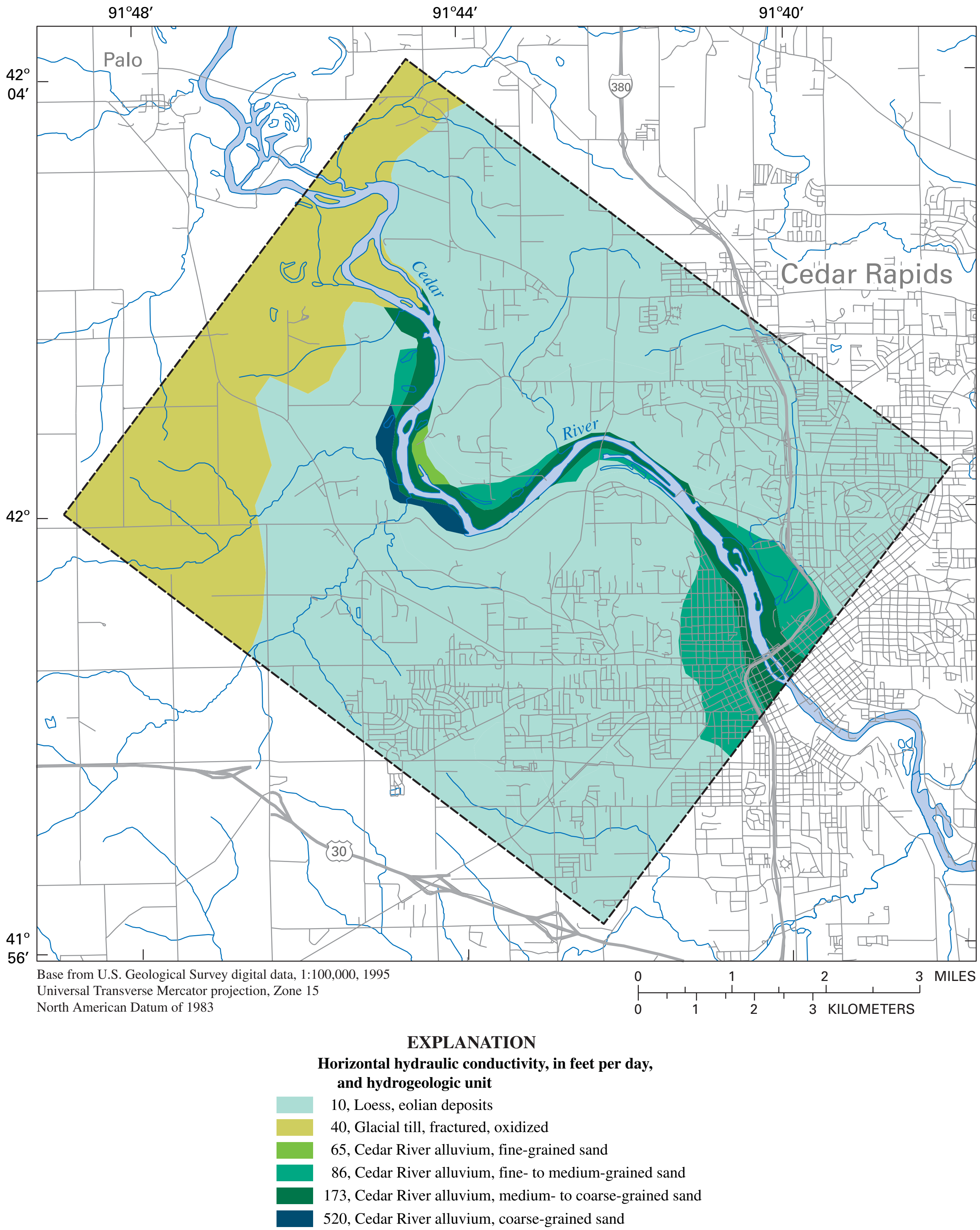
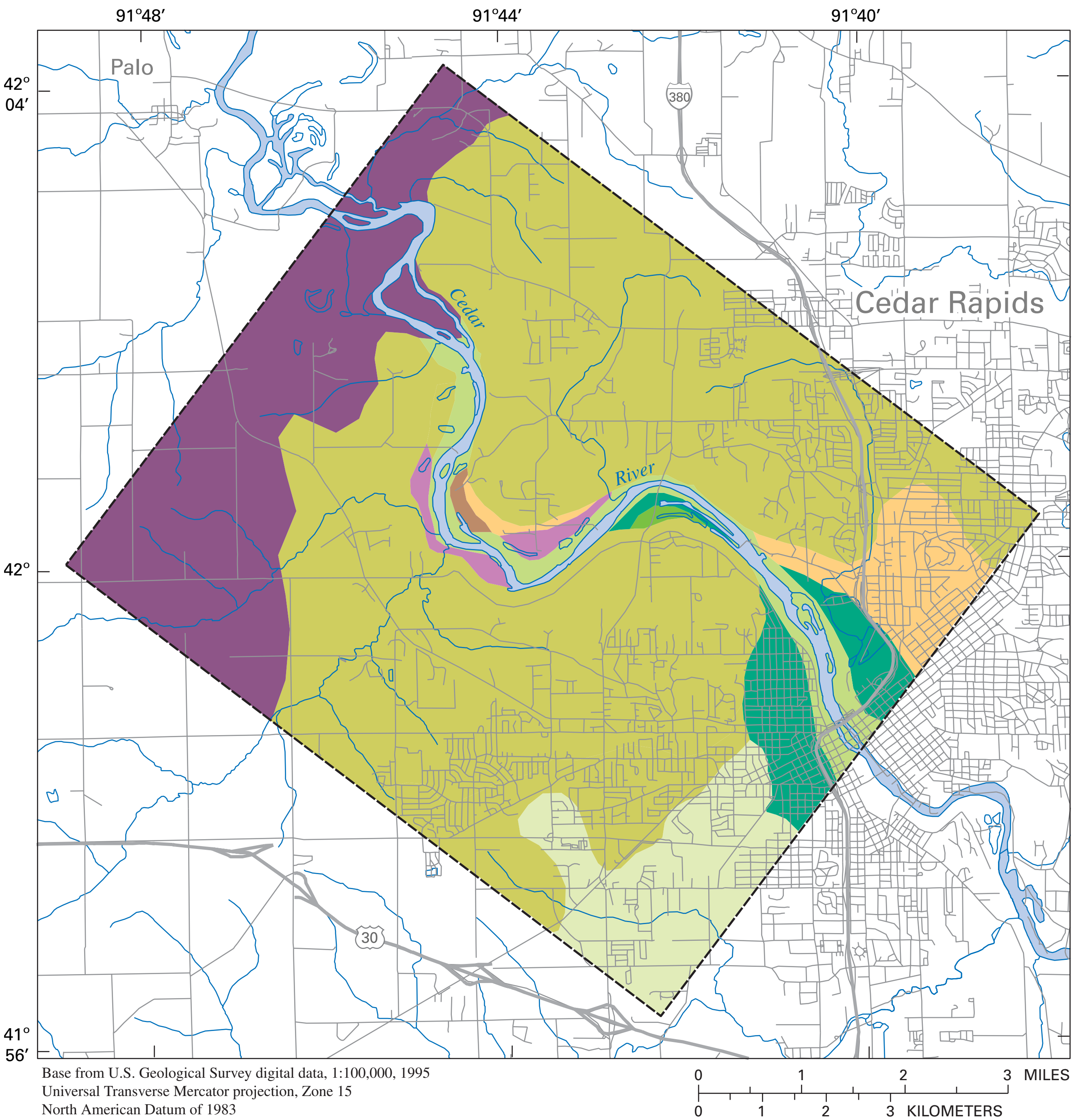


Figure 6. Extent of modeled area and horizontal hydraulic conductivity in model layer 1.



EXPLANATION

Horizontal hydraulic conductivity, in feet per day, and hydrogeologic unit

- 4, Glacial till, unfractured, unoxidized
- 9, Cedar River alluvium, silty fine-grained sand
- 40, Glacial till, fractured, oxidized
- 65, Cedar River alluvium, fine-grained sand
- 86, Cedar River alluvium, fine- to medium-grained sand
- 346, Cedar River alluvium, medium- to coarse-grained sand
- 432, Cedar River alluvium. medium- to coarse-grained sand
- 500, Buried-channel aquifer
- 600, Cedar River alluvium, coarse-grained sand

Figure 7. Extent of modeled area and horizontal hydraulic conductivity in model layer 2.

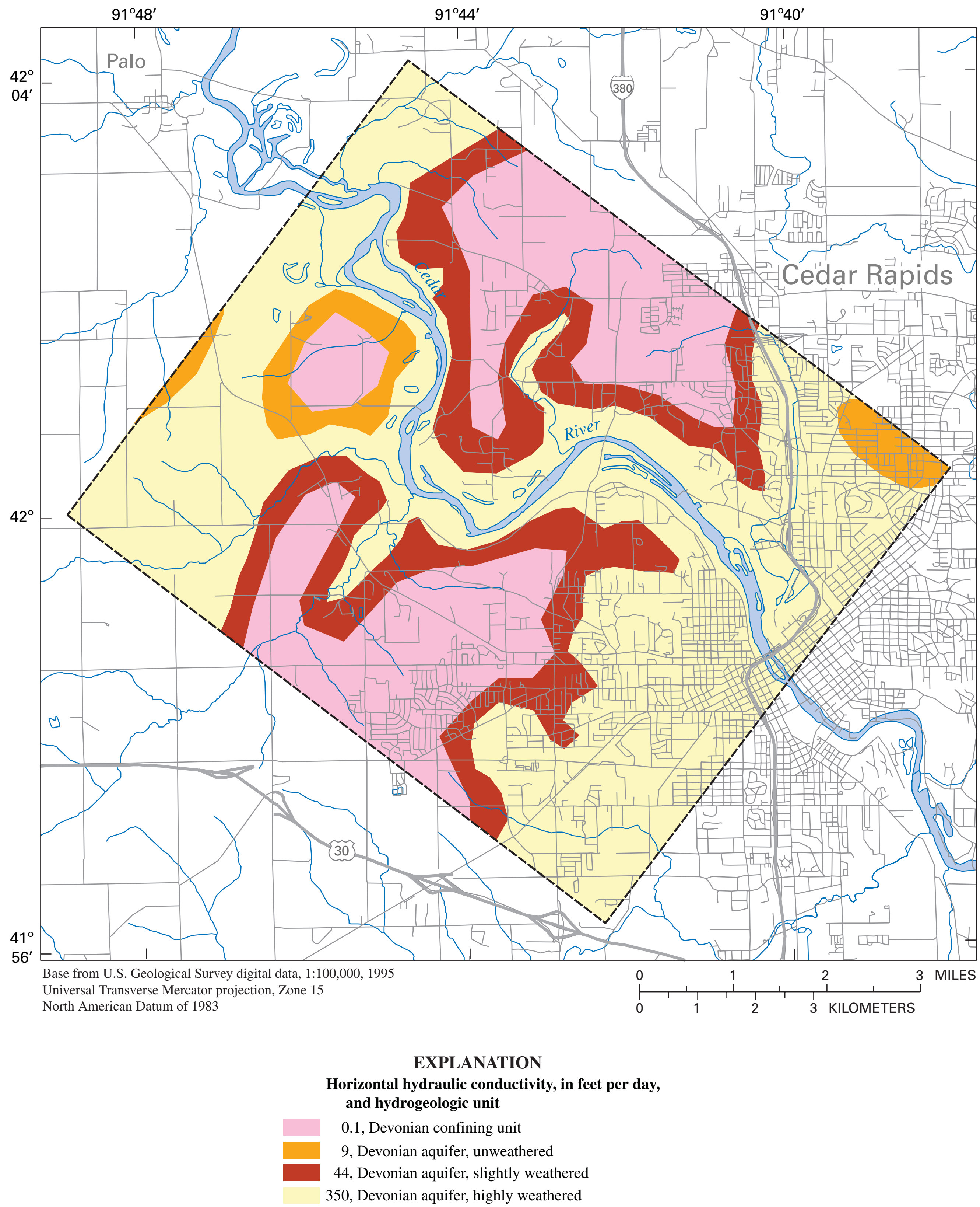


Figure 8. Extent of modeled area and horizontal hydraulic conductivity in model layer 3.

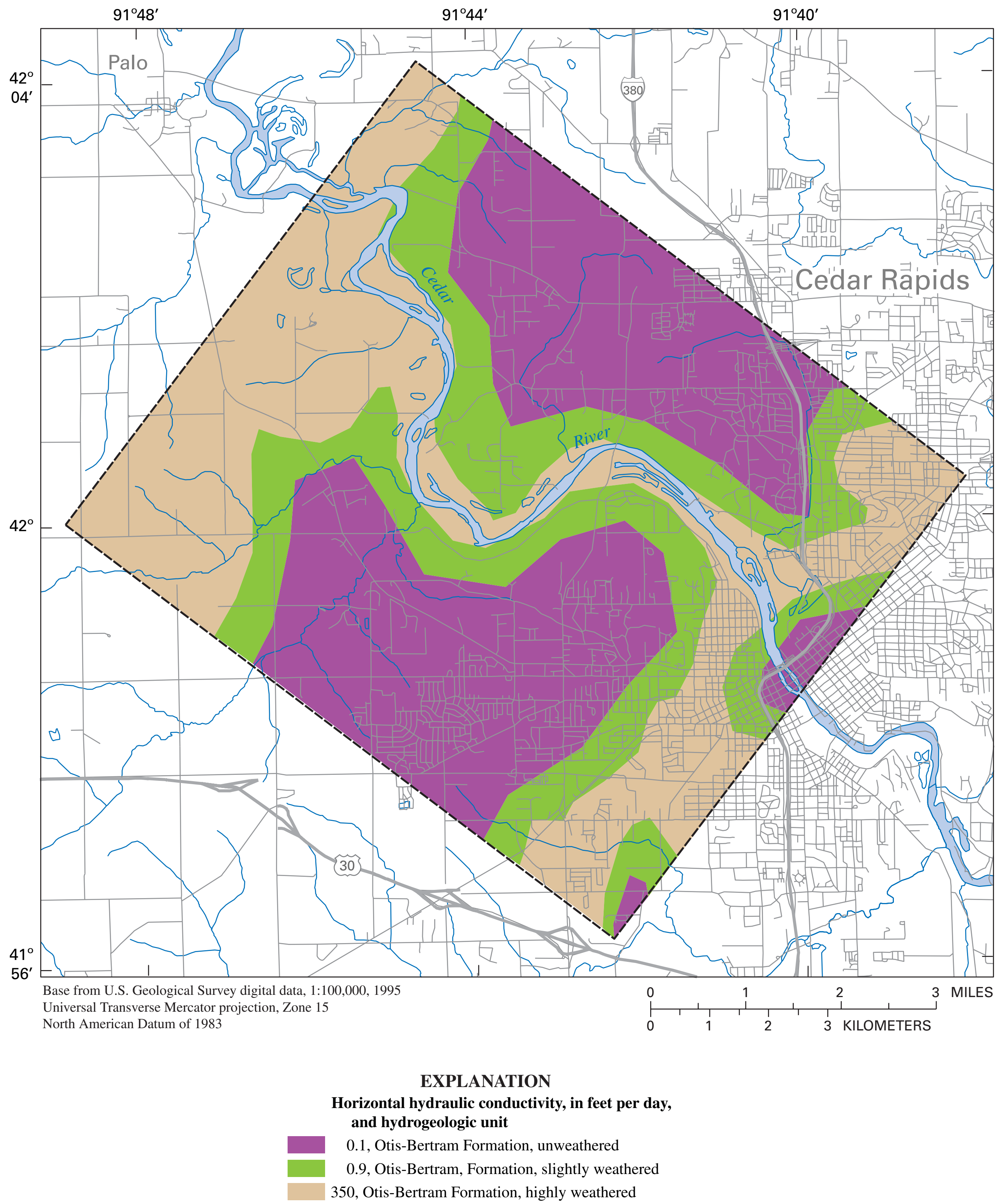


Figure 9. Extent of modeled area and horizontal hydraulic conductivity in model layer 4.

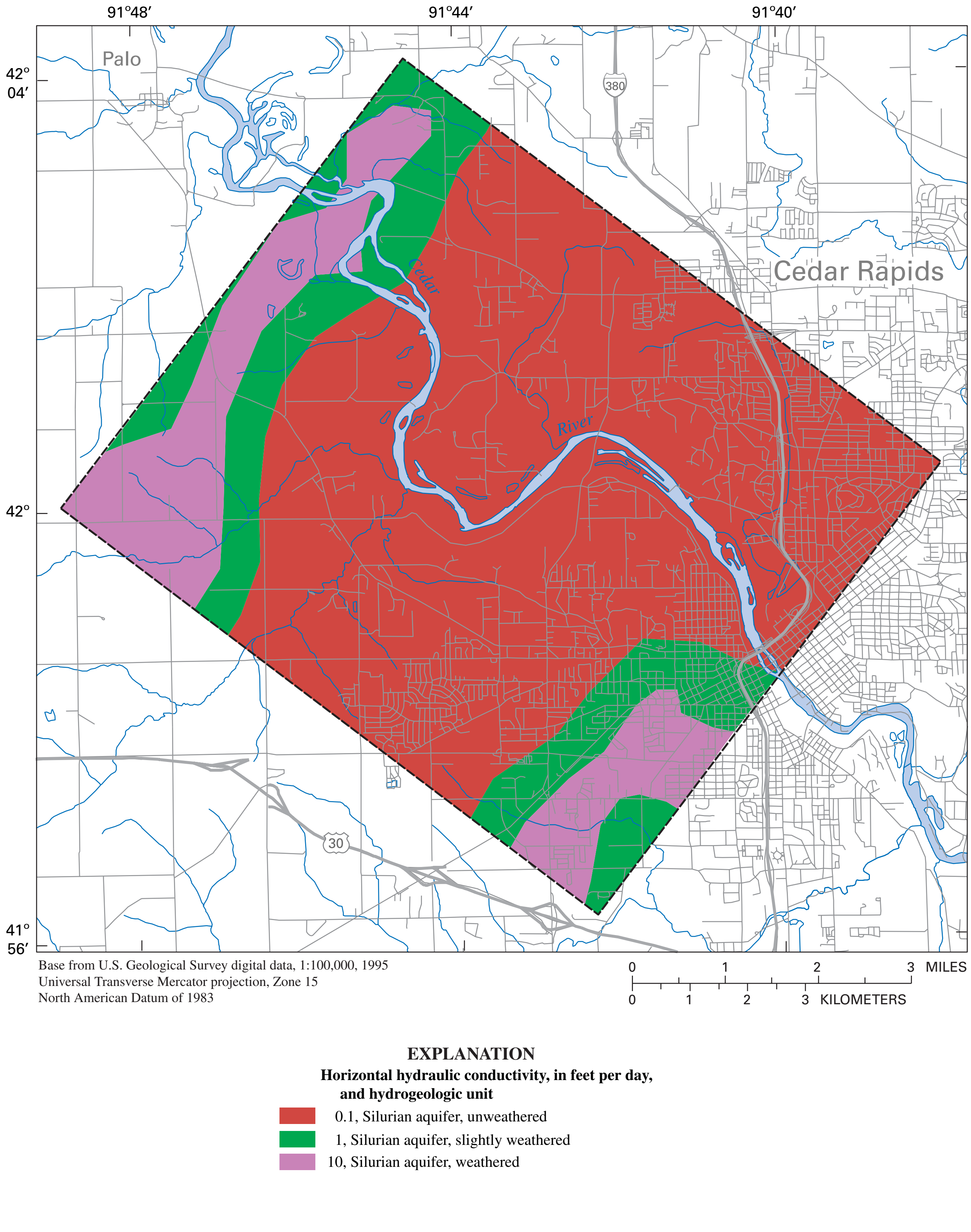


Figure 10. Extent of modeled area and horizontal hydraulic conductivity in model layer 5.

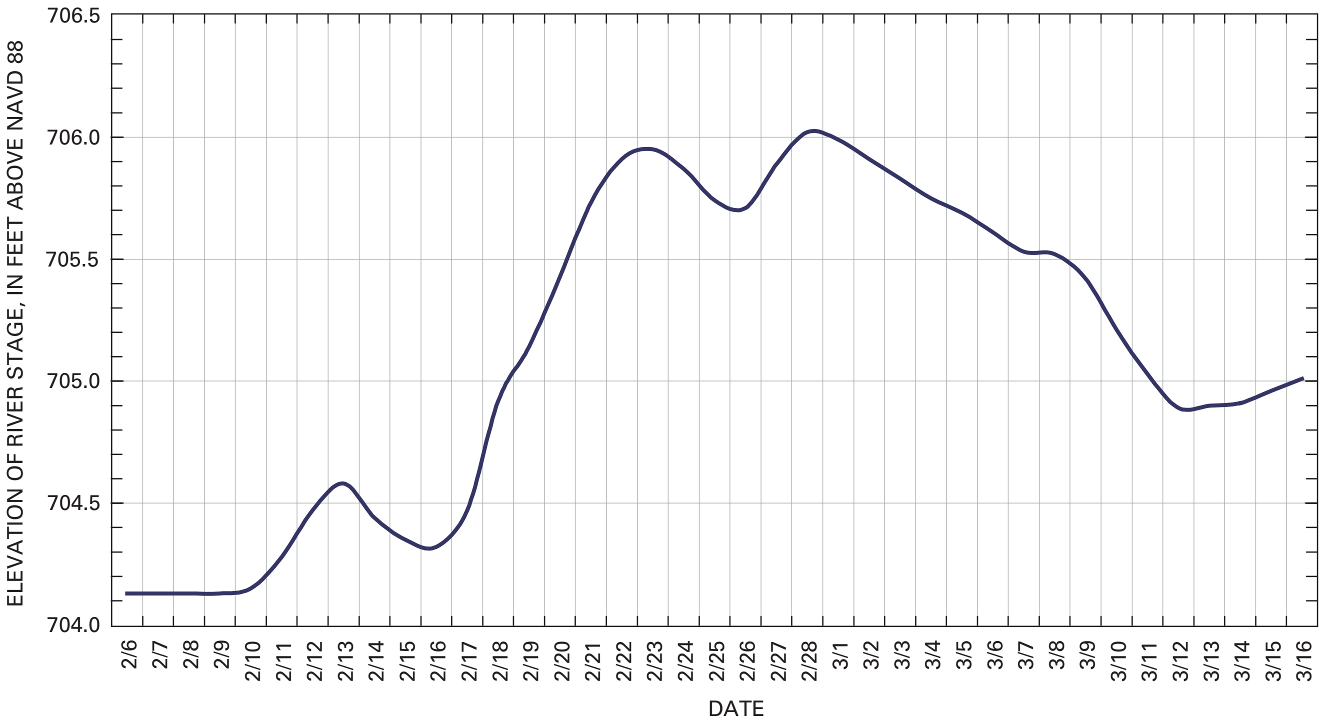


Figure 11. Hydrograph showing river stage at Cedar River at Cedar Rapids, Iowa, gaging station, February 6, 1998, to March 16, 1998.

The transient simulation required additional model parameters not needed for the steady-state simulation. Specific storage was assigned to all model layers, except for layer 1, which was specified as unconfined and assigned a specific yield of 0.40-0.42 ft^{-1}. Specific storage values for the various lithologies were estimated from published values by Anderson and Woessner (1992) and ranged from 0.002 ft^{-1} in glacial till to 0.00001 ft^{-1} in the bedrock. Specific-yield values were applied to all model layers defined as convertible (layers 2, 3, and 4) or confined (layer 5) and were estimated from published values typical for the various lithologies in the study area (Anderson and Woessner, 1992). The simulated specific yield ranged from 0.01 in the Otis and Bertram Formations to 0.45 in the coarse-grained sand of the buried-channel and Cedar River alluvial aquifers. Storage values used for the various geologic materials simulated in the ground-water flow model are summarized in table 4.

Model Calibration

The ground-water flow model was calibrated by adjusting the value and distribution of model input parameters so that the resulting model output matched measured water levels and other hydrologic observations within an acceptable level of accuracy. Changes to hydrogeologic parameter values were evaluated during the calibration process to assure that the change implemented was within the acceptable range of variability of the parameter. After each change in model parameter value, model output was generated and compared with measured data to evaluate the effect of the selected parameter change. The model accuracy was calculated using the root mean square error (RMSE) (Anderson and Woessner, 1992) comparison between water-level measurements and simulated water levels. Model accuracy is increased as RMSE (eq. 1) is decreased. Average model error (AVEH) also was used during the calibration process to evaluate model bias. Model bias occurs when the difference between simulated and observed water levels is predominately positive or negative.

$$RMSE = \sqrt{\frac{\sum_{1}^{N}(M-S)^2}{N}} \qquad (1)$$

where:

M is the measured water level;
S is the simulated water level; and
N is the number of observations.

The model was considered calibrated when the following criteria were satisfied:

1. Incremental parameter changes in model input did not result in a smaller RMSE for model layers 2 and 3, which include the Cedar River alluvial aquifer and Devonian aquifer, respectively, and an AVEH closer to zero;

2. The RMSE is less than 2 ft for layers 2 and 3;
3. The simulated ground-water flow directions in the model compared favorably with those determined from water-level measurements and previously published potentiometric surface maps of the Devonian and Silurian aquifers;
4. The simulated streamflow loss from the Cedar River to the Cedar Rapids well fields compares favorably with the estimated base-flow streamflow and measured streamflow values for the assumed steady-state time period; and
5. The simulated transient water levels and the measured water levels during the transient calibration period react to the effects of variable stresses through time in a logical manner throughout the simulation.

Steady-State Calibration

Steady-state water-level data were obtained during a synoptic measurement on December 21, 1998. The data are considered to be a close approximation of steady-state conditions. It is important to note that due to the constant variability in river stage, precipitation, and pumpage, the Cedar River alluvial aquifer may only reach approximate steady-state conditions for limited periods of time.

As the model was constructed, assumptions were necessary to reduce the instability of the model. The model was initially simplified, with uniform hydraulic conductivity for each model layer and constant riverbed conductance throughout the model. As calibration proceeded, complexity was systematically integrated into the model to improve the model output and to better represent actual conditions by increasing the variability of hydraulic conductivity, adding pumpage, and adjusting other hydrogeologic parameters of the model area to the extent supported by the available hydrogeologic data.

Surface-elevation conflicts between the model layers were corrected using the GMS software. The elevation of the bedrock contacts was preserved, allowing the other surface elevations to change slightly to eliminate overlapping layer surfaces and maintain a positive thickness for all model layers.

The extent of dry cells in the model area was monitored throughout the calibration process. Dry cells occur during a simulation when the head in a cell falls below the bottom elevation of the cell. In the Cedar Rapids area, it is conceptually valid that many of the cells in layer 1 and 2 would become dry during the simulation due to the small geologic unit thicknesses in the upland area and constant 15-ft thickness of layer 1. Dry cells in these areas represent a water-table surface that is below the bottom of the cell in that layer. Dry cells in the Devonian bedrock are conceptually more problematic, although, their occurrence along the steep elevation change in the bluff areas near the river valley is hypothetically valid assuming that these steep exposures are well drained and the water table is deeper than the Devonian rocks. Model parameters were adjusted to minimize the number of dry cells in layers 1 through 3 as indicated by the conceptual model. The initial conceptual model assumed that layers 2 and 3 were wet throughout the model area; however, that assumption was changed during calibration because no reasonable parameter value used could produce such a result.

The RMSE for the calibrated steady-state model was calculated using water-level data from most of the observation wells in the model area. Wells CRM23 and CRM28 in the Seminole well field (fig. 2) were not used in the calculation because of significant differences in water levels compared to nearby wells; thus, these water levels were considered to be atypical of the alluvium in that area on December 21, 1998. Water levels measured in other observation wells near CRM23 and CRM28 produced a good model fit and appeared to be realistic. The RMSE for the calibrated steady-state model is 1.44 ft; the AVEH is -0.26 ft. The RMSE for the Devonian and Silurian aquifers (layers 3 and 4) is 0.87 ft; the AVEH is 0.82 ft. The difference between the simulated and measured water levels is due to the model's inability to represent the complex ground-water flow system.

Transient Calibration

Transient calibration of the ground-water flow model to hydrologic conditions measured from February 6, 1998, to March 16, 1998, was completed by comparing the change in simulated water level to the change in measured water level. Changes in river stage, recharge, and evapotranspiration with respect to time, were measured or estimated and included in the simulation. The changes reflect a "spring-thaw event," a period of time that is best characterized as a condition that ranged from frozen soil and snow cover to snowmelt, soil thaw, and rain. Thirty-nine 1-day stress periods were used to simulate the variable pumping from the municipal wells that occurred during this time frame (table 5) and the change in Cedar River stage (table 6, fig. 11). The initial conditions for the transient model were established by a 50-day simulation using stresses associated with February 6, 1998, for which recharge was zero to simulate frozen soil conditions and an order of magnitude decrease in riverbed conductance to simulate siltation due to low streamflow in the Cedar River during the preceding winter months. The riverbed conductance was increased to the assumed steady-state levels after stress period 5 (February 10, 1998), which coincides with the beginning of the simulated increase in river stage and flow to represent scour of some of the riverbed siltation due to the increased streamflow. Recharge was increased and decreased during stress periods by using a multiplication factor applied to the steady-state recharge rate to account for periods of rain and snowmelt (fig. 12). Recharge during periods of no precipitation was assumed to be zero.

Some model parameters common to both the steady-state and transient simulations produced adequate results during the steady-state model calibration and were further refined during the transient-model calibration process. These adjustments improved both the steady-state and transient simulation and produced a better fit to the measured data.

Table 5. Municipal pumpage rates used in the transient ground-water flow model calibration.

[Wells listed in table 2 that are not listed in this table had no simulated pumpage during the transient simulation; negative number indicates withdrawal; ft^3/s, cubic feet per second]

Stress period	Pumpage (ft^3/s)										
	West well field (fig. 2), well number							Seminole well field (fig. 2), well number			
	W11	W10	W9	W7	W4	W3	W2	S23	S19	S17	S15
1	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
2	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
3	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
4	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
5	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
6	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
7	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-1.671	-2.228
8	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
9	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
10	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
11	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
12	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
13	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-2.228
14	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	-1.114
15	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	0.000
16	-2.408	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	0.000
17	-1.806	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	0.000
18	0.000	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	0.000	-2.228	0.000
19	0.000	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	-2.408	-2.228	0.000
20	0.000	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	-1.873	-1.114	0.000
21	0.000	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	-1.873	0.000	0.000
22	0.000	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	-1.873	0.000	0.000
23	0.000	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	-1.873	0.000	0.000
24	0.000	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	-1.873	0.000	0.000
25	0.000	-2.248	-2.408	-2.248	-2.248	-2.248	0.000	-2.248	-1.873	0.000	0.000
26	0.000	-2.248	-2.408	-2.248	-2.248	-2.248	-2.408	-2.248	-1.873	0.000	0.000
27	0.000	-2.248	-2.408	-2.248	-1.124	-2.248	-2.408	-2.248	-1.873	0.000	0.000
28	0.000	-2.248	-2.408	-2.248	0.000	-2.248	-2.408	-2.248	-1.873	0.000	0.000
29	0.000	-2.248	-2.408	-2.248	0.000	-2.248	-2.408	-2.248	-1.873	0.000	-2.228
30	0.000	-2.248	-2.408	-2.248	0.000	-2.248	-2.408	-2.248	-1.873	0.000	-2.228
31	0.000	-2.248	-2.408	-2.248	0.000	-2.248	0.000	-2.248	-1.873	0.000	-2.228
32	0.000	-2.248	-2.408	-2.248	0.000	-2.248	0.000	-2.248	-1.873	0.000	-2.228
33	0.000	-2.248	-2.408	-2.248	0.000	-2.248	0.000	-2.248	-1.873	0.000	-2.228
34	0.000	-2.248	-2.408	-2.248	0.000	-2.248	0.000	-2.248	-1.873	0.000	-2.228
35	0.000	-2.248	-2.408	-2.248	0.000	-2.248	0.000	-2.248	-1.873	0.000	-2.228
36	0.000	-2.248	-2.408	-2.248	0.000	-2.248	0.000	-2.248	-1.873	0.000	-2.228
37	0.000	-2.248	-2.408	-2.248	0.000	-2.248	0.000	-2.248	-1.873	0.000	-2.228
38	0.000	-2.248	-2.408	-2.248	0.000	-2.248	0.000	-2.248	-1.873	0.000	-2.228
39	0.000	-2.248	-2.408	-2.248	0.000	-2.248	0.000	-2.248	-1.873	0.000	-2.228

Table 5. Municipal pumpage rates used in the transient ground-water flow model calibration.—Continued

Stress period	Pumpage (ft³/s)											
	Seminole well field (fig. 2), well number										East well field (fig. 2), well number	
	S14	S13	S11	S9	S8	S7	S6	S5	S4	S2	E20	E18
1	-2.408	-2.408	0.000	-2.408	-2.408	-2.408	0.000	0.000	0.000	-2.408	0.000	-2.408
2	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	0.000	0.000	-2.228	0.000	0.000
3	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	0.000	0.000	-2.228	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	-2.228	0.000	0.000	0.000	-2.228	0.000	-0.562
5	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	0.000	0.000	-1.671	0.000	-1.124
6	-2.248	-2.248	0.000	0.000	0.000	-1.114	0.000	0.000	0.000	-1.114	0.000	0.000
7	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	0.000	0.000	-2.228	0.000	0.000
8	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	0.000	0.000	-2.228	0.000	0.000
9	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	0.000	0.000	-2.228	0.000	0.000
10	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	0.000	0.000	-2.228	0.000	0.000
11	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	0.000	0.000	0.000	0.000	-0.562
12	-2.248	-2.248	-2.408	0.000	0.000	-2.228	-2.408	0.000	0.000	-2.228	0.000	0.000
13	-2.248	-2.248	-1.686	0.000	0.000	-2.228	-1.686	0.000	0.000	-2.228	0.000	0.000
14	-1.124	-1.124	0.000	-0.937	-1.114	-2.228	0.000	-2.408	0.000	-2.228	0.000	-1.124
15	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-1.124	-2.408	-2.228	0.000	-1.124
16	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-0.937	-2.228	0.000	0.000
17	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	0.000	0.000
18	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	-2.408	-1.124
19	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	0.000	-2.228	-1.124	-2.248
20	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	0.000	-2.228	0.000	-2.248
21	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	0.000	-2.228	0.000	-2.248
22	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	0.000	-2.228	0.000	-2.248
23	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	0.000	-2.228	0.000	-2.248
24	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	0.000	-2.228	0.000	-1.686
25	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-0.937	-2.228	0.000	-1.686
26	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	-1.124	-0.562
27	-1.124	-1.124	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	-2.248	0.000
28	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	-2.248	0.000
29	-1.124	-1.124	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	-2.248	-1.686
30	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	-2.248	0.000
31	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	0.000	-2.248	0.000
32	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	0.000	0.000	-1.686
33	0.000	0.000	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	0.000	0.000	0.000
34	-2.248	-2.248	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	0.000	0.000
35	-2.248	-2.248	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	0.000	0.000
36	-2.248	-2.248	-2.248	0.000	0.000	-2.228	-2.248	-2.248	-1.873	-2.228	0.000	0.000
37	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	-2.248	-1.873	-2.228	0.000	0.000
38	-2.248	-2.248	0.000	0.000	0.000	-2.228	0.000	-2.248	-0.468	-2.228	0.000	0.000
39	-2.248	-2.248	-2.248	0.000	0.000	-2.228	-2.248	-1.686	0.000	-2.228	0.000	0.000

Table 5. Municipal pumpage rates used in the transient ground-water flow model calibration.—Continued

Stress period	Pumpage (ft^3/s)									
	East well field (fig. 2), well number								Collector wells (fig. 2), well number	
	E17	E16	E14	E13	E10	E4	E3	E2	RANEY1	RANEY2
1	-2.408	-2.408	-2.408	-2.408	-2.408	-2.408	-2.408	-2.408	-5.581	-9.469
2	-1.124	0.000	-2.248	-2.248	0.000	-2.248	-2.565	0.000	-5.581	-9.469
3	-1.686	0.000	-2.248	-2.248	0.000	-2.248	-2.565	0.000	-5.581	-9.469
4	0.000	-2.248	-2.248	-2.248	0.000	-2.248	-2.565	0.000	-5.581	-9.469
5	-0.562	-2.248	-2.248	-2.248	0.000	-1.124	-2.565	-0.562	-5.581	-9.469
6	0.000	-2.248	-2.248	-2.248	0.000	-2.248	-2.565	0.000	-4.185	-7.106
7	0.000	-2.248	-2.248	-2.248	0.000	-2.248	-2.565	0.000	-5.581	-9.469
8	0.000	-2.248	-2.248	-2.248	0.000	-2.248	-2.565	0.000	-5.581	-9.469
9	0.000	-2.248	-2.248	-2.248	0.000	-2.248	-2.565	0.000	-5.581	-9.469
10	0.000	-2.248	-2.248	-2.248	0.000	-2.248	-2.565	0.000	-5.581	-9.469
11	-1.124	-2.248	-2.248	-2.248	0.000	-2.248	-2.565	-1.124	-5.581	-9.469
12	0.000	-1.124	-2.248	-2.248	0.000	-2.248	-2.565	-1.124	-5.581	-9.469
13	0.000	-1.124	-2.248	-2.248	0.000	-2.248	-2.565	-2.248	-5.581	-9.469
14	-1.124	-0.562	-2.248	-2.248	0.000	-2.248	-2.565	-2.248	-5.581	-9.469
15	-0.562	-0.562	-1.686	-1.686	0.000	-2.248	-2.565	-2.248	-5.581	-9.469
16	0.000	0.000	-1.686	-1.686	0.000	-2.248	-2.565	-2.248	-5.581	-9.469
17	0.000	-2.248	-2.248	-2.248	0.000	-2.248	-2.565	-2.248	-5.581	-9.469
18	-1.124	0.000	-2.248	-2.248	0.000	-2.248	-2.565	-2.248	-5.581	-9.469
19	-2.248	0.000	-2.248	-2.248	0.000	-1.124	-2.565	-2.248	-5.581	-9.469
20	-2.248	-2.248	-2.248	-2.248	0.000	0.000	-1.923	-1.686	-5.581	-9.469
21	-2.248	-2.248	-2.248	-2.248	0.000	0.000	0.000	0.000	-5.581	-9.469
22	-2.248	-2.248	-2.248	-2.248	0.000	0.000	0.000	-2.248	-5.581	-9.469
23	-2.248	-2.248	-2.248	-2.248	0.000	0.000	0.000	-2.248	-5.581	-9.469
24	-2.248	-2.248	-2.248	0.000	0.000	0.000	0.000	-1.686	-5.581	-9.469
25	-2.248	-2.248	-1.686	0.000	0.000	0.000	0.000	-2.248	-5.581	-9.469
26	-2.248	-2.248	0.000	0.000	-0.937	0.000	0.000	-2.248	-5.581	-9.469
27	-2.248	-2.248	-2.248	0.000	-0.937	0.000	0.000	-2.248	-5.581	-9.469
28	-2.248	-2.248	-2.248	0.000	0.000	0.000	-1.282	-2.248	-5.581	-9.469
29	-2.248	-2.248	-2.248	-0.562	0.000	0.000	-2.565	-2.248	-5.581	-9.469
30	-2.248	-2.248	-2.248	0.000	0.000	0.000	-2.565	-2.248	-5.581	-9.469
31	-2.248	-2.248	-2.248	0.000	0.000	-1.124	0.000	0.000	-5.581	-9.469
32	-2.248	-2.248	-1.124	0.000	0.000	0.000	-2.565	-2.248	-5.581	-9.469
33	-2.248	-2.248	-1.686	-1.686	0.000	0.000	-2.565	-2.248	-5.581	-9.469
34	-2.248	-2.248	-1.124	-1.124	-1.873	0.000	-2.565	-2.248	-5.581	-9.469
35	-2.248	-2.248	0.000	0.000	-1.873	0.000	-2.565	-2.248	-5.581	-9.469
36	-2.248	-2.248	0.000	0.000	-1.873	0.000	-2.565	-2.248	-5.581	-9.469
37	0.000	0.000	-1.124	-1.124	0.000	0.000	-2.565	-2.248	-5.581	-9.469
38	0.000	0.000	-2.248	-2.248	0.000	0.000	-2.565	-2.248	-5.581	-9.469
39	-2.248	-2.248	-1.124	-2.248	0.000	0.000	-2.565	-2.248	-5.581	-9.469

Table 6. Cedar River stage during the transient ground-water simulation and incremental adjustment factor used in the transient river package.

[NAVD 88, North American Vertical Datum of 1988]

Stress period	Date of simulation	Cedar River at Cedar Rapids gage datum (feet above NAVD 88)	Estimated stage above gaging-station datum (feet)	Estimated stage (feet above NAVD 88)	Change in Cedar River stage from stress period one (feet)
1	02/06/98	700.47	3.66	704.13	0.00
2	02/07/98	700.47	3.66	704.13	0.00
3	02/08/98	700.47	3.66	704.13	0.00
4	02/09/98	700.47	3.66	704.13	0.00
5	02/10/98	700.47	3.68	704.15	0.02
6	02/11/98	700.47	3.81	704.28	0.15
7	02/12/98	700.47	4.00	704.47	0.34
8	02/13/98	700.47	4.11	704.58	0.45
9	02/14/98	700.47	3.97	704.44	0.31
10	02/15/98	700.47	3.88	704.35	0.22
11	02/16/98	700.47	3.85	704.32	0.19
12	02/17/98	700.47	4.00	704.47	0.34
13	02/18/98	700.47	4.45	704.92	0.79
14	02/19/98	700.47	4.67	705.14	1.01
15	02/20/98	700.47	4.96	705.43	1.30
16	02/21/98	700.47	5.26	705.73	1.60
17	02/22/98	700.47	5.44	705.91	1.78
18	02/23/98	700.47	5.48	705.95	1.82
19	02/24/98	700.47	5.40	705.87	1.74
20	02/25/98	700.47	5.27	705.74	1.61
21	02/26/98	700.47	5.24	705.71	1.58
22	02/27/98	700.47	5.42	705.89	1.76
23	02/28/98	700.47	5.55	706.02	1.89
24	03/01/98	700.47	5.52	705.99	1.86
25	03/02/98	700.47	5.44	705.91	1.78
26	03/03/98	700.47	5.36	705.83	1.70
27	03/04/98	700.47	5.28	705.75	1.62
28	03/05/98	700.47	5.22	705.69	1.56
29	03/06/98	700.47	5.14	705.61	1.48
30	03/07/98	700.47	5.06	705.53	1.40
31	03/08/98	700.47	5.05	705.52	1.39
32	03/09/98	700.47	4.95	705.42	1.29
33	03/10/98	700.47	4.74	705.21	1.08
34	03/11/98	700.47	4.56	705.03	0.90
35	03/12/98	700.47	4.42	704.89	0.76
36	03/13/98	700.47	4.43	704.90	0.77
37	03/14/98	700.47	4.44	704.91	0.78
38	03/15/98	700.47	4.49	704.96	0.83
39	03/16/98	700.47	4.54	705.01	0.88

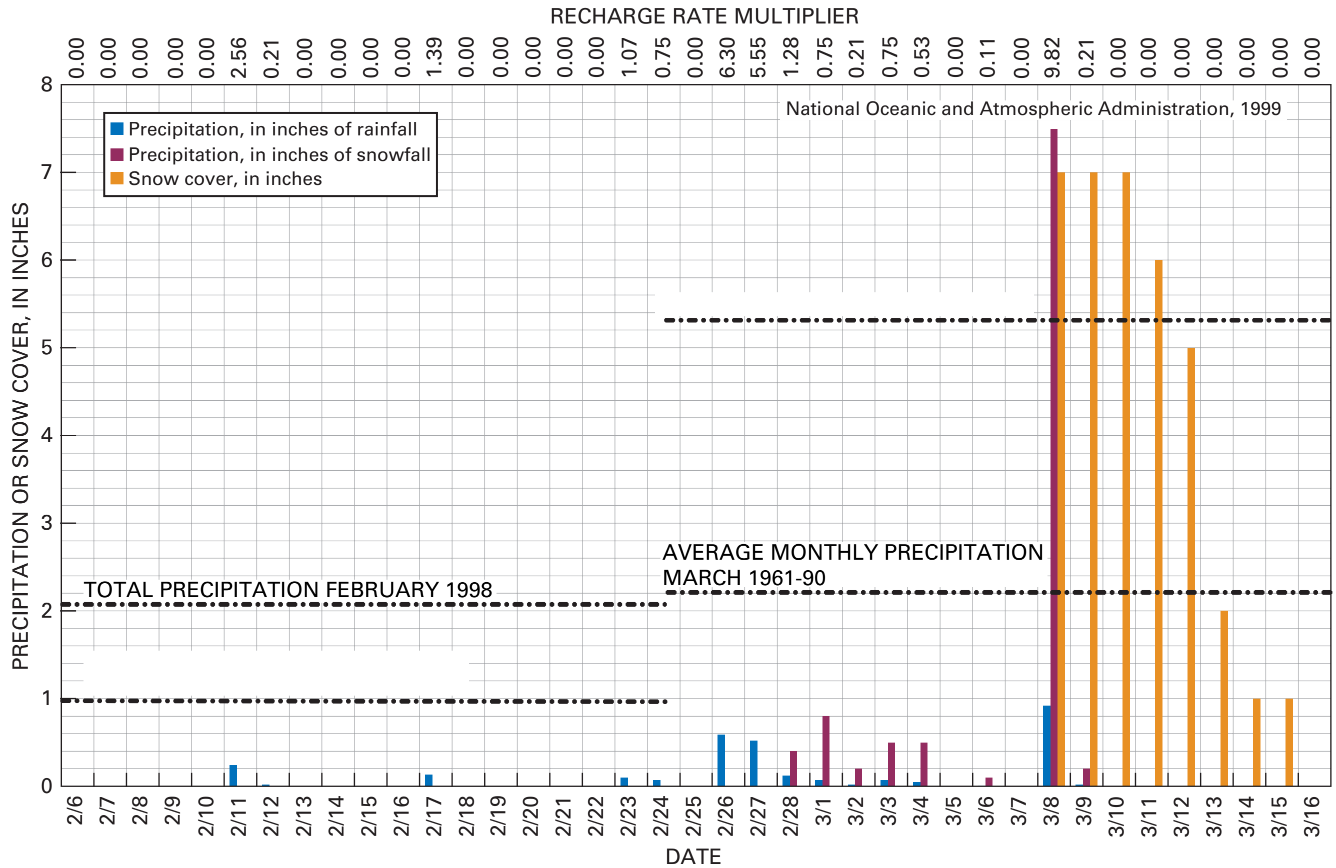


Figure 12. Precipitation and snow cover at the Eastern Iowa Airport near Cedar Rapids, Iowa, and corresponding recharge multiplier for each transient model stress period.

The simulated transient water levels for cells near most (15 of 23) of the observation wells (table 7) react to the changing stresses in the transient simulation similarly to measured water levels as illustrated by wells CRM11, CRM12, and CRM18 (fig. 13). Differences between simulated water levels and measured water levels at some locations are possibly due to pumpage or other stresses not accounted for in the transient model.

Sensitivity Analysis

A sensitivity analysis evaluates the response of the model to incremental changes in parameters to determine which parameters have the greatest effect on results. Model parameters were incrementally varied by at least one order of magnitude to test for sensitivity. The RMSE was used to quantify the effect of a parameter change on the steady-state model results.

Results of the sensitivity analysis for each change in a parameter is listed in table 8, which includes the effect of the parameter change on the resulting overall model RMSE and on the volumetric budget of the Cedar River. The model is most sensitive to tributary streambed (drain cell) conductance and horizontal hydraulic conductivity in layer 2. Substantial change in model fit was noted when the hydraulic conductivity in layer 5 is increased or decreased by an order of magnitude; however, only one observation well measures that change, and this may skew the actual significance of the parameter change on layer 5 results. The total amount of water moving into or out of the river is most sensitive to Cedar River riverbed conductance, horizontal hydraulic conductivity in layer 2, and recharge.

Some parameters in the model, when adjusted more than two orders of magnitude, had little effect on the final solution. The model is insensitive to hydraulic conductivities of layers 3 and 4, which is likely due to the minor extent of the geologic units (fig. 5) represented by these two layers near the observation wells. The model also is insensitive to changes in the general-head boundary conductance, which is likely due to the distance between the boundaries and the alluvium where water levels were measured. If improvement of the model is desired, additional data collection would be directed toward refining the most sensitive parameter(s).

Table 7. Difference between measured and simulated water levels in selected wells within the study area, February 6, 1998, to March 16, 1998.

[Difference, in feet, between measured and simulated water level (measured minus simulated)]

Date	Stress period	CRM3	CRM4	CRM6	CRM7	CRM9	CRM11	CRM12	CRM15	CRM16
02/06/98	1	0.39	-5.08	8.54	-0.68	-0.81	-4.79	1.08	-5.27	-5.63
02/07/98	2	0.08	-5.57	8.38	-0.81	-0.93	-4.68	0.82	-6.24	-6.52
02/08/98	3	-0.81	-5.87	8.10	-0.95	-1.04	-4.64	0.42	-6.90	-7.17
02/09/98	4	-0.93	-6.08	7.90	-1.08	-1.06	-4.63	0.32	-7.45	-7.66
02/10/98	5	-1.07	-6.22	7.68	-1.30	-1.25	-4.71	0.23	-7.89	-7.92
02/11/98	6	-1.27	-6.37	7.80	-1.20	-1.07	-5.03	0.19	-8.43	-8.09
02/12/98	7	-1.43	-6.71	7.34	-1.33	-1.42	-5.16	0.20	-8.60	-8.27
02/13/98	8	-1.41	-6.92	7.24	-1.43	-1.42	-5.23	0.15	-8.74	-8.38
02/14/98	9	-0.94	-6.66	7.23	-1.47	-1.52	-5.29	0.12	-8.63	-8.67
02/15/98	10	-0.91	-7.40	7.17	-1.38	-1.41	-4.50	0.26	-8.93	-8.61
02/16/98	11	-1.29	-7.20	7.43	-1.29	-1.19	-3.54	0.45	-8.98	-8.53
02/17/98	12	-1.95	-7.57	7.66	-1.22	-0.49	-4.19	0.63	-9.03	-7.80
02/18/98	13	-2.03	-7.88	6.98	-1.68	-1.53	-4.32	0.70	-9.14	-7.79
02/19/98	14	-2.14	-8.17	6.52	-2.06	-2.05	-4.57	0.76	-9.40	-8.33
02/20/98	15	-3.47	-8.38	6.31	-2.15	-2.09	-4.96	0.80	-9.86	-8.27
02/21/98	16	-4.26	-8.18	6.38	-2.03	-2.17	-5.19	0.79	-10.14	-9.10
02/22/98	17	-4.27	-7.58	6.54	-2.00	-2.06	-5.25	0.79	-10.29	-8.36
02/23/98	18	-4.41	-6.44	6.81	-2.11	-2.10	-5.47	0.81	-10.40	-7.40
02/24/98	19	-4.20	-5.02	7.33	-2.08	-2.23	-5.56	0.72	-10.35	-7.09
02/25/98	20	-4.99	-4.54	7.31	-2.39	-2.33	-6.13	0.66	-10.44	-6.83
02/26/98	21	-5.36	-3.82	8.17	-2.09	-0.99	-6.41	0.47	-10.38	-6.72
02/27/98	22	-5.04	-3.09	8.42	-1.93	-0.99	-6.15	0.35	-10.24	-6.36
02/28/98	23	-4.65	-2.57	8.04	-2.17	-2.28	-5.86	0.38	-10.08	-5.79
03/01/98	24	-3.40	-1.89	8.14	-2.21	-2.41	-5.71	0.37	-9.79	-5.27
03/02/98	25	-4.21	-1.55	8.24	-2.19	-2.29	-5.65	0.35	-9.50	-4.90
03/03/98	26	-4.34	-1.34	8.43	-2.13	-2.30	-5.57	0.46	-9.18	-4.65
03/04/98	27	-4.07	-1.29	8.48	-2.17	-2.11	-5.64	0.59	-8.75	-4.82
03/05/98	28	-4.12	-0.51	8.46	-2.15	-1.94	-5.53	0.48	-8.07	-4.46
03/06/98	29	-4.02	-0.60	8.59	-2.06	-1.89	-5.37	0.35	-7.66	-4.45
03/07/98	30	-4.08	-1.19	8.74	-1.88	-1.89	-6.01	0.19	-7.45	-4.26
03/08/98	31	-4.63	-1.45	9.18	-1.67	-1.64	-6.79	-0.01	-7.41	-4.13
03/09/98	32	-4.19	-1.21	8.94	-1.85	-1.86	-6.84	-0.10	-7.07	-4.12
03/10/98	33	-3.26	-1.08	9.70	-1.64	-1.78	-6.67	-0.16	-6.67	-4.17
03/11/98	34	-2.49	-0.83	10.19	-0.99	-1.09	-6.21	0.00	-6.20	-4.02
03/12/98	35	-2.20	-0.37	10.41	-0.37	-0.48	-5.88	0.27	-6.00	-4.15
03/13/98	36	-1.34	-0.60	9.84	-0.18	-0.14	-5.54	0.36	-6.30	-4.15
03/14/98	37	-1.56	-0.63	9.77	-1.29	-1.19	-5.36	0.12	-6.32	-4.28
03/15/98	38	-1.77	-0.90	9.86	-1.39	-1.47	-5.60	-0.12	-6.43	-4.60
03/16/98	39	-1.78	-0.90	9.54	-1.50	-1.48	-5.74	-0.14	-6.38	-4.81
Maximum		0.39	-0.37	10.41	-0.18	-0.14	-3.54	1.08	-5.27	-4.02
Minimum		-5.36	-8.38	6.31	-2.39	-2.41	-6.84	-0.16	-10.44	-9.10
Mean		-2.76	-4.09	8.15	-1.60	-1.55	-5.39	0.39	-8.33	-6.32

Table 7. Difference between measured and simulated water levels in selected wells within the study area, February 6, 1998, to March 16, 1998.—Continued

[Difference, in feet, between measured and simulated water level (measured minus simulated)]

Date	Stress period	CRM17	CRM18	CRM19	CRM22	CRM23	CRM24	CRM25	CRM27	CRM28
02/06/98	1	-5.21	-5.39	-4.32	0.08	-2.69	-2.96	-0.81	-0.84	-8.99
02/07/98	2	-6.21	-5.93	-4.70	-0.12	-3.00	-3.19	-0.71	-0.46	-9.69
02/08/98	3	-6.79	-6.24	-4.96	-0.29	-3.25	-3.40	-0.81	-0.54	-10.25
02/09/98	4	-7.28	-6.56	-5.32	-0.40	-3.43	-3.54	-0.93	-0.63	-10.76
02/10/98	5	-7.48	-6.77	-5.82	-0.55	-3.60	-3.70	-1.08	-0.78	-11.10
02/11/98	6	-8.02	-6.92	-5.82	-0.74	-3.79	-3.89	-1.31	-1.02	-11.20
02/12/98	7	-7.83	-7.01	-5.74	-0.89	-3.97	-4.05	-1.50	-1.19	-11.36
02/13/98	8	-7.90	-7.15	-6.06	-0.89	-4.04	-4.08	-1.56	-1.21	-11.45
02/14/98	9	-8.26	-7.03	-5.90	-0.85	-4.06	-4.06	-1.56	-0.78	-11.47
02/15/98	10	-8.20	-7.34	-6.19	-0.84	-4.06	-4.05	-1.42	-0.75	-11.49
02/16/98	11	-8.30	-7.24	-6.27	-0.74	-4.01	-3.98	-1.42	-1.19	-11.45
02/17/98	12	-7.50	-7.76	-6.54	-1.11	-4.16	-4.25	-1.36	-1.60	-10.33
02/18/98	13	-7.47	-7.78	-6.75	-1.29	-4.28	-4.41	-1.70	-1.61	-9.65
02/19/98	14	-7.70	-8.00	-7.07	-1.43	-4.34	-4.52	-1.68	-1.60	-10.20
02/20/98	15	-7.80	-8.10	-6.74	-2.08	-3.83	-3.39	-1.81	-2.53	-10.88
02/21/98	16	-8.58	-7.80	-5.62	-3.11	-3.49	-2.85	-1.97	-2.89	-12.26
02/22/98	17	-7.89	-7.17	-5.01	-2.85	-3.50	-2.99	-2.08	-2.64	-11.81
02/23/98	18	-7.05	-6.60	-3.50	-1.62	-2.37	-2.50	-2.17	-2.59	-11.05
02/24/98	19	-6.73	-5.94	-2.37	-1.52	-1.64	-2.14	-2.28	-2.42	-10.94
02/25/98	20	-6.78	-6.18	-1.86	-4.18	-2.53	-1.89	-2.52	-3.01	-10.91
02/26/98	21	-6.36	-6.22	-3.33	-10.91	-2.74	-2.94	-2.26	-3.51	-10.82
02/27/98	22	-6.10	-5.65	-3.88	-9.89	-2.65	-3.06	-2.37	-3.41	-10.65
02/28/98	23	-6.08	-4.93	-4.21	-4.34	-2.74	-2.11	-2.74	-3.06	-10.48
03/01/98	24	-5.37	-4.58	-3.85	-2.61	-2.46	-1.74	-2.53	-1.85	-10.19
03/02/98	25	-4.80	-4.38	-2.95	-2.88	-3.83	-1.27	-2.34	-2.66	-9.94
03/03/98	26	-4.64	-4.21	-2.48	-2.72	-3.65	-2.54	-2.22	-2.74	-9.79
03/04/98	27	-4.79	-4.27	-1.63	-2.39	-3.18	-2.39	-2.15	-2.37	-9.67
03/05/98	28	-4.83	-3.85	-0.18	-2.41	-3.18	-2.32	-2.02	-2.37	-9.58
03/06/98	29	-4.81	-3.92	-0.97	-2.27	-3.03	-2.12	-1.94	-2.22	-9.57
03/07/98	30	-4.37	-4.02	0.70	-2.35	-3.05	-1.89	-1.91	-2.23	-9.57
03/08/98	31	-4.51	-4.09	1.42	-5.20	-3.52	-1.80	-1.95	-2.79	-9.65
03/09/98	32	-3.83	-3.86	0.63	-2.45	-3.16	-2.46	-1.80	-2.38	-9.65
03/10/98	33	0.57	-3.59	0.05	-2.25	-2.96	-2.16	-1.74	-1.48	-9.78
03/11/98	34	-0.27	-3.50	1.03	-1.55	-2.41	-1.50	-1.37	-0.88	-9.17
03/12/98	35	-0.24	-3.32	1.77	-0.58	-1.66	-1.03	-1.17	-0.52	-9.26
03/13/98	36	-4.04	-3.72	2.62	0.55	0.06	-0.23	0.02	0.57	-9.20
03/14/98	37	-1.74	-3.77	3.52	-0.62	-0.07	0.47	0.52	0.40	-9.67
03/15/98	38	-0.99	-3.95	4.22	-0.59	0.12	-0.77	0.34	0.16	-9.96
03/16/98	39	-2.53	-4.08	4.82	-0.94	-0.28	-0.66	0.06	-0.05	-10.08
Maximum		0.57	-3.32	4.82	0.55	0.12	0.47	0.52	0.57	-8.99
Minimum		-8.58	-8.10	-7.07	-10.91	-4.34	-4.52	-2.74	-3.51	-12.26
Mean		-5.61	-5.61	-2.80	-2.10	-2.94	-2.62	-1.54	-1.63	-10.36

Table 8. Sensitivity analysis results for each model parameter.

[ft^3/s, cubic feet per second; --, no data]

Model parameter		Factor used to change parameter	Root mean square error (feet)	Total flow into alluvium from Cedar River (ft^3/s)	Total flow out of alluvium to Cedar River (ft^3/s)
Calibrated steady-state model		--	1.44	59.8	51.3
Recharge - infiltration of precipitation		0.10	1.51	62.0	51.2
		10.00	1.94	42.4	99.7
Cedar River bed conductance		0.10	2.87	44.4	39.4
		10.00	1.31	154.4	149.9
Tributary streambed conductance		0.10	2.20	54.0	48.5
		10.00	2.26	57.9	33.3
General-head boundary conductance		0.10	1.43	61.7	36.9
		10.00	1.46	58.2	65.8
Layer 1	Horizontal hydraulic conductivity	0.10	1.92	57.9	52.3
		10.00	1.89	65.9	68.3
	Vertical hydraulic conductivity	0.10	2.12	52.7	47.2
		10.00	1.45	62.3	58.6
Layer 2	Horizontal hydraulic conductivity	0.10	3.02	33.7	34.0
		10.00	2.90	54.5	102.7
	Vertical hydraulic conductivity	0.10	2.23	54.8	45.1
		10.00	1.43	61.2	52.9
Layer 3	Horizontal hydraulic conductivity	0.10	1.55	61.4	49.2
		10.00	1.56	53.5	65.4
	Vertical hydraulic conductivity	0.10	1.43	59.8	50.8
		10.00	1.44	59.8	51.4
Layer 4	Horizontal hydraulic conductivity	0.10	1.42	60.3	50.2
		10.00	1.77	57.4	57.4
	Vertical hydraulic conductivity	0.10	1.43	60.0	50.0
		10.00	1.44	59.6	52.2
Layer 5	Horizontal hydraulic conductivity	0.10	1.51	61.6	45.2
		10.00	4.11	50.3	74.7
	Vertical hydraulic conductivity	0.10	4.14	60.0	49.6
		10.00	1.47	60.2	52.3

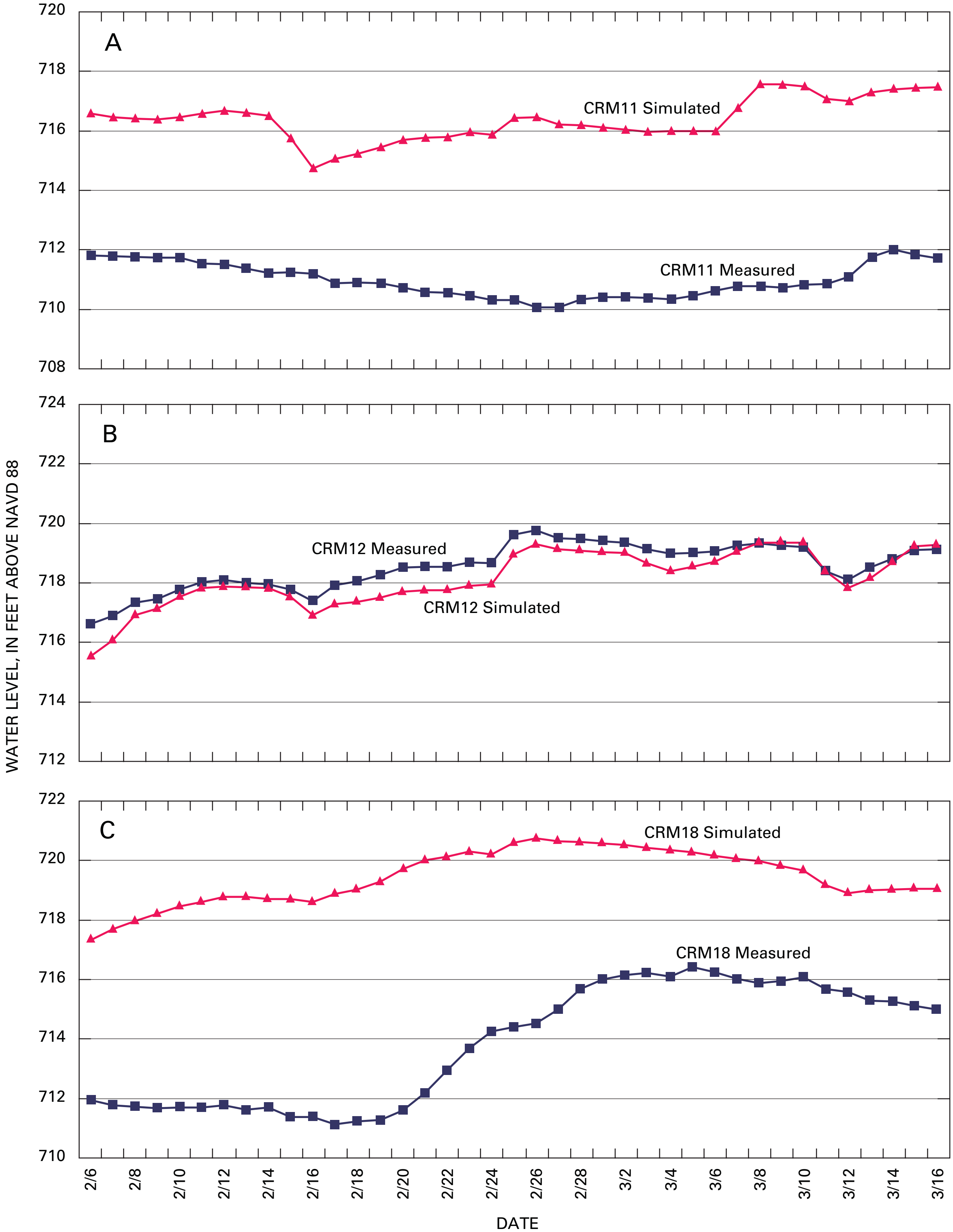


Figure 13. Simulated water levels in layer 2 compared to measured water levels in layer 2 for observation wells (A) CRM11, (B) CRM12, (C) CRM18, February 6, 1998, to March 16, 1998.

Model Limitations

The ground-water flow model described in this report is an approximation of a complex ground-water flow system that can be used by water planners to help estimate the ground-water system's response to variable stresses, whether anthropogenic or climatic. However, the model is limited in complexity with respect to the actual flow system and the following limitations should be noted:

1. The size of the model area is extensive and the number of model cells greatly exceeds the number of observation sites used for the calibration of the steady-state and transient models. The accuracy to which this model represents the area outside of the Cedar Rapids well fields is unknown due to the lack of data in those areas.
2. The model is a simplified version of a complex hydrogeologic system. Although, conceptually, the lithology throughout the Cedar River alluvial aquifer is heterogeneous, the aquifer was divided into zones of similar hydraulic conductivities to decrease computation times and increase the stability of the model.
3. The steady-state simulation used to establish hydrogeologic properties of the study area assumed that inflow equaled outflow on December 21, 1998. If this assumption was not correct, then the change in storage would contribute to model error.
4. The transient model is calibrated to a very specific and short time interval that tests the conceptual model with limited climatic stresses. Uncertainty may be introduced in simulations of different climatic situations and durations.
5. The transient data set is small compared to the number of model cells and the extent of the Cedar Rapids well fields. Some wells located in the same area have different comparison results, which could be due to unaccounted for changes in model parameters or stresses.

Steady-State Results and Hypothetical Pumping Scenarios

The steady-state model calculates a water level at each cell centroid and a ground-water flux across each cell face. The simulated potentiometric surface for the Quaternary deposits, including the Cedar River alluvial aquifer (model layer 2), is shown in figure 14, areas with no potentiometric contour lines are upland areas with dry cells in layer 2. Model results indicate that ground-water flow is predominately from the upland glacial deposits to the Cedar River alluvial aquifer and then discharged either to the Cedar River or to municipal pumpage. These results compare reasonably with the configuration of the potentiometric surface of the alluvial aquifer measured on December 21, 1998 (fig. 4). Beyond the part of the alluvial aquifer in the vicinity of the municipal wells, where measured water-level data are sparse, the model compares reasonably to the conceptual ground-water flow pattern.

The movement of water in the model is quantified by gradients between adjacent cells and layers. Most of the water in the model moves towards layer 2, primarily the model layer representative of the Cedar River alluvial aquifer and the municipal pumpage. Simulated steady-state discharge of the ground-water flow system through the alluvial aquifer to the Cedar River is 51.3 ft^3/s, whereas 59.8 ft^3/s of Cedar River water flows into the alluvial aquifer (table 9). Thus, there are gaining and losing reaches of the Cedar River with a net loss of 8.5 ft^3/s. This loss of streamflow appears to be a reasonable simulation of the interaction between the Cedar River and Cedar River alluvial aquifer.

The water budget for the calibrated steady-state model was used to evaluate the model and determine if the model results were consistent with the simplified conceptual model. The primary sources of inflow to the modeled area are infiltration from the Cedar River (53.0 percent) and regional flow across general-head boundaries (34.1 percent). The primary sources of outflow from the modeled area are discharge to the Cedar River (45.4 percent) and pumpage (44.8 percent) (table 9).

Several steady-state pumping scenarios were simulated using the calibrated steady-state model. All parameters were left unchanged from the steady-state model with the exception of pumpage. The first scenario reduced pumpage at all municipal wells to zero, producing results that could be assumed to be predevelopment conditions of the alluvial aquifer. In predevelopment conditions, most of the ground-water recharge would be from precipitation and most of the ground-water discharge would be to the Cedar River. In the northwestern portion of the model area just south of Palo where the Cedar River channel becomes braided and more complex, water moves into the Cedar River alluvial aquifer from the Cedar River (16 ft^3/s, table 9). The presence of this losing reach in the northwestern part of the model area may be due to the simplified representation of this complex river-channel configuration in that portion of the model and may not be representative of steady-state conditions with no pumpage. However, losing reaches of the Cedar River have been noted in other areas of the Cedar River where water use is minor (Turco, 2002), indicating that the losing reach in this scenario may actually occur under predevelopment conditions. As expected, there is no river leakage into the Cedar River alluvial aquifer near the three Cedar Rapids well fields when pumpage is zero.

Comparison of the predevelopment flow budget to the steady-state flow budget indicates that the steady-state pumpage of 50.6 ft^3/s is primarily accounted for by an increase of 43.8 ft^3/s in Cedar River inflow to the alluvial aquifer and 6.5 ft^3/s of reduced outflow to the Cedar River (table 9). This water budget indicates that more than 99 percent of the water needed to supply the pumping is derived from the Cedar River.

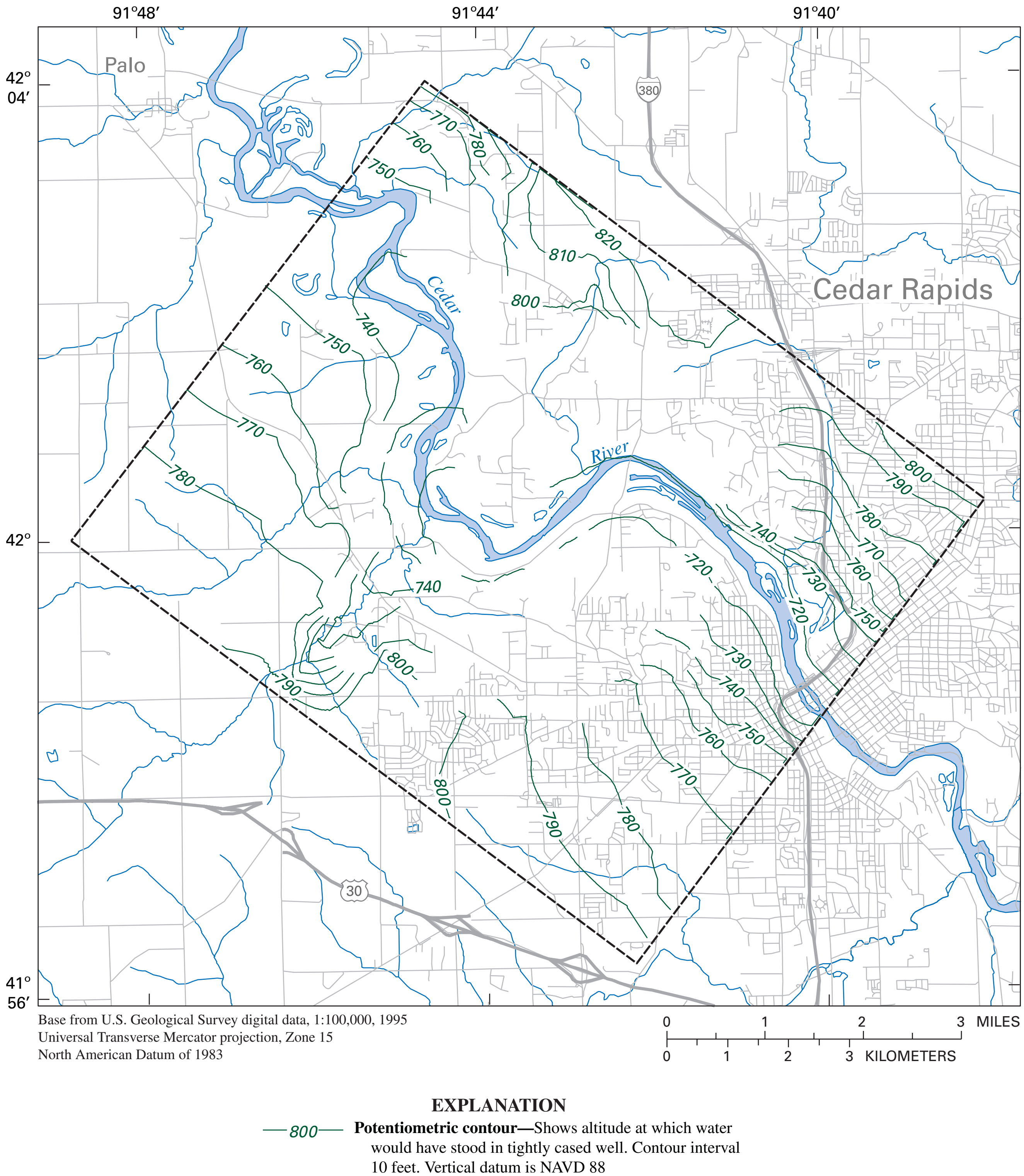


Figure 14. Simulated potentiometric surface of model layer 2 near Cedar Rapids, Iowa, under steady-state conditions. Areas with missing contour lines are upland areas with dry cells.

Table 9. Water budgets for hypothetical steady-state pumping scenarios.

[Inflow, water added to the ground-water system; outflow, water being removed from the ground-water system; pumpage, ground-water withdrawal by the City of Cedar Rapids, in cubic feet per second (ft^3/s)]

Budget component	Total pumpage at zero, predevelopment condition				Total pumpage at assumed steady-state condition				Total pumpage at about double the assumed steady-state condition			
	Inflow (ft^3/s)	Percentage of total inflow	Outflow (ft^3/s)	Percentage of total outflow	Inflow (ft^3/s)	Percentage of total inflow	Outflow (ft^3/s)	Percentage of total outflow	Inflow (ft^3/s)	Percentage of total inflow	Outflow (ft^3/s)	Percentage of total outflow
Recharge from infiltration of precipitation	14.6	21.1	0.0	0.0	14.6	12.9	0.0	0.0	14.6	9.0	0.0	0.0
Flow between Cedar River and alluvium	16.0	23.2	57.8	83.7	59.8	53.0	51.3	45.4	109.7	67.3	50.6	31.1
Flow from tributary streams to alluvium	.0	.0	10.8	15.7	.0	.0	10.6	9.4	.0	.0	10.5	6.5
Pumpage	.0	.0	.0	.0	.0	.0	50.6	44.8	.0	.0	101.1	62.2
General-head boundary	38.5	55.7	.4	.6	38.5	34.1	.4	.4	38.5	23.7	.4	.2
Total	69.1	100.0	69.0	100.0	112.9	100.0	112.9	100.0	162.8	100.0	162.6	100.0

The second scenario increased the overall pumpage of the calibrated steady-state model (101.1 ft^3/s) by a factor of two. Initial simulations caused two wells in the East well field to go dry, mathematically eliminating their pumpage from the volumetric calculation and therefore reducing the total pumpage from the alluvial aquifer. To correct this situation and to ensure that the alluvium was stressed at about double the steady-state values during this scenario, a portion of the pumpage from those wells was assigned to a nearby well in the East well field. The simulated total infiltration from the Cedar River to the alluvium is 109.7 ft^3/s, including the inflow north of the well fields near Palo. For the approximately 100 years of record for the Cedar River at Cedar Rapids gaging station, streamflow has exceeded 680 ft^3/s 90 percent of the time. The amount of induced infiltration is about 16 percent of this low flow. More than 99.5 percent of the pumpage is derived from water infiltrating from the Cedar River. There was little change (0.7 ft^3/s) between the steady-state scenario and the nearly doubled steady-state scenario in the amount of water discharged from the alluvial aquifer to the river indicating that the gaining reaches of the river may not be affected much by the additional pumpage.

Model results show that the Cedar River is in good hydraulic connection with the underlying alluvium and that the effects of the backwater siltation upstream from the low-head dam are small. With the high degree of connection with the Cedar River and the proximity of the municipal wells to the Cedar River, it seems reasonable that as long as there is sufficient flow in the Cedar River, ground-water availability in the Cedar Rapids area will not be significantly affected.

Transient Results and Hypothetical Pumping Scenarios

The transient pumping scenarios were developed to evaluate the timing of changes in water levels and ground-water flow due to changes in pumping. During the transient pumpage scenarios, all hydrogeologic parameters were left unchanged from the calibrated steady-state model. The stage of the Cedar River, the rate of recharge from infiltration of precipitation, and the rate of evapotranspiration also were held constant at steady-state values for each stress period. The only parameter varied was pumpage. The simulation consisted of 31 stress periods. Each of the first 30 stress periods are 1 day in length. Stress period 31 is 30 days long. Initial pumpage from all wells was zero, and incrementally increased every stress period until the full pumpage was reached at stress period 31 (fig. 15). This pumpage was then held constant for the remainder of the simulation. The final pumpage amount was larger than the amount for the steady-state scenarios because all wells were pumping rather than selected wells.

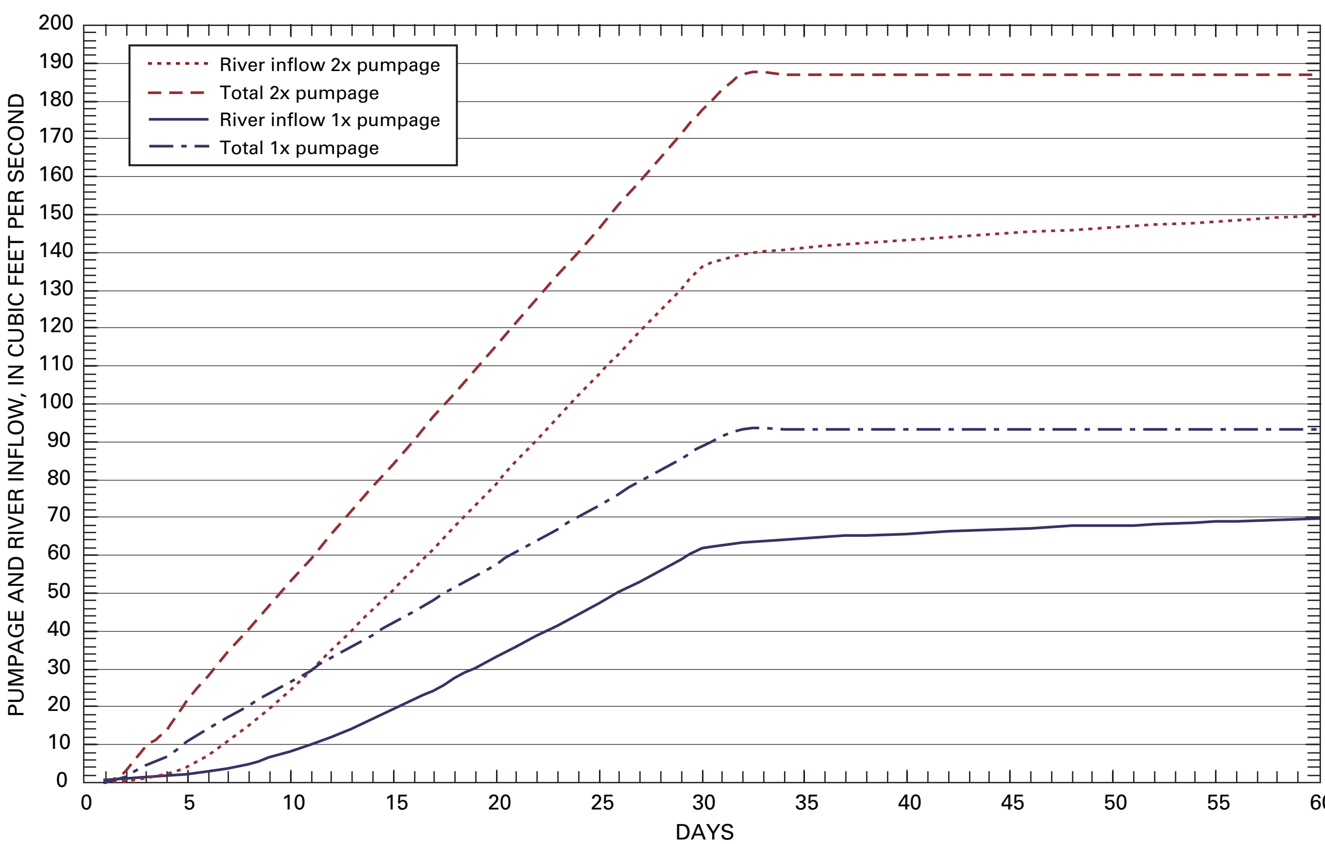


Figure 15. Pumpage and river inflow for transient model scenarios.

The first transient scenario had a final pumpage rate of about 93.4 ft^3/s and shows that water begins to enter the alluvial aquifer from the Cedar River in less than 1 day after pumping begins. Induced recharge from the river continues to increase until, after about 15 days, the change in pumpage is about the same as the change in inflow from the Cedar River. Induced recharge continues to increase at a rate similar to the rate of pumpage increase until pumpage levels off. At that point, the induced recharge increases at a much slower rate.

The second transient scenario involved increasing pumpage to about twice the rate of the first transient scenario, 186.9 ft^3/s. The rate in inflow from the Cedar River is about the same as the rate of pumpage after about 12 days during this scenario. The time it takes before an initial change in inflow from the Cedar River remains less than 1 day (fig. 15).

Assuming that the induced recharge will meet 99 percent of the pumpage demand at equilibrium and that the rate of induced recharge will continue to decrease at a constant rate until equilibrium is reached, both transient simulations indicate that nearly 150 days will be needed to reach equilibrium between pumpage and river inflow.

Summary

The Cedar River alluvial aquifer is the primary source of municipal water in the Cedar Rapids, Iowa, area. Since 1992, the U.S. Geological Survey (USGS), in cooperation with the City of Cedar Rapids, has investigated the hydrogeology and water quality of the Cedar River alluvial aquifer. Since 1999, efforts have been underway to refine the analysis of ground-water/surface-water interactions reported in earlier efforts to focus specifically on the Cedar Rapids well field area.

The study area is located in east-central Iowa and encompasses an area of about 45 mi^2 from Palo, Iowa, southeast to Cedar Rapids, surrounding the Cedar River alluvial aquifer. The area consists of a relatively flat alluvial valley bounded by upland areas. The Cedar River flows through the alluvial valley in the central portion of the study area, predominately from the northwest to the southeast. Alluvial deposits of aquifer material occur primarily as sand and gravel on the inside of river channel bends. Three Cedar Rapids municipal well fields (Seminole, West, and East) are located primarily north and east of the Cedar River. Two radial collector wells are located across from the Seminole well field, west of the Cedar River. Land use in much of the northwestern part of the study area is agricultural. Annual precipitation in the study area averages about 36.39 in/yr.

Ground-water and surface-water data were collected during the study to better define the hydrogeology of the Cedar River alluvial aquifer and Devonian and Silurian aquifers, and to assist in construction of the ground-water flow model. Measured ground-water levels were used to evaluate the local flow directions in the study area, to evaluate the seasonal variation in horizontal and vertical ground-water flow, to aid in the development and validation of the conceptual ground-water flow system, and to aid in the calibration of steady-state and transient simulations. Streamflow and river-stage data have been collected periodically from 1902 to 2003 on the Cedar River in the study area as part of the USGS streamflow-observation network in Iowa.

Unconsolidated geologic deposits and shallow bedrock units are in direct hydraulic connection in various combinations throughout the study area. The Cedar River alluvial aquifer is composed of sand, gravel, and minor amounts of silt and clay. The thickness of the alluvial aquifer decreases as distance from the Cedar River increases; the thinnest deposits are adjacent to the valley walls. Tributary stream alluvial aquifers and localized deposits of loess and eolian sand overlie the glacial till in the study area. A buried-channel aquifer is located along the northwestern border of the model area. The unconsolidated material in the upland areas bordering the alluvial aquifers in the study area consists predominately of glacial till. The Devonian aquifer is the uppermost bedrock in most of the study area outside the river valley and consists of fractured and unfractured limestone and dolomite. The Otis and Bertram Formations of Devonian age, composed predominately of limestone, dolomite, and a basal shale, form a local confining unit that restricts the flow of water between the Devonian and the underlying Silurian bedrock. The Silurian aquifer consists primarily of dolomite. In the Cedar River alluvial valley, the Devonian bedrock units, including the Otis and Bertram Formations, have been completely eroded leaving the Silurian bedrock as the uppermost bedrock unit. The Maquoketa Shale (Formation) of Ordovician age underlies the Silurian bedrock and is a regional confining unit.

The ground-water flow system in the study area consists of two main components, the unconsolidated Quaternary deposits and the underlying bedrock that has a variable fracture density. In the absence of anthropogenic stresses on the Cedar River alluvial aquifer, ground-water flow is typically towards the Cedar River and down the Cedar River valley. Ground-water flow in the Devonian and Silurian aquifers is a regional flow system. Recharge to the bedrock aquifers occurs regionally where the bedrock is exposed at land surface or through vertical flow from overlying Quaternary deposits.

Ground-water flow was simulated for the Cedar River alluvial aquifer and the Devonian and Silurian aquifers using the USGS's three-dimensional finite-difference ground-water flow model MODFLOW. The flow model was constructed to simulate steady-state conditions and transient conditions. A transient simulation was performed to evaluate the effect of hypothetical pumping scenarios on the timing of water infiltrating the alluvial aquifer from the Cedar River. The model was discretized into 223 rows and 354 columns of cells. Cell sizes range from about 50 ft on a side near the Cedar River and the Cedar Rapids municipal wells to 1,500 ft on a side near the model boundaries and farthest away from the Cedar Rapids municipal well fields. The model grid covers approximately 45 mi^2 and simulates ground-water flow in five layers, which include all hydrogeologic units.

The ground-water flow model was calibrated by adjusting the value of model input parameters so that the resulting model output matched measured water levels and other hydrologic observations with a reasonable level of accuracy. Presumed steady-state water-level data were obtained during a synoptic water-level measurement on December 21, 1998. The root mean square error for the calibrated steady-state model is 1.44 ft; the average model error is -0.26 ft. Transient calibration of the ground-water flow model to hydrologic conditions measured from February 6, 1998, to March 16, 1998, was completed by comparing the change in simulated water levels to the change in nearby measured water levels. The calibrated transient water levels near most of the observation wells responded similarly to measured water levels and the transient simulation compares reasonably with the conceptual flow model.

The sensitivity of the model to incremental changes in parameter values and the limitations of this model are important considerations. The model is most sensitive to drain cell tributary streambed conductance and horizontal hydraulic conductivity in layer 2. The model is limited in complexity with respect to the actual system and the total number of observations available for calibration compared to the number of model cells is very small, which substantially contributes to the uncertainty of this model.

Steady-state model water levels indicate that ground-water flow is predominately from the upland deposits to the Cedar River alluvial aquifer and then is discharged either to the Cedar River or to municipal pumpage. Most of the water moving in the ground-water flow model moves towards the Cedar River alluvial aquifer. The primary sources of inflow to the modeled area are infiltration from the Cedar River (53.0 percent) and regional flow across general-head boundaries (34.1 percent). The primary sources of outflow from the modeled area are discharge to the Cedar River (45.4 percent) and pumpage (44.8 percent). The current steady-state pumpage has increased the rate of inflow from the Cedar River to the alluvial aquifer by 43.8 ft^3/s and reduced the rate of outflow from the alluvial aquifer to the Cedar River by 6.5 ft^3/s over pre-development conditions. More than 99 percent of the water discharging from municipal wells infiltrates from the Cedar River. Results from steady-state pumpage scenarios indicate that the Cedar River alluvium can sustain double the steady-state pumpage with minimal effect on ground-water availability provided sufficient flow is available in the Cedar River to provide recharge to the aquifer.

Transient hypothetical pumpage scenarios were used to show the effect of changes in pumpage on the timing of infiltration of water from the Cedar River. Transient scenarios showed that as pumpage is increased from zero, river inflow begins to increase in less than 1 day. As pumpage from the Cedar Rapids well fields increases, infiltration of water into the alluvial aquifer from the Cedar River increases, and nearly 150 days may be needed for river infiltration to equilibrate with municipal pumpage.

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