USGS

science for a changing world

Prepared in cooperation with the
CEDAR FALLS UTILITIES

Simulation of Ground-Water Flow in the Silurian-Devonian Aquifer, Cedar Falls, Iowa

Water-Resources Investigations Report 02–4081

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

Rec'd
(2)
8/2/02

Date: July 22, 2002

Mail Stop 415

Memorandum

To: U.S. Geological Survey, Information Services, Bldg. 810
Box 25286, MS 306, Denver Federal Center, Denver, Colorado

From: District Chief, Colorado District, Water Resources Division

Subject: New U.S. Geological Survey Water-Resources Investigations Report

The following report was authorized by John Helgesen for the Director on February 27, 2002 for distribution. A reproducible copy is enclosed.

TITLE: Simulated Ground-Water Flow in the Silurian-Devonian Aquifer, Cedar Falls, Iowa

AUTHOR: Michael J. Turco

CONTENTS: : 40 p., ______ over-size sheets (for examples, larger than 8 1/2 x 11 inches)

Depositories: See monthly list of "New Publications of the U.S. Geological Survey" for addresses of libraries and Earth Science Information Centers (ESIC).

1. NC - Library, Reston, Virginia
2. Da - Library, Denver, Colorado
3. M - Library, Menlo Park, California
4. Wb - USDI, Natural Resources Library, Washington, D.C.

ORIGINATING OFFICE

Name: District Chief, WRD, USGS
Address: Bldg. 53, Denver Federal Center
MS 415, Box 25046
Denver, CO 80225

Release date: July 22, 2002

PRICE:
Fiche $ ______
Paper $ ______

Area: Colorado

Telephone: (303) 236-4882

USGS WRIR No.: 02-4081

Copies to: Chief, Editing and Manuscript Prep. Unit, Colorado District
Marilyn Billone, Publications Coordination

William F. Horak, Jr.

Simulation of Ground-Water Flow in the Silurian-Devonian Aquifer, Cedar Falls, Iowa

By Michael J. Turco

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 02–4081

Prepared in cooperation with the
CEDAR FALLS UTILITIES

Iowa City, Iowa
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
P. O. Box 1230
Iowa City, Iowa 52244

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
Denver Federal Center
Denver, CO 80225

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
million gallons (Mgal)	3,785	cubic meter
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second
foot squared per day (ft^2/d)	0.09290	meter squared per day

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

$$°C = \frac{(°F - 32)}{1.8}$$

Abbreviated water-quality units used in this report: Chemical concentrations are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams and micrograms per liter are units expressing the concentration of chemical constituents in solution as weight (milligrams or micrograms) of solute per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value of milligrams per liter is the same as for concentrations in parts per million. The numerical value of micrograms per liter is the same as for concentrations in parts per billion.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Simulation of Ground-Water Flow in the Silurian-Devonian Aquifer, Cedar Falls, Iowa

By Michael J. Turco

Abstract

The Silurian-Devonian bedrock aquifer in the Cedar Falls, Iowa, area provides large quantities of good quality ground water for municipal water suppliers as well as private residential users. The highly transmissive nature of the Silurian-Devonian aquifer material, due to fractures and karst features in the area and areas of thin, overlying Quaternary deposits, results in a ground-water supply vulnerable to contamination. To address these concerns, the U.S. Geological Survey, in cooperation with Cedar Falls Utilities, conducted a study from 1998 to 2001 to evaluate the hydrogeology and simulate the ground-water flow in the Silurian-Devonian bedrock aquifer in the Cedar Falls area.

A steady-state, ground-water flow model was constructed for a 200-square-mile area including Black Hawk County and small portions of Benton, Bremer, Buchanan, Butler, Grundy, and Tama Counties in northeast Iowa. The Silurian-Devonian aquifer was modeled using ground-water and surface-water data collected from April 1998 to February 1999 to help conceptualize the ground-water flow system. A potentiometric surface map constructed using the mean water-level from April 1998 to February 1999 shows predominant ground-water flow is toward the Cedar River. The modeled area was discretized into a 220-row by 180-column grid with cells measuring 500 feet by 500 feet, including the cities of Cedar Falls, Waterloo, and Evansdale. Three model layers were used to simulate flow in the surficial Quaternary aquifers, the Devonian-age rock, and the Silurian-age rock.

The shape of the simulated potentiometric surfaces and the direction and magnitude of the simulated ground-water flow is similar to the potentiometric surface and flow directions interpreted from the mean measured water levels. The simulated ground-water flow is predominantly toward the Cedar River. The primary sources of inflow to the Quaternary and Silurian-Devonian aquifers are recharge from precipitation and leakage from the Cedar River. The primary sources of outflow from the flow system are municipal ground-water withdrawals (pumpage) and leakage to the Cedar River and its tributaries. With the exception of the main pumping centers, where increased withdrawals may cause localized mixing, there is little evidence of mixing between the Devonian-age and Silurian-age rock units.

INTRODUCTION

The Silurian-Devonian aquifer in the Cedar Falls, Iowa, area provides large quantities of good quality ground water for municipal water suppliers as well as private residential users. Ground-water yields at individual wells can be more than 2,000 gal/min. However, the highly transmissive nature of this bedrock aquifer material due to the high density of fractures and karst features in the area, and areas of thin overlying unconsolidated deposits (20 to 100 ft) result in a ground-water supply vulnerable to contamination. Both historical and current land uses result in the potential for contamination of the aquifer. A long-term trend toward larger nitrate concentrations (Schaap, 1999) and an increased number of detections of trace organic compounds have been reported for specific municipal water-supply wells (Paul Mallinger, Cedar Falls Utilities, written commun., 1997).

To address these concerns, the U.S. Geological Survey (USGS), in cooperation with Cedar Falls Utilities, conducted a study from April 1998 to September 2001 to evaluate the hydrogeology of the Silurian-Devonian aquifer in the Cedar Falls area. The objectives of the study were to (1) evaluate the hydrogeology and (2) simulate the ground-water flow in the Silurian-Devonian aquifer under current (1998) pumping conditions. The purpose of this report is to describe the results of the study. Hydrogeologic and water-quality data used in this report were collected from April 1998 to February 1999.

The results of the study can be used by Cedar Falls Utilities (CFU) to establish a wellhead protection program and manage the development of the ground-water resource. The establishment of a wellhead protection program can educate people living and working in areas contributing recharge to wells about practices that prevent ground-water contamination and encourage the protection of the water supply for future generations. This study advances the understanding of ground-water flow to pumping wells in a fractured carbonate aquifer, and results of the study can be used by other water managers and planners using water supplies from similar hydrogeologic systems.

Description of Study Area

The study area covers approximately 200 mi^2 in northeast Iowa and includes Black Hawk County and small portions of Benton, Bremer, Buchanan, Butler, Grundy, and Tama Counties (fig. 1). The topography of the alluvial valley along the Cedar River in the study area is relatively flat. Uplands consisting of pre-Illinoian glacial deposits extend to the northeast and southwest. Land use in the study area is predominantly agricultural, including large areas of cropland and small livestock or poultry farms. Total average annual precipitation at Waterloo, 1961–90, just southeast of Cedar Falls, was 33.70 inches. During the same time interval, average monthly precipitation ranged from 0.80 inch during January to 4.88 inches during July, and average monthly temperature ranged from 14.6°F in January to 73.9°F in July (National Oceanic and Atmospheric Administration, 1998).

Acknowledgments

The author thanks the many well owners and operators that allowed USGS personnel to measure their wells during this study, specifically Cedar Falls Utilities, the University of Northern Iowa, and Waterloo Water Works, without which this study would not have been possible.

METHODS OF INVESTIGATION

Ground-water and surface-water data were collected during the study to help define the hydrogeology of the Silurian-Devonian aquifer and to assist in constructing a ground-water flow model. Data were collected at 63 ground-water sites (observation, municipal-supply, industrial-supply, and residential-supply wells) and one surface-water site (fig. 2). Previously conducted aquifer tests, completed at the time of well construction by the well driller or owner, were evaluated to determine aquifer hydraulic properties. Wells used for this study were selected on the basis of their location and primary aquifer, with an emphasis on spatial distribution throughout the study area of wells open to the Silurian-Devonian aquifer.

Ground-water flow in the study area was simulated using the USGS-developed MODFLOW model (McDonald and Harbaugh, 1988). MODFLOW model parameters were input using the Department of Defense Groundwater Modeling System (GMS) (Brigham Young University, 1998) preprocessor. The model was used to obtain a better understanding of the ground-water flow patterns of the Silurian-Devonian aquifer in the study area and provide a quantitative estimate of the water budget in the study area.

Surface-Water Measurements

Streamflow and stage data were collected periodically from 1998 to 1999 as part of the USGS streamflow network in Iowa (May and others, 1998; Nalley and others, 1999). Discharge and stage data were used to calibrate the ground-water flow model and estimate the stage of the rivers used in the model. Discharge and stage measurements on the Cedar River were made at Waterloo, Iowa (fig. 3), southeast of Cedar Falls, and on Beaver Creek were made at New Hartford, Iowa, west of the study area.

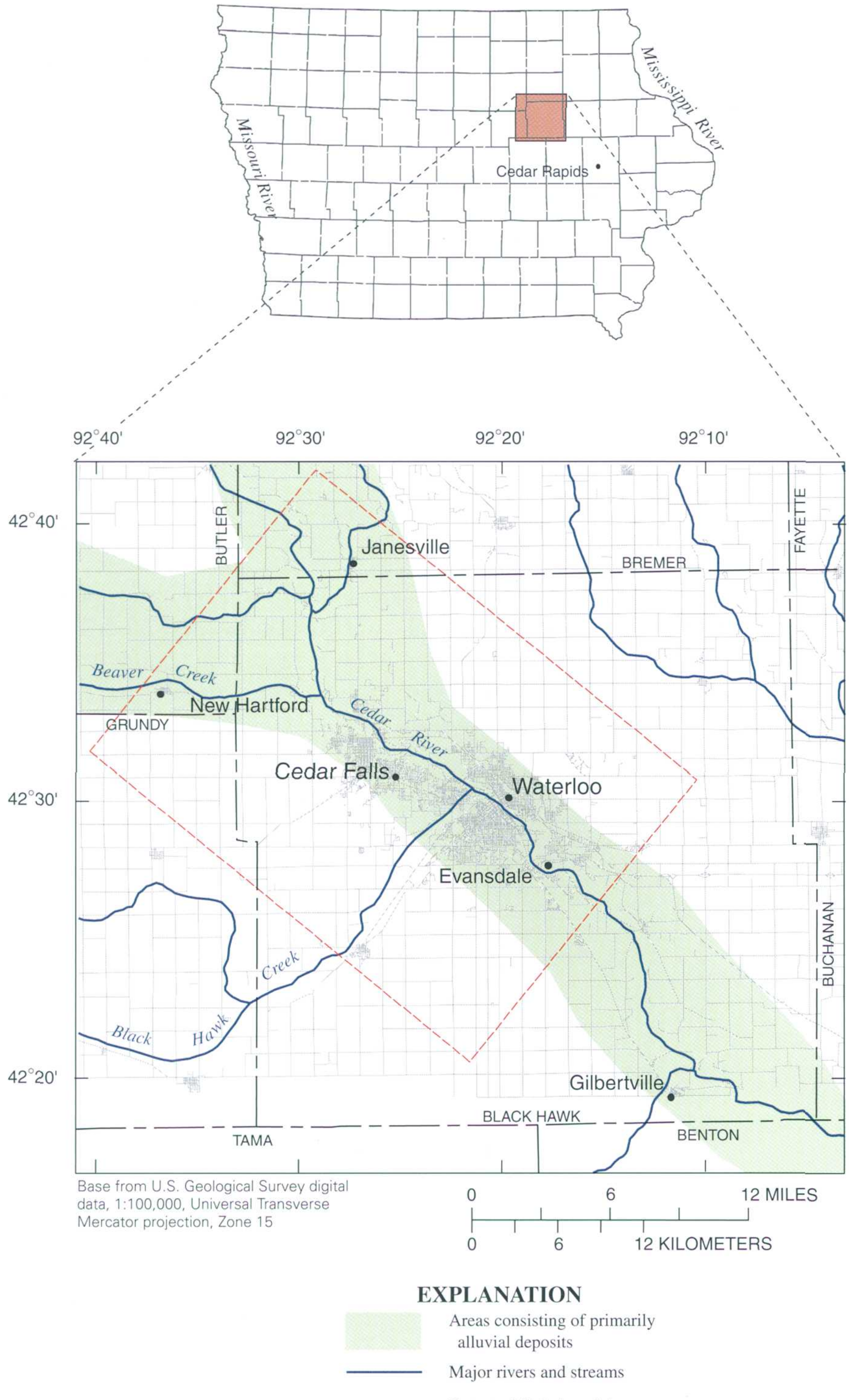


Figure 1. Location of study area.

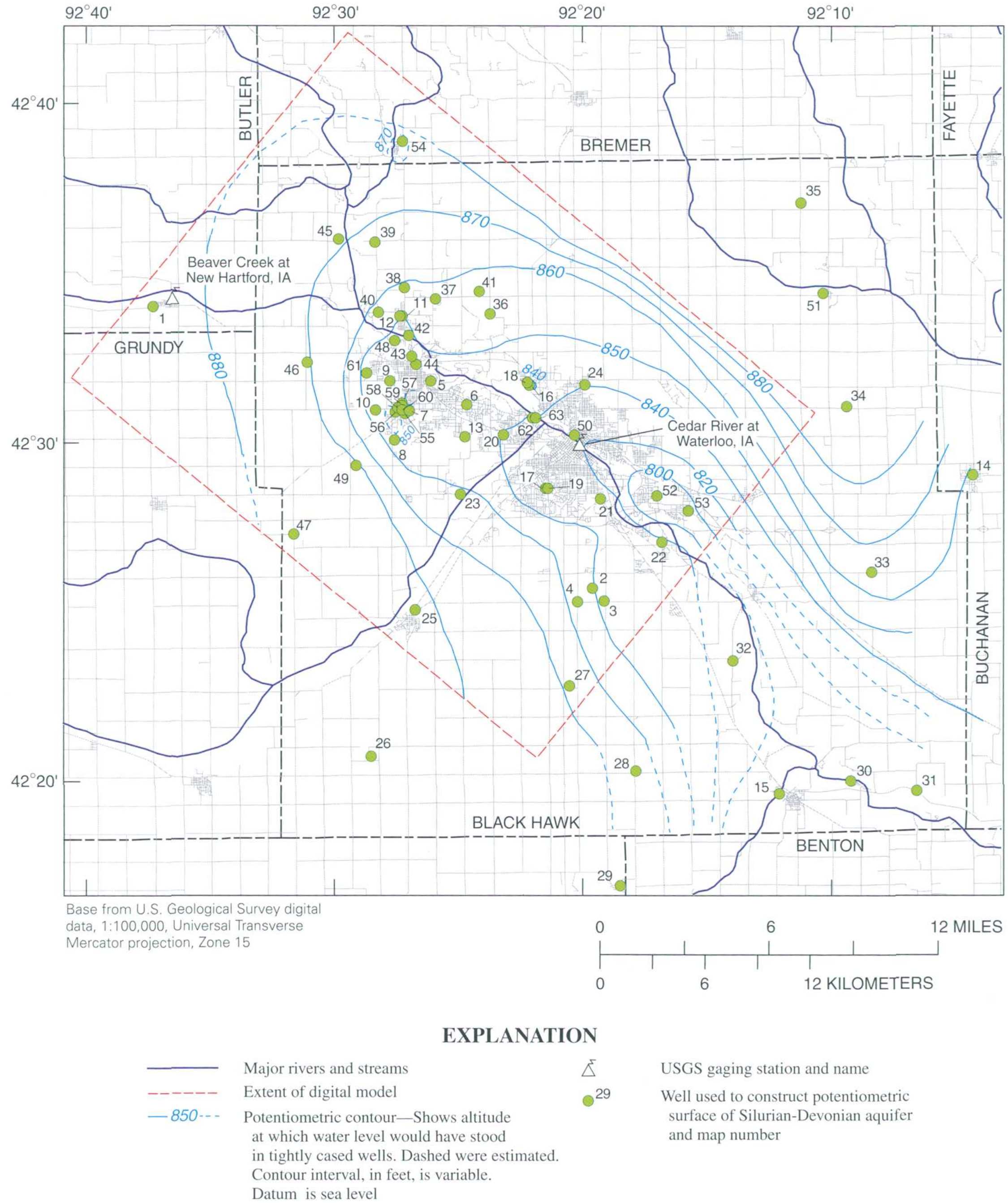


Figure 2. Extent of digital model, location of data-collection sites, and potentiometric surface constructed from mean measured water levels for the Silurian-Devonian aquifer, April 1998 to February 1999.

Ground-Water-Level Measurements

Ground-water levels (table 1) were measured bimonthly from April 1998 to February 1999 with a calibrated steel tape or an airline. Ground-water levels were recorded to the nearest 0.01 ft when using a steel tape and to the nearest 1 ft when using an airline. Ground-water levels were used to evaluate seasonal variations in horizontal and vertical components of flow directions, to help conceptualize the ground-water flow system, and to aid in the calibration of the ground-water flow model.

Well Construction and Nomenclature

Ground-water-level data were collected at wells constructed by private drillers prior to this study. Wells

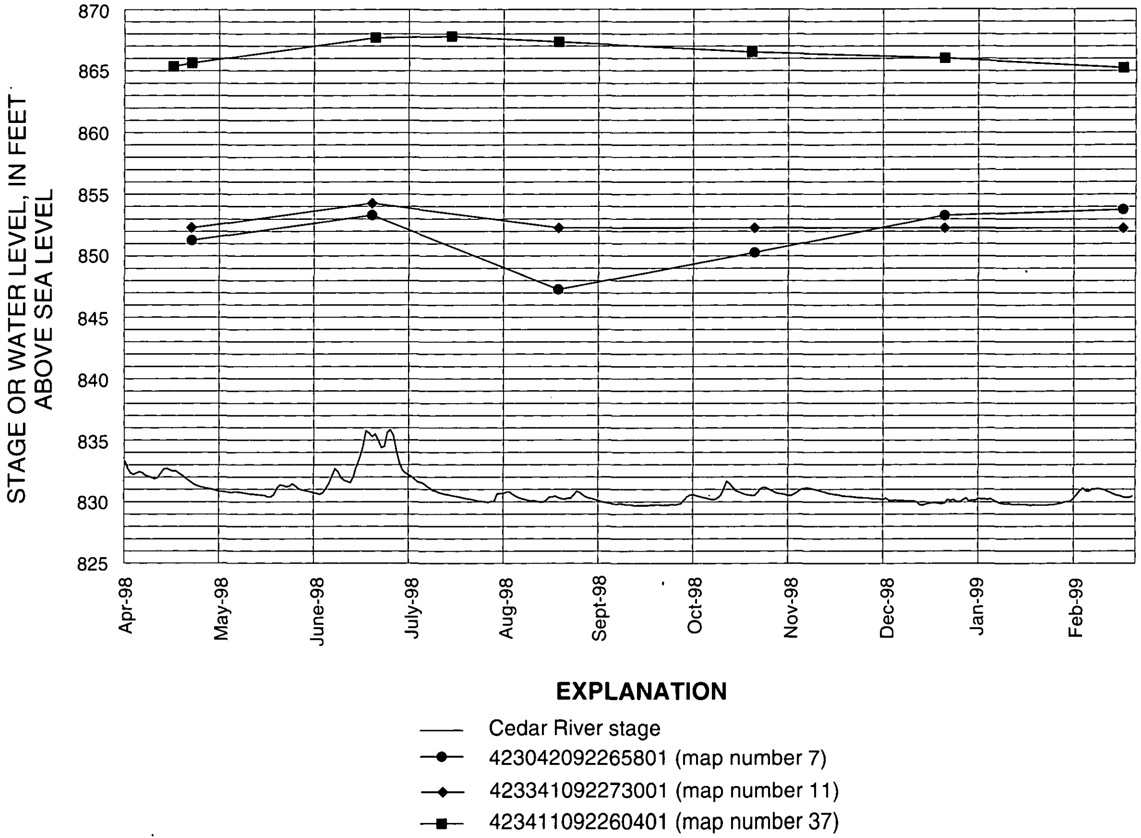


Figure 3. Cedar River stage at Waterloo, Iowa, and measured water levels in three wells near Cedar Falls, Iowa (see table 1 and figure 2 for location of wells and river gages).

completed in the Silurian-Devonian aquifer were constructed with open holes in the bedrock. All wells used in this study had casing material consisting of polyvinylchloride (PVC) or steel.

All wells were surveyed with a global positioning system (GPS) to determine their latitude and longitude. Differentially corrected GPS was used to establish an altitude for each well's measuring point so that all water levels could be converted to a common datum (sea level). Wells used in this study are designated by a unique 15-digit station-identification number that was assigned in the USGS Ground-Water Site Information database.

Aquifer Properties

Specific-capacity data for wells with previous aquifer-test data were evaluated to estimate hydraulic conductivity of the geologic material adjacent to the open interval of the well. In this report, hydraulic conductivity refers to horizontal hydraulic conductivity unless specifically referred to as vertical hydraulic conductivity. The hydraulic conductivity was calculated using a modified Theis equation for estimating transmissivity from specific-capacity data, and the available thickness of the aquifer adjacent to the well (Theis and others, 1963).

HYDROGEOLOGY

Hydrogeologic information relevant to the study of the ground-water flow system and description of the conceptual ground-water flow model is presented in the following section. The geology of the bedrock units in the study area is discussed in more detail in reports by Anderson (1983), Horick (1984), Hansen (1975), Olcott (1992), and Witzke (1988). Geologic units within the study area and their water-bearing characteristics are summarized in table 2.

Table 1. Well data and statistical summary of measured water levels, April 1998–February 1999

[USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds]

Map number (fig. 2)	USGS site identification	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface (feet above sea level)	Maximum altitude of measured water level (feet above sea level)	Mean altitude of measured water level (feet above sea level)	Minimum altitude of measured water level (feet above sea level)	Depth of well (feet below land surface)	Primary aquifer	Model layer
1	423401092373601	423400	923750	897.86	882.86	881.29	879.86	165	Devonian	2
2	422516092193501	422516	921935	940.96	843.12	840.70	839.65	110	Devonian	2
3	422452092190601	422452	921906	909.24	839.59	837.27	836.12	86	Devonian	2
4	422451092201401	422451	922014	954.70	844.53	842.39	841.34	141	Devonian	2
5	423139092261401	423140	922620	858.80	848.80	846.80	845.80	150	Devonian	2
6	423053092244701	423055	922445	934.54	846.54	843.54	840.54	183	Devonian	2
7	423042092265801	423045	922710	881.28	853.78	851.38	847.28	145	Devonian	2
8	422948092281201	422950	922750	959.93	844.93	843.93	839.93	227	Devonian	2
9	423143092275801	423140	922800	941.90	845.90	843.90	841.90	170	Devonian	2
10	423045092283401	423045	922835	941.59	841.59	840.59	838.59	216	Devonian	2
11	423341092273001	423340	922730	876.12	854.12	851.12	846.12	275	Devonian	2
12	423341092273301	423340	922735	876.26	854.26	850.26	839.26	275	Devonian	2
13	422956092245101	422956	922451	901.76	849.76	846.76	844.76	200	Devonian	2
14	422838092034201	422838	920342	988.75	927.05	856.65	812.75	365	Devonian	2
15	421857092115601	421855	921155	836.11	793.11	748.91	736.96	250	Silurian	3
16	423131092224201	423130	922210	859.04	843.04	840.04	832.04	190	Devonian	2
17	422818092212801	422820	922130	951.43	833.43	830.43	827.43	206	Devonian	2
18	423200092224001	423135	922215	857.45	852.45	843.45	842.45	204	Silurian	3
19	422819092212701	422820	922125	951.83	835.83	828.83	823.83	215	Devonian	2
20	423002092231101	423000	922315	925.51	842.51	839.51	837.51	208	Devonian	2
21	422801092191401	422800	921915	850.89	844.89	834.89	824.89	138	Devonian	2
22	422638092164001	422640	921640	834.90	828.90	824.90	820.90	145	Devonian	2
23	422810092250401	422810	922505	879.00	857.00	853.00	850.00	225	Devonian	2
24	423131092195201	423131	921952	871.74	848.74	843.74	839.74	151	Devonian	2
25	422439092270101	422439	922701	881.89	875.90	872.37	868.89	230	Devonian	2
26	422009092285201	422009	922852	999.51	876.54	873.13	869.51	247	Devonian	2
27	422217092203601	422217	922036	953.90	861.86	858.99	856.63	235	Devonian	2
28	421939092175201	421939	921752	913.84	873.53	859.27	850.29	240	Devonian	2
29	421608092183401	421608	921834	975.80	857.99	854.32	851.77	360	Devonian	2
30	421917092085501	421917	920855	811.65	802.40	796.42	794.37	120	Devonian	2
31	421859092061201	421859	920612	823.47	796.79	791.41	788.43	110	Devonian	2
32	422300092134801	422300	921348	822.93	814.15	810.5	808.96	85	Devonian	2

Table 1. Well data and statistical summary of measured water levels, April 1998–February 1999—Continued

[USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds]

Map number (fig. 2)	USGS site identification	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface (feet above sea level)	Maximum altitude of measured water level (feet above sea level)	Mean altitude of measured water level (feet above sea level)	Minimum altitude of measured water level (feet above sea level)	Depth of well (feet below land surface)	Primary aquifer	Model layer
33	422542092075801	422542	920758	968.23	869.66	867.04	863.23	265	Devonian	2
34	423047092085701	423047	920857	992.54	907.63	907.07	906.53	220	Devonian	2
35	423702092104601	423702	921046	1011.08	972.48	971.70	969.32	200	Devonian	2
36	423343092234701	423343	922347	864.05	857.35	855.10	851.05	120	Devonian	2
37	423411092260401	423411	922604	872.54	857.80	856.45	855.24	103	Devonian	2
38	423431092272301	423431	922723	877.30	860.80	859.22	856.20	140	Devonian	2
39	423556092283601	423556	922836	926.48	871.89	869.15	864.48	90	Devonian	2
40	423346092282901	423346	922829	867.68	859.21	856.94	855.25	160	Devonian	2
41	423423092241301	423423	922413	873.90	852.64	851.12	850.40	150	Devonian	2
42	423303092271201	423303	922712	862.70	852.23	849.89	848.27	120	Devonian	2
43	423225092270401	423225	922704	857.95	850.31	847.62	846.48	200	Devonian	2
44	423210092265201	423210	922652	873.99	849.58	847.11	845.34	120	Devonian	2
45	423601092300601	423601	923006	888.41	874.63	871.23	869.54	128	Devonian	2
46	423216092312801	423216	923128	970.82	884.25	878.72	872.82	133	Devonian	2
47	422658092320201	422658	923202	965.22	882.32	878.00	876.27	160	Devonian	2
48	423254092274801	423254	922748	862.06	849.92	849.75	849.58	150	Devonian	2
49	422904092292601	422904	922926	942.50	868.98	868.12	867.32	190	Devonian	2
50	422959092201701	422959	922017	845.00	827.09	826.53	825.46	[1]150	Devonian	2
51	423416092095701	423415	920955	949.78	907.78	893.78	881.78	320	Silurian	3
52	422804092165301	422805	921655	837.82	823.82	782.82	762.82	305	Silurian	3
53	422737092153501	422737	921535	836.79	795.79	787.79	779.79	305	Devonian	2
54	423902092272502	423900	922725	887.47	869.47	866.27	861.47	125	Silurian	3
55	423039092272401	423039	922724	887.52	847.02	843.45	836.52	180	Devonian	2
56	423043092274701	423043	922747	914.49	846.99	839.69	815.49	194	Devonian	2
57	423059092273101	423059	922731	932.72	847.72	844.02	837.47	195	Devonian	2
58	423051092274001	423051	922740	922.87	847.62	843.67	840.62	200	Devonian	2
59	423055092273001	423055	922730	941.12	848.87	845.26	839.87	190	Devonian	2
60	423046092273001	423046	922730	913.63	846.88	843.63	838.13	195	Devonian	2
61	423156092285701	423156	922857	964.35	852.35	849.25	841.19	248	Devonian	2
62	423027092220601	423030	922205	853.13	828.13	822.13	819.13	250	Devonian	2
63	423030092215701	423030	922155	858.91	843.16	840.74	838.66	78	Devonian	2

[1]Depth unknown, but estimated on the basis of similar nearby wells.

Table 2. Hydrogeologic units in the study area and their water-bearing characteristics

[gpm, gallons per minute]

Hydrogeologic unit[1]	General thickness[1] (feet)	Age of rock unit[2]	Potential well yield	Lithology[1]	Equivalent layer in the ground-water flow model
Alluvial, glacial-drift, and buried-channel aquifers	20–250	Quaternary	Well yields variable, 3–25 gpm, not a widely used source of water.	Medium- to coarse-grained sand; fine-grained sand and silt.	Layer 1
Silurian-Devonian aquifer	10–200	Devonian	Permeability is assumed to vary dependent upon proximity to the Cedar River. Well yields in excess of 2,500 gpm with minimal drawdown.	Highly fractured limestone, dolomite, and shale. May locally have a karst topography (Horick, 1984).	Layer 2
	10–300	Silurian	Permeability dependent upon the number and density of fractures and degree of dolomitization. Well yields typically 300 gpm.	Dolomite with some limestone and chert.	Layer 3
Confining unit	100–300	Ordovician	Well yields very small; regional confining unit.	Shale and dolomite.	Basal (no-flow) boundary

[1]Modified from Horick (1984) and Olcott (1992).
[2]Age classifications of rocks are those of the Iowa Department of Natural Resources, Geological Survey Bureau.

Geology and Water-Bearing Characteristics

The Quaternary-age deposits comprise a surficial aquifer system that ranges in thickness from about 20 ft to 250 ft in the study area (Iowa Geological Survey Bureau, 1999). Quaternary-age deposits include alluvial, glacial-drift, and buried-channel materials with variable permeabilities both vertically and horizontally. The glacial deposits in Iowa are rich in clay, which may indicate a lower permeability in some locations (Olcott, 1992). The “sand” and “coarse-sand” alluvial units described in the descriptive well logs for CFU water-supply wells (Paul Mallinger, Cedar Falls Utilities, written commun., 1997) may provide only limited protection against contaminants in surface water and shallow ground water from leaching to the underlying bedrock units (Hallberg and others, 1996).

The uppermost bedrock consists of rocks of Devonian age (table 2). The Devonian-age rocks unconformably overlie Silurian-age rocks and consist primarily of limestone, dolomite, and shale but locally include minor amounts of sandstone (Witzke and others, 1988). In the study area, the thickness of the Devonian-age rocks varies from about 10 ft in the northeast to about 200 ft to the southwest. This rock unit has a significant occurrence of fractures. Fractures allow ground-water flow along discrete paths, resulting in increasing solution activity along the fractures (Knochenmus and Robinson, 1996). Fracturing and dissolution of aquifer material is known as secondary permeability. The relative amount of secondary permeability appears to be greatest nearest the Cedar River. The primary orientation of the fractures is assumed to coincide with the orientation of the Cedar River, which may flow along this regional fracture pattern. Video well logs (Paul Mallinger, Cedar Falls Utilities, written commun., 1998) show a high density and occurrence of fractures in the Devonian-age rocks, some of them large, in CFU municipal-supply wells. The transmissivity in the Devonian-age rock, calculated using available specific capacity data, decreases as distance from the Cedar River increases. Most production wells in the study area are completed in the highly fractured rocks of Devonian age because large amounts of good quality water have been available historically.

The Silurian-age rocks consist primarily of dolomite, with some limestone and minor amounts of chert (table 2) (Iowa Geological Survey Bureau, 1999). The elevation of the contact between the

Silurian-age rocks and Devonian-age rocks was estimated by using descriptive well logs from the Iowa Geological Survey Bureau (1999). Altitudes derived from these logs were used to estimate the uppermost occurrence of Silurian-age rock in the study area. The thickness of the Silurian-age rocks varies from about 10 to 300 ft. Silurian-age rocks are assumed to be fractured to a lesser degree than Devonian-age rocks because they are not the uppermost bedrock unit. In instances where the Silurian-age portion of the Silurian-Devonian aquifer is the uppermost bedrock unit, such as in the Cedar River Valley south of the study area, the estimated amount of secondary permeability is comparable to the fractured Devonian rock in this study area.

The rocks of Devonian and Silurian age commonly are considered to be one hydrogeologic unit because they are often in hydraulic connection. Silurian-age rocks are usually the primary source of water to wells completed in this aquifer system throughout its main use area in Iowa, so the unit became locally known as the Silurian-Devonian aquifer (Horick, 1984). The Silurian-Devonian aquifer is absent in extreme northeastern Iowa and is more than 700 ft thick in southwestern Iowa (Horick, 1984). The thickness of the Silurian-Devonian aquifer, in the study area, is estimated to be about 20 to 500 ft.

Transmissivity of the Silurian-Devonian aquifer is highly variable, depending on the degree of interconnection between the fractures and bedding planes (Schaap, 1999). Transmissivity in the study area reaches a maximum of about 360,000 ft^2/d in areas where the Silurian-Devonian aquifer underlies Quaternary deposits of the Cedar River alluvium. Transmissivity may be about 1,200 ft^2/d where the aquifer is confined (Olcott, 1992) by Mississippian-age rock units outside the study area.

Rocks of Ordovician age underlie the Silurian-Devonian aquifer. The uppermost Ordovician-age rocks consist of shale, dolomite, and limestone (Olcott, 1992). The uppermost occurrence of Ordovician-age rocks was estimated using descriptive well logs from the Iowa Geological Survey Bureau (1999). Due to the lithology of this rock unit, it is considered to be a regional confining unit, restricting vertical ground-water flow into or from the Silurian-Devonian aquifer in the study area.

Surface Water

The Cedar River is the major surface-water feature in the study area. The river has its headwaters in southern Minnesota and flows southeasterly to its confluence with the Mississippi River in southeast Iowa. The fall, or change in stage, from Janesville, Iowa, to Waterloo, Iowa, is about 60 ft. Large variations in river stage are reflected in the water level of wells near the river (fig. 3). A potentiometric surface map by Horick (1984) shows that the Cedar River, in general, receives ground-water discharge from the Silurian-Devonian aquifer throughout most of the study area. However, the Cedar River is a slightly losing reach north of Cedar Falls, from just south of Janesville, Iowa, to just north of Cedar Falls, Iowa (Mark Savoca, U.S. Geological Survey, written commun., 2001). Base flow at Waterloo, Iowa, from April 1998 to February 1999 was estimated to be between 600 ft^3/s and 1,100 ft^3/s by hydrograph separation.

Ground Water

Rocks of Devonian and, to a lesser extent, Silurian age contain numerous fractures which provide openings for ground-water movement and storage. Hydraulic conductivity describes the ability of geologic materials to transmit water and depends upon the size, orientation, density, and the degree of connection of fractures and pores. Driscoll (1986) and Freeze and Cherry (1979) provide a general range of hydraulic conductivities for various lithologies (table 3). Horick (1984) estimated the transmissivity for the Silurian and Devonian rocks to range from 200 ft^2/d to 361,000 ft^2/d statewide. Assuming a uniform thickness of 300 ft, hydraulic conductivities in the Silurian- and Devonian-age rocks range from about 1 ft/d to 1,200 ft/d statewide. Transmissivity values for this study were estimated using specific-capacity data available for each of the network wells used in this study. Estimated transmissivities throughout the Silurian-Devonian aquifer in the study area vary over several orders of magnitude, with larger values near the Cedar River. The probable cause for this heterogeneity is due to the spatial variability of increased secondary permeability near the Cedar River.

Table 3. Estimated horizontal hydraulic conductivity in the study area

[--, data not available]

Lithology	Horizontal hydraulic conductivity, in feet per day			
	Modified from Driscoll (1986)	Modified from Freeze and Cherry (1979)	From aquifer-test analysis in this study[1]	Parameter value in ground-water flow model
Glacial till	3.2×10^{-7}–30	2.8×10^{-6}–2.8	--	--
Clay	3.2×10^{-7}–3.2×10^{-4}	2.8×10^{-3}–28	--	4
Silty sand	--	2.8–280	--	90
Fine to coarse sand	3.2×10^{-2}–3.2×10^{3}	2.8–10,000	--	360–450
Sand and gravel	--	--	--	--
Limestone and dolomite (unjointed crystalline)	3.2×10^{-1}–3.2×10^{-5}	--	--	--
Limestone and dolomite (highly fractured)	3.2×10^{-1}–1,000	10–100,000	600–300,000	1,000
Limestone and dolomite (moderately fractured)	--	--	300–600	100–240
Limestone and dolomite (slightly fractured)	--	--	0.1–300	10–40

[1]Horizontal hydraulic conductivity estimated using specific capacity data (Theis and others, 1963) and uniform thickness of the aquifer material.

There is an appreciable difference in the water-yielding characteristics between the Quaternary-age materials, Devonian-age rocks, and Silurian-age rocks. Most ground-water movement occurs in the Devonian-age rocks (Horick, 1984), and although the lithology of the Silurian- and Devonian-age rocks are similar, the hydraulic properties, due to increased occurrences of secondary permeability in the Devonian-age rocks, are significantly different. For example, one municipal supply well, open to both Devonian and Silurian-age rocks, had about an 80-percent reduction in production when the section of the well open to the Devonian-age rocks was cased, negating their contribution (Paul Mallinger, oral commun., 1999). Due to this hydraulic difference, the Silurian-Devonian aquifer was evaluated as two separate hydrogeologic units in direct connection consisting of the Devonian-age and Silurian-age rocks.

The potentiometric surface, based on mean water-level altitudes from April 1998 to February 1999, indicates that the regional ground-water flow in the Silurian-Devonian aquifer in the study area is toward the Cedar River from northeast to southwest and then toward the southeast down the Cedar River valley (fig. 2). There is some local flow to pumping centers in the Cedar Falls and Waterloo area and farther south near Evansdale. The potentiometric surface created for this report compares favorably in shape and gradient in the Cedar Falls area to a previously mapped potentiometric surface created by Horick (1984) in 1980 for the Silurian-Devonian aquifer.

Recharge to the ground-water flow system is predominantly from infiltration of precipitation. Discharge from the ground-water flow system includes, but is not limited to, flow to the Cedar River and pumping wells.

SIMULATION OF GROUND-WATER FLOW

The ground-water flow model described in this report is a simplified mathematical approximation of the complex physical system. Limited onsite observations and hydrogeologic data were used to conceptualize the ground-water flow system. However, a calibrated model can aid in understanding and quantifying the ground-water flow system. The model also can be used to estimate effects of varying stresses on ground-water levels and the recharge and discharge of ground water.

The flow model was constructed to simulate steady-state 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. Mean water levels within the study area from April 1998 to February 1999 were considered to be an acceptable estimate of steady-state conditions. Ground-water levels measured in most wells during this period had little variation. The stage of the Cedar River and Beaver Creek was simulated assuming base-flow conditions. Recharge, used to account for precipitation and evapotranspiration, was assumed to be the average daily recharge to the system.

Model Description and Boundary Conditions

The modeled area was discretized into a 220-row by 180-column grid with cells measuring 500 ft by 500 ft. The model grid covers an area of 20.8 mi by 17.0 mi, or about 355 mi^2. The grid was aligned so that the Cedar River coincided with the y-axes. Three layers were used to simulate flow: layer 1 represents the Quaternary alluvial and glacial deposits, layer 2 represents the Devonian-age portion of the Silurian-Devonian aquifer, and layer 3 represents the Silurian-age portion of the Silurian-Devonian aquifer. The Silurian-Devonian aquifer was simulated using two layers because differences were observed in the well yields of the Silurian- and Devonian-age rocks, and because secondary permeability is assumed to be less of a factor in the deeper Silurian-age rocks. Cells within the model grid are identified by row, column, and layer. Ground-water flow in layer 1 was simulated as unconfined because of water-table conditions present in the surficial deposits, and ground-water flow in layer 2 and 3 was simulated as confined. A small number of cells in layer 1, associated with a thin amount of Quaternary material or a boundary, were simulated as dry,

Boundary conditions were specified for the model (figs. 4, 5, and 6) to simulate flow entering or leaving along the edge of the modeled area in relation to the features within the modeled area. Recharge from precipitation to the upper surface of the flow model was represented as a nonuniform specified-flux boundary. Recharge is discussed in more detail in the following section on "Model Parameters."

No-flow boundaries were used to simulate areas where lateral ground-water flow is interpreted to be parallel with the boundary, such as along ground-water flow lines, or is considered to be insignificant, such as a contact with a nonaquifer material. The bottom of the model is the top of the Ordovician-age rocks, which form a relatively impermeable regional confining unit. Flow lines constructed from the mean water levels during the study period define the southeastern no-flow boundary for all model layers.

Lateral ground-water flow from geologic materials laterally adjacent to the modeled aquifers was simulated with general-head boundaries. General-head boundaries were used along the northeastern, northwestern, and southwestern edges of layer 1 to simulate subsurface flow from the glacial deposits near the model boundaries to the alluvium in the Cedar River Valley, and along northeastern, northwestern, and southwestern limit of layer 2 and layer 3 to simulate regional ground-water flow in the Devonian and Silurian aquifers, respectively. For all general-head boundaries, a constant-head source, estimated to be similar in magnitude to the measured potentiometric surface shown in figure 3, was specified 1 mi from the closest active cell in the model. The hydraulic conductivity of the area between the constant-head source and the active cell was assumed to be equal to the nearest active cell.

The Cedar River and Beaver Creek were simulated using river cells that allow leakage to and from layer 1. River stage is specified for each river cell. River stage was interpreted along the river reach from the USGS gaging data at Waterloo, Iowa, and New Hartford, Iowa, for the Cedar River and Beaver Creek, respectively, and the USGS Cedar Falls 7.5-minute topographic map. Riverbed elevation was assumed to be 5 ft below stage and the thickness of the riverbed material was assumed to be 1 ft throughout the model area. The riverbed conductance term is a function of the riverbed thickness, the length of the river reach, and the width of the river channel. The amount of leakage between the river cells and layer 1 is calculated using the head difference between the river cells and layer 1 and the riverbed conductance term. A vertical hydraulic conductivity of 3 ft/d was assumed for river-bed material for the Cedar River and Beaver Creek.

Model Parameters

Model parameters are numerical values assigned to individual cells in the model array and are used in the flow equations that simulate ground-water flow in the modeled area. Parameters are assigned to the center of each model cell and represent an average value for the entire cell. Uniform values of parameters can be assigned to groups of model cells to represent the spatial distribution of altitudes of the model layers, hydraulic conductivity, recharge, and ground-water pumpage. Model grid orientation and pumpage locations are shown in figures 4, 5, and 6.

Model layers were constructed using altitudes of geologic contacts interpolated from descriptive well logs recorded during well construction. Geologic contacts used in the model were the Quaternary and Devonian, the Devonian and Silurian, and the Silurian

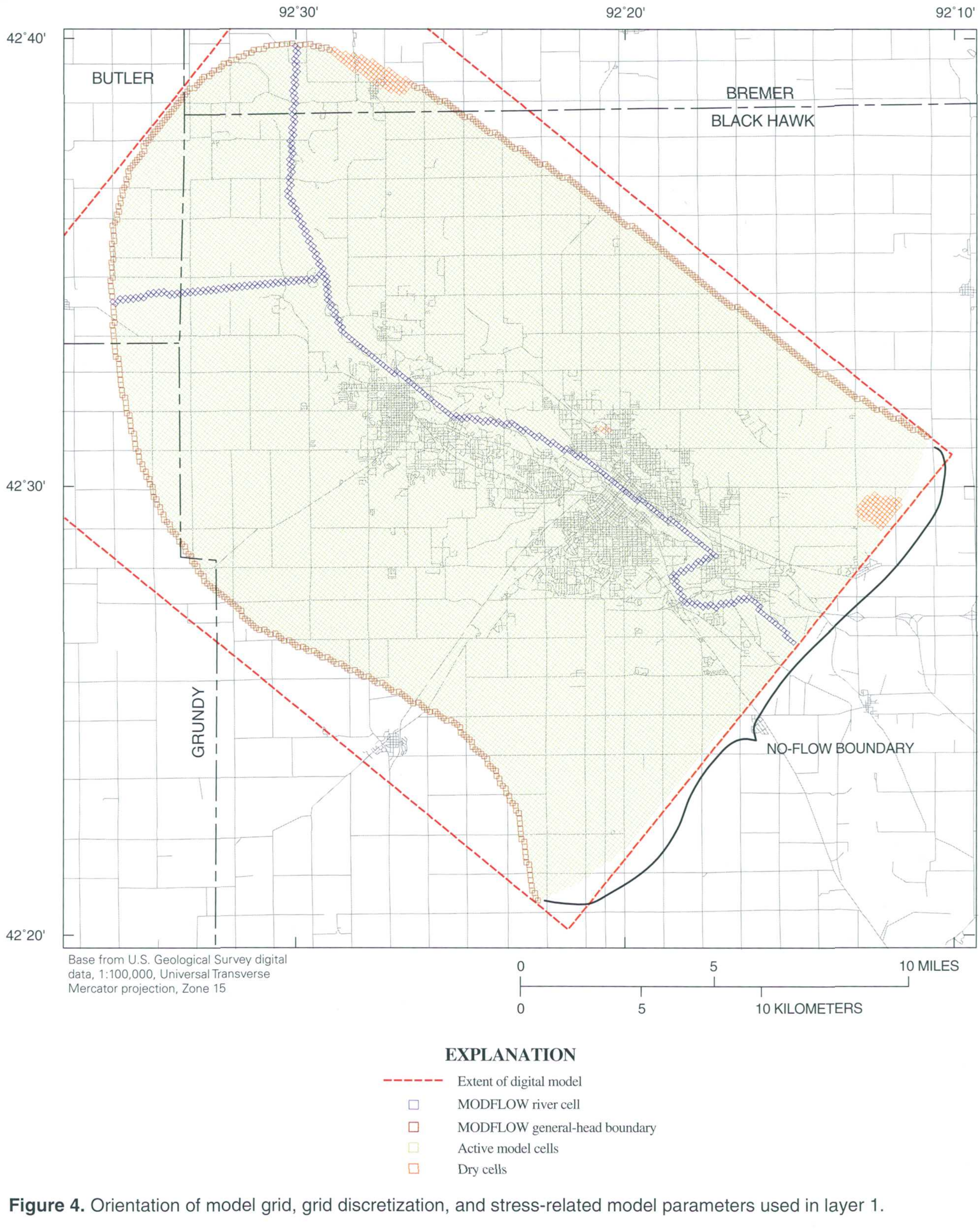
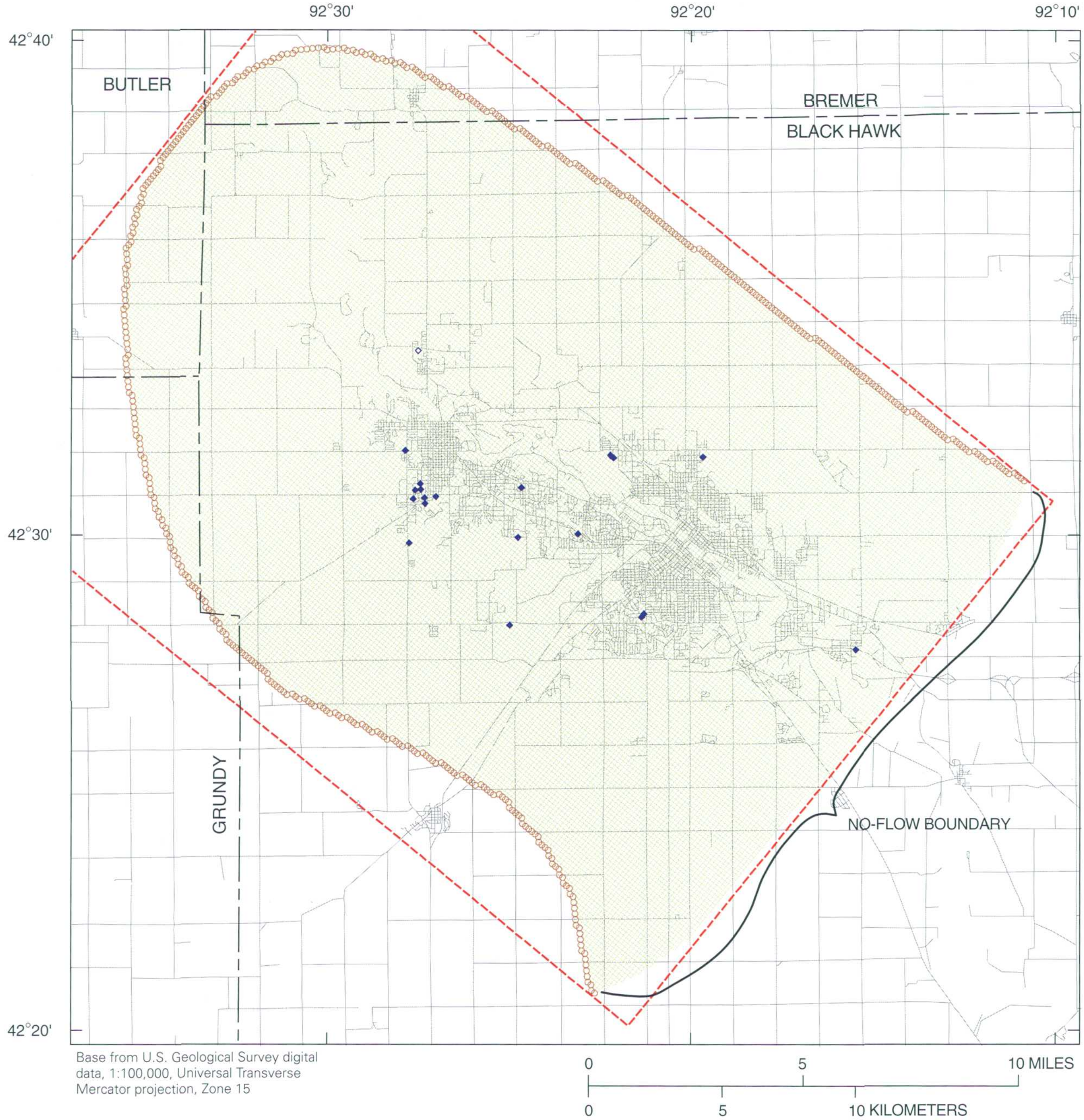


Figure 4. Orientation of model grid, grid discretization, and stress-related model parameters used in layer 1.



EXPLANATION

- Extent of digital model
- MODFLOW well
- MODFLOW general-head boundary
- Active model cells

Figure 5. Orientation of model grid, grid discretization, and stress-related model parameters used in layer 2.

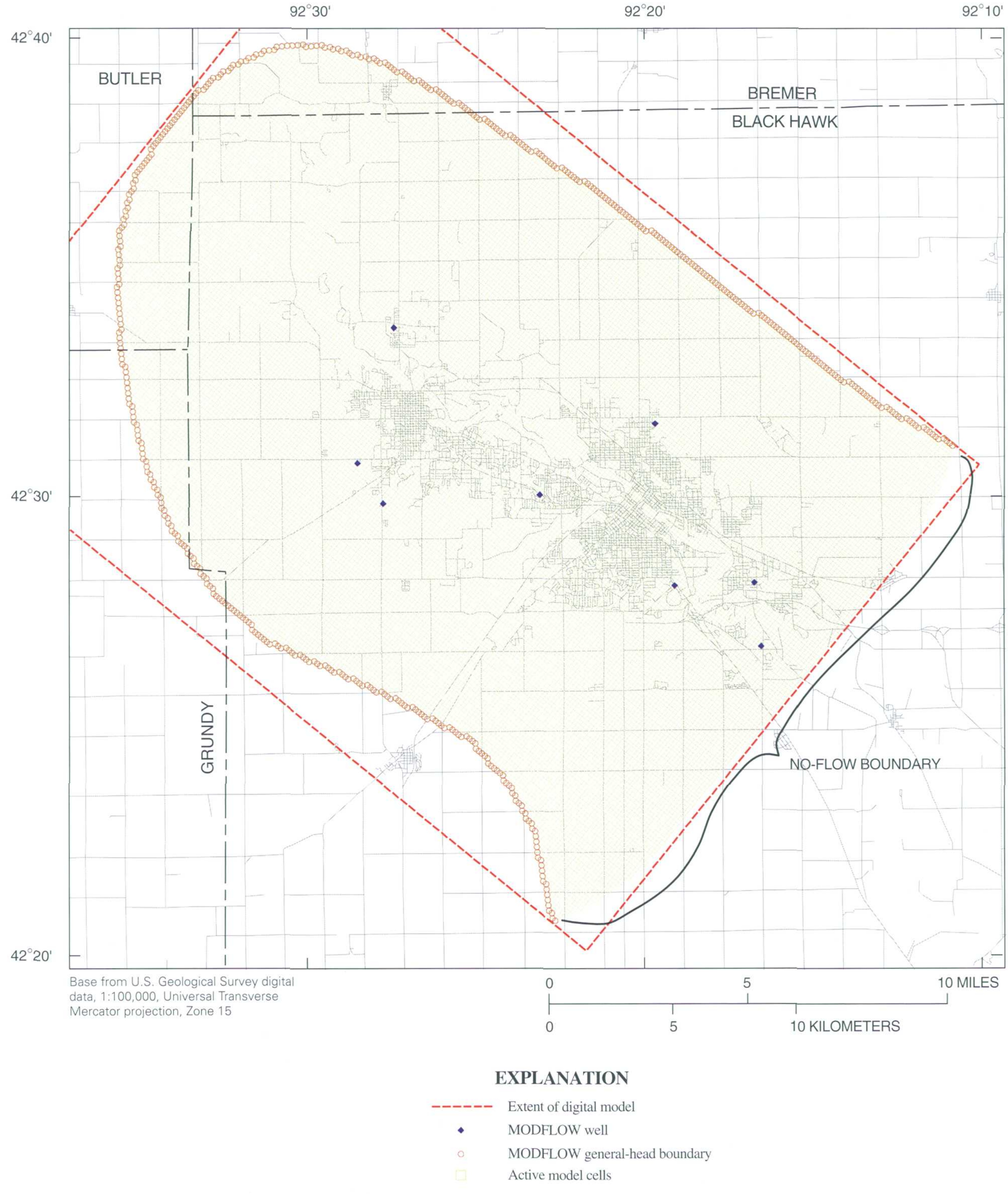


Figure 6. Orientation of model grid, grid discretization, and stress-related model parameters used in layer 3.

and Ordovician contacts. Altitudes of each contact were interpolated by the preprocessor using the inverse distance-weighted method (IDW) to the model grid.

Hydraulic conductivity in layer 1 was estimated using available aquifer-test data from private drillers or contractors or published representative hydraulic conductivities for similar geologic materials. Hydraulic conductivities used for model layers 2 and 3 account for the estimated degree of secondary permeability present. Hydraulic conductivities in layer 1, 2, and 3 range from 4 to 450 ft/d, 10 to 1,000 ft/d, and 40 to 100 ft/d, respectively (figs. 7, 8, and 9).

Vertical leakance is required by the model to control the rate of ground-water flow between layers. Vertical leakance between model layers in hydraulic contact, such as in this model, is calculated from the distance of each layer between its node and the common layer contact and the vertical hydraulic conductivity of each layer (McDonald and Harbaugh, 1988, equation 51). Vertical hydraulic conductivities in the model were estimated to be about 10 percent of the horizontal hydraulic conductivity for layers 1 and 3. Vertical hydraulic conductivities in all layers were adjusted during the calibration process, and some cells in layer 2 have a vertical hydraulic conductivity value less than or greater than 10 percent of the horizontal hydraulic conductivity. A no-flow boundary was simulated at the bottom of layer 3; therefore, no vertical leakance was simulated.

Recharge in the Cedar Falls area was assumed to be about 10 percent less than the previously published recharge rate calculated by Schulmeyer and Schnoebelen (1998) in Cedar Rapids, Iowa, because the annual average precipitation in Waterloo, Iowa, is 33.70 inches whereas the annual average precipitation in Cedar Rapids, Iowa, is 36.39 inches (National Oceanic and Atmospheric Administration, 1998). The recharge rate of 1.6×10^{-3} ft/d (7.1 in/yr) was assigned cells in layer 1 that represent alluvial material in the Cedar River Valley and to account for infiltration of runoff from upland areas and larger vertical hydraulic conductivity of sandy soils (Schulmeyer and Schnoebelen, 1998). A recharge rate of 1.4×10^{-3} ft/d (6.3 in/yr) was assigned to all remaining cells in layer 1. The rates of recharge specified for this model have accounted for the effects of evapotranspiration.

Types of discharge from the flow system included in the model were ground-water pumpage, river leakage, and flow across general-head boundaries. Pumpage during the study period varied depending on the season, with larger withdrawals during the spring and summer. Ground-water withdrawals were simulated using a specified negative flux located at a cell node associated with a producing well. Water users in the study area had pumpage that ranged from about 8,000 gal/d to 2.5 Mgal/d.

Model Calibration

The model calibration process used for this model minimized the differences between model-calculated ground-water levels and measured ground-water levels by adjusting model parameters. The mean ground-water levels calculated for each network well from measured water levels during the study period were used as a basis for calibration. The mean water levels for the study period were used as the calibration target because most of the major pumpage data used in the model was averaged from the annual pumpage for 1998 calendar year, from the total monthly pumpage during the 1998 calendar year, or from the latest available pumpage data; and although there is seasonal variation of water level in the Silurian-Devonian aquifer, historical trends show little variation during the study period. Hydraulic conductivity, vertical leakance, riverbed conductance, and general-head boundary conductance were parameters that were varied, within reasonable limits, during numerous simulations until the root-mean-squared error (RMSE) (Anderson and Woessner, 1992) between the mean measured water levels for all wells inside the model boundary and simulated water levels in respective corresponding model cells was less than 5 ft. Model calibration was further refined by continuing to vary model parameters until the average head difference (AVEH) and RMSE were minimized. The AVEH is an indicator of model bias and is the sum of the differences between simulated and measured water levels divided by the total number of measurements. The RMSE (eq. 1) indicates the magnitude of error between simulated and measured values.

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

where

M is the measured water level,

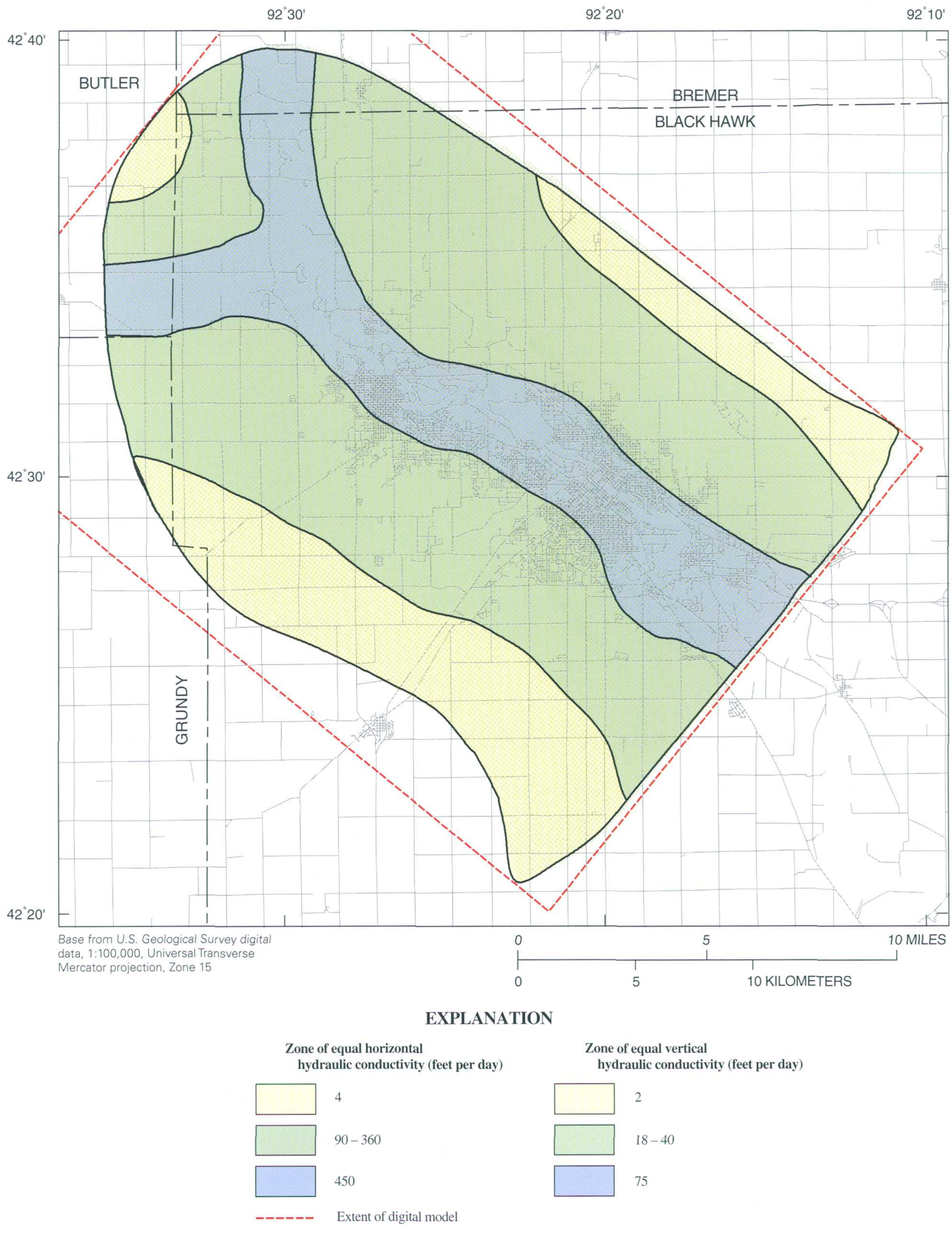


Figure 7. Distribution of horizontal and vertical hydraulic conductivity, layer 1.

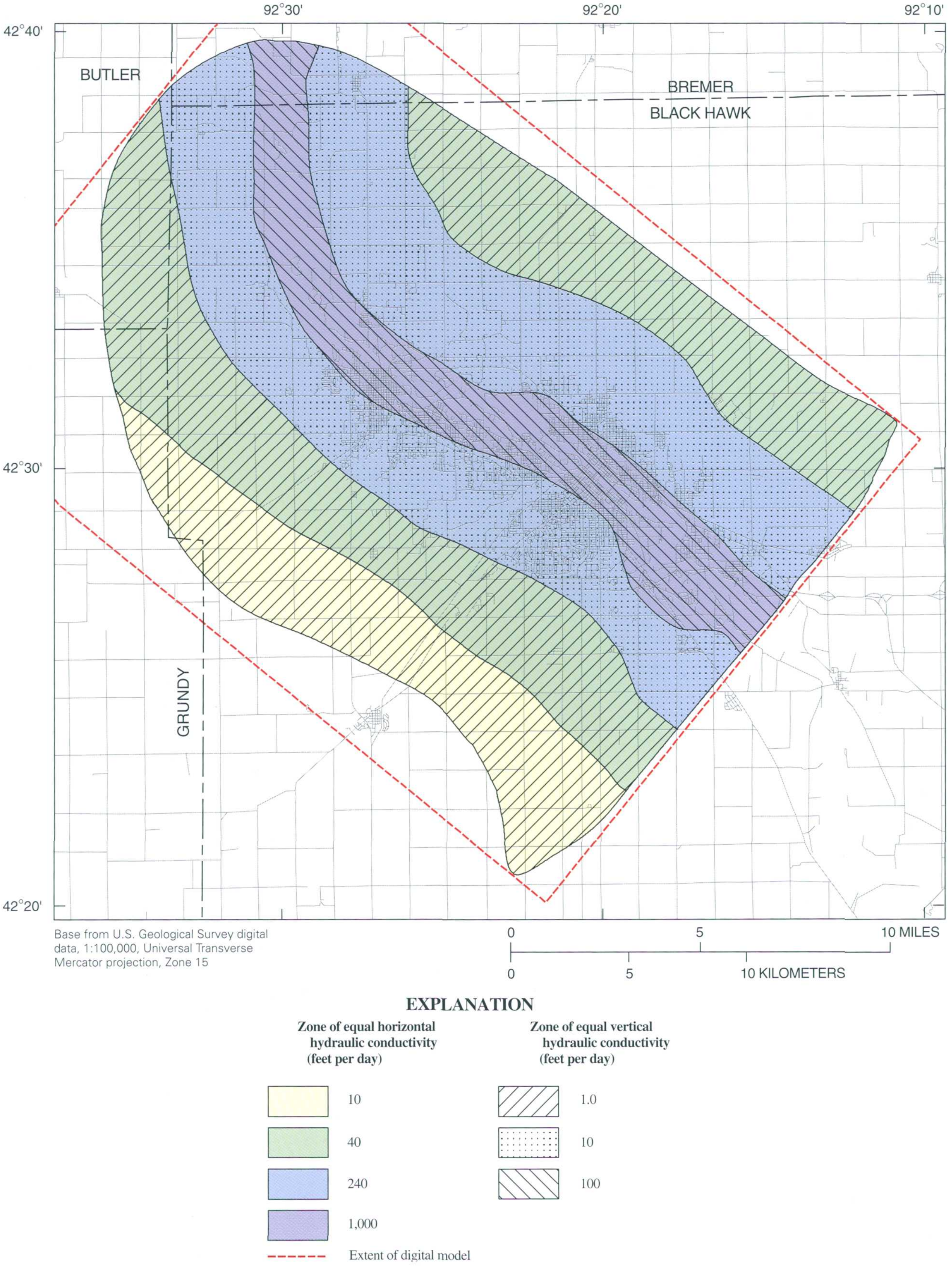


Figure 8. Distribution of horizontal and vertical hydraulic conductivity, layer 2.

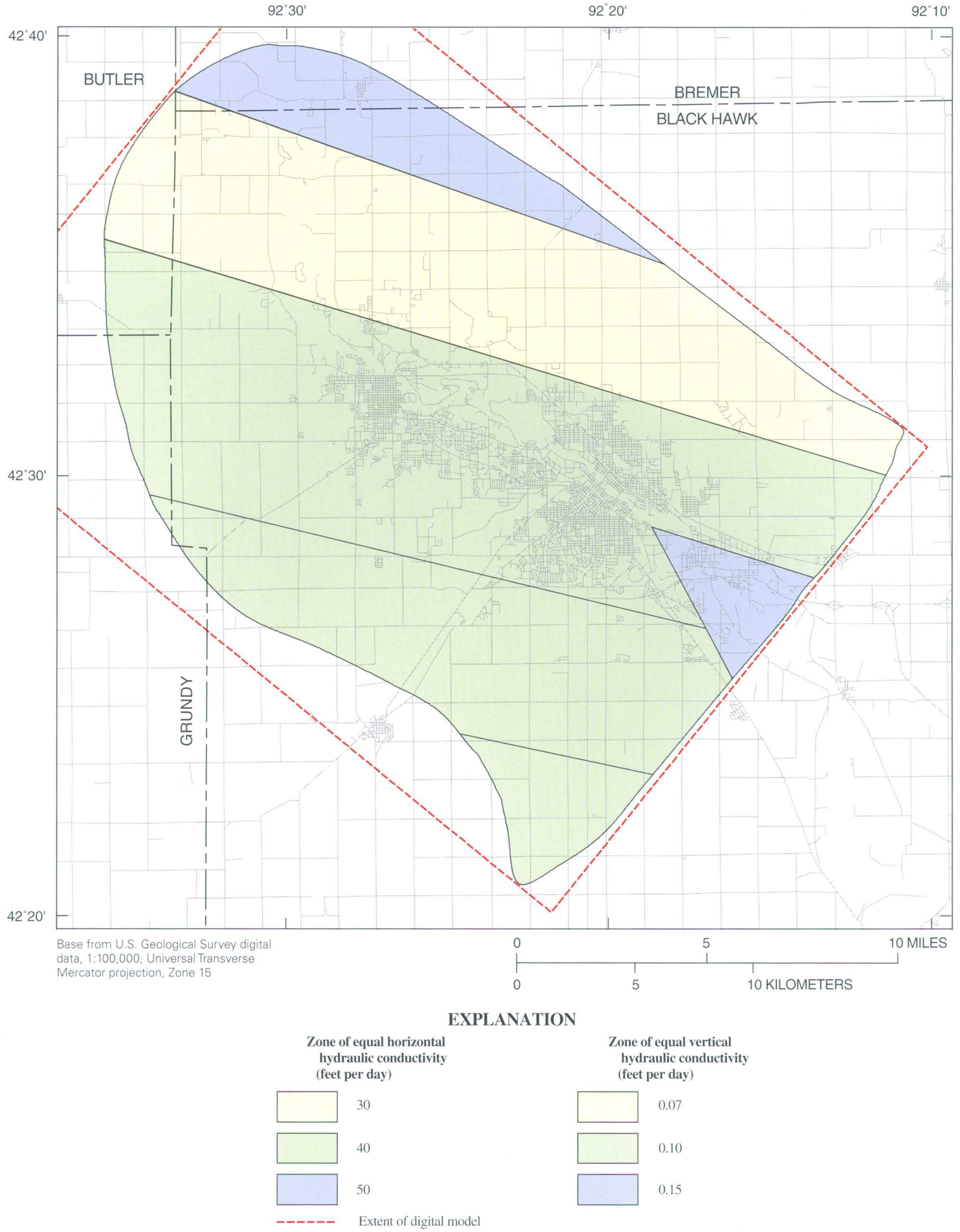


Figure 9. Distribution of horizontal and vertical hydraulic conductivity, layer 3.

S is the water level simulated by the model, and
N is the number of observations.

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

1. Parameter value changes did not result in an AVEH closer to 0 and a smaller RMSE for model layers 2 and 3.
2. The RMSE was less than 5 ft for layers 2 and 3.
3. The simulated ground-water flow directions in layers 2 and 3 compared favorably with those determined using the measured ground-water levels during the study period.
4. The simulated discharge to the Cedar River from the aquifer compared favorably with the estimated base flow.

The RMSE for the calibrated model was calculated using water-level data from most wells within the model boundary. Four wells located inside the model area were not included in the calibration process because they were located extremely close to a model boundary or were affected by pumpage not included in the simulation. The RMSE of the calibrated model is 4.14 ft; the AVEH is 1.29 ft. The RMSE for the Devonian-age and Silurian-age rock is 4.11 ft and 0.51 ft, respectively. The difference between the simulated and measured water levels likely is because the model is a simplified representation of a complex ground-water flow system (table 4).

The simulated potentiometric surface of the Devonian and the Silurian units is similar to the mean measured potentiometric map shown in figure 2. The direction and gradient of ground-water flow is similar throughout most of the modeled area with the exception of areas near the model boundaries, in which simulated gradients are less than the measured gradients.

Simulated discharge to the Cedar River is 73 ft^3/s, which is about 10 percent of the estimated base flow. This is an adequate simulation of the connection between the Cedar River and the adjacent Quaternary aquifer because this model simulates only a small portion of the Cedar River Basin and does not simulate smaller tributary streams that contribute water to the Cedar River.

Sensitivity Analysis

The model was constructed using parameters to solve mathematical equations that simulate the ground-water flow system in the Quaternary alluvial and glacial material and the Devonian- and Silurian-age bedrock in the study area. A sensitivity analysis evaluates the response of the calibrated model to variations in parameter values and determines which parameters have the greatest effect on the results. All model parameters, with the exception of the general-head boundary and riverbed conductance, were varied using a multiplication factor of 10 to 0.1. The general-head boundary conductance and the riverbed conductance were varied using a multiplication factor of 1,000 to 0.001, due to the relatively small effect of these parameters on the model at smaller factors (table 6). In some instances, the application of a multiplication factor caused the model to fail to converge to a solution. Model sensitivity was measured with the RMSE (eq. 1) using the difference between simulated and measured ground-water levels in layers 2 and 3. In general, improvement in parameter measurements or data sets that have the most effect on the model will result in improvements in the model simulation.

Water levels were most sensitive to changes in horizontal hydraulic conductivity in all layers and recharge in layer 1. Moderate sensitivity was associated with river conductance and general-head-boundary conductance decreases. Water levels were insensitive to vertical hydraulic conductivity in layers 1 and 2. Varying the horizontal hydraulic conductivity in layer 1 and layer 2 had the greatest effect on the proportion of total inflow and outflow from the rivers (table 5). Increases in riverbed conductance and general-head-boundary conductance showed no significant change in the RMSE; however, decreases in the general-head-boundary conductance by 2 or more orders of magnitude resulted in a RMSE above 100 or nonconvergence of the solution.

The sensitivity of the model to the Cedar River riverbed conductance was evaluated. The conductance terms were increased and decreased by 3 orders of magnitude, and the change in flow in and out of the river and across general-head boundaries was compared to the total volumetric rate of water entering and leaving the model. In the calibrated model, Cedar River cells account for 15.70 percent of the total inflow and 41.90 percent of the total outflow. When conductance values were decreased by 3 orders of magnitude, percentage of total inflow decreased to near zero. When conductance values were increased by 3 orders of magnitude, total inflow increased to 41.72 percent (fig. 10).

Table 4. Simulated ground-water level and deviation from the mean measured water level in wells located within the modeled area

[USGS, U.S. Geological Survey]

Map number (fig. 2)	USGS site identification	Primary aquifer	Simulated altitude of water level (feet)	Deviation from mean measured water level (feet)
2	422516092193501	Devonian	843.85	3.149
3	422452092190601	Devonian	844.15	6.881
4	422451092201401	Devonian	847.76	5.365
5	423139092261401	Devonian	847.87	1.070
6	423053092244701	Devonian	845.43	1.894
7	423042092265801	Devonian	844.20	−7.179
8	422948092281201	Devonian	844.96	1.027
9	423143092275801	Devonian	846.93	3.028
10	423045092283401	Devonian	849.43	8.841
11	423341092273001	Devonian	854.00	2.879
12	423341092273301	Devonian	854.08	3.823
13	422956092245101	Devonian	845.38	−1.382
16	423131092224201	Devonian	843.06	3.022
17	422818092212801	Devonian	832.71	2.281
19	422819092212701	Devonian	832.61	3.779
20	423002092231101	Devonian	841.25	1.735
21	422801092191401	Devonian	834.46	−0.434
22	422638092164001	Devonian	829.36	4.458
23	422810092250401	Devonian	849.30	−3.700
24	423131092195201	Devonian	843.59	−0.150
36	423343092234701	Devonian	858.03	2.925
37	423411092260401	Devonian	859.16	2.710
38	423431092272301	Devonian	859.64	0.417
39	423556092283601	Devonian	870.25	1.099
40	423346092282901	Devonian	855.27	−1.671
41	423423092241301	Devonian	862.80	11.678
42	423303092271201	Devonian	851.78	1.887
43	423225092270401	Devonian	849.89	2.27
44	423210092265201	Devonian	849.22	2.108
45	423601092300601	Devonian	872.70	1.473
46	423216092312801	Devonian	866.91	−11.815
48	423254092274801	Devonian	851.92	2.171
49	422904092292601	Devonian	861.64	−6.475
53	422737092153501	Devonian	792.01	4.223
55	423039092272401	Devonian	842.86	−0.589
56	423043092274701	Devonian	842.26	2.569
57	423059092273101	Devonian	843.01	−1.011
58	423051092274001	Devonian	842.42	−1.246
59	423055092273001	Devonian	842.24	−3.024
60	423046092273001	Devonian	842.17	−1.464
61	423156092285701	Devonian	853.54	4.288
63	423030092215701	Devonian	841.52	0.779
18	423200092224001	Silurian	844.13	0.677
52	422804092165301	Silurian	782.58	−0.238

Table 5. Results of the sensitivity analyses of the calibrated steady-state ground-water flow model for the Silurian-Devonian aquifer near Cedar Falls, Iowa

Parameter	Factor used to change parameter	Root mean square error (feet)	Percentage of total flow IN from river leakage	Percentage of total flow OUT to river leakage	Percentage of total IN from general head boundary	Percentage of total OUT to general head boundary
Calibrated flow model	--	4.14	15.70	41.90	23.00	5.89
Areal recharge rate	× 0.10	4.85	40.59	23.32	50.60	1.93
	× 10.0	32.25	0.00	67.25	0.06	24.32
Layer 1						
Horizontal hydraulic conductivity	× 0.10	6.87	18.06	34.70	17.45	10.40
	× 10.0	5.38	11.99	59.61	41.03	0.17
Vertical hydraulic conductivity	× 0.10	4.14	17.21	41.62	22.61	5.54
	× 10.0	4.14	15.80	42.02	23.07	6.00
Layer 2						
Horizontal hydraulic conductivity	× 0.20	36.25	15.60	27.84	17.05	14.89
	× 5.0	7.21	10.04	64.62	48.03	0.09
Vertical hydraulic conductivity	× 0.10	4.61	15.66	41.45	21.26	4.91
	× 10.0	4.67	15.67	42.10	23.51	6.18
Layer 3						
Horizontal hydraulic conductivity	× 0.1	29.48	18.78	37.96	17.92	8.27
	× 10.0	8.56	7.99	57.87	43.62	1.01
Vertical hydraulic conductivity	× 0.1	5.99	14.70	40.64	23.78	7.05
	× 10.0	5.25	16.12	42.64	22.99	5.57
General-head boundary conductance						
Layer 1	× 0.0001	4.14	17.57	43.09	16.69	1.01
	× 1,000.0	4.79	2.53	34.10	71.46	43.78
Layer 2	× 0.0001	4.19	15.89	43.20	20.57	2.76
	× 1,000.0	4.08	15.75	41.04	25.03	8.58
Layer 3	× 0.0001	4.10	16.15	41.63	21.34	5.21
	× 1,000.0	4.18	15.32	41.96	24.88	7.18
Riverbed conductance (Cedar River and Beaver Creek)	× 0.0001	31.01	0.00	2.29	17.79	27.78
	× 1,000.0	4.26	41.72	58.55	17.57	6.78

Table 6. Simulated water budget under steady-state conditions

[Inflow, water added to the ground-water system; ft^3/d, cubic feet per day; outflow, water being removed from the ground-water system; pumpage, ground-water withdrawals by Cedar Falls Utilities, University of Northern Iowa, Waterloo Water Works, and City of Evansdale]

Budget component	Inflow (ft^3/d)	Percentage of total inflow	Outflow (ft^3/d)	Percentage of total outflow
Recharge from precipitation	9,561,000	61.3	0	0
River leakage—Cedar River	2,453,000	15.7	6,330,000	40.6
River leakage—Beaver Creek	0	0	221,000	1.4
Pumpage	0	0	8,130,000	52.1
General-head boundary (layer 1)	2,132,000	13.7	43,000	0.3
General-head boundary (layer 2)	690,800	4.4	724,000	4.6
General-head boundary (layer 3)	771,800	4.9	161,000	1.0
Total	**15,608,600**	**100.0**	**15,609,000**	**100.0**

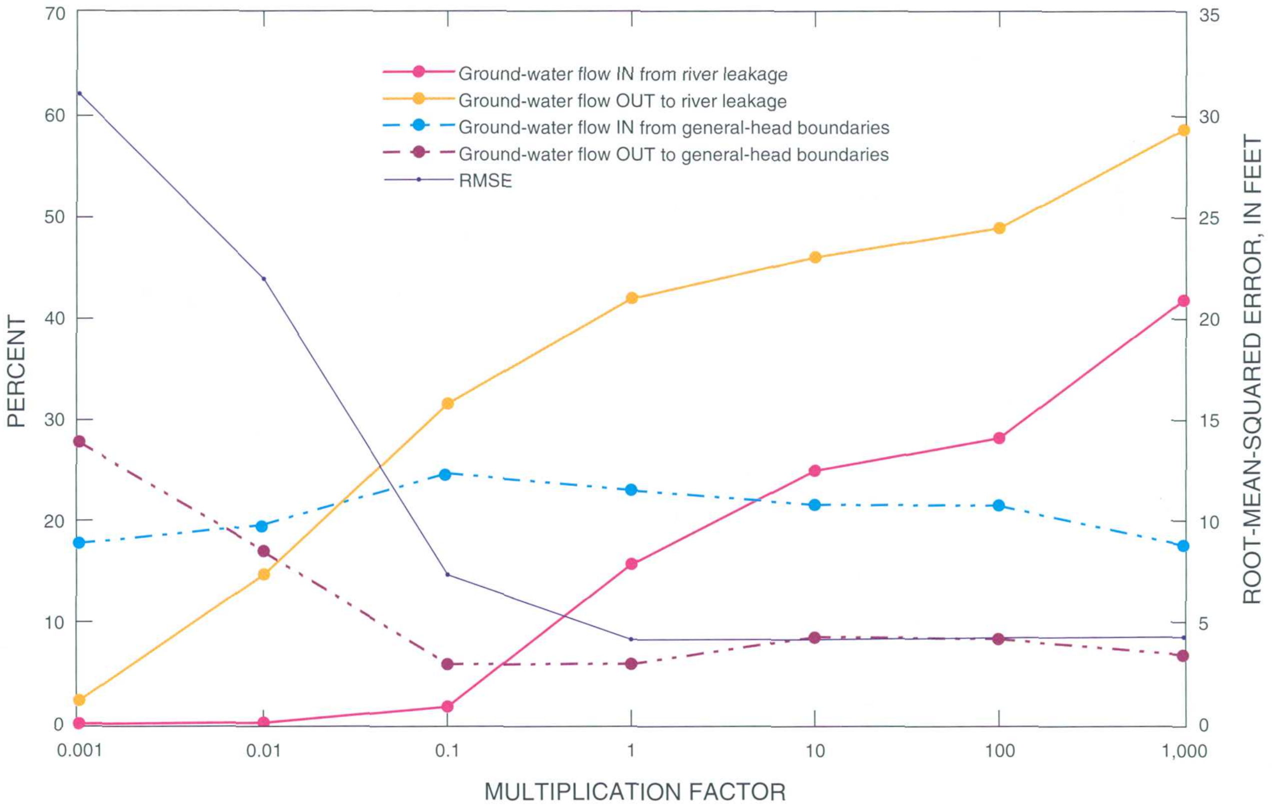


Figure 10. Proportion of simulated inflow and outflow from river leakage and general-head boundaries as a result of varying riverbed conductance and corresponding root-mean-squared error.

Model Limitations

The ground-water flow model described in this report is a simulation of the physical ground-water system and is useful as an aid in evaluating the ground-water flow system in the study area. However, the following limitations to this model should be considered:

1. The presence of joints and fractures in the Silurian-Devonian aquifer may introduce significant uncertainty into the model. The density and distribution of these features was not determined during this study. Orientations of the fractures can be inferred from the channel of the Cedar River, which is assumed to flow along these orientations. Fracture orientation was not included in the model parameters. The effect of fractures on hydraulic conductivity was assumed to decrease as distance from the Cedar River increased and is included in the model.
2. Model input parameters are assigned to the node of each model cell. The nodal value is then used by the model as representative of conditions throughout the cell. This representation of uniformity throughout the cell is a potential source of model uncertainty in that model parameters probably are not uniform throughout a cell or group of cells. While the lithology across the modeled area is basically homogeneous, the distribution of hydraulic conductivity is heterogeneous and may change significantly across a modeled cell.
3. Small well withdrawals were not included in the model. The major pumpage from municipalities in the study area account for the main stress on the system, and minor pumpage from residences

and small industries is assumed to produce no significant effect on the modeled area.

4. The ground-water flow model was constructed to simulate steady-state conditions (the volumetric rate of water flowing into the system is the same as the volumetric rate of water flowing out of the system). Results of the ground-water flow model may not be valid when these conditions are not prevalent, as may be the case in the spring and early summer when Cedar River levels are the greatest and thunderstorms frequently produce large amounts of rainfall.
5. The steady-state flow model does not account for transient conditions. This steady-state model does not take into account the amount of time it may take to reach equilibrium. Varying climatic and hydrologic conditions and noncontinuous pumpage may complicate the amount of time it takes for this model to reach equilibrium.
6. Riverbed conductance values used in the model are derived from the iterative model calibration process rather than from field measurements. Measurements of riverbed conductance, if available in the future and used in this model, may be different than the estimated values used in this model and may produce different results.

Simulation Results

The model calculates a water level at each of the cell nodes and a ground-water flux across each cell face. Figure 11 shows the simulated potentiometric surface for layer 2 of the model. Model results for layer 2 indicate that ground water generally flows toward the Cedar River and slightly down the Cedar River Valley. The difference between the maximum and the minimum simulated water level in layer 2 is about 70 ft. Bends in the potentiometric surface contours coincide with the channel in the Cedar River and Beaver Creek, which indicates the effects of these streams on the ground-water flow patterns in this area. Water in the northern part of the simulated modeled area tends to flow away from the river near the model boundary, which may be caused by unaccounted for variations along the model boundary. Model results for layer 3, shown in figure 12, indicate the effects of pumpage on the potentiometric surface of the Silurian aquifer. Municipal pumping likely has caused some decline in ground-water levels in layer 3, as evidenced by the closed 790-ft contour in the area near Evansdale, Iowa. Simulation results indicate that ground-water flow in layer 3 is toward the Cedar River and down the Cedar River Valley, much like in layer 2. The difference between the maximum and minimum simulated water levels in layer 3 is about 90 ft. The northern area of layers 2 and 3 exhibits a much shallower gradient than the southern area, which could be due to the lack of significant pumpage in those areas.

There are 43,200 data points used by the model to simulate potentiometric surfaces of the Devonian and Silurian portions of the Silurian-Devonian aquifer. The shape of the simulated potentiometric surfaces and the direction and magnitude of the simulated ground-water flow is similar to the potentiometric surface for the Silurian-Devonian aquifer and flow directions interpreted from the mean measured water levels. Simulated flow is predominantly horizontal in the Devonian- and Silurian-age rocks, so that little mixing may occur between the two units. Vertical ground-water flow is predominantly downward from the alluvium to the Devonian-age rock, probably due mainly to pumpage (table 7). Areas with significant pumpage, such as Cedar Falls and Waterloo, may cause localized mixing of water in the Devonian- and Silurian-age rocks.

The water budget for the calibrated flow model was used to evaluate the sources of inflow and outflow for the model and to determine if model results were consistent with the simplified conceptualization of the flow system used to construct the flow model. Total inflow to the modeled area was calculated to be 15,609,000 ft^3/d; total outflow from the modeled area was calculated to be 15,608,000 ft^3/d, yielding a percent discrepancy of less than 0.01.

Primary sources of inflow to the model are precipitation (61.3 percent) and Cedar River leakage (15.7 percent). Infiltration of precipitation is predominantly through the overlying alluvial material.

Primary sources of outflow are pumpage (52.1 percent) and leakage to the Cedar River (40.6 percent) (table 6). River leakage is discharged from the Quaternary alluvial deposits; and municipal pumpage withdraws water from the Devonian- and Silurian-age rock units. The large volume of river leakage is consistent with the conceptualization of subsurface regional flow into the study area and infiltration of precipitation from the overlying Quaternary deposits, which then is discharged to the Cedar River and tributary streams.

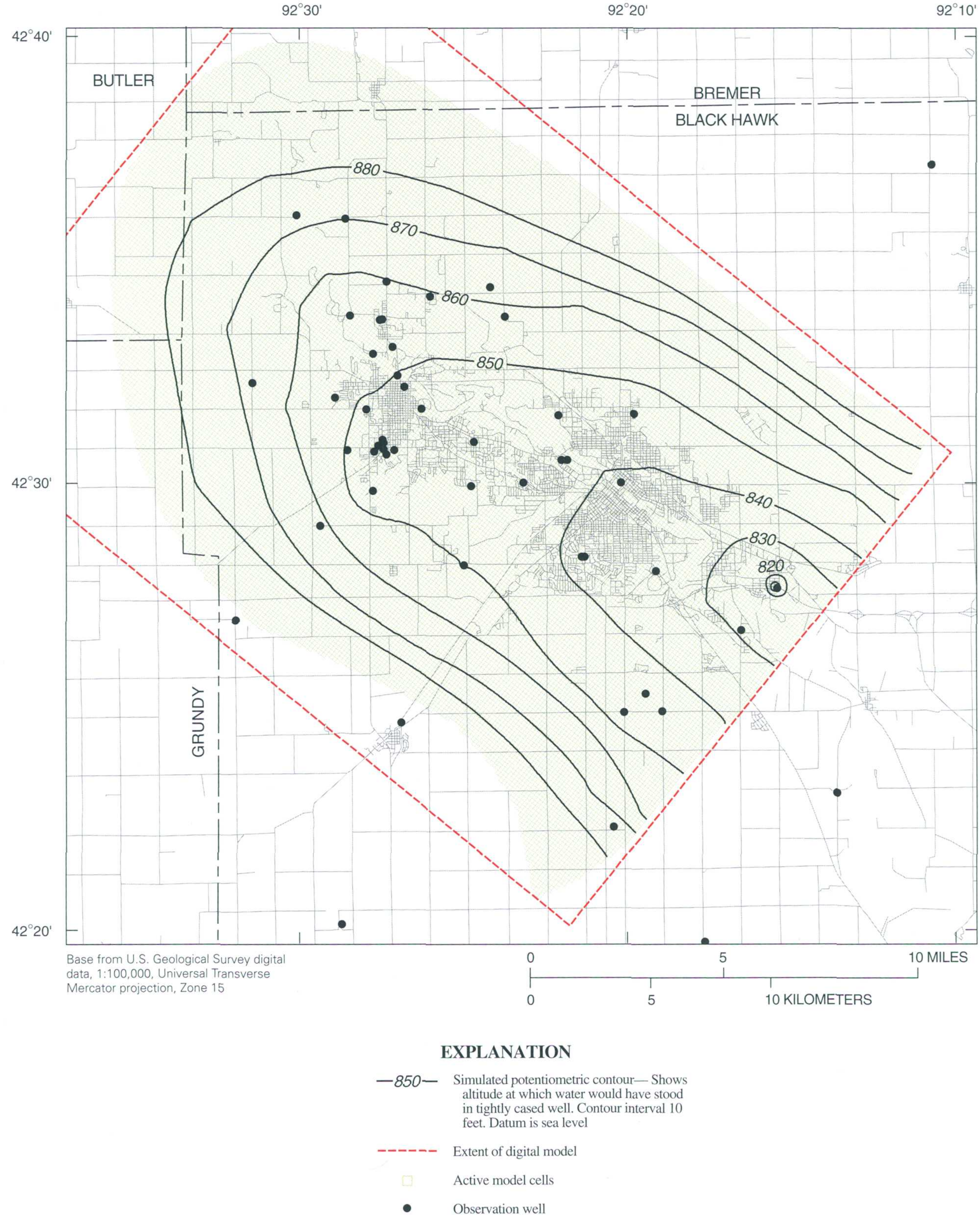


Figure 11. Simulated potentiometric surface in the Devonian-age rock.

Figure 12. Simulated potentiometric surface in the Silurian-age rock.

Table 7. Well characteristics, nitrate levels, and pumpage information for active Cedar Falls Utilities municipal-supply wells, 1999

[Data from Cedar Falls Utilities annual water report, 1999, and well logs; mg/L, milligrams per liter; N/A, data not available; <, less than; gpm, gallons per minute]

Cedar Falls Utilities municipal well number (fig. 14)	Year constructed	Altitude of land surface (feet above sea level)	Total depth (in feet below land surface)	Thickness of alluvial material (feet)	Altitude of bottom of casing (feet above sea level)	Length of open hole (feet)	Average nitrite plus nitrate nitrogen, dissolved[1] (mg/L as N)	Average 1999 pumpage (gpm)
2	1956	858	150	10	818	110	N/A	0
3	1957	935	183	94	769	20	7.98	2,614
5	1961	876	145	31	786	55	3.73	2,407
6	1967	959	227	115	825	93	<1.00	2,125
7	1967	941	170	100	870	99	<1.00	1,673
8	1971	941	216	105	800	75	<1.00	1,849
9	1971	875	275	30	707	107	7.88	769
10	1971	875	275	30	707	107	6.76	2,228
11	1993	895	200	60	815	75	2.98	1,516

[1]Nitrite plus nitrate concentrations provided by Keystone Lab, Cedar Rapids, Iowa, for Cedar Falls Utilities.

SUMMARY

The Silurian-Devonian bedrock aquifer in the Cedar Falls, Iowa, area provides large quantities of good quality ground water for municipal water suppliers as well as private residential users. The highly transmissive nature of the bedrock aquifer material, due to fractures and karst features in the area and areas of thin, overlying unconsolidated deposits, results in a ground-water supply vulnerable to contamination. To address these concerns, the U.S. Geological Survey (USGS), in cooperation with Cedar Falls Utilities, conducted a study from April 1998 to September 2001 to evaluate the hydrogeology of the Silurian-Devonian bedrock aquifer in the Cedar Falls area and simulate the ground-water flow in the Silurian-Devonian aquifer under current (1998) pumping conditions. The results of the study can be used by Cedar Falls Utilities (CFU) to establish a well-head protection program and manage the development of the ground-water resource. The study area covers approximately 200 mi^2 in northeast Iowa and includes Black Hawk County and small portions of Benton, Bremer, Buchanan, Butler, Grundy, and Tama Counties.

Ground-water and surface-water data were collected during the study to help define the hydrogeology of the Silurian-Devonian aquifer and to assist in constructing a ground-water flow model. Ground-water levels were measured bimonthly from April 1998 to February 1999 with a calibrated steel tape or an airline. Available well tests were used to estimate the hydraulic conductivity of the geologic material adjacent to the open interval of the well. Streamflow and stage data were collected periodically from 1998 to 1999 as part of the USGS streamflow network in Iowa.

The Quaternary-age deposits comprise a surficial aquifer system that ranges in thickness from about 20 ft to 250 ft and include alluvial, glacial-drift, and buried-channel materials with variable permeabilities both vertically and horizontally. The uppermost bedrock unit consists of Devonian-age rocks consisting primarily of limestone, dolomite, and shale but locally includes minor amounts of sandstone. This rock unit has a significant occurrence of fractures or secondary permeability. The relative amount of secondary permeability appears to be greatest nearest the Cedar River. The Silurian-age rocks consist primarily of dolomite with minor amounts of chert and are assumed to have less secondary permeability with respect to the Devonian-age rocks. Transmissivity of the Silurian-Devonian aquifer is highly variable, depending on the degree of interconnection between the fractures and bedding plane and the rock-age unit.

Ground-water flow in the study area was simulated using the USGS-developed MODFLOW model (McDonald and Harbaugh, 1988) to obtain a better understanding of the ground-water flow patterns of the Silurian-Devonian aquifer in the study area, to provide a quantitative estimate of the water budget in the study area.

The flow model was constructed to simulate steady-state conditions. Steady-state conditions occur when the volume of water entering a system equals the volume of water flowing out of the system. Mean water levels within the study area from April 1998 to February 1999 were considered to be an acceptable estimate of steady-state conditions.

The modeled area was discretized into a 220-row by 180-column grid with cells measuring 500 ft by 500 ft. The grid was aligned so that the Cedar River coincided with the y-axis. Three layers were used to simulate flow: layer 1 represents the Quaternary alluvial and glacial deposits, layer 2 represents the Devonian-age portion of the Silurian-Devonian aquifer, and layer 3 represents the Silurian-age portion of the Silurian-Devonian aquifer.

Natural boundaries to the model were not in close proximity to the study area to use as model boundaries. Boundary conditions were specified for the model to simulate flow along the edge of the modeled area in relation to the features within the modeled area. The upper surface of layer 1 represents unconfined water-table conditions. Recharge from precipitation to the upper surface of the flow model was represented as a nonuniform specified-flux boundary. No-flow boundaries were used to simulate areas where lateral ground-water flow is interpreted to be parallel with the boundary, such as along ground-water flow lines, or is considered to be insignificant, such as a contact with a nonaquifer material. The bottom of the model is the top of the Ordovician-age rock, a relatively impermeable regional confining unit. Lateral ground-water flow from geologic materials adjacent to the model layers was simulated with a general-head boundary. The Cedar River and Beaver Creek were simulated using river cells that allow leakage to and from layer 1.

Model architecture and hydraulic properties were estimated using well log data from previously constructed private or municipal wells. Hydraulic conductivity in layer 1 was estimated using aquifer test data completed by private drillers or contractors during well construction or published average hydraulic conductivities for similar geologic materials. Hydraulic conductivities for all model layers are a function of the estimated degree of secondary permeability present. Vertical leakance is required by the model to control the rate of ground-water flow between layers. Recharge in the Cedar Falls area was assumed to be about 10 percent less than the recharge in Cedar Rapids, Iowa.

The calibration process used in this model minimized the differences between simulated ground-water levels and measured ground-water levels by adjusting model parameters. The mean ground-water levels calculated for each network well from measured water levels during the study interval were used as a basis for calibration. The RMSE for the calibrated model, calculated from most network wells within the model boundary, is 4.14 ft; the AVEH is 1.29 ft. A difference between the simulated and measured water levels likely is because the model is a simplified representation of a complex ground-water flow system.

Water levels were most sensitive to changes in horizontal hydraulic conductivity in all layers and recharge in layer 1. Increases in riverbed conductance and general-head-boundary conductance showed no significant change in the RMSE; however, decreases in the general-head-boundary conductance by 2 or more orders of magnitude resulted in a RMSE above 100 or inability of the model to reach a solution.

The model calculates a water level at each of the cell nodes and a ground-water flux across each cell face. Primary sources of inflow to the model are precipitation (61.3 percent) and Cedar River leakage (15.7 percent). Primary sources of outflow are pumpage (52.1 percent) and river discharge (40.6 percent). There is little evidence of mixing between the Devonian- and Silurian-age rock units with the exception of the main pumping centers, where increased withdrawals may cause localized mixing between them.

REFERENCES

Anderson, M.P., and Woessner, W.W., 1992, Applied groundwater modeling—Simulation of flow and advective transport: San Diego, Academic Press, Inc., 381 p.

Anderson, W.I., 1983, Geology of Iowa—Over two billion years of change: Ames, Iowa State University Press, 268 p.

Brigham Young University, 1998, The Department of Defense Groundwater Modeling System: Provo, Utah, Brigham Young University—Engineering Computer Graphics Laboratory.

Driscoll, F.G., 1986, Groundwater and wells (second edition): St. Paul, Minn., U.S. Filter/Johnson Screens, 1089 p.

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

Hallberg, G.R., Riley, D.G., Kantamneni, J.R., Weyer, P.J., and Kelley, R.D., 1996, Assessment of Iowa Safe Drinking Water Act monitoring data—1987–1995: University of Iowa Hygienic Laboratory Research Report 97–1, 132 p.

Hansen, R.E., 1975, Bedrock topography of northeast Iowa: U.S. Geological Survey Miscellaneous Investigations Map I–717, 1 sheet, scale 1:125,000.

Horick, P.J., 1984, Silurian-Devonian aquifer in Iowa: State of Iowa, Iowa Geological Survey Miscellaneous Map Series 10.

Iowa Geological Survey Bureau, 1999, GEOSAM data retrieval system for various wells: accessed January 29, 1999, at URL http://www.igsb.uiowa.edu/geosam/.

Knochenmus, L.A., and Robinson, J.L., 1996, Descriptions of anisotropy and heterogeneity and their effect on ground-water flow and areas of contribution to public supply wells in a karst carbonate aquifer system: U.S. Geological Survey Water-Supply Paper 2475, 47 p.

Lucey, K.J., Kuzinar, R.L., and Caldwell, J.P., 1995, Hydrogeology and water quality of the Mississippi River Alluvium near Muscatine, Iowa, June 1992 through June 1994: U.S. Geological Survey Water-Resources Investigations Report 95–4047, 74 p.

May, J.E., Gorman, J.G., Goodrich, R.D., Miller, V.E., Turco, M.J., and Linhart, S.M., 1998, Water resources data, Iowa, water year 1998—v. 1. Surface water—Mississippi River Basin: U.S. Geological Survey Water Data Report IA–98–1, 374 p.

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

Nalley, G.M., Gorman, J.G., Goodrich, R.D., Miller, V.E., Turco, M.J., and Linhart, S.M., 1999, Water resources data, Iowa, water year 1999—v. 1. Surface water—Mississippi River Basin: U.S. Geological Survey Water Data Report IA–99–1, 363 p.

National Oceanic and Atmospheric Administration, 1998, Climatological data, Iowa, annual summary: Asheville, N.C., National Climatic Data Center, v. 109, no. 13, 23 p.

Olcott, P.G., 1992, Ground water atlas of the United States—Segment 9 (Iowa, Michigan, Minnesota, Wisconsin): U.S. Geological Survey Hydrologic Investigations Atlas 730–J, 31 p.

Parker, M.C., 1971, The Maquoketa Formation (Upper Ordovician) in Iowa: Iowa City, Iowa Geological Survey Miscellaneous Map Series1, 5 sheets, scale 1:1,267,000.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94–464, 6 chaps.

Schaap, B.D., 1999, Concentrations and possible sources of nitrate in water from the Silurian-Devonian aquifer, Cedar Falls, Iowa: U.S. Geological Survey Water-Resources Investigations Report 99–4106, 19 p.

Schulmeyer, P.M., and Schnoebelen, D.J., 1998, Hydrogeology and water quality in the Cedar Rapids area, Iowa, 1992–96: U.S. Geological Survey Water-Resources Investigations Report 97–4261, 77 p.

Theis, C.V., Brown, R.H., and Meyer, R.R., 1963, Estimating the transmissivity of aquifers from the specific capacity of wells, *in* Bentall, Ray, compiler, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536–I, p. 331–341.

Witzke, B.J., Bunker, B.J., and Rogers, F.S., 1988, Eifelian through Lower Frasnian stratigraphy and deposition in the Iowa area, central Midcontinent, U.S.A., *in* McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the world: Canadian Society of Petroleum Geologists, Memoir 14, v. I—Regional syntheses, p. 221–250.

APPENDIX

Table A1. Iowa Department of Natural Resources–Geological Survey Bureau (IDNR–GSB) well logs used to estimate the elevation of the top of each rock-age interval and the thickness of water bearing units in the study area

[ddmmss, degrees, minutes, seconds; Qtr, Quaternary; Miss, Mississippian; Dev, Devonian; Sil, Silurian; Ord, Ordovician]

IDNR–GSB well number[1]	County[1]	Latitude[2] (ddmmss)	Longitude[2] (ddmmss)	Altitude of land surface[1] (feet above sea level)	Depth of well[1] (feet below land surface)	Distance to top of rock-age interval[1] (feet below land surface)				
						Qtr[1]	Miss[1]	Dev[1]	Sil[1]	Ord[1]
26975	Benton	420502	921213	900	1,880	0	--	285	515	697
1	Benton	420518	915252	788	1,519	0	--	17	150	435
4879	Benton	420221	921052	944	330	0	--	242	--	--
20343	Benton	421213	915123	885	210	0	--	60	--	--
21112	Benton	421005	915034	865	245	0	--	118	230	--
22289	Benton	420745	915502	905	175	0	--	142	--	--
219	Benton	421022	920134	780	1,508	0	--	115	150	350
276	Benton	420950	920043	813	320	0	--	70	200	--
8959	Benton	420812	920320	925	403	0	--	185	335	--
3239	Benton	420838	920849	868	1,622	0	--	25	305	521
1689	Benton	421029	921752	980	636	0	--	178	475	607
9067	Benton	420727	921119	978	205	0	--	160	--	--
19439	Benton	421355	915107	905	245	0	--	140	234	--
11586	Benton	421329	915246	908	560	0	--	150	275	--
431	Benton	421309	915924	890	635	0	--	90	280	490
1932	Benton	421431	920802	924	251	0	--	81	232	--
15308	Black Hawk	422153	920941	893	270	0	--	165	250	--
16010	Black Hawk	421930	920459	875	128	0	--	40	--	--
23018	Black Hawk	421904	921125	825	1,400	0	--	--	--	250
8515	Black Hawk	421842	921531	949	315	0	--	112	--	--
2778	Black Hawk	421936	922349	991	296	0	--	194	--	--
1735	Black Hawk	422028	922550	988	347	0	--	205	--	--
2148	Black Hawk	421856	923158	1,007	335	0	--	194	--	--
10616	Black Hawk	422451	921623	835	222	0	--	--	145	--
5006	Black Hawk	422317	921752	928	202	0	--	160	--	--
9599	Black Hawk	422540	922122	965	226	0	--	215	--	--
4602	Black Hawk	422346	922238	960	222	0	--	170	--	--
1938	Black Hawk	422517	923054	986	220	0	--	150	--	--
30059	Black Hawk	422540	923050	1,010	271	0	--	215	--	--
10419	Black Hawk	422421	922736	890	165	0	--	70	--	--
14445	Black Hawk	423227	921332	931	225	0	--	--	165	--
5370	Black Hawk	422958	921555	925	960	0	--	115	165	312
2750	Black Hawk	422820	921811	839	200	0	--	65	130	--
13835	Black Hawk	423002	922313	926	208	0	--	113	--	--
30060	Black Hawk	423019	922048	851	1,378	0	--	20	200	300
15788	Black Hawk	422955	921959	846	156	0	--	22	140	--
7447	Black Hawk	422831	922507	930	278	0	--	145	--	--
18612	Black Hawk	423058	922735	922	205	0	--	82	--	--
9362	Black Hawk	423515	921104	997	230	0	--	--	160	--
8576	Black Hawk	422927	923053	997	235	0	--	160	--	--
1287	Black Hawk	423356	920936	981	272	0	--	149	228	--
8519	Black Hawk	423504	921421	996	680	0	--	--	--	265
9275	Black Hawk	423411	921324	988	300	0	--	--	272	--
16109	Black Hawk	423649	922104	981	150	0	--	--	100	--
9257	Black Hawk	423713	922708	876	120	0	--	90	--	--

Table A1. Iowa Department of Natural Resources–Geological Survey Bureau (IDNR–GSB) well logs used to estimate the elevation of the top of each rock-age interval and the thickness of water bearing units in the study area—Continued

[ddmmss, degrees, minutes, seconds; Qtr, Quaternary; Miss, Mississippian; Dev, Devonian; Sil, Silurian; Ord, Ordovician]

IDNR–GSB well number[1]	County[1]	Latitude[2] (ddmmss)	Longitude[2] (ddmmss)	Altitude of land surface[1] (feet above sea level)	Depth of well[1] (feet below land surface)	Distance to top of rock-age interval[1] (feet below land surface)				
						Qtr[1]	Miss[1]	Dev[1]	Sil[1]	Ord[1]
17624	Black Hawk	423411	323108	913	158	0	--	113	--	--
10605	Black Hawk	423353	922654	869	150	0	--	115	--	--
4591	Bremer	424012	920754	1,010	180	0	--	--	161	--
13058	Bremer	424250	921747	1,022	375	0	--	--	--	235
1544	Bremer	424217	921330	1,039	952	0	--	80	120	150
5754	Bremer	423914	921746	1,038	880	0	--	--	257	285
21048	Bremer	424236	922423	1,005	150	0	--	108	135	--
2036	Bremer	424119	922510	1,017	804	0	--	50	128	146
30066	Bremer	424031	922011	947	410	0	--	--	--	162
20380	Bremer	424008	921945	1,003	191	0	--	115	135	185
9780	Bremer	424007	922138	1,054	220	0	--	135	168	--
70	Bremer	424336	922811	918	1,720	0	--	10	90	110
4613	Bremer	424112	922902	1,008	220	0	--	72	165	198
11754	Bremer	423859	922722	935	150	0	--	35	95	148
15543	Bremer	424722	922444	1,040	372	0	--	--	--	270
14461	Bremer	424632	922559	1,026	370	0	--	--	183	185
14004	Bremer	424737	922822	1,004	129	0	--	--	94	--
9037	Bremer	424458	923054	995	145	0	--	70	115	--
6004	Buchanan	422226	914030	1,021	200	0	--	181	--	--
8773	Buchanan	422025	914631	905	107	0	--	80	--	--
3894	Buchanan	421903	920015	838	405	0	--	15	181	385
3714	Buchanan	422836	915317	933	293	0	--	11	120	--
1856	Buchanan	422810	915316	935	307	0	--	25	100	295
9382	Buchanan	422854	920353	992	380	0	--	40	185	375
27529	Buchanan	423557	913828	1,042	1,195	0	--	--	75	150
27535	Buchanan	423707	915416	995	1,201	0	--	--	47	67
14135	Buchanan	423813	920243	994	1,292	0	--	28	114	193
1578	Buchanan	422718	915531	981	352	0	--	--	155	341
16147	Buchanan	422748	915401	907	265	0	--	15	65	260
9469	Buchanan	422540	915557	959	180	0	--	160	162	--
5783	Buchanan	422631	920229	996	235	0	--	78	230	--
14428	Butler	423640	923549	896	3,595	0	--	122	316	353
7854	Butler	423357	923744	891	165	0	--	65	--	--
2024	Butler	423753	924840	1,033	332	0	--	110	--	--
8598	Butler	423551	930026	1,039	440	0	--	45	--	--
12971	Butler	423852	924641	972	186	0	--	160	--	--
824	Butler	424703	924006	942	230	0	--	35	--	--
14016	Butler	424440	914948	1,047	205	0	--	145	--	--
1246	Fayette	423847	914856	1,119	205	0	--	--	175	--
4631	Fayette	424051	915519	1,045	1,315	0	--	--	50	160
26318	Fayette	424014	915459	1,032	1,200	0	--	--	25	160
22974	Fayette	423940	920150	1,015	665	0	--	5	15	70
7201	Fayette	424447	914025	1,147	1,312	0	--	--	89	200
1277	Fayette	424629	914115	1,094	155	0	--	--	15	125

Table A1. Iowa Department of Natural Resources–Geological Survey Bureau (IDNR–GSB) well logs used to estimate the elevation of the top of each rock-age interval and the thickness of water bearing units in the study area—Continued

[ddmmss, degrees, minutes, seconds; Qtr, Quaternary; Miss, Mississippian; Dev, Devonian; Sil, Silurian; Ord, Ordovician]

IDNR–GSB well number[1]	County[1]	Latitude[2] (ddmmss)	Longitude[2] (ddmmss)	Altitude of land surface[1] (feet above sea level)	Depth of well[1] (feet below land surface)	Distance to top of rock-age interval[1] (feet below land surface)				
						Qtr[1]	Miss[1]	Dev[1]	Sil[1]	Ord[1]
13037	Fayette	424412	914155	1,163	150	0	--	--	135	--
2407	Fayette	424635	915300	1,093	126	0	--	5	80	--
8873	Fayette	424619	915247	1,117	850	0	--	39	110	200
16863	Fayette	424902	920322	1,111	175	0	--	--	155	--
12148	Fayette	425348	913802	1,184	216	0	--	--	--	60
10025	Fayette	425312	914016	1,130	770	0	--	--	--	400
2847	Fayette	425327	914703	1,169	294	0	--	--	60	136
17048	Fayette	425026	914849	1,068	1,238	0	--	20	65	150
20131	Fayette	425001	915726	1,159	152	0	--	118	125	--
18145	Fayette	425052	920446	1,072	360	0	--	--	--	220
17237	Fayette	425519	913759	1,032	60	0	--	--	--	5
5639	Grundy	421739	924935	1,081	500	0	--	415	--	--
25187	Grundy	421326	924913	1,038	118	0	45	115	--	--
13810	Grundy	421320	924652	1,048	160	0	132	159	--	--
8832	Grundy	421721	925859	1,041	125	0	75	--	--	--
2109	Grundy	421509	925611	1,053	133	0	90	--	--	--
9262	Grundy	422221	923212	912	235	0	--	140	--	--
210	Grundy	421929	923552	945	350	0	--	160	--	--
12199	Grundy	422156	924558	984	551	0	--	115	--	--
12059	Grundy	422107	924527	1,011	100	0	--	--	--	--
17954	Grundy	421755	924004	970	549	0	--	85	--	--
13188	Grundy	421816	925039	1,098	728	0	--	142	--	--
30488	Grundy	422236	925718	1,105	875	0	--	180	--	--
30489	Grundy	422806	923747	953	292	0	--	--	--	--
1825	Grundy	422636	924337	1,019	376	0	--	170	--	--
10984	Grundy	422610	925527	1,089	2,050	0	--	150	775	845
2141	Grundy	422857	923534	1,022	317	0	--	170	--	--
2719	Grundy	423049	924534	1,058	415	0	--	219	--	--
1611	Grundy	423019	924721	1,063	339	0	--	202	--	--
4025	Grundy	422900	924616	1,055	420	0	--	260	--	--
3626	Tama	420540	912037	878	392	0	--	197	--	--
1861	Tama	420351	921800	892	620	0	--	215	460	--
30967	Tama	420626	922857	933	435	0	--	360	--	--
30969	Tama	420706	923456	1,078	499	0	--	332	--	--
12665	Tama	420955	921821	978	1,880	0	--	160	464	625
14136	Tama	421132	922748	924	1,813	0	--	231	505	673
1707	Tama	421056	922555	970	435	0	--	232	--	--
2061	Tama	420930	922706	986	765	0	--	310	--	--
1424	Tama	420747	923743	1,032	445	0	--	235	--	--
1674	Tama	420753	924409	982	885	0	11	57	775	880
18143	Tama	421417	923616	1,019	415	0	--	305	--	--
4064	Tama	421548	924126	1,069	528	0	--	181	--	--
3626	Tama	420540	912037	878	392	0	--	197	--	--

[1]From Iowa Department of Natural Resources–Geological Survey Bureau virtual GEOSAM database; http://www.igsb.uiowa.edu/geosam_map/ last accessed 01/29/1999.

[2]Calculated from public land survey description using IDNR–GSB conversion calculator; http://www.igsb.uiowa.edu/getutm/ last accessed 01/29/1999.

☆ U.S. GOVERNMENT PRINTING OFFICE: 2002 — 773-096 / 47107 Region No. 8

Michael J. Turco—SIMULATION OF GROUND-WATER FLOW IN THE SILURIAN-DEVONIAN AQUIFER, CEDAR FALLS, IOWA

USGS/WRIR 02–4081

Printed on recycled paper