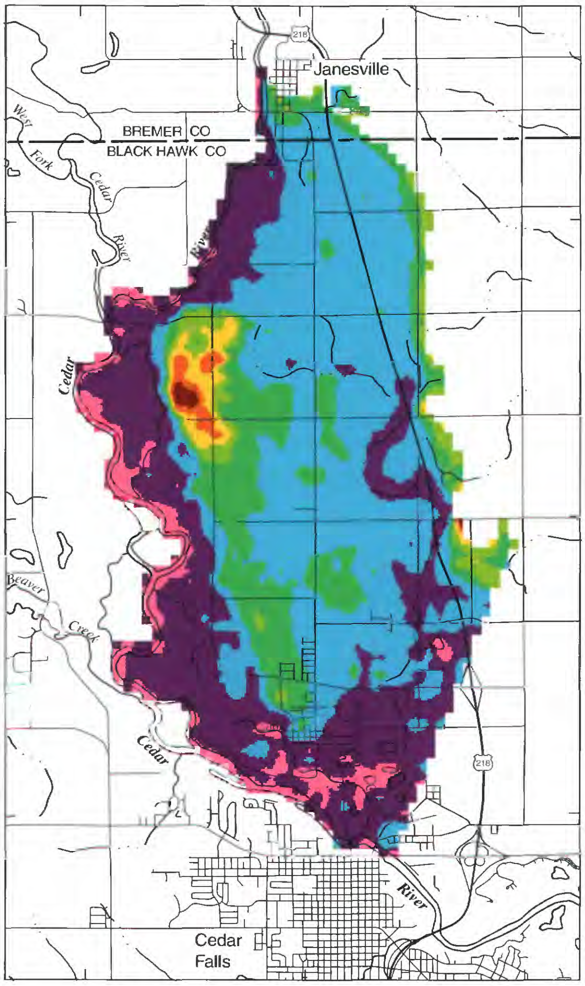
Prepared in cooperation with
BLACK HAWK COUNTY, IOWA

Simulation of Ground-Water Flow in the Cedar River Alluvium, Northwest Black Hawk County and Southwest Bremer County, Iowa

Water-Resources Investigations Report 03–4080



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

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By Bryan D. Schaap, Mark E. Savoca, and Michael J. Turco

U.S. GEOLOGICAL SURVEY

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Iowa City, Iowa
2003

U.S. DEPARTMENT OF THE INTERIOR
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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)	3,785	cubic meters per day
foot squared per day (ft^2/d)	0.0929	meter squared per day

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), unless otherwise noted.

Simulation of Ground-Water Flow in the Cedar River Alluvium, Northwest Black Hawk County and Southwest Bremer County, Iowa

By Bryan D. Schaap, Mark E. Savoca, *and* Michael J. Turco

Abstract

Flooding and high ground-water levels after large or frequent rainstorms have occurred in an area of about 30 square miles along the eastern bank of the Cedar River from Cedar Falls in northwest Black Hawk County to Janesville in southwest Bremer County, Iowa. The U.S. Geological Survey, in cooperation with Black Hawk County, conducted a hydrologic study of the Cedar River alluvium in the northwest Black Hawk and southwest Bremer Counties, to improve understanding of the ground-water flow system and evaluate the effects of hypothetical variations in recharge and discharge conditions.

A steady-state ground-water flow model was constructed for the area using November 2001 hydrologic conditions. The model was discretized into an 83-row by 47-column grid of cells measuring approximately 500 feet by 500 feet. Two model layers, one for the alluvium and one for the underlying bedrock units, were used to represent flow in the area.

Precipitation during 2001 was similar to historical normals. Precipitation during 1999, especially during the summer when flooding occurred, was well above the historical normals. Borings in the unconsolidated deposits in the study area confirmed the presence of a bedrock valley dipping to the south in the central part of the study area. Water-level measurements in 2001 indicate that ground-water flow in much of the alluvial aquifer parallels the direction of flow in the Cedar River toward the south rather than following shorter flow paths to the west toward the Cedar River.

Under steady-state conditions and 2001 pumpage, primary sources of inflow to the ground-water flow system are the Cedar River (65.5 percent), recharge through infiltration of precipitation and upland runoff (31.4 percent), and subsurface flow across the lateral boundaries (3.1 percent). The primary components of outflow from the ground-water flow system are intermittent streams (56.0 percent) and the Cedar River (43.7 percent).

Two hypothetical scenarios were used to assess the potential effects of higher river levels and increased recharge compared to the steady-state conditions. For one scenario, river levels were set to bankfull conditions, and a recharge of 1.2 times the steady-state rate was applied. This simulation was used to evaluate the effects of wet conditions. This scenario led to increased water levels, in general, and large areas of shallow (0 to 10 feet) depths to water along the eastern part of the model area near Highway 218. For the second scenario, conditions were the same as for the first scenario, but streambed conductance of intermittent streams modeled as drains was increased to 10 times the steady-state value to simulate increased flow of water from the shallow ground-water flow system. The area with depth to water of 0 to 10 feet along the eastern part of the model area was substantially smaller than that of the first scenario.

In general, once high ground-water levels occur, either because of high Cedar River water

levels or above normal local precipitation or both, ground-water in the central part of the study area along Highway 218 flows toward the south rather than following shorter flow paths to the Cedar River. Intermittent streams in the study area discharge substantial amounts of water from the ground-water flow system.

INTRODUCTION

Flooding and high ground-water levels after large or frequent rainstorms have occurred in an area of about 30 mi^2 along the eastern bank of the Cedar River from Cedar Falls in northwest Black Hawk County to Janesville in southwest Bremer County, Iowa (fig. 1). The Cedar River alluvium underlies the river valley and consists primarily of fluvial and glaciofluvial sand and gravel deposits. Ground-water levels in these deposits are influenced by recharge from precipitation and intermittent stream losses, changing stage in the Cedar River, and nearby municipal supply-well withdrawals. An extensive natural or artificial surface-water drainage network has not developed in the area, and changes in land use may affect surface-water and ground-water movement. Protection of property and infrastructure in the area requires an assessment of the factors that affect the movement of water from areas of recharge to areas of discharge.

The U.S. Geological Survey (USGS), in cooperation with the Black Hawk County Board of Supervisors and the County Engineer's office, conducted a hydrologic study of the Cedar River alluvium in northwest Black Hawk County and a small part of southwest Bremer County to improve understanding of the ground-water flow system.

Purpose and Scope

The purposes of this report are (1) to delineate and characterize the extent of unconsolidated deposits in the study area, (2) to describe hydrologic data used to facilitate analysis of surface-water and ground-water movement in the study area, and (3) to describe development of a ground-water flow model and the simulation of aquifer response to selected stresses.

This report describes the hydrogeology of a 30-mi^2 area in northwest Black Hawk County and extreme southwest Bremer County (model area, fig. 1). Model results are presented to evaluate simulated aquifer response to climatic and anthropogenic stresses. Hydrogeologic data were collected from October 2000 through November 2001.

Description of Study Area

The study area covers about 53 mi^2 along the Cedar River in northwest Black Hawk County and southwest Bremer County, Iowa, and contains a 30-mi^2 model area where ground-water flow was simulated (fig. 1). The area consists of a relatively flat alluvial valley bounded by low hills that separate the alluvial valley from upland areas. The Cedar River alluvium underlies the alluvial valley and consists primarily of fluvial and glaciofluvial sand and gravel deposits. The Cedar River alluvial aquifer is composed of the Cedar River alluvium. Upland areas consist primarily of glacial deposits (loess and till). Bedrock consisting of limestone and dolomite of Silurian and Devonian age underlies the alluvium and glacial deposits. The Silurian-Devonian aquifer is composed of the limestone and dolomite bedrock. Land-surface altitude in the river valley within the study area ranges between 850 and 890 ft above sea level and increases to 950 ft above sea level in the upland area. Within the alluvial valley, there is an isolated area with altitudes higher than 940 ft. Based on a small amount of test-hole data, this isolated area was assumed to consist of loess, glacial till, and bedrock. The south- to south-east-flowing Cedar River occupies the western edge of the alluvial valley, and several intermittent streams drain the upland area.

Land use in the study area is primarily agricultural; corn and soybeans are the principal crops. Forested areas are present along the Cedar River and along a few upland drainages. Rural residences are present throughout the study area; suburban and urban areas are located in and around Cedar Falls in the southern part of the study area. Active and formerly active sandpits are present in the southern part of the area. The City of Cedar Falls operates two municipal water-supply wells within the study area in northern Cedar Falls. These wells withdraw water from the Silurian-Devonian aquifer, which underlies the alluvial aquifer.

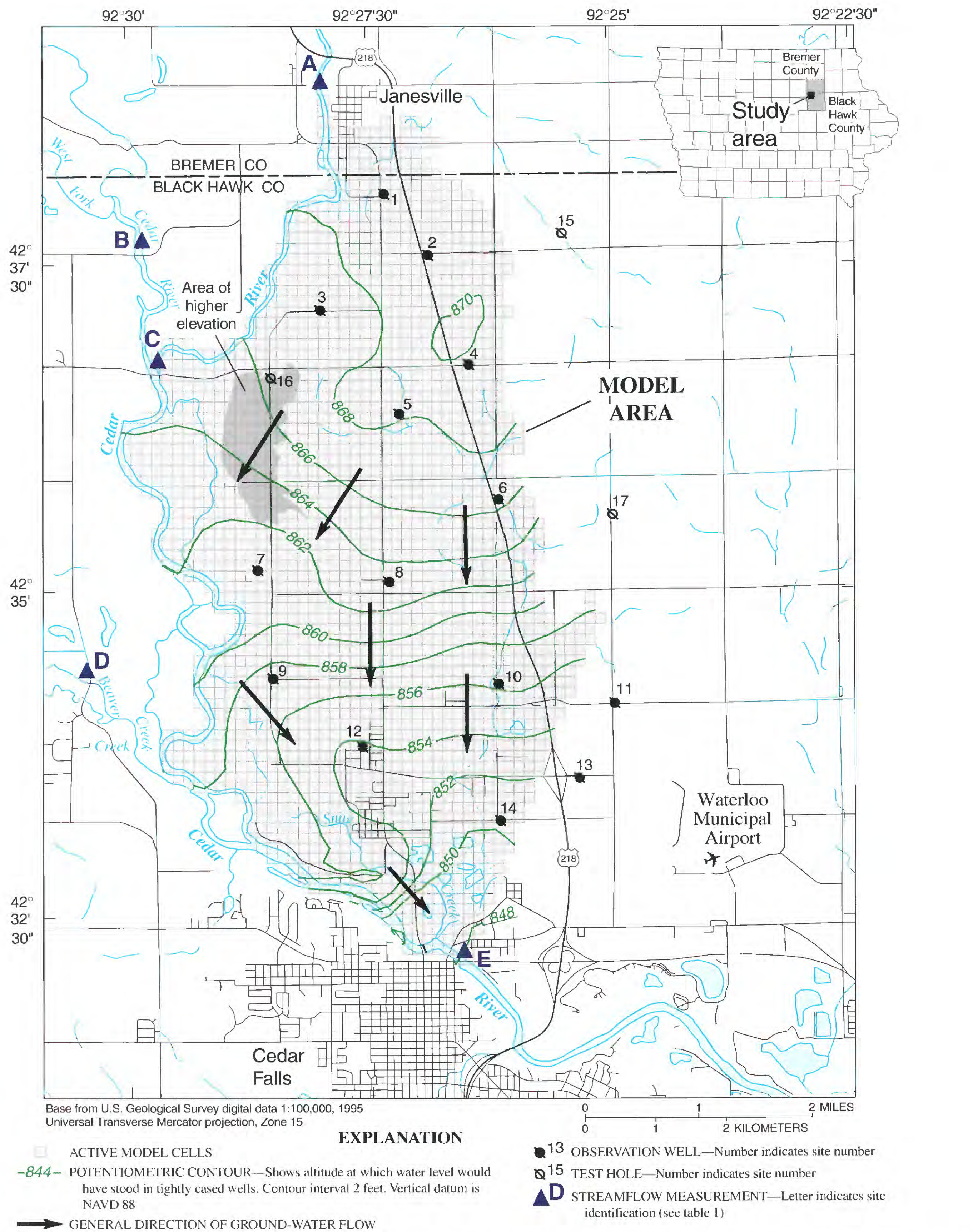

Figure 1. Location of study area, extent of digital model, location of data-collection sites, and measured potentiometric surface of the Cedar River alluvial aquifer, November 13–14, 2001.

Previous Studies

Ground water is an important resource in eastern Iowa and has been the subject of many studies in recent years. Several ground-water flow models have been developed for areas with similar geologic settings to this investigation.

For each of these models, flow in an alluvial aquifer and Silurian-Devonian aquifer was simulated for steady-state conditions. For some of the models, the Silurian-Devonian aquifer was represented by one layer and sometimes two layers. For the Muscatine (Lucey and others, 1995; Lucey, 1997; Savoca and others, 2002), Cedar Rapids (Schulmeyer and Schnoebelen, 1998), and Burlington (Boyd, 2001) models, calibration was accomplished by assuming that the system had reached steady-state conditions during a fall through winter period. Evapotranspiration was assumed to be minimal, and recharge was not simulated with the extreme variations associated with rapid snowmelt of spring or thunderstorms of summer.

The regional Cedar Falls model (Turco, 2002) was concerned primarily with the Silurian-Devonian aquifer. Calibration was to the mean water levels from April 1998 to February 1999, but water levels in most wells measured during this period had little variation (Turco, 2002, p. 10).

Concentrations and possible sources of nitrate in water from the Silurian-Devonian aquifer in Cedar Falls were studied by Schaap (1999). Water samples were collected from four wells that were located within the study area described in this report. Analysis of limited chlorofluorocarbon and isotope data indicated that water was moving along predominantly horizontal ground-water flow paths through the Silurian-Devonian aquifer.

Acknowledgments

The authors thank the private landowners, the City of Cedar Falls, and Black Hawk County for allowing the USGS to install and collect data from observation wells on private and public property in the study area. Water-supply well withdrawals for 2001 were provided by the City of Cedar Falls. Geologic information in the vicinity of Highway 218 was provided by the Iowa Department of Transportation. Observation-well altitudes and periodic water levels were measured by personnel from the Black Hawk County Engineer's office. Additional mapping and hydrologic data were provided by Black Hawk County through the Federal Emergency Management Agency's Cooperating Technical Communities program and the Rock Island District, U.S. Army Corps of Engineers Planning Assistance to States program, respectively. Ken Hedmark's (USGS) guidance and participation during well installation is greatly appreciated.

METHODS OF INVESTIGATION

Several types of data were collected and evaluated during the study to help define the hydrogeology of the Cedar River alluvium and to assist in the development of a ground-water flow model. The study included collection of precipitation, river stage and discharge measurements; construction of wells and measurement of ground-water levels, and determination of aquifer properties. Additional hydrogeologic data were obtained from the Iowa Department of Natural Resources–Geological Survey Bureau and Iowa Department of Transportation.

Precipitation Measurements

Precipitation measurements were used to determine relations between rainfall, ground-water levels, and river stage. Precipitation data were collected by a tipping-bucket recorder installed at the site of well 5 (fig. 1). Precipitation amounts were recorded every 15 minutes to the nearest 0.01 inch. Precipitation records also were obtained from the National Weather Service station at the Waterloo Municipal Airport located about 3 mi southeast from the center of the study area.

Figure 2 presents cumulative precipitation data collected at the Waterloo airport. From 1971 through 2000, the mean annual precipitation was 33.15 inches. During that 30-year period, the minimum annual total of 18.99 inches was recorded during 1988 and the maximum annual total of 53.07 inches was recorded during 1993 (National Oceanic and Atmospheric Administration, 2002). The difference of 34.08 inches between these two extremes indicates that for any specific year, precipitation can vary greatly from "normal" conditions.

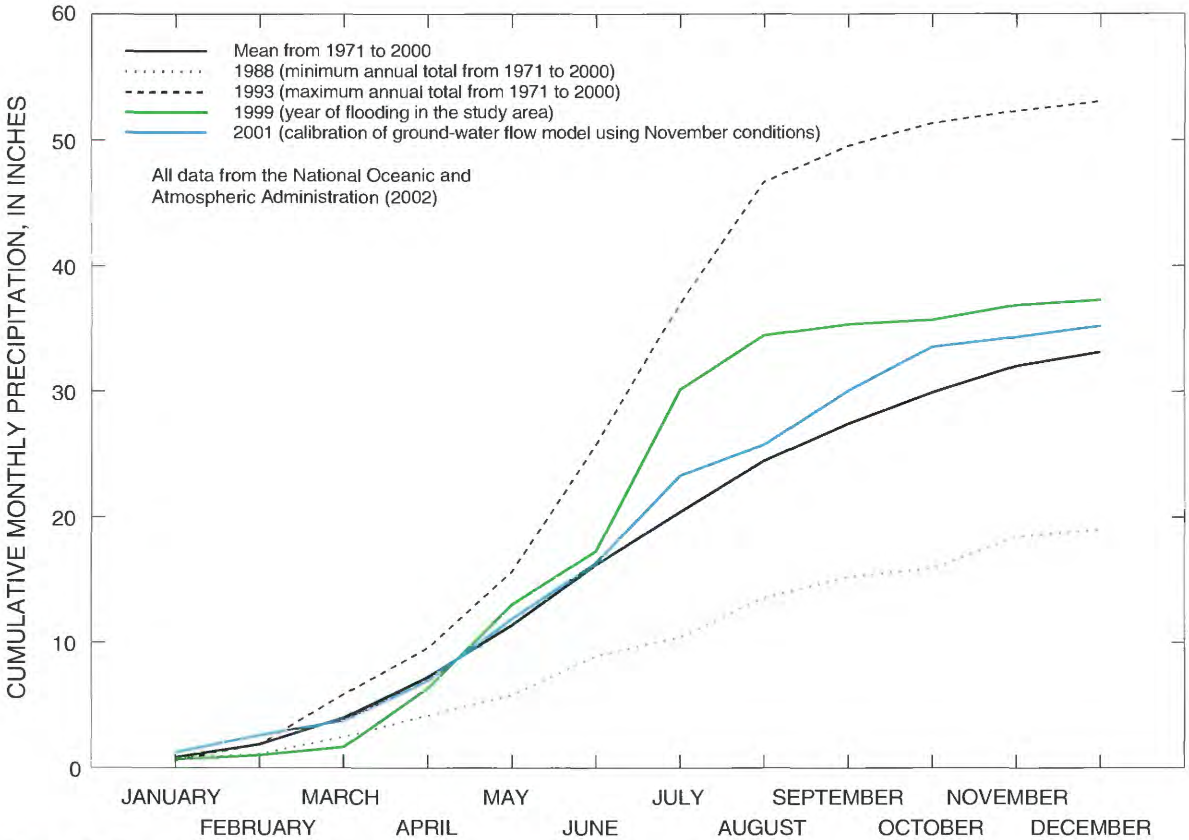

Figure 2. Cumulative precipitation at the Waterloo, Iowa, airport for selected years.

Surface-Water Stage and Streamflow Measurements

The Cedar River is the major surface-water feature in the area. Information about the stage and streamflow of the river is useful for understanding the ground-water flow in the Cedar River alluvium. For this study, stage information was collected in conjunction with streamflow information at selected points along the Cedar River and its tributaries (fig. 1).

Stage refers to the vertical distance between the river surface and a specific reference altitude. Streamflow is the amount of water moving through the river, and it is described in units of volume per time, such as cubic feet per second (ft^3/s). The relation between stage and streamflow is determined primarily by the river channel shape, which may be quite variable along the length of the river.

Stage

Stage is relatively easy to measure and comparisons can be made to water levels in aquifers to determine hydraulic gradients between the river and the aquifers. For this study, stage information for the Cedar River was collected at selected bridge crossings and at USGS streamflow-gaging sites (fig. 1).

Within the study area, the stage of the Cedar River varied by more than 15 ft during 1999 (Ballew and Eash, 2001) and also during 1961 (Schwob, 1963). During the 1999 flood, the gradient of the river surface between Janesville and the southern end of the study area was about 2.18 ft/mi. When the measurements were made for a 1999 low-flow water-surface profile and a November 13–14, 2001, water-surface profile, the gradients were about 2.38 ft/mi and 2.36 ft/mi, respectively. Figure 3 shows the gradient of the Cedar River in the study area for selected flow conditions.

Bankfull stages are defined by the National Weather Service for selected locations, typically those with gaging stations. For the Cedar River at Janesville gaging station, the altitude of the bankfull stage is 877.23 ft (National Weather Service, 2002a). For the Cedar River at Waterloo gaging station, the altitude of the bankfull stage is 833.58 ft (National Weather Service, 2002b). For selected locations along the

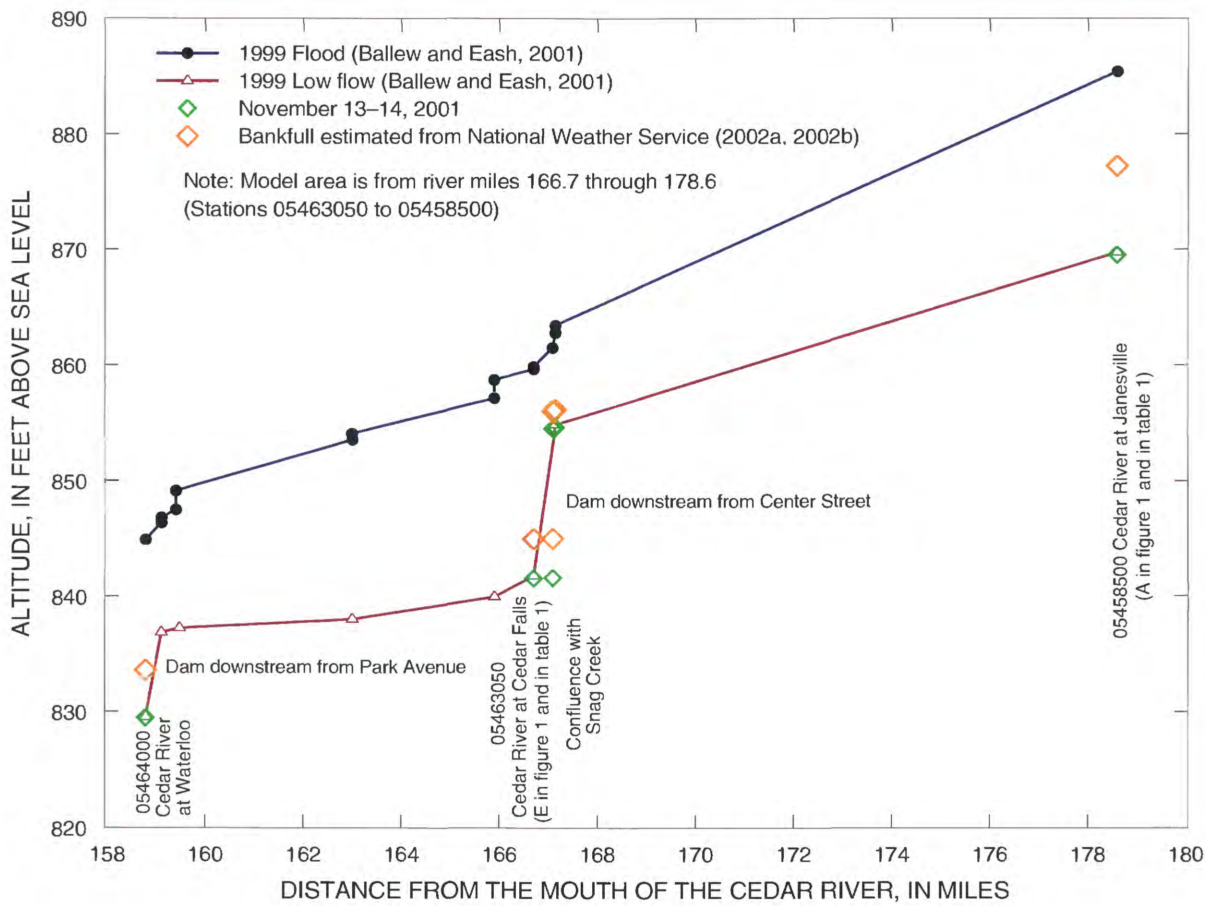

Figure 3. Cedar River stage in the study area for selected flow conditions.

Cedar River, stage was estimated by linear interpolation using the specified bankfull stages and historical stage information from earlier studies (Ballew and Eash, 2001; Schwob, 1963). For the southern extent of the Cedar River along the study area boundary, the altitude of the river stage during bankfull conditions was estimated as 844.98 ft, with a gradient of 2.71 ft/mi. Of the estimated 32.35 ft of fall from the upstream to the downstream end of the study area, about 11 ft occurs at the Cedar River dam between Center Street and the confluence with Snag Creek.

Streamflow

During November 13–14, 2001, streamflow measurements (table 1) were made at selected river sites in and near the study area (fig. 1) to investigate the interaction between the river and the ground-water system. Site selection was affected by several factors, including ease of access, so not all of the drainage area of the Cedar River is accounted for with these measurements. Streamflow measurements were made during November 2000 from a different set of sites at higher flow. The November 2000 measurements indicated that upstream from the West Fork Cedar River, the Cedar River was losing water to the ground-water system and downstream from the West Fork Cedar River to Waterloo, the Cedar River was gaining water from the ground-water system. However, the November 2001 streamflow measurements indicated that during these low-flow conditions, the losses or gains appear to be minimal and may be within the limits of measurement error.

Well Construction and Nomenclature

Test-hole and observation-well boring locations were selected to provide adequate spatial coverage of the study area (fig. 1). These borings provide information about the distribution of geologic materials and water levels in the Cedar River alluvium. This infor-

Table 1. Selected streamflow measurements in the Cedar River Basin on November 13–14, 2001

[ft^3s, cubic feet per second]

Site (fig. 1)	Station name	Streamflow (ft^3s)	Measurement type
A	05458500 Cedar River at Janesville	360	Recorded daily mean
B	05462300 West Fork Cedar River near Janesville	577	Wading
C	05462400 Confluence of the West Fork Cedar River and the Cedar River below Janesville	991	Wading
D	05463030 Beaver Creek near Cedar Falls	89	Wading
E	05463050 Cedar River at Cedar Falls	1,070	Wading
Not shown	05464000 Cedar River at Waterloo	1,170	Recorded daily mean

mation is used in the construction and calibration of the ground-water flow model. Test holes were drilled at three sites to characterize deposits underlying the upland area and to help define the eastern model boundary. Wells were not installed at test-hole locations. USGS personnel used a hand-held global positioning system (GPS) unit to determine the horizontal location (latitude and longitude) of test holes and observation wells.

Observation wells were installed at 14 sites in the Cedar River alluvium by using procedures described by Lapham and others (1995). Boreholes were drilled using 4.25-inch inside-diameter, continuous-flight, hollow-stem augers. Observation-well boreholes were drilled to bedrock or to the limits of the drill rig being used. Samples of auger cuttings were collected at major lithologic changes during drilling, and a description (driller's log) of alluvial materials encountered was recorded for each well (Appendix). The augers were left in place during well construction to prevent borehole collapse. Wells were constructed of 2-inch inside-diameter, flush-threaded, polyvinyl-chloride (PVC) pipe and 5 ft of 0.02-inch slotted PVC screen at the base of each well. Well depths ranged from about 17 to 47 ft below land surface. Alluvial material was allowed to fill the annular space around the screen during removal of the augers to form a natural filter pack extending about 2 ft above the top of the screen. An artificial sand-filter pack was emplaced around the screen in wells having fine-grained material adjacent to the screened interval (wells 2 and 4). A bentonite clay seal was placed above the filter pack, and the remainder of the borehole was backfilled with native material to within a few feet of land surface. A lockable, protective steel casing set in a cement pad was installed at land surface to protect the well casing and prevent infiltration of surface water down the borehole. Wells were developed after completion by pumping until the water was visually clear of sediment.

Maps depicting the thickness of unconsolidated deposits and the altitude of the Silurian-Devonian bedrock surface in the study area were constructed from available geologic information obtained from well and test-boring records of the Iowa Department of Natural Resources–Geological Survey Bureau, Iowa Department of Transportation, and USGS. A water-table surface map for the Cedar River alluvium was constructed from water-level altitudes measured at USGS observation wells and selected Cedar River sites on November 13–14, 2001 (fig. 1).

Table 2 lists the ground-water sites used for data collection in the study and includes well-construction data. Observation wells and test holes are designated by local site identifier (for example, 6) and USGS station identification number (for example, the USGS station identification number for site 6 is 423547092260901). The 15-digit station identification number contains site location information; the first six numbers describe latitude (degrees, minutes, seconds), the next seven numbers describe longitude (degrees, minutes, seconds), and the last two numbers sequentially differentiate between closely spaced sites.

Ground-Water-Level Measurements

Altitudes of measuring points on all wells were surveyed to sea-level datum and all water-level measurements were reported as altitudes above NGVD 88. Periodic ground-water-level measurements were

Table 2. Data-collection sites and observation-well construction data

[LSD, land-surface altitude in feet above NAVD 1988, North American Vertical Datum of 1988; MP, measuring-point altitude in feet above NAVD 1988; NA, no well installed, test hole]

Site name (fig. 1)	Station identification number	LSD	MP	Total well depth (feet below land surface)	Depth (in feet) of screened interval (top/bottom)
1	423808092271901	887.60	890.99	42	37/42
2	423740092265201	884.75	887.23	22.5	17.5/22.5
3	423715092275901	877.36	879.91	27.5	22.5/27.5
4	423650092262701	881.88	885.04	16.75	11.75/16.75
5	423627092271101	877.16	880.46	39	34/39
6	423547092260901	875.80	879.36	21	16/21
7	423515092283901	882.80	885.16	22.7	17.7/22.7
8	423510092271801	874.53	877.81	41	36/41
9	423426092283001	867.11	870.63	42	37/42
10	423423092261001	864.42	867.60	31.5	26.5/31.5
11	423414092245801	872.32	874.45	42.5	37.5/42.5
12	423354092273501	875.22	878.72	42	37/42
13	423339092252001	871.52	873.98	42	37/42
14	423320092261001	866.02	869.14	47	42/47
15	423743092252801	933.57	NA	NA	NA
16	423637092283001	906.71	NA	NA	NA
17	423533092245801	931.65	NA	NA	NA

obtained from 14 observation wells completed in the Cedar River alluvium and 3 domestic wells completed in the underlying Devonian-age limestone by using a calibrated electronic tape. Periodic measurements varied from twice a month during the winter to once a week during the remainder of the year when greater water-level fluctuations occur. Two observation wells (5 and 8) were equipped with continuous-data recorders and vented pressure transducers to collect hourly water levels. Periodic and continuous ground-water levels were recorded to the nearest 0.01 ft. Water levels were used to help conceptualize the ground-water flow system and calibrate the ground-water flow model.

Determination of Aquifer Properties

Slug tests were conducted in the 14 observation wells (table 3) completed in the Cedar River alluvium in northwestern Black Hawk County, Iowa, on May 14–17, 2001, and December 3, 2001. The slug tests were conducted to estimate horizontal hydraulic-conductivity values for the Cedar River alluvium. These values were used to estimate the distribution of horizontal hydraulic conductivity in the ground-water flow model prior to calibration. A slug constructed of a sand-filled, 1.25-inch outer-diameter PVC pipe was used to displace the static water level in observation wells. Water-level changes were measured with pressure transducers and data recorders. Slug-test results were analyzed using the Bouwer and Rice method for partially penetrating wells (Bouwer, 1989). The following assumptions are specified for the Bouwer and Rice method: (1) unconfined aquifer of "apparently" infinite extent; (2) homogeneous, isotropic aquifer of uniform thickness; (3) water table is horizontal prior to the test; (4) instantaneous change in head at start of test; (5) inertia of water column and non-linear well losses are negligible; (6) well storage is not negligible and is taken into account; (7) the flow to the well is in steady state; and (8) there is no flow above the water table.

The results of the slug tests (table 3) are affected by the degree to which conditions fail to match these assumptions. Even if all of the natural conditions are

Table 3. Horizontal hydraulic conductivity values estimated with slug tests and used in the ground-water flow model for the Cedar River alluvium in northwest Black Hawk County, Iowa, 2001

[NA, well is outside model area]

Site name (fig. 1)	Lithology near screened interval of well	Horizontal hydraulic conductivity	
		Estimate based on slug test (feet per day)	Value used in flow model cell (feet per day)
1	Coarse sand	18	63
2	Medium to coarse sand, silt, and clay with artificial sand pack	47	63
3	Coarse to medium sand	100	338
4	Fine to medium sand and clay with artificial sand pack	0.09	10
5	Very coarse sand and gravel	100	338
6	Medium sand	100	563
7	Medium to very coarse sand and gravel	20	338
8	Coarse to medium sand	200	938
9	Medium to fine sand	25	338
10	Medium to coarse sand and gravel	200	1,063
11	Very coarse sand and gravel	100	NA
12	Clay with medium to coarse natural sand pack	15	563
13	Medium to coarse sand	100	NA
14	Medium to very coarse sand	30	338

ideal, the alluvium is affected by the drilling of the well. The practical result of the slug test is an estimated hydraulic conductivity value for a small, disturbed portion of the alluvium, and this value may be much different than the hydraulic conductivity properties that affect the movement of ground water on a larger scale, such as the cell size used in the ground-water flow model.

Ground-Water Flow Model

Ground-water flow in the study area was simulated with MODFLOW, a computer program developed by McDonald and Harbaugh (1988). The program simulates flow in three dimensions by using a block-centered, finite-difference approach, which simultaneously solves a series of mathematical equations that describe saturated ground-water flow. The finite-difference equations were solved using the strongly implicit procedure.

HYDROGEOLOGY

The occurrence and movement of ground water in the study area is influenced by the distribution and physical properties of geologic materials. A description of the hydrogeology of the study area is given below. Detailed descriptions of the hydrogeology of the area are given by Anderson (1983), Horick (1984), Hansen (1975), Olcott (1992), and Witzke and others (1988).

Geology and Water-Bearing Characteristics

The Cedar River alluvium that underlies the river valley consists of unconsolidated deposits of sand, gravel, silt, and clay (table 4). The deposits are of fluvial and glaciofluvial origin and range in thickness from about 20 to 160 ft in the study area (fig. 4). Distinct zones in the alluvium are not defined; however, fining-upwards sequences were observed at several wells (Appendix). Upland areas adjacent to the alluvial valley are underlain by loess and glacial till

Table 4. Hydrogeologic units in the study area and their water-bearing characteristics

[gpm, gallons per minute]

Hydrogeologic unit[1]	Geologic unit	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	Cedar River alluvium, glacial deposits	20–250	Quaternary	Well yields variable, 3–25 gpm, not a widely used source of water.	Medium to coarse sand; fine sand and silt. Loess, silty clay and fine sand; till, clay, and some pebbles.	Layer 1
Silurian-Devonian aquifer	Undifferentiated	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, gypsum, 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 2
Confining unit	Maquoketa Formation	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.

(table 4). The unconsolidated silts and clays of the loess and glacial till range in thickness from about 20 to 160 ft in the study area. Isolated deposits of glacial till are present at the base of the alluvium within the valley. These glacial till deposits may represent erosional remnants of a once more continuous till cover in the area that was subsequently removed by Holocene-age fluvial erosion. Unconsolidated deposits are underlain by rocks of Devonian and Silurian age (fig. 5) that consist of limestone and dolomite with interbedded deposits of gypsum and shale (table 4). Devonian-age rocks are 75 to 100 ft thick and Silurian-age rocks are about 100 ft thick (Horick, 1984; Olcott, 1992). The underlying Ordovician-age Maquoketa Formation, a regional confining unit (table 4), consists predominantly of shale and is about 300 ft thick (Horick, 1984; Olcott, 1992). A buried bedrock valley, possibly formed by erosion from a paleochannel of the Cedar River, underlies the central part of the study area (fig. 5). This bedrock feature was initially depicted by Hansen (1975).

Surface Water

Studies done of high-flow and low-flow conditions along the Cedar River indicate that during 1999 flooding and low-flow conditions, the river stage steadily decreased from Janesville downstream to the dam at river mile 167.09 near Cedar Falls (fig. 3). During the 1999 flood, the maximum streamflow at Janesville was 42,200 ft^3/s and at Waterloo was 69,300 ft^3/s (Ballew and Eash, 2001).

Discharge of the Cedar River during the November 2001 measurements (table 1) was about 100 ft^3/s less than when the low-flow profile measurements of river surface were made during 1999 (Ballew and Eash, 2001).

Figure 6 shows the streamflow recorded at the USGS continuous-record gaging station 05458500 Cedar River at Janesville in the northern part of the study area. During 2001, streamflow varied during the spring and early summer but was fairly stable during the remainder of the year, including November, when the hydrologic system was assumed to be at steady-

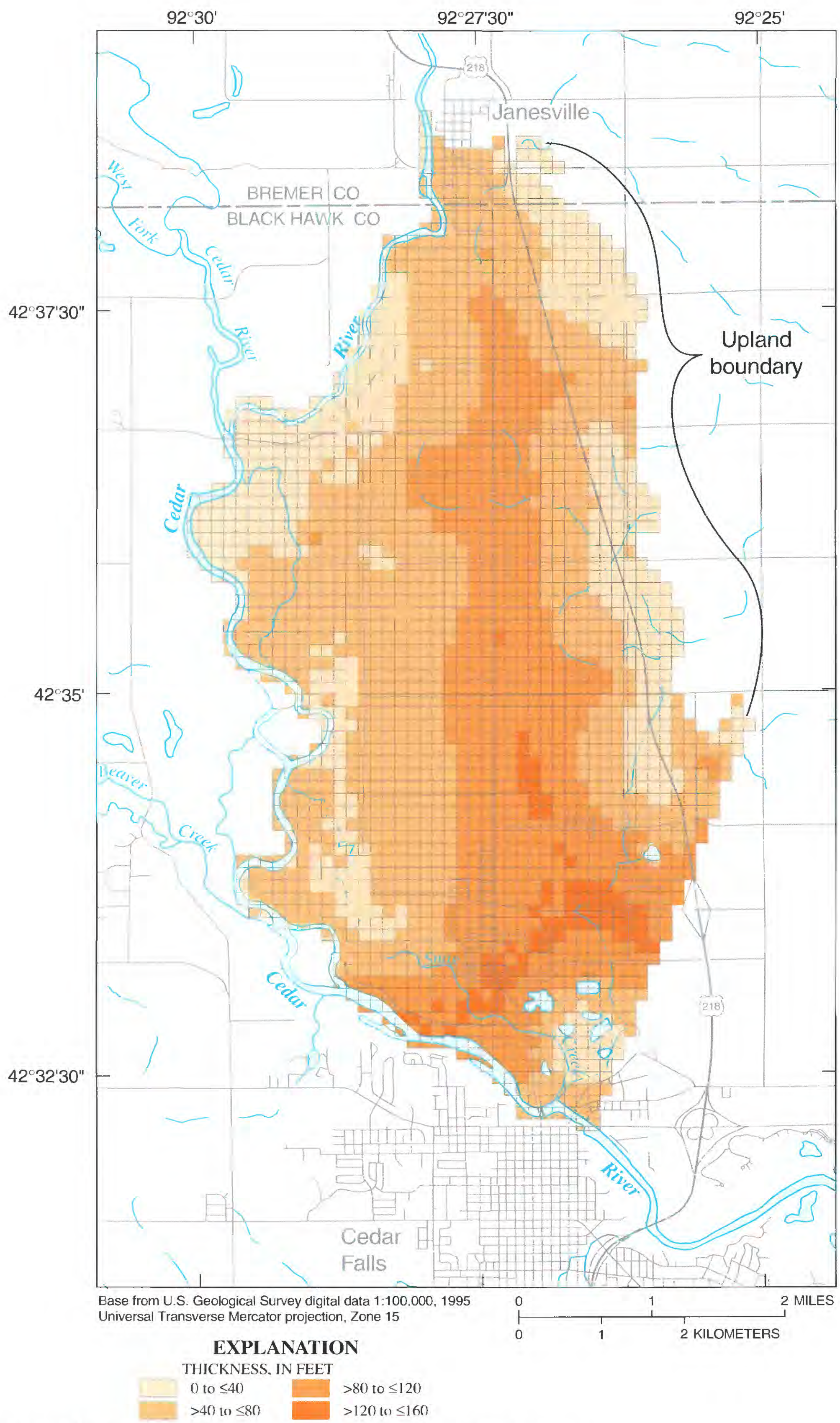

Figure 4. Thickness of unconsolidated materials in the study area.

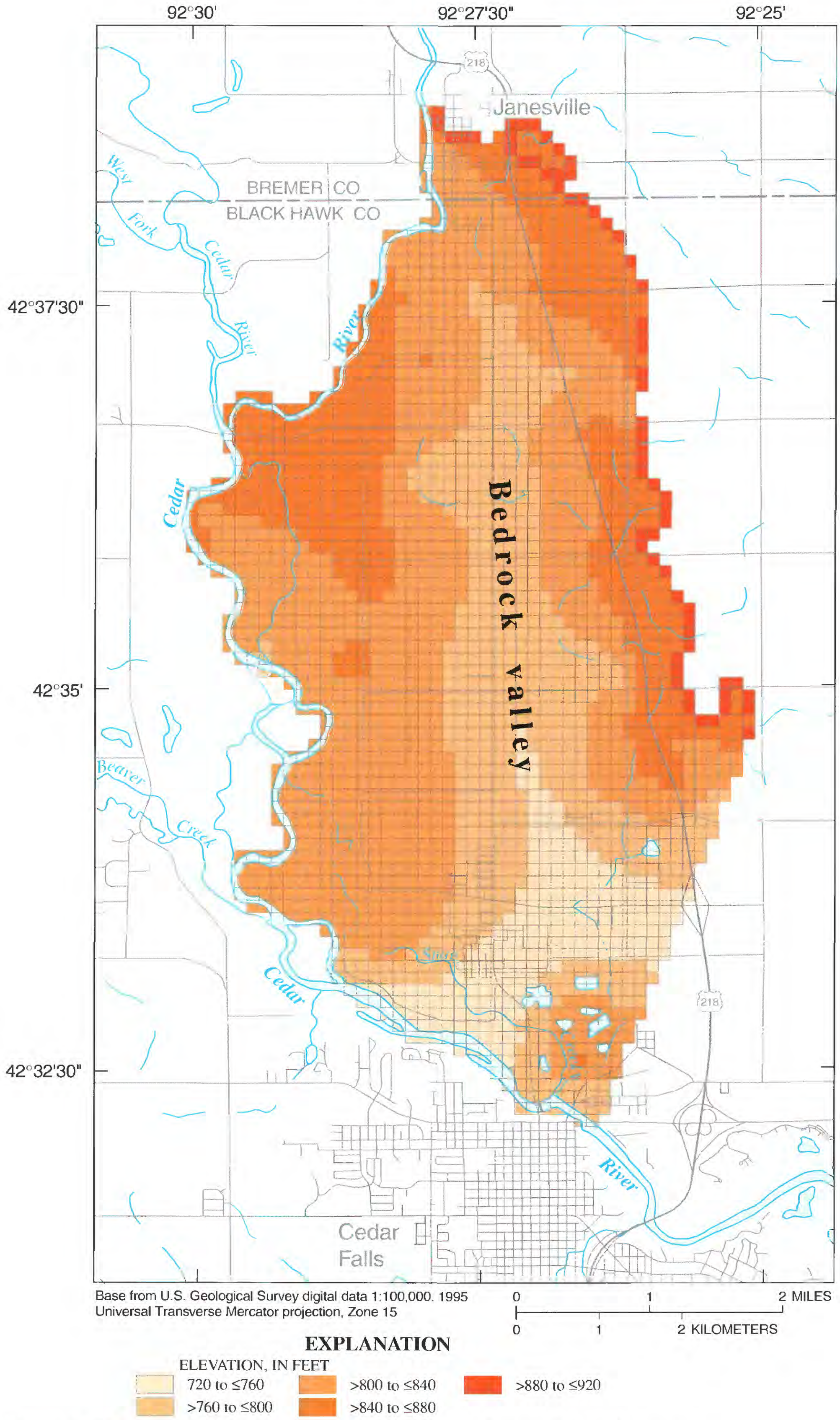

Figure 5. Altitude and configuration of the bedrock surface in the study area.

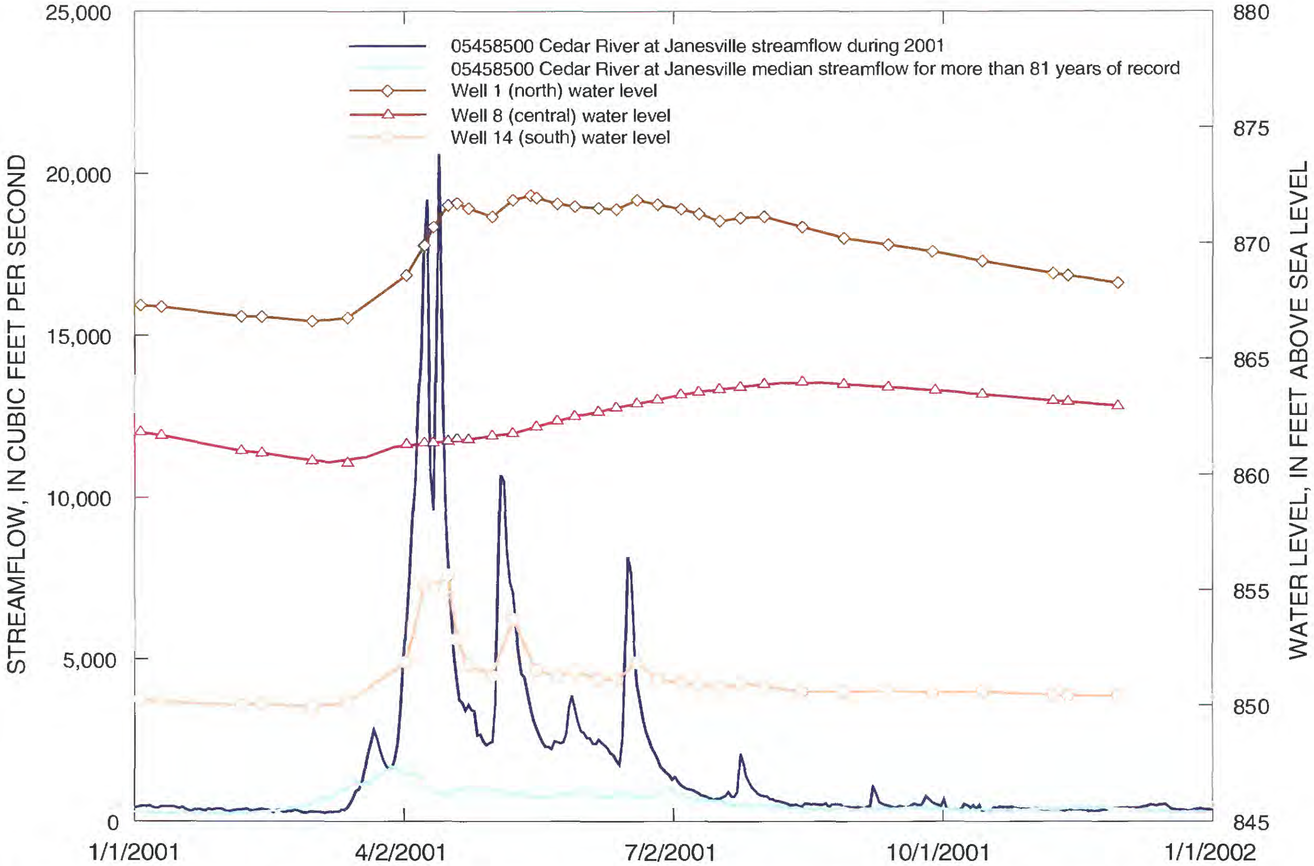

Figure 6. *Cedar River at Janesville, Iowa, discharge and measured water levels in three wells in the study area.*

state conditions for this report. Long-term records from this station indicate that the amount of streamflow during the fall of 2001 was similar to median streamflow during the Novembers of more than 81 years of record. Also, these long-term records indicate a similar pattern to that of 2001, with streamflow at a fairly stable level for much of the year including late fall.

Ground Water

Hydraulic conductivity describes the ability of geologic materials to transmit water. Hydraulic conductivity for unconsolidated materials such as the Cedar River alluvium generally varies with particle size. Clays and silts tend to have lesser hydraulic-conductivity values, whereas sands and gravels tend to have greater hydraulic-conductivity values (Todd, 1980). For this report, hydraulic conductivities in the Cedar River alluvium were estimated with slug-test analyses in 14 observation wells (table 3). Estimated hydraulic-conductivity values measured in the observation wells ranged over four orders of magnitude (table 3). The wide range of hydraulic-conductivity values reflects the natural heterogeneity of geologic materials. Hydraulic conductivities used in the calibrated flow model differed from the estimated slug-test values. Typically, the values used in the model described in this report are greater than the slug-test values, but they are often within an order of magnitude. The horizontal hydraulic-conductivity values used in the model ranged over three orders of magnitude (table 3).

Ground water in the alluvium is unconfined. Ground water in the underlying bedrock likely is confined in most parts of the model area, as described by Turco (2002). The direction of ground-water flow in the alluvium generally is from the upland areas toward the Cedar River. Figure 1 shows water levels in the Cedar River alluvium on November 13–14, 2001.

The direction of ground-water flow in the alluvium parallels the direction of flow in the Cedar River but occurs down the center of the alluvial valley coincident with the bedrock valley. This may indicate that ground water in the eastern and central part of the study area drains predominantly to the south toward the Cedar River rather than taking a shorter flow path westward to the Cedar River. The regional direction of ground-water flow in the underlying bedrock generally is from the northwest toward the southeast, but variations in the general regional direction of flow occur locally (Turco, 2002). Water levels measured in observation wells for this report are summarized in table 5 and listed in table 6. Water levels in the alluvium tended to be highest in spring, corresponding to high Cedar River stages, or later in the summer or fall corresponding with some time lag after increased rainfall from thunderstorms, depending on the location within the model area (figs. 1 and 6).

Sources of water (recharge) to the alluvium in the study area include precipitation, the river when river stages are greater than water levels in the alluvium, runoff from adjacent upland areas, ground water from the underlying bedrock, and subsurface flow from areas adjacent to the study area. Water in the alluvium may be removed (discharged) by well withdrawals, flow to rivers and drains, flow to the underlying bedrock, subsurface flow to areas adjacent to the study area, and evapotranspiration during the growing season.

Table 5. Ground-water levels measured in observation wells in northwest Black Hawk County, Iowa, on November 13–14, 2001, and values simulated by using the ground-water flow model

[All water levels in feet above North American Vertical Datum of 1988 (NAVD 88); NA, site not within model area]

Site name (fig. 1)	Water-level altitude (feet above NAVD 1988 level)	
	Measured on November 13–14, 2001	Simulated by flow model
1	868.60	869.02
2	869.37	868.27
3	867.28	866.70
4	869.70	866.27
5	868.08	864.81
6	866.26	863.13
7	860.54	861.68
8	863.15	861.06
9	857.26	859.14
10	856.16	858.14
11	854.28	NA
12	853.87	856.86
13	851.83	NA
14	850.43	852.97

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement		Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)			Depth to water (feet bls)	Altitude (feet above NAVD 88)
1	10–12–00	18.86	868.74	2	10–13–00	15.56	869.19
	10–31–00	19.35	868.25		10–31–00	16.23	868.52
	11–14–00	19.50	868.10		11–14–00	16.72	868.03
	12–01–00	19.84	867.76		12–01–00	17.27	867.48
	12–14–00	20.05	867.55		12–14–00	17.73	867.02
	01–03–01	20.30	867.30		01–03–01	18.16	866.59
	01–10–01	20.36	867.24		01–10–01	18.41	866.34
	02–06–01	20.77	866.83		02–06–01	19.17	865.58
	02–13–01	20.79	866.81		02–13–01	19.23	865.52
	03–02–01	20.99	866.61		03–02–01	19.49	865.26
	03–14–01	20.84	866.76		03–14–01	19.08	865.67
	04–03–01	18.99	868.61		04–03–01	16.74	868.01
	04–09–01	17.71	869.89		04–09–01	15.80	868.95
	04–12–01	16.92	870.68		04–12–01	15.61	869.14
	04–17–01	15.98	871.62		04–17–01	15.16	869.59
	04–20–01	15.87	871.73		04–20–01	15.02	869.73
	04–24–01	16.11	871.49		04–24–01	15.21	869.54
	05–02–01	16.47	871.13		05–02–01	15.26	869.49
	05–09–01	15.75	871.85		05–09–01	14.56	870.19
	05–15–01	15.56	872.04		05–16–01	14.17	870.58
	05–17–01	15.66	871.94		05–17–01	14.14	870.61
	05–24–01	15.91	871.69		05–24–01	14.15	870.60
	05–30–01	16.03	871.57		05–30–01	14.13	870.62
	06–07–01	16.09	871.51		06–07–01	13.81	870.94
	06–13–01	16.14	871.46		06–13–01	13.67	871.08
	06–20–01	15.75	871.85		06–20–01	13.43	871.32
	06–27–01	15.94	871.66		06–27–01	13.52	871.23
	07–05–01	16.15	871.45		07–05–01	13.43	871.32
	07–11–01	16.35	871.25		07–11–01	13.57	871.18
	07–18–01	16.65	870.95		07–18–01	ND	ND
	07–25–01	16.52	871.08		07–25–01	13.20	871.55
	08–02–01	16.46	871.14		08–02–01	ND	ND
	08–15–01	16.91	870.69		08–15–01	13.29	871.46
	08–29–01	17.39	870.21		08–29–01	13.68	871.07
	09–13–01	17.67	869.93		09–13–01	13.85	870.90
	09–28–01	17.97	869.63		09–28–01	13.68	871.07
	10–15–01	18.37	869.23		10–15–01	14.71	870.04
	11–08–01	18.91	868.69		11–08–01	15.31	869.44
	11–13–01	19.00	868.60		11–13–01	15.38	869.37
	11–30–01	19.32	868.28		11–30–01	15.85	868.90

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
3	10–13–00	10.17	867.19
	10–31–00	10.57	866.79
	11–14–00	10.71	866.65
	12–01–00	10.94	866.42
	12–14–00	11.16	866.20
	01–03–01	ND	ND
	01–10–01	11.44	865.92
	02–06–01	11.84	865.52
	02–13–01	11.89	865.47
	03–02–01	12.07	865.29
	03–14–01	11.95	865.41
	04–03–01	10.36	867.00
	04–09–01	2.84	874.52
	04–12–01	3.83	873.53
	04–17–01	4.11	873.25
	04–20–01	4.94	872.42
	04–24–01	5.91	871.45
	05–02–01	7.00	870.36
	05–09–01	5.54	871.82
	05–16–01	6.20	871.16
	05–17–01	6.37	870.99
	05–24–01	7.09	870.27
	05–30–01	7.31	870.05
	06–07–01	6.99	870.37
	06–13–01	7.19	870.17
	06–20–01	6.69	870.67
	06–27–01	7.06	870.30
	07–05–01	7.04	870.32
	07–11–01	7.54	869.82
	07–18–01	8.00	869.36
	07–25–01	7.60	869.76
	08–02–01	7.88	869.48
	08–15–01	8.44	868.92
	08–29–01	8.87	868.49
	09–13–01	8.92	868.44
	09–28–01	9.23	868.13
	10–15–01	9.61	867.75
	11–08–01	10.02	867.34
	11–13–01	10.08	867.28
	11–30–01	10.35	867.01
4	10–13–00	13.19	868.69
	10–31–00	13.73	868.15
	11–14–00	14.04	867.84
	12–01–00	14.75	867.13
	12–14–00	15.58	866.30
	01–03–01	16.25	865.63
	01–10–01	16.48	865.40
	02–06–01	16.86	865.02
	02–13–01	16.86	865.02
	03–02–01	17.07	864.81
	03–14–01	10.42	871.46
	04–03–01	11.45	870.43
	04–09–01	11.85	870.03
	04–12–01	12.02	869.86
	04–17–01	11.77	870.11
	04–20–01	11.77	870.11
	04–24–01	11.87	870.01
	05–02–01	12.01	869.87
	05–09–01	11.61	870.27
	05–16–01	11.08	870.80
	05–17–01	11.23	870.65
	05–24–01	11.65	870.23
	05–30–01	11.82	870.06
	06–07–01	10.73	871.15
	06–13–01	10.93	870.95
	06–20–01	11.13	870.75
	06–27–01	11.15	870.73
	07–05–01	10.57	871.31
	07–11–01	10.87	871.01
	07–18–01	11.02	870.86
	07–25–01	9.76	872.12
	08–02–01	10.40	871.48
	08–15–01	10.63	871.25
	08–29–01	10.89	870.99
	09–13–01	10.84	871.04
	09–28–01	11.26	870.62
	10–15–01	11.77	870.11
	11–08–01	12.17	869.71
	11–13–01	12.18	869.70
	11–30–01	12.57	869.31

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
5	10–12–00	9.27	867.89
	10–31–00	9.89	867.27
	11–14–00	10.26	866.90
	12–01–00	10.78	866.38
	12–14–00	11.15	866.01
	01–03–01	11.62	865.54
	01–10–01	11.80	865.36
	02–06–01	12.48	864.68
	02–13–01	12.62	864.54
	03–02–01	12.94	864.22
	03–14–01	12.88	864.28
	04–03–01	11.17	865.99
	04–09–01	10.83	866.33
	04–12–01	10.64	866.52
	04–17–01	10.22	866.94
	04–20–01	9.88	867.28
	04–24–01	9.75	867.41
	05–02–01	ND	ND
	05–09–01	9.15	868.01
	05–16–01	8.27	868.89
	05–17–01	8.22	868.94
	05–24–01	8.08	869.08
	05–30–01	8.07	869.09
	06–07–01	7.67	869.49
	06–13–01	7.42	869.74
	06–20–01	7.32	869.84
	06–27–01	7.32	869.84
	07–05–01	7.17	869.99
	07–11–01	7.26	869.90
	07–18–01	7.39	869.77
	07–25–01	6.95	870.21
	08–02–01	6.81	870.35
	08–15–01	7.10	870.06
	08–29–01	7.51	869.65
	09–13–01	7.70	869.46
	09–28–01	8.13	869.03
	10–15–01	8.58	868.58
	11–08–01	9.03	868.13
	11–13–01	9.08	868.08
	11–30–01	9.48	867.68

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
6	10–13–00	9.87	865.93
	10–31–00	10.42	865.38
	11–14–00	10.72	865.08
	12–01–00	11.26	864.54
	12–14–00	11.72	864.08
	01–03–01	12.28	863.52
	01–10–01	12.45	863.35
	02–06–01	13.18	862.62
	02–13–01	13.29	862.51
	03–02–01	13.62	862.18
	03–14–01	13.39	862.41
	04–03–01	11.39	864.41
	04–09–01	11.14	864.66
	04–12–01	11.00	864.80
	04–17–01	10.74	865.06
	04–20–01	10.52	865.28
	04–24–01	10.53	865.27
	05–02–01	10.42	865.38
	05–09–01	9.94	865.86
	05–16–01	8.50	867.30
	05–17–01	8.48	867.32
	05–24–01	8.59	867.21
	05–30–01	8.70	867.10
	06–07–01	7.65	868.15
	06–13–01	7.45	868.35
	06–20–01	7.59	868.21
	06–27–01	7.83	867.97
	07–05–01	7.54	868.26
	07–11–01	7.59	868.21
	07–18–01	7.90	867.90
	07–25–01	7.31	868.49
	08–02–01	6.79	869.01
	08–15–01	7.53	868.27
	08–29–01	8.11	867.69
	09–13–01	8.23	867.57
	09–28–01	8.66	867.14
	10–15–01	9.09	866.71
	11–08–01	9.45	866.35
	11–13–01	9.54	866.26
	11–30–01	9.97	865.83

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
7	10–12–00	21.57	861.23
	10–31–00	22.03	860.77
	11–14–00	22.25	860.55
	12–01–00	22.47	860.33
	12–14–00	22.65	860.15
	01–03–01	ND	ND
	01–10–01	ND	ND
	02–06–01	ND	ND
	02–13–01	ND	ND
	03–02–01	ND	ND
	03–14–01	ND	ND
	04–03–01	21.66	861.14
	04–09–01	18.96	863.84
	04–12–01	18.31	864.49
	04–17–01	17.47	865.33
	04–20–01	17.94	864.86
	04–24–01	18.44	864.36
	05–02–01	18.98	863.82
	05–09–01	17.99	864.81
	05–15–01	18.17	864.63
	05–17–01	18.30	864.50
	05–24–01	18.69	864.11
	05–30–01	18.73	864.07
	06–07–01	18.82	863.98
	06–13–01	18.89	863.91
	06–20–01	18.40	864.40
	06–27–01	18.71	864.09
	07–05–01	18.93	863.87
	07–11–01	19.09	863.71
	07–18–01	19.32	863.48
	07–25–01	19.50	863.30
	08–02–01	19.65	863.15
	08–15–01	20.02	862.78
	08–29–01	20.54	862.26
	09–13–01	20.93	861.87
	09–28–01	21.27	861.53
	10–15–01	21.71	861.09
	11–08–01	22.19	860.61
	11–13–01	22.26	860.54
	11–30–01	22.52	860.28
8	10–12–00	10.86	863.67
	10–31–00	11.26	863.27
	11–14–00	11.57	862.96
	12–01–00	11.91	862.62
	12–14–00	12.30	862.23
	01–03–01	12.70	861.83
	01–10–01	12.86	861.67
	02–06–01	13.50	861.03
	02–13–01	13.60	860.93
	03–02–01	13.94	860.59
	03–14–01	14.02	860.51
	04–03–01	13.23	861.30
	04–09–01	13.17	861.36
	04–12–01	13.17	861.36
	04–17–01	13.09	861.44
	04–20–01	12.97	861.56
	04–24–01	13.01	861.52
	05–02–01	12.86	861.67
	05–09–01	12.76	861.77
	05–16–01	12.53	862.00
	05–17–01	12.47	862.06
	05–24–01	12.22	862.31
	05–30–01	12.03	862.50
	06–07–01	11.82	862.71
	06–13–01	11.64	862.89
	06–20–01	11.47	863.06
	06–27–01	11.30	863.23
	07–05–01	11.09	863.44
	07–11–01	10.97	863.56
	07–18–01	10.85	863.68
	07–25–01	10.75	863.78
	08–02–01	10.63	863.90
	08–15–01	10.54	863.99
	08–29–01	10.63	863.90
	09–13–01	10.75	863.78
	09–28–01	10.90	863.63
	10–15–01	11.06	863.47
	11–08–01	11.35	863.18
	11–13–01	11.38	863.15
	11–30–01	11.58	862.95

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
9	10–12–00	9.51	857.60
	10–31–00	9.68	857.43
	11–14–00	9.64	857.47
	12–01–00	9.71	857.40
	12–14–00	9.88	857.23
	01–03–01	10.00	857.11
	01–10–01	10.02	857.09
	02–06–01	10.20	856.91
	02–13–01	10.22	856.89
	03–02–01	10.31	856.80
	03–14–01	10.00	857.11
	04–03–01	7.39	859.72
	04–09–01	4.38	862.73
	04–12–01	5.26	861.85
	04–17–01	4.77	862.34
	04–20–01	5.94	861.17
	04–24–01	6.81	860.30
	05–02–01	7.67	859.44
	05–09–01	5.78	861.33
	05–15–01	6.86	860.25
	05–17–01	7.17	859.94
	05–24–01	7.86	859.25
	05–30–01	7.60	859.51
	06–07–01	7.90	859.21
	06–13–01	8.08	859.03
	06–20–01	7.30	859.81
	06–27–01	7.93	859.18
	07–05–01	8.34	858.77
	07–11–01	8.59	858.52
	07–18–01	8.79	858.32
	07–25–01	8.48	858.63
	08–02–01	8.88	858.23
	08–15–01	9.17	857.94
	08–29–01	9.38	857.73
	09–13–01	9.37	857.74
	09–28–01	9.57	857.54
	10–15–01	9.67	857.44
	11–08–01	9.83	857.28
	11–13–01	9.85	857.26
	11–30–01	9.97	857.14

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
10	10–12–00	7.78	856.64
	10–31–00	8.27	856.15
	11–14–00	8.51	855.91
	12–01–00	8.90	855.52
	12–14–00	9.13	855.29
	01–03–01	9.50	854.92
	01–10–01	9.61	854.81
	02–06–01	10.11	854.31
	02–13–01	10.18	854.24
	03–02–01	10.46	853.96
	03–14–01	10.29	854.13
	04–03–01	9.27	855.15
	04–09–01	9.03	855.39
	04–12–01	8.89	855.53
	04–17–01	8.65	855.77
	04–20–01	8.47	855.95
	04–24–01	8.37	856.05
	05–02–01	8.21	856.21
	05–09–01	7.91	856.51
	05–15–01	7.63	856.79
	05–17–01	7.58	856.84
	05–24–01	7.45	856.97
	05–30–01	7.36	857.06
	06–07–01	6.88	857.54
	06–13–01	6.77	857.65
	06–20–01	6.53	857.89
	06–27–01	6.58	857.84
	07–05–01	6.05	858.37
	07–11–01	6.37	858.05
	07–18–01	6.76	857.66
	07–25–01	5.64	858.78
	08–02–01	5.87	858.55
	08–15–01	6.41	858.01
	08–29–01	6.89	857.53
	09–13–01	7.07	857.35
	09–28–01	7.58	856.84
	10–15–01	7.92	856.50
	11–08–01	8.20	856.22
	11–13–01	8.26	856.16
	11–30–01	8.47	855.95

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
11	10–12–00	17.75	854.57
	10–31–00	18.31	854.01
	11–14–00	18.59	853.73
	12–01–00	18.84	853.48
	12–14–00	19.07	853.25
	01–03–01	19.41	852.91
	01–10–01	19.51	852.81
	02–06–01	20.00	852.32
	02–13–01	20.08	852.24
	03–02–01	20.31	852.01
	03–14–01	19.99	852.33
	04–03–01	18.37	853.95
	04–09–01	18.47	853.85
	04–12–01	17.69	854.63
	04–17–01	17.29	855.03
	04–20–01	17.00	855.32
	04–24–01	16.98	855.34
	05–02–01	16.94	855.38
	05–09–01	16.72	855.60
	05–14–01	16.43	855.89
	05–17–01	16.32	856.00
	05–24–01	16.24	856.08
	05–30–01	16.21	856.11
	06–07–01	16.12	856.20
	06–13–01	16.08	856.24
	06–20–01	15.93	856.39
	06–27–01	15.81	856.51
	07–05–01	15.91	856.41
	07–11–01	16.02	856.30
	07–18–01	16.23	856.09
	07–25–01	16.22	856.10
	08–02–01	16.05	856.27
	08–15–01	16.40	855.92
	08–29–01	16.80	855.52
	09–13–01	17.21	855.11
	09–28–01	17.52	854.80
	10–15–01	17.90	854.42
	11–08–01	18.01	854.31
	11–13–01	18.04	854.28
	11–30–01	18.21	854.11
12	10–12–00	20.39	854.83
	10–31–00	20.80	854.42
	11–14–00	21.04	854.18
	12–01–00	21.26	853.96
	12–14–00	21.49	853.73
	01–03–01	21.80	853.42
	01–10–01	21.86	853.36
	02–06–01	22.23	852.99
	02–13–01	22.29	852.93
	03–02–01	22.51	852.71
	03–14–01	22.58	852.64
	04–03–01	21.87	853.35
	04–09–01	21.66	853.56
	04–12–01	21.56	853.66
	04–17–01	21.33	853.89
	04–20–01	21.14	854.08
	04–24–01	20.98	854.24
	05–02–01	20.58	854.64
	05–09–01	20.41	854.81
	05–15–01	20.19	855.03
	05–17–01	20.13	855.09
	05–24–01	19.99	855.23
	05–30–01	19.92	855.30
	06–07–01	19.83	855.39
	06–13–01	19.79	855.43
	06–20–01	19.76	855.46
	06–27–01	19.75	855.47
	07–05–01	19.79	855.43
	07–11–01	19.84	855.38
	07–18–01	19.93	855.29
	07–25–01	19.97	855.25
	08–02–01	20.04	855.18
	08–15–01	20.22	855.00
	08–29–01	20.43	854.79
	09–13–01	20.65	854.57
	09–28–01	20.84	854.38
	10–15–01	21.08	854.14
	11–08–01	21.33	853.89
	11–13–01	21.35	853.87
	11–30–01	21.49	853.73

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
13	10–12–00	19.44	852.08
	10–31–00	19.87	851.65
	11–14–00	19.99	851.53
	12–01–00	20.16	851.36
	12–14–00	20.31	851.21
	01–03–01	20.57	850.95
	01–10–01	20.66	850.86
	02–06–01	21.05	850.47
	02–13–01	21.10	850.42
	03–02–01	21.30	850.22
	03–14–01	21.21	850.31
	04–03–01	19.61	851.91
	04–09–01	18.91	852.61
	04–12–01	18.74	852.78
	04–17–01	18.05	853.47
	04–20–01	17.91	853.61
	04–24–01	17.98	853.54
	05–02–01	18.12	853.40
	05–09–01	17.78	853.74
	05–14–01	17.64	853.88
	05–17–01	17.64	853.88
	05–24–01	17.79	853.73
	05–30–01	17.74	853.78
	06–07–01	17.82	853.70
	06–13–01	17.84	853.68
	06–20–01	17.60	853.92
	06–27–01	17.61	853.91
	07–05–01	17.84	853.68
	07–11–01	18.00	853.52
	07–18–01	18.26	853.26
	07–25–01	18.37	853.15
	08–02–01	18.26	853.26
	08–15–01	18.56	852.96
	08–29–01	18.86	852.66
	09–13–01	19.12	852.40
	09–28–01	19.37	852.15
	10–15–01	19.70	851.82
	11–08–01	19.68	851.84
	11–13–01	19.69	851.83
	11–30–01	19.76	851.76

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
14	10–12–00	15.62	850.40
	10–31–00	15.71	850.31
	11–14–00	15.66	850.36
	12–01–00	15.78	850.24
	12–14–00	15.82	850.20
	01–03–01	15.77	850.25
	01–10–01	15.87	850.15
	02–06–01	16.00	850.02
	02–13–01	15.96	850.06
	03–02–01	16.07	849.95
	03–14–01	15.88	850.14
	04–03–01	14.15	851.87
	04–09–01	10.80	855.22
	04–12–01	10.97	855.05
	04–17–01	10.38	855.64
	04–20–01	13.16	852.86
	04–24–01	14.24	851.78
	05–02–01	14.73	851.29
	05–09–01	12.28	853.74
	05–15–01	14.25	851.77
	05–17–01	14.49	851.53
	05–24–01	14.78	851.24
	05–30–01	14.54	851.48
	06–07–01	14.85	851.17
	06–13–01	14.92	851.10
	06–20–01	14.17	851.85
	06–27–01	14.89	851.13
	07–05–01	15.04	850.98
	07–11–01	15.14	850.88
	07–18–01	15.26	850.76
	07–25–01	15.04	850.98
	08–02–01	15.19	850.83
	08–15–01	15.42	850.60
	08–29–01	15.42	850.60
	09–13–01	15.39	850.63
	09–28–01	15.48	850.54
	10–15–01	15.42	850.60
	11–08–01	15.57	850.45
	11–13–01	15.59	850.43
	11–30–01	15.60	850.42

SIMULATION OF GROUND-WATER FLOW

A ground-water flow model is a simplified mathematical approximation of the physical flow system. The flow model for this study was used to help understand the shallow ground-water flow system, identify sources of water to the Cedar River alluvium, and evaluate the potential effects of variations in recharge rates and discharge conditions. Onsite observations and hydrogeologic data were used to estimate hydraulic properties of the flow system. While adequate for the purposes of this report, the model likely is not suitable to conduct accurate predictive analyses because of the uncertainty associated with estimated hydraulic properties and other model limitations.

The flow model was constructed by assuming steady-state conditions. Steady-state conditions occur when the volume of water flowing into the system equals the volume of water flowing out of the system. Hydrologic conditions within the study area in November 2001 were considered to be a good approximation of steady-state conditions. Ground-water levels measured in observation wells in November 2001 were about the same as ground-water levels in October 2001 and December 2001 (table 6). Streamflow of the Cedar River was relatively constant (fig. 6) and there was relatively little rainfall during this time (fig. 2). Results of the ground-water flow model may not be valid when conditions are not steady state. Steady-state conditions do not occur when ground-water levels rapidly change such as during late spring and early summer when the Cedar River stage rapidly changes or after large amounts of rainfall.

The flow model was developed by conceptualizing the ground-water system on the basis of onsite observations and hydrogeologic data collected during the period of study and the results of a ground-water flow model constructed by Turco (2002) for a larger area of the Cedar River alluvium and underlying bedrock of Silurian and Devonian age, which includes the study area described in this report. Spatial limits of the model were established by using existing natural hydrologic boundaries and defining distant boundaries for areas without existing natural boundaries. The Maquoketa Formation, a regional confining unit underlying the study area, was used as a boundary beneath the study area. The upland areas bordering the alluvial valley were used as a lateral boundary on the east. The main channel of the Cedar River was used as a lateral boundary for the alluvium on the west and southwest. Distant boundaries were specified to account for subsurface flow in the bedrock from the northeast. Most ground-water flow in the unconsolidated deposits was assumed to occur in the alluvium rather than in adjacent, less permeable tills. The alluvium, bedrock, and rivers were assumed to be in hydraulic connection.

Model Description and Boundary Conditions

The model consists of two layers. Layer 1 represents the unconsolidated deposits and layer 2 represents the bedrock of Silurian and Devonian age. Flow in layer 1 is simulated as unconfined (water-table conditions) and flow in layer 2 is simulated as confined.

An 83-row by 47-column grid was used to discretize the area of study into a grid of approximately 500-ft by 500-ft cells for each of the model layers (figs. 7 and 8). The cell area was identical in each layer, but the vertical dimension varied with layer thickness. The active cells of layer 1 coincide with the area where the alluvium is present. The model code calculates the hydraulic head (ground-water-level altitude) at the center, or node, of each active cell and a ground-water flux across each cell face based on water-level gradients between adjacent active cell nodes. Cells are identified by a row, column, and layer designation.

The Cedar River is simulated by river cells (fig. 7) that allow movement of water through the river bottom to or from layer 1 based on riverbed conductance and the difference in hydraulic heads between the river and layer 1. Conductance is the product of the vertical hydraulic conductivity of the bed material, and the length and width of the reach in the cell, divided by bed-material thickness (McDonald and Harbaugh, 1988). No onsite measurements of bed-material thickness or hydraulic properties were made, so an estimated bed-material thickness of 1 ft was used for the river cells. The vertical hydraulic conductivity of bed materials was initially estimated on the basis of expected lithologies and modified during model calibration. A river cell will provide or receive as much water as the model requires to reach a mathematical solution. However, if the head in the cell that contains the river were to go dry, then the contribution of the

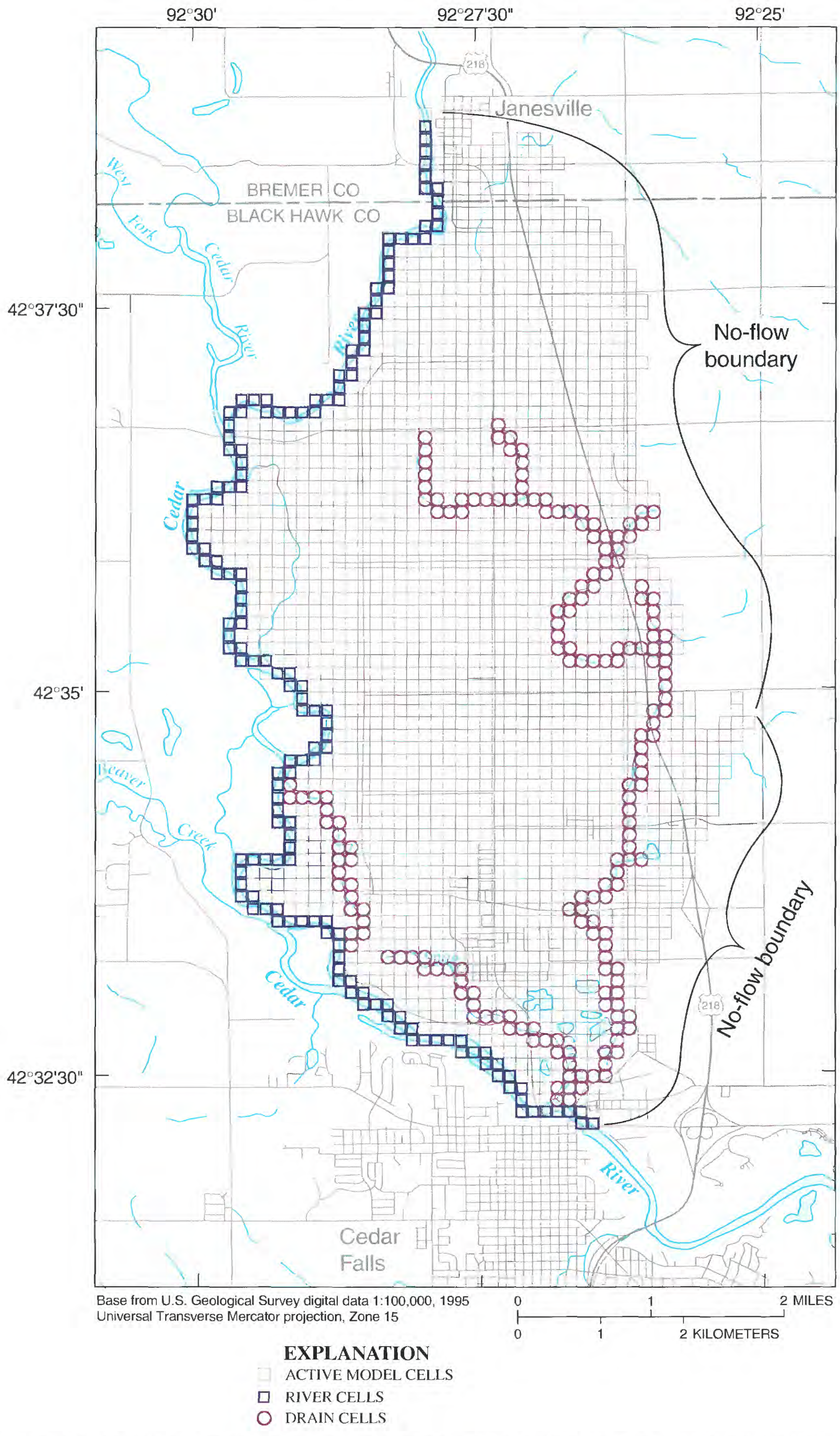

Figure 7. Orientation of model grid, grid discretization, and stress-related model parameters used in layer 1.

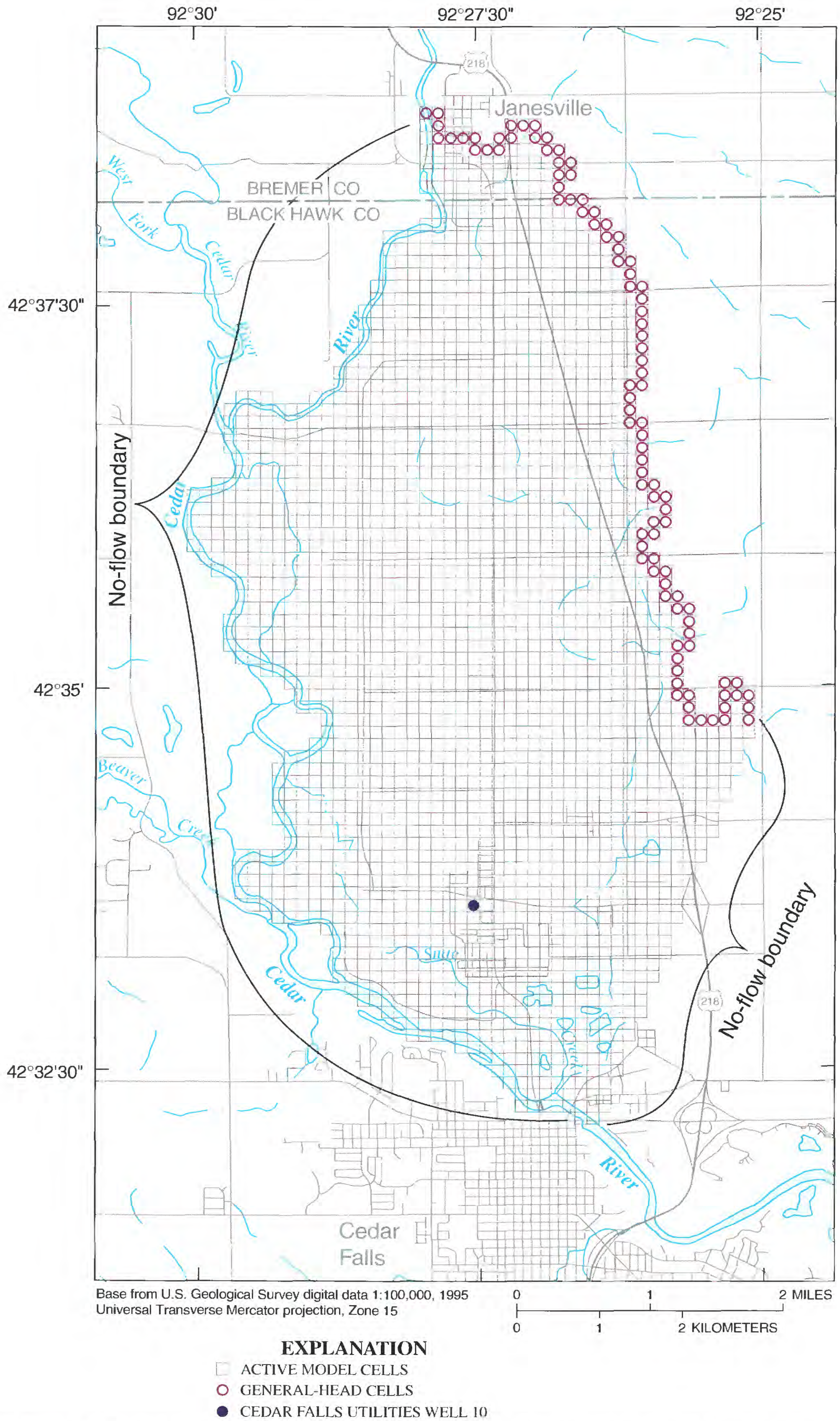

Figure 8. Orientation of model grid, grid discretization, and stress-related model parameters used in layer 2.

river in that cell would be negated. Long-term records for the Cedar River show that there was at least some streamflow during some of the extended drier periods of the 1900s, and it is unlikely that the river cells would go dry. The Cedar River serves as the western boundary of the model area. In the regional model developed by Turco (2002), aquifer properties and water movement were approximately symmetrical about the Cedar River. There are no major pumping centers to the west of the Cedar River in the study area to induce flow from the alluvium or bedrock in the model area.

Intermittent streams that contain water only during high water-table conditions can be simulated in MODFLOW with drains. Ground water can move into drains and is then removed from the ground-water system, but water cannot move from the drains into the ground-water system. Drain locations (fig. 7) were estimated from USGS 7.5-minute topographic maps and discussion with staff members of the Black Hawk County Engineering Department. Observations made in the study area during November 2001 noted there was no water in the intermittent streams at that time. No onsite measurements of intermittent stream widths or depths were made. A geometry of the drains was estimated that resulted in a uniform conductivity value that was assigned to all of the drains.

The upper boundary of the model area is a free surface that represents the water table. A specified-flux boundary is used to represent spatial recharge to layer 1. No-flow boundaries are used to simulate the limits of the model area where ground-water flow is assumed to be insignificant or in areas where aquifer material is absent. The bottom of the modeled system is the top of the relatively impermeable Maquoketa Formation and is represented by a no-flow boundary at the bottom of layer 2. The lateral hydrologic boundaries formed by the relatively impermeable glacial till adjacent to the alluvium (layer 1) establish logical hydrologic limits for modeling ground-water flow in the alluvium. These boundaries are modeled as no-flow boundaries.

General-head cells are used to simulate lateral model boundaries where ground water can enter or leave the system. Flow across the boundary is proportional to the differences between hydraulic head in the cells at the model boundary and hydraulic head assigned at a distance outside the model. General-head cells are used at the northeastern limits of layer 2 to simulate subsurface flow into and out of the model area through the bedrock of Silurian and Devonian age in proportion to relative hydraulic-head differences between the cells at the model boundary and the regional potentiometric surface outside the model area. The regional Cedar Falls model (Turco, 2000) indicates ground water generally flows north to south or northeast to southwest in the model area described in this report.

Model Parameters

Model parameters are variables assigned to individual cells in the model array and are used in the flow equations that simulate ground-water flow within the modeled area. Parameters assigned to the node of each active cell represent an average value for the entire cell. Parameters were used in the model to represent horizontal and vertical hydraulic conductivity, recharge by precipitation, and ground water pumped from the ground-water flow system.

Transmissivity (hydraulic conductivity multiplied by the saturated thickness) is used by the model to solve the ground-water flow equations. Hydraulic conductivity and thickness were specified for each cell in layers 1 and 2, and the model calculated the corresponding transmissivity.

In general, the spatial distribution of hydraulic conductivity for the layer 1 cells was based on the slug-test results (table 3) for the observation wells completed in the alluvium. The slug-test results were used to create computer-generated contours, and the areas between the contours were assigned values equal to the average of the bounding contour lines. Some adjustments were made to this distribution based on the geology of the study area. The isolated high-altitude area in the northern part of the model area was delineated using the 900-foot contour as a guide (fig. 1). Based on the assumption that this area might be an erosional remnant, the horizontal hydraulic-conductivity value of the underlying bedrock of layer 2 was assigned to this higher altitude area. The vertical hydraulic conductivity of the alluvium assigned for all cells in layer 1 was one-tenth of the horizontal hydraulic conductivity. That vertical hydraulic conductivity was about twice the value of the vertical hydraulic conductivity of the underlying bedrock. Initial hydraulic conductivity values were adjusted during the model calibration process. The area of large horizontal hydraulic conductivity in the southeastern part of the model area appeared to be associated with the bedrock valley, so the areas were adjusted in recognition that the bedrock valley continues to the southeast of the model area. Assigned horizontal hydraulic conductivity values were adjusted as part of the calibration process described later, but the basic geometry described above was maintained. Figure 9 shows the distribution of horizontal and hydraulic conductivity in layer 1 after the model was calibrated for steady-state conditions.

Hydraulic conductivity for the layer 2 cells was based on the distribution of hydraulic conductivity used for the development of the regional Cedar Falls model (Turco, 2002). The Cedar Falls model used two separate layers to represent the bedrock of Silurian and Devonian age (Turco, 2002). For the Devonian-age layer, horizontal and vertical hydraulic conductivity was greatest near the Cedar River and decreased with the distance from the Cedar River (Turco, 2002, p. 17). For the Silurian-age layer, horizontal and vertical hydraulic conductivity decreased from north to south (Turco, 2002, p. 18) in the area of interest for the model described in this report. Combining the information from the two layers in the Cedar Falls model produced five zones of different horizontal and vertical hydraulic conductivity for layer 2 of the model described in this report (fig. 10). The values were not adjusted as the model described in this report was calibrated to steady-state conditions.

A net recharge rate of 0.0022 ft/d was used in the model to account for precipitation infiltrating to the water table. During the 30 days of November 2001, 0.80 inch of precipitation was recorded at the Waterloo airport. Infiltration of runoff from upland areas to the east of the model area was accounted for by increasing the recharge at model cells along the eastern boundary to 0.022 ft/d.

Types of discharge from the flow system included in the model were ground-water pumpage, flow to the river and drains, and flow across general-head boundaries. For most of the period of data collection for this report, the City of Cedar Falls pumped only one of its two municipal wells (well 10, fig. 8) at a relatively constant rate of 12,450 ft^3/d (Jerald Lukensmeyer, City of Cedar Falls, oral commun., June 2001). Flow from the river and drains and flow across general-head boundaries were calculated by the model. Evapotranspiration was not considered as a significant form of discharge during late fall steady-state conditions.

Model Calibration

Model calibration is a process in which the differences between simulated ground-water levels and measured ground-water levels are minimized by adjusting model parameters. Ground-water levels measured on November 13–14, 2001, were used as a basis for calibration. Hydraulic conductivity, vertical leakance, drain and streambed conductance, and flow across model boundaries were varied iteratively until the differences between measured water levels and simulated water levels in respective corresponding model cells were within about 3 ft. Model calibration was further refined by continuing to vary model parameters until the average head difference (AVEH) and root-mean-squared error (RMSE) were minimized.

The AVEH is an indicator of systematic error and is the sum of the differences between measured and simulated water levels divided by the total number of measurements. It approaches zero when the sum of the differences between measured and simulated ground-water levels that are greater than zero equals the sum of the differences that are less than zero.

The RMSE is a measure of the magnitude of error between measured and simulated ground-water levels over the entire model area (Anderson and Woessner, 1992). Table 5 lists water levels measured in observation wells on November 13–14, 2001, and water levels simulated by the calibrated model. The AVEH for the calibrated model was 0.16 ft. The RMSE for the calibrated model was 2.30 ft. The discrepancy between measured and simulated water levels likely results from the fact that the model is a simplified representation of a complex ground-water system. For example, the model represents heterogeneous aquifer properties with discretized model parameters estimated from few onsite measurements.

The steady-state model was considered calibrated when the following criteria were met:

1. Incremental changes in model input parameters did not produce an AVEH closer to zero or a smaller RMSE for all layers in the model,
2. The RMSE represented a small percentage of the range of measured ground-water levels, and
3. Simulated lateral ground-water flow directions approximated flow directions interpreted from the water-table map in the alluvium constructed using water levels measured on November 13–14, 2001.

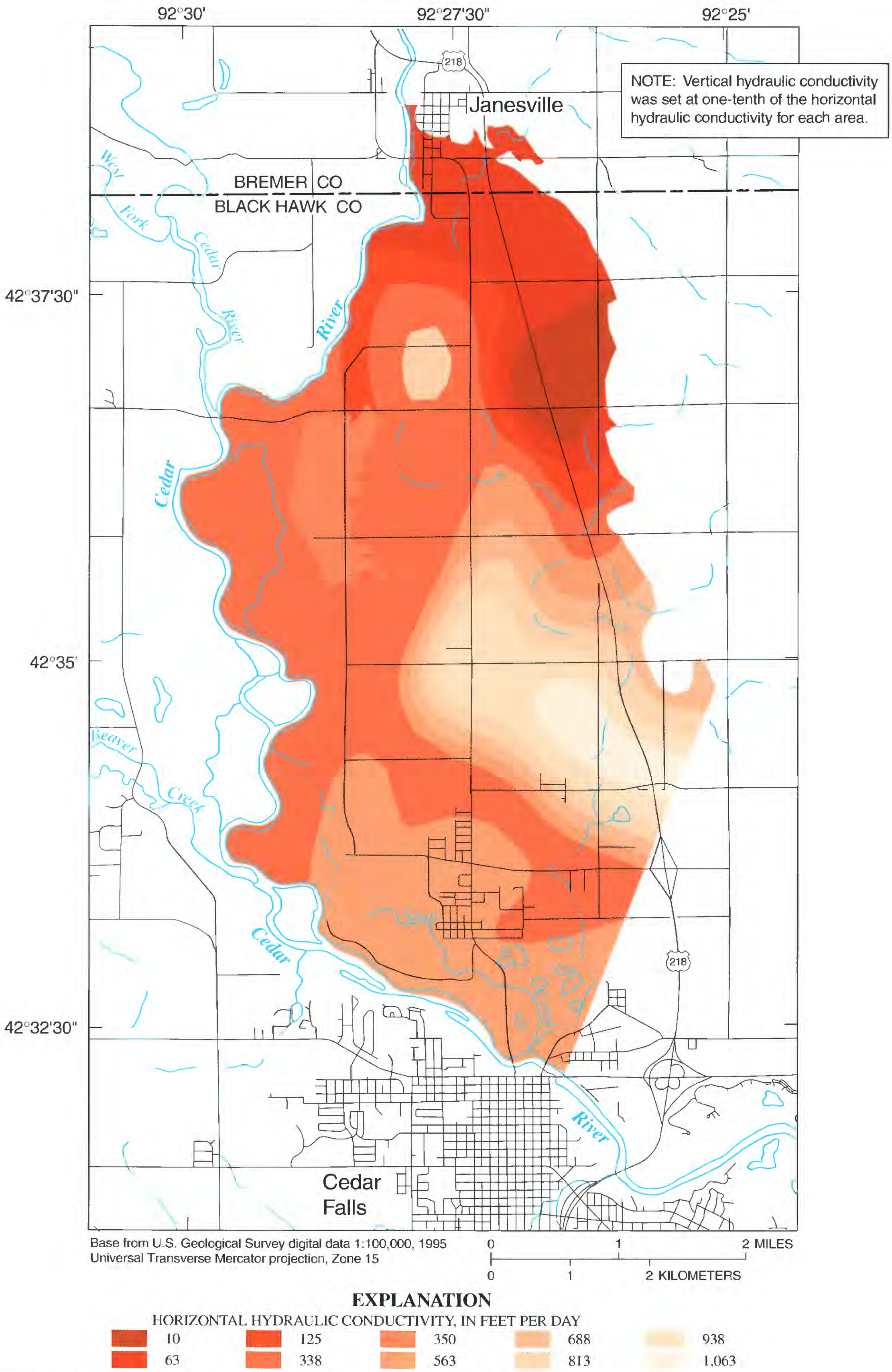

Figure 9. Distribution of horizontal hydraulic conductivity in layer 1.

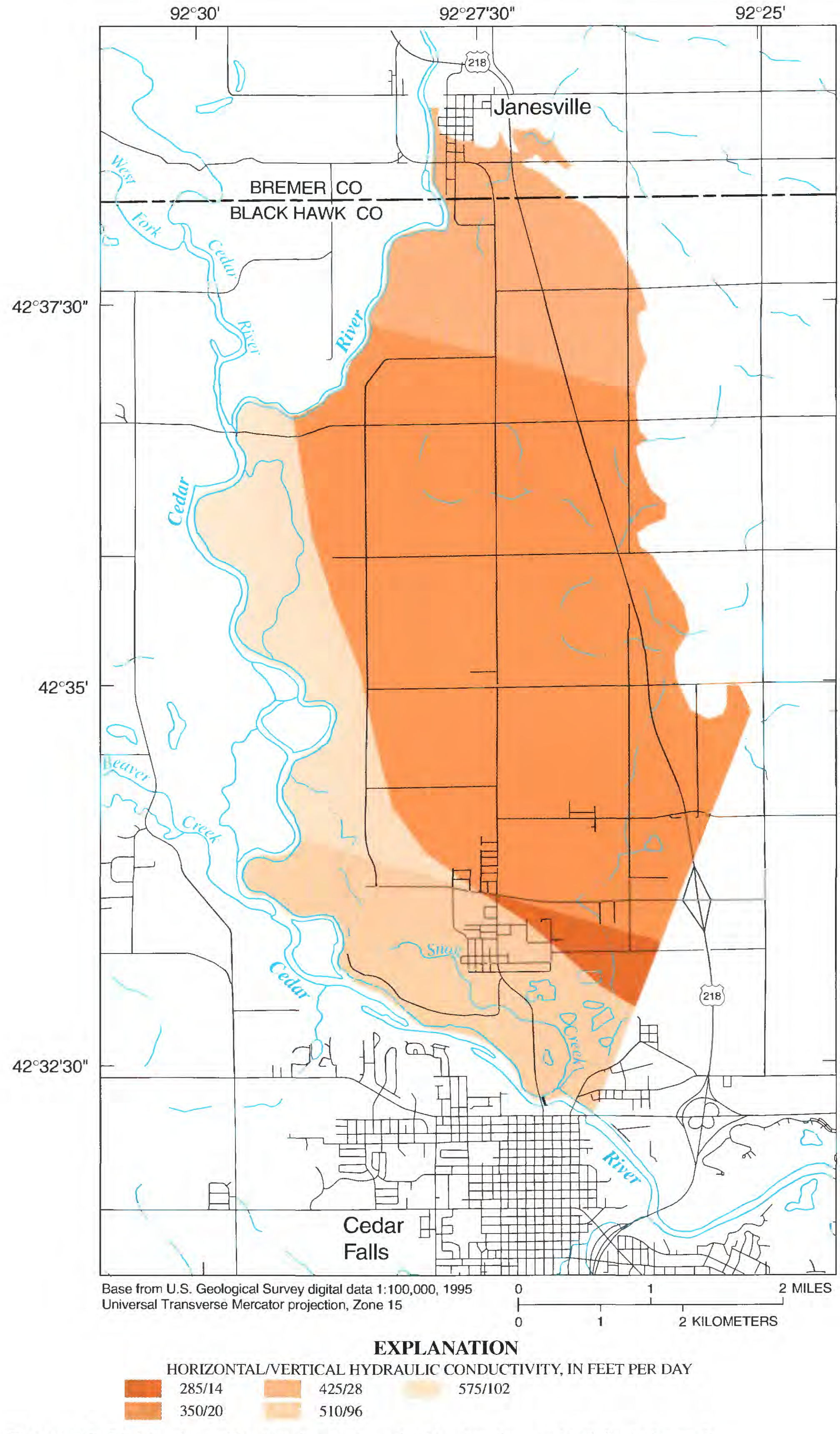

Figure 10. Distribution of horizontal and vertical hydraulic conductivity in layer 2.

Streamflow measurements were made in the Cedar River and selected tributaries during low-flow conditions in November 2001. Measured losses and gains were minimal and probably within limits of measurement error; therefore, the model was not calibrated to leakage to or from the Cedar River. During model calibration, drainbed conductivity was adjusted to 16.4 (ft^2/d)/ft, based on the distribution of the differences between the observed water levels and the simulated water levels in layer 1 and examination of the flow budget.

Sensitivity Analysis

The calibrated model is influenced by uncertainty resulting from limited knowledge of the spatial variation of parameter values and uncertainty associated with the definition of boundary conditions. A sensitivity analysis establishes the effect of parameter uncertainty on the calibrated model by documenting the response of the model-simulated water-level changes and flux to incremental changes in parameter values. The model is sensitive to a parameter when changes in the parameter value produce substantial changes in model response. If improvement in the model is desired, additional data collection could be directed toward improving the accuracy of the most sensitive parameters.

Simulated water-level response to incremental changes in selected input parameters is shown in figure 11. The RMSE is plotted against the multiplication factor used to vary the parameters. The calibrated model parameters are represented by a multiplication factor of 1. The multiplication factor was applied uniformly to the entire model for the indicated parameter and ranged from 0.1 to 10. The parameter being tested was adjusted while the remaining model param-

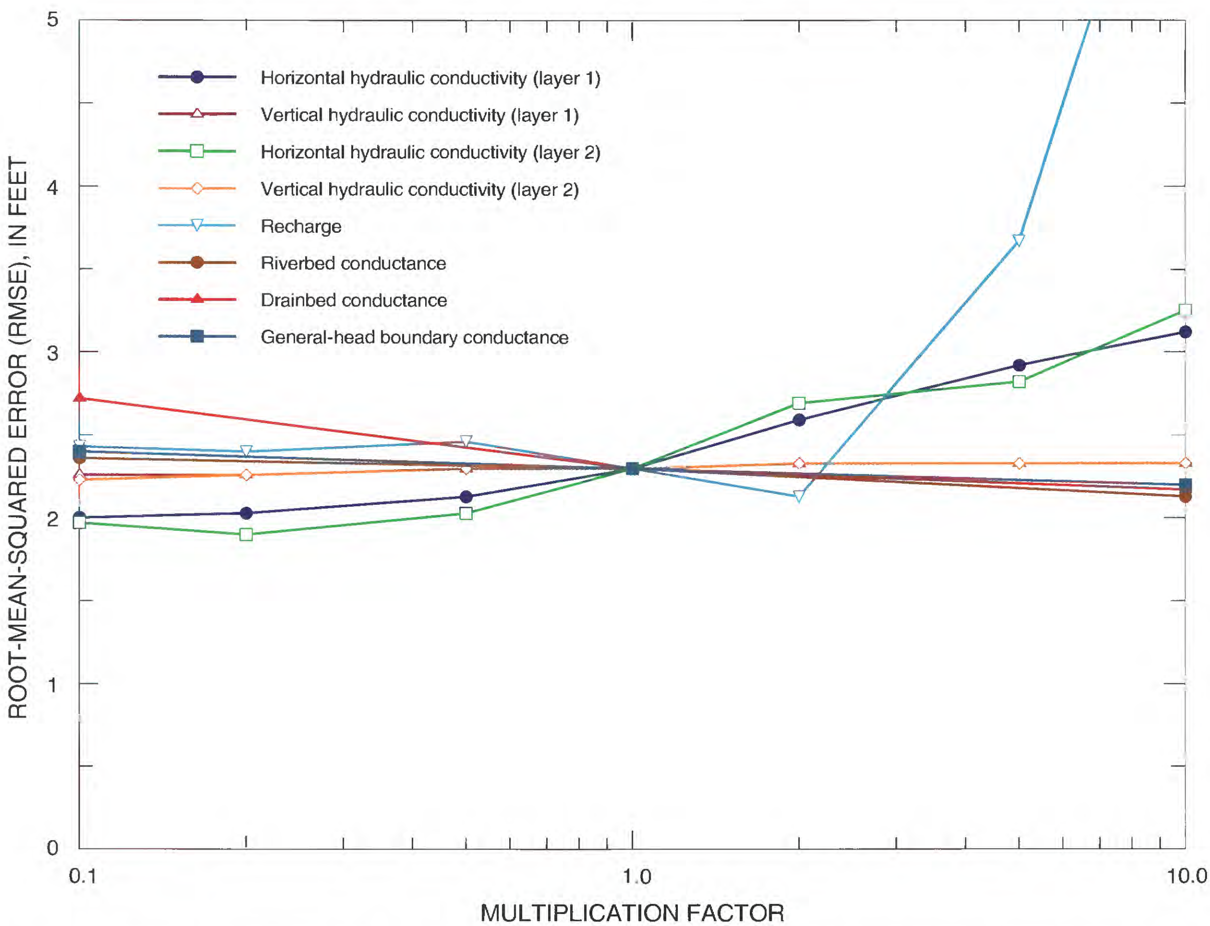

Figure 11. Sensitivity analysis of selected model parameters based on the root-mean-squared error in heads compared to observation wells in the alluvial aquifer.

eters were held at the calibrated values. Water levels were most sensitive to recharge and to horizontal hydraulic conductivity in layers 1 and 2. Water levels were insensitive to vertical hydraulic conductivity in layers 1 and 2 and the conductance of the riverbed, drainbed, and general-head boundary.

The sensitivity of simulated river leakage was evaluated by varying model input parameters and determining the proportion of simulated inflow to the ground-water flow system obtained from the Cedar River. River leakage was most sensitive to recharge and horizontal hydraulic conductivity in layer 2, whereas horizontal hydraulic conductivity in layer 1 and vertical hydraulic conductivity in layers 1 and 2 had less of an effect (fig. 12).

The calibrated model uses hydraulic conductivity that ranges from 1.97 ft/d (north) to 1.64 ft/d (south) for the general-head boundary, and flow entering the model from the general-head boundary is about 3.1 percent of the total. Increasing the hydraulic conductivity of the general-head boundary by a factor of 100 leads to a contribution from the bedrock of about 17.9 percent of the total flow. Decreasing the hydraulic conductivity of the general-head boundary by a factor of 100 of the calibrated model value leads to a contribution from the bedrock of much less than 1 percent.

Model Limitations

The ground-water flow model constructed for this report simulates the flow system under steady-state conditions. However, several model limitations should be considered. Model input parameters, such as horizontal and vertical hydraulic conductivity and recharge from precipitation, are specified at the node of each active cell and represent an average for the entire cell. The assumptions of uniformity for the entire cell introduce inaccuracies because of the heterogeneous nature of geologic materials and the variability of climatic conditions. The steady-state model assumes that inflows to the ground-water system equal outflows. If inflows were not equal to outflows in November 2001, the resultant change in ground-water storage would be a source of model error. For example, water levels could have been either rising or falling during the assumed equilibrium conditions.

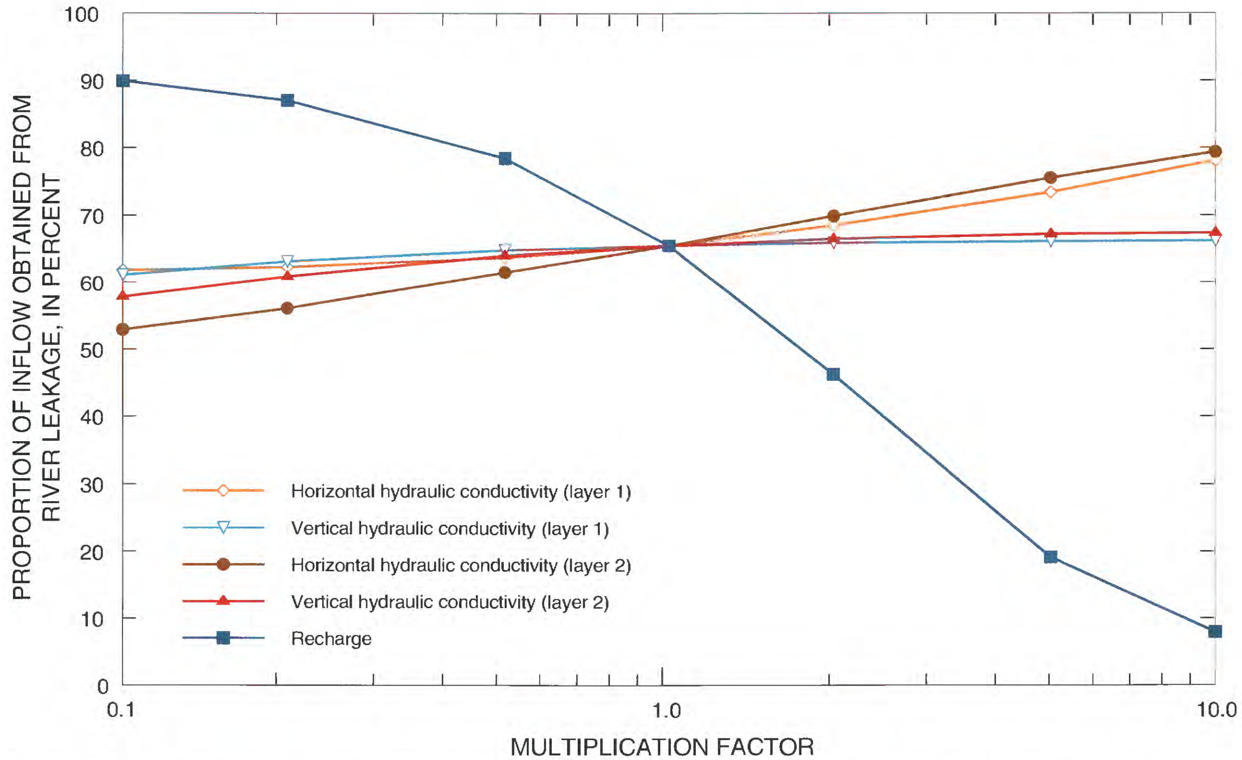

Figure 12. Proportion of simulated inflow from river leakage as a result of varying selected model parameters.

The steady-state flow model does not account for dynamic (transient) conditions (natural or anthropogenic). The steady-state model does not indicate the time needed to reach equilibrium conditions. Attaining equilibrium might take a substantial period of time and is complicated by varying climatic and hydrologic conditions and noncontinuous municipal pumping.

Simulation Results

The calibrated model was used to simulate steady-state conditions as approximated by hydrologic conditions during November 2001. The model calculates a ground-water-level altitude at the node of each cell from which a simulated water-table surface in the alluvium was constructed. The model also calculates a ground-water flux between cells from which a simulated water budget is computed. Ground-water flow directions derived from analysis of the simulated ground-water-level altitudes, and inflows and outflows quantified in the water budget, assist in developing an improved understanding of the ground-water flow system.

The simulated water-table surface for layer 1 is shown in figure 13. A comparison between simulated water levels at the observation well locations and water levels measured November 13–14, 2001, is shown in table 5. The simulated water levels show the general direction of ground-water flow in the alluvium to be toward the south, with little apparent preferential flow toward the Cedar River. Figure 14 shows the approximate depth to the top of the water table in the model area.

The sources of the water recharging the alluvium can be identified from an analysis of the water budget (table 7). Under assumed steady-state conditions and 2001 pumpage, the model calculated about 3.97 million ft^3/d of flow into and out of the ground-water system. The difference between the calculated inflow and outflow was less than 1 percent and was due to the model approximating a solution to the mathematical equations.

Primary sources of inflow to the model are the Cedar River (65.5 percent) and infiltration of precipitation and upland runoff (31.4 percent). All of these sources of inflow enter the ground-water system through the alluvium.

The primary components of outflow from the ground-water system are flow to the drains (56 percent) and the Cedar River (43.7 percent), which leaves the system through the alluvium. The pumpage from the bedrock and flow across the general-head boundaries of the model account for less than 1 percent of the total outflow.

Table 7. Simulated water budgets

[Inflow, water added to the ground-water system; ft^3/d, cubic feet per day; outflow, water removed from the ground-water system; pumpage—municipal, ground-water withdrawals by Cedar Falls Utilities]

Budget component	Steady state	Scenario 1	Scenario 2
Inflow (ft^3/d)			
Recharge from precipitation and upland runoff	1,244,718	1,493,662	1,493,662
Leakage—Cedar River	2,597,458	2.657.807	5,729131
Leakage—drains (intermittent streams)	0	0	0
Subsurface flow across outer boundaries	123,170	4.885	26,215
Pumpage—municipal	0	0	0
Total inflow	**3,965,360**	**4,156,356**	**7,248,976**
Outflow (ft^3/d)			
Recharge from precipitation and upland runoff	0	0	0
Leakage—Cedar River	1,733,658	1,000,159	198,845
Leakage—drains (intermittent streams)	2,219,276	2,994,001	6,916,031
Subsurface flow across outer boundaries	0	149,747	121,673
Pumpage—municipal	12,450	12,450	12,450
Total outflow	**3,965,395**	**4,156,356**	**7,248,976**

Scenario 1–Bankfull river conditions, recharge 1.2 times calibration conditions.

Scenario 2–Bankfull river conditions, recharge 1.2 times calibration conditions, and drainbed conductance 10 times calibration conditions.

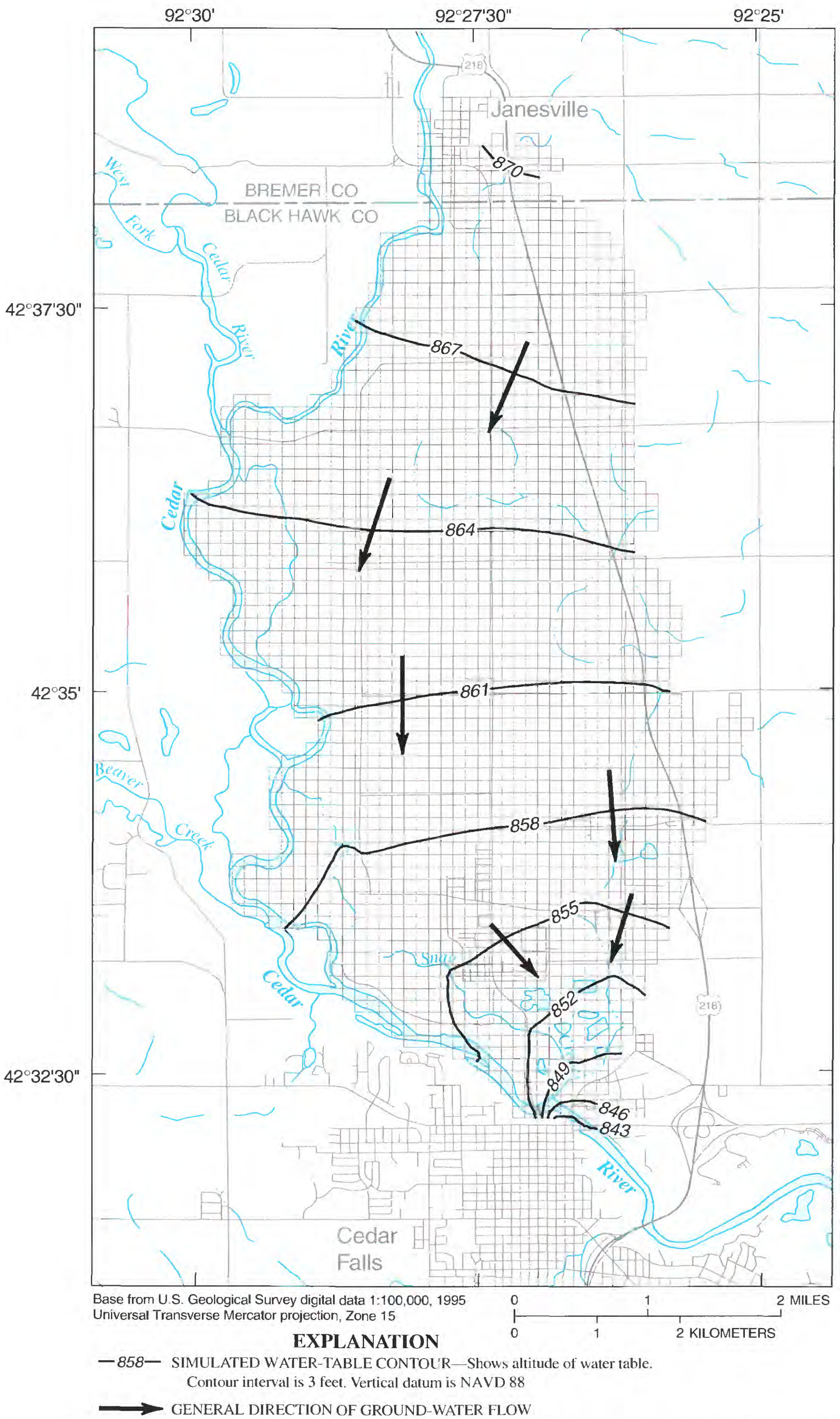

Figure 13. Simulated water-table surface in the Cedar River alluvium, November 13–14, 2001.

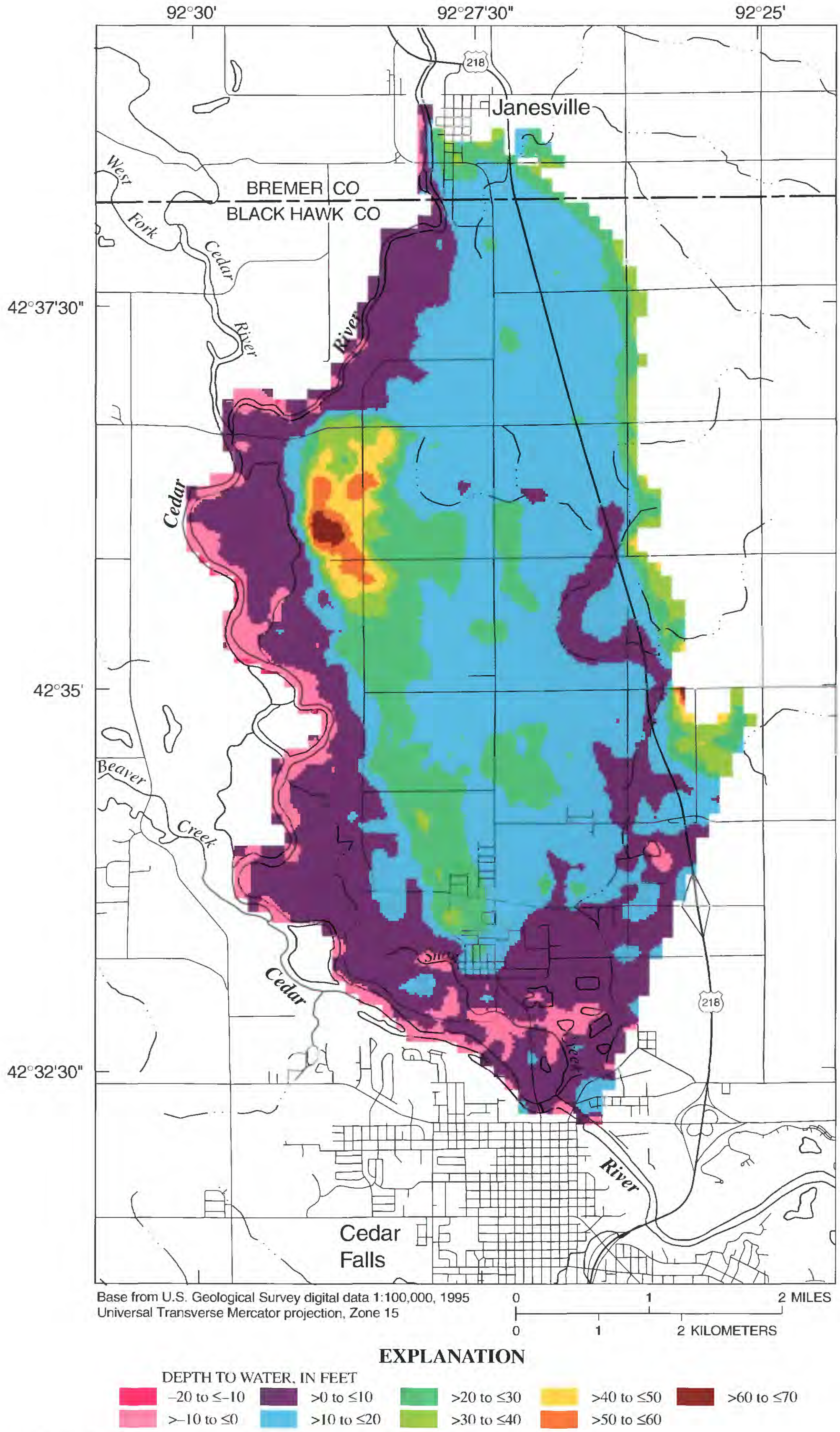

Figure 14. Depth to water table for steady-state calibrated model.

Results of the calibrated steady-state flow model support the interpretation that ground-water flow in the alluvium is primarily toward the south. This direction of flow is probably enhanced by the greater hydraulic conductivity of the unconsolidated materials in the southern and eastern parts of the study area and possibly by the lower Cedar River stage in the southern part of the study area. Shallow depths to the water table occur in areas near Highway 218. The intermittent streams simulated with drain cells remove more water from the ground-water flow system than does the Cedar River; however, the amount of time required to accomplish this removal is not known.

Two hypothetical scenarios were used to assess the potential effects of higher river levels and increased local recharge compared to the steady-state conditions. River levels higher than the steady-state model might be associated with a large recharge event, such as a large rainstorm that affects a large part of the drainage basin or snowmelt in the spring. The higher river levels for these scenarios were based on bankfull levels established by the National Weather Service for the Cedar River at Janesville (National Weather Service, 2002a) and Cedar River at Waterloo (National Weather Service, 2002b) gaging stations and estimating river levels between these two points by considering low-flow and flood-profile information collected during 1999 (Ballew and Eash, 2001). Recharge greater than the steady-state model might be associated with a greater than normal increase in precipitation in the study area.

For the first hypothetical scenario, river levels were set to bankfull conditions, and a recharge rate of 1.2 times the steady-state rate was applied to simulate wet conditions in the study area. This scenario led to increased water levels in general. Of particular interest are the large areas with shallow (0 to 10 ft) depths to water in the eastern part of the model area along Highway 218 (fig. 15). Also, there was a strikingly reduced (over 0.7 million ft^3/d) simulated discharge of the ground-water flow system to the Cedar River, probably due to the higher river stages that reduce or eliminate gradients favorable for ground-water discharge to the river. The result is that the intermittent streams (drains) in the study area are required to remove additional water.

For the second hypothetical scenario, conditions were the same as for the first, but drain conductance was increased to 10 times the value used in the calibrated steady-state model to simulate the effect of increasing the amount of drainage in the model area. The area with depth to water of 0 to 10 ft along the eastern part of the model area is substantially smaller than for the first hypothetical scenario (fig. 16) indicating that an increase in the ability to remove water from the alluvium through drains will result in lower water levels in the area near the drains. The flow budget for this scenario reflects the tenfold increase in discharge from the drain cells.

In general, it appears that once high ground-water levels in the central part of the study area develop, either because of high Cedar River water levels or above normal local precipitation, or both, ground-water flow from the central part of the study area near Highway 218 is toward the south rather than by shorter flow paths to the Cedar River to the west. The intermittent streams contribute significantly to discharging water from the ground-water flow system during wet conditions.

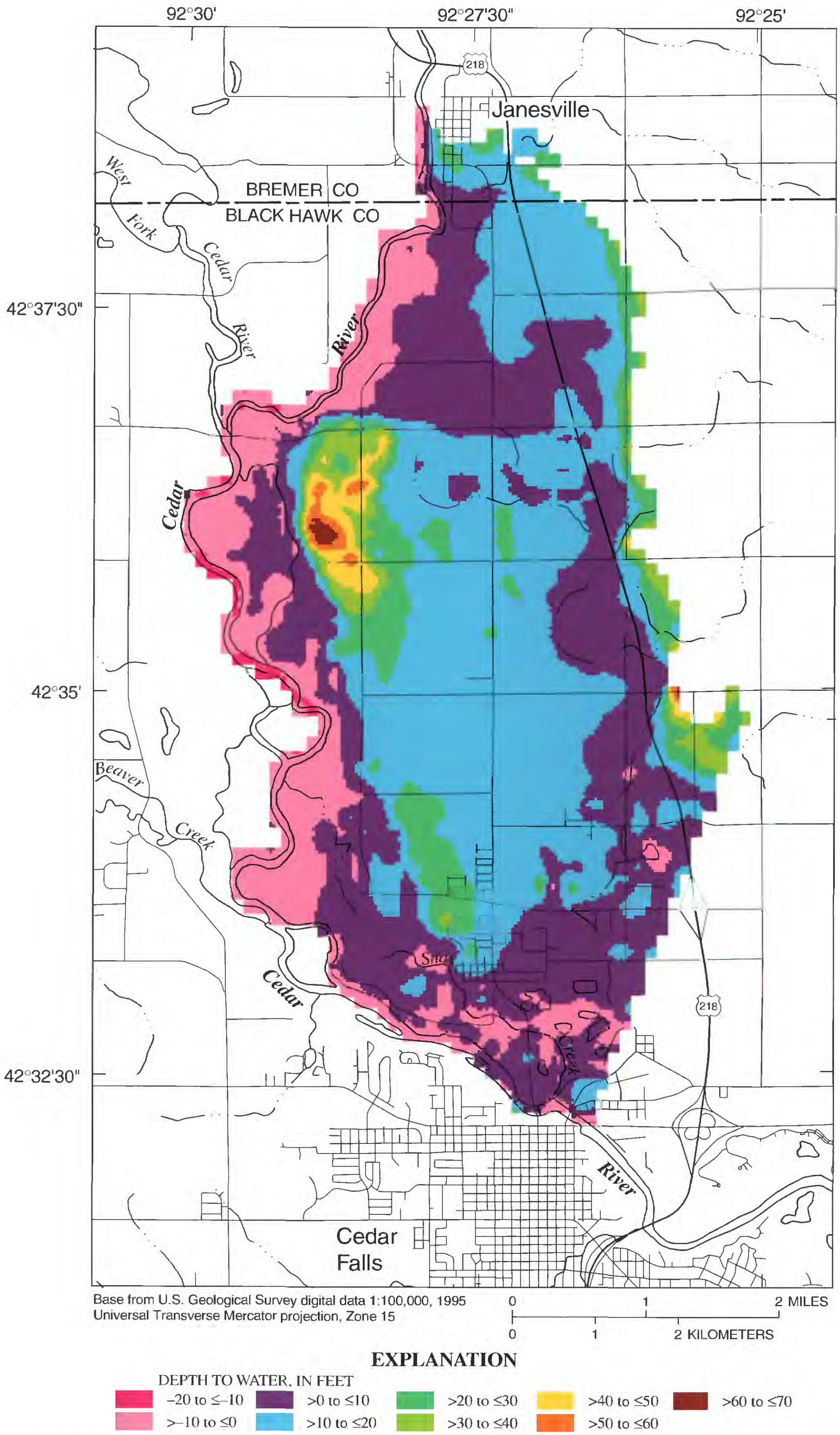

Figure 15. Depth to water table for the high-river, high-recharge, steady-state scenario.

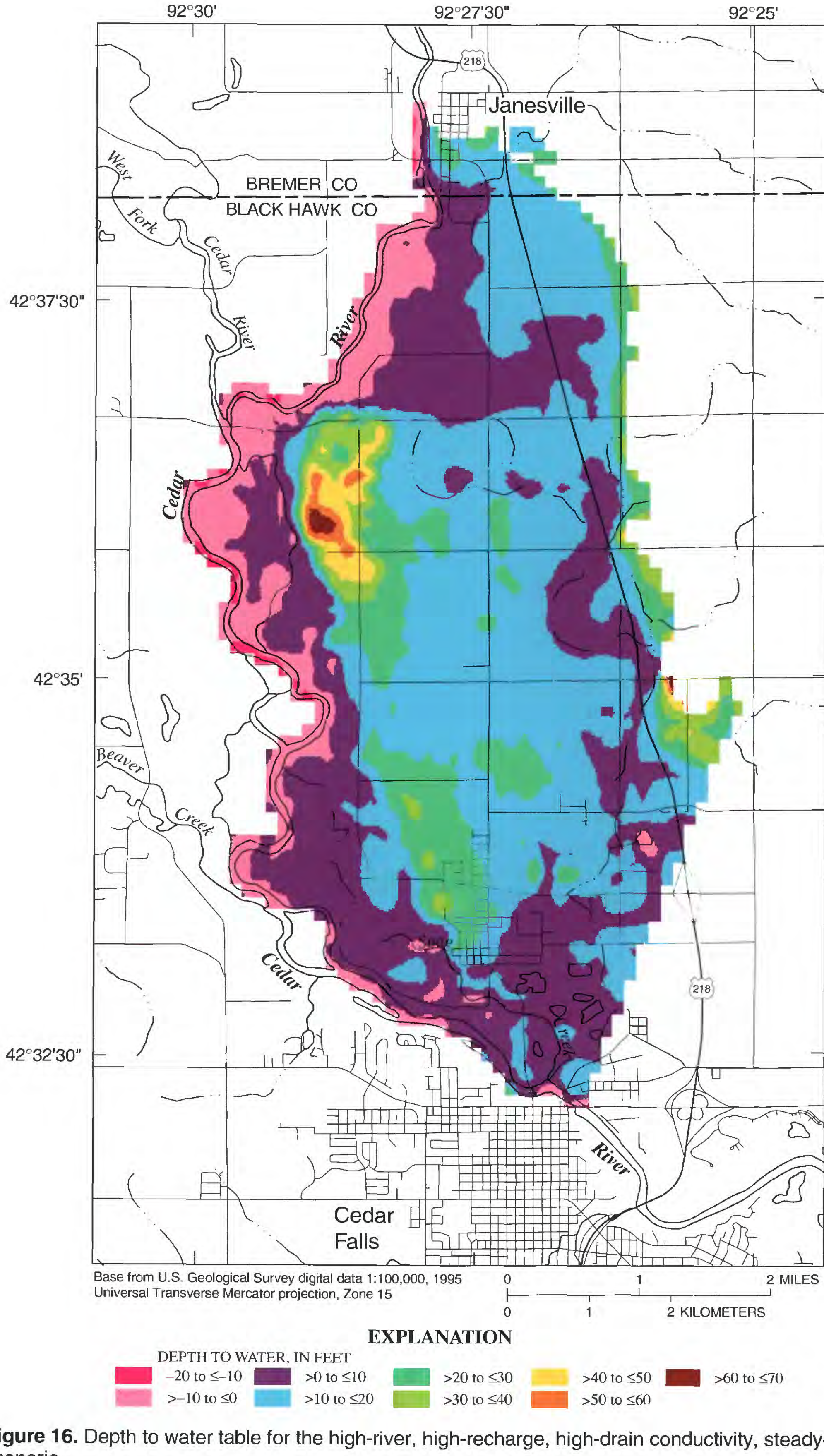

Figure 16. Depth to water table for the high-river, high-recharge, high-drain conductivity, steady-state scenario.

SUMMARY

The USGS, in cooperation with the Black Hawk County Board of Supervisors and the County Engineer's office, conducted a hydrologic study of the Cedar River alluvium in northwest Black Hawk and southwest Bremer Counties, Iowa, to improve understanding of the ground-water flow system, particularly during times of flooding and high ground-water levels. The purposes of this report are (1) to delineate and characterize the extent of unconsolidated deposits in the study area, (2) to describe hydrologic data used to facilitate analysis of surface-water and ground-water movement in the study area, and (3) to describe development of a ground-water flow model and the simulation of aquifer response to selected stresses.

Streamflow measurements made during November 2001 indicated that during these low-flow conditions, flow to and from the Cedar River to the ground-water system were within the limits of measurement error. A water-table surface map for the Cedar River alluvium was constructed from water-level measurements recorded at USGS observation wells and selected Cedar River sites on November 13–14, 2001, which shows the direction of ground-water flow in the alluvium is generally parallel to and east of the Cedar River. A bedrock valley, possibly formed by erosion from a paleochannel of the Cedar River, underlies the central part of the study area. Hydraulic conductivities in the Cedar River alluvium were estimated with slug-test analyses in 14 observation wells. The estimated hydraulic conductivity values in the observation wells ranged over four orders of magnitude, which is an indication of the natural heterogeneity of geologic materials, and are largest in the eastern and southeastern parts of the study area.

The ground-water flow model consists of two layers. In general, layer 1 represents the unconsolidated deposits and layer 2 represents the bedrock of Silurian and Devonian age. Flow in layer 1 is simulated as unconfined (water-table conditions) and flow in layer 2 is simulated as confined. An 83-row by 47-column grid was used to discretize part of the study area (model area) into a grid of approximately 500-ft by 500-ft cells. The active cells of layer 1 in the model coincide with the area where the alluvium is present.

Simulated water levels were most sensitive to recharge and to horizontal hydraulic conductivity in layers 1 and 2. Water levels were insensitive to vertical hydraulic conductivity in layers 1 and 2 and in the conductance of the riverbed, drainbed, and general-head boundary. River leakage was most sensitive to recharge and horizontal hydraulic conductivity in layer 2, whereas horizontal hydraulic conductivity in layer 1 and vertical hydraulic conductivity in layer 1 and 2 had less of an effect.

Primary sources of inflow to the ground-water flow system are Cedar River leakage (65.5 percent) and infiltration of precipitation and upland runoff (31.4 percent). All of these sources of inflow enter the system through the alluvium.

The primary components of outflow from the ground-water system are leakage to the drains (56 percent) and the Cedar River (43.7 percent), which leaves the system through the alluvium. Pumpage from the bedrock and flow across the general-head boundaries of the model account for less than 1 percent of the total ground-water outflow.

Two hypothetical scenarios were used to assess the potential effects of higher river levels and increased local recharge compared to the steady-state conditions. For the first hypothetical scenario, river levels were set to bankfull conditions and a recharge rate of 1.2 times the steady-state rate was applied to simulate wet conditions in the study area. This scenario led to increased water levels in general and a large area of shallow (0 to 10 ft) depths to water along the eastern part of the model area near Highway 218.

For the second hypothetical scenario, conditions were the same as for first, but drain conductance was increased to 10 times the value used in calibrated steady-state model to simulate the effect of increasing the amount of drainage in the model area. The area with depth to water of 0 to 10 ft along the eastern part of the model area is substantially smaller than for the first hypothetical scenario.

In general, it appears that once high ground-water levels develop, either because of high Cedar River water levels or above normal local precipitation or both, ground-water flow from the central part of the study area along Highway 218 is toward the south rather than shorter flow paths to the Cedar River. Intermittent streams play an important part in discharging water from the ground-water flow system.

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APPENDIX

Appendix. Description of drilled test holes and geologic information

[(lf), lithic fragments]

Test-hole identifier[1] (fig. 1)	Location land net [2]	Geologic unit	Drilled depth, feet below land surface	Driller's log/cuttings description
1	T90N–R14W–01BCCC (42°38′09″92°27′20″)	Quaternary-age alluvium	0–4	Soil, silty
			4–6	Clay, silty
			6–10	Sand, medium to fine
			10–26	Sand, medium with pebbles (lf)
			26–75	Sand, medium to coarse, with pebbles (lf)
2	T90N–R14W–12BAB (42°37′41″ 92°26′53″)	Quaternary-age alluvium	0–2	Soil, clayey
			2–5	Clay, silty
			5–10	Sand, fine with pebbles (lf)
			10–15	Sand, fine to medium with pebbles (lf)
			15–18	Sand, medium to coarse with pebbles (lf)
			18–23	Till, initially silty to clay
			23	Bedrock, no cuttings
3	T90N–R14W–11ACC (42°37′16″ 92°28′00″)	Quaternary-age alluvium	0–4	Soil, silty
			4–10	Sand, medium
			10–15	Sand, medium to coarse with pebbles (lf)
			15–28	Sand, coarse to medium with pebbles (lf)
4	T90N–R14W–12DDC (42°36′50″ 92°26′28″)	Quaternary-age alluvium	0–4	Soil, silty
			4–14	Sand, medium with pebbles (lf)
			14–17.5	Till, silty sandy clay
			17.5	Bedrock, no cuttings
5	T90N–R14W–13BCC (42°36′28″ 92°27′11″)	Quaternary-age alluvium	0–3	Soil, silty
			3–4	Sand, fine to medium with pebbles (lf)
			4–25	Sand, medium to coarse with pebbles (lf)
			25–35	Sand, very coarse with pebbles (lf)
			35–42.5	Sand and gravel, very coarse
6	T90N–R13W–19BBC (42°35′48″ 92°26′10″)	Quaternary-age alluvium	0–5	Soil, silty with pebbles (lf)
			5–21.5	Sand, medium with pebbles (lf)
7	T90N–R14W–22DDB (42°35′16″ 92°28′40″)	Quaternary-age alluvium	0–5	Soil, silty
			5–10	Sand, fine to medium
			10–20	Sand, medium to coarse with pebbles (lf)
			20–28.5	Sand and gravel, very coarse
			28.5	Bedrock, no cuttings
8	T90N–R14W–24CCC (42°35′11″ 92°27′18″)	Quaternary-age alluvium	0–2	Soil, silty
			2–4	Sand, medium with pebbles (lf)
			4–11	Sand, medium to coarse with pebbles (lf)
			11–42	Sand, coarse to medium with pebbles (lf)
9	T90N–R14W–26CBC (42°34′26″ 92°28′31″)	Quaternary-age alluvium	0–4	Soil, silty
			4–10	Sand, fine
			10–12	Sand, fine to medium with pebbles (lf)
			12–18	Sand, medium to coarse with pebbles (lf)
			18–30	Sand, coarse to medium with pebbles (lf)
			30–42	Sand, medium to fine with pebbles (lf)
10	T90N–R13W–30CCB (42°34′23″ 92°26′11″)	Quaternary-age alluvium	0–4	Soil, silty
			4–10	Sand, fine
			10–12	Sand, fine to medium with pebbles (lf)
			12–18	Sand, medium to coarse with pebbles (lf)
			18–30	Sand, coarse to medium with pebbles (lf)
			30–42	Sand, medium to fine with pebbles (lf)

Appendix. Description of drilled test holes and geologic information—Continued

[(lf), lithic fragments]

Test-hole identifier[1] (fig. 1)	Location land net [2]	Geologic unit	Drilled depth, feet below land surface	Driller's log/cuttings description
11	T90N–R13W–29CCC (42°34′14″ 92°24′58″)	Quaternary-age alluvium	0–4	Soil, silty sandy
			4–16	Sand, medium to coarse with pebbles (lf)
			16–17	Sand, medium to coarse
			17–25	Sand, medium to coarse with pebbles (lf)
			25–47	Sand and gravel, very coarse with pebbles (lf)
12	T90N–R14W–35ADB (42°33′55″ 92°27′36″)	Quaternary-age alluvium	0–3	Soil, silty clay
			3–6	Clay, silty
			6–15	Sand, medium to fine
			15–25	Sand, fine with few pebbles (lf)
			25–36	Sand, medium to coarse with pebbles (lf)
			36–42	Till, clay
13	T90N–R13W–31DBD (42°33′40″ 92°25′21″)	Quaternary-age alluvium	0–2	Soil, silty
			2–4	Silt, clayey
			4–25	Sand, medium to coarse with pebbles (lf)
			25–43	Sand, medium to coarse
14	T89N–R13W–06BBB (42°33′21″ 92°26′10″)	Quaternary-age alluvium	0–1	Soil, silty
			1–3	Sand, medium
			3–9	Sand, fine to medium with pebbles (lf)
			9–18	Sand, fine to medium, few pebbles
			18–25	Sand, medium to coarse, few pebbles
			25–45	Sand, very coarse grained
			45–65	Sand, medium to coarse with pebbles (lf)
			65–77.5	Till, clay
15	T90N–R13W–06DCC (42°37′43″ 92°25′28″)	Pleistocene-age loess and till	0–1	Soil, silty
			1–13	Sand, fine, silty
			13–15	Sand , fine, silty clay
			15–21	Loess, silty clay
			21–29	Till, clay
16	T90N–R14W–15AAD (42°36′38″ 92°28′30″)	Pleistocene-age loess and till	0–2	Soil, sandy
			2–7	Sand, fine to medium
			7–15	Sand, fine, silty with depth
			15–26	Till, silty clay with pebbles
17	T90N–R13W–20BCC (42°35′34″ 92°24′58″)	Pleistocene-age loess and till	0–2	Soil, silty
			2–10	Sand, fine, silty
			10–14	Loess, silty clay, some fine sand
			14–23	Till, clay
			23–37	Till, clay with some pebbles (lf)

[1] Sites 1 to 17 drilled by U.S. Geological Survey, September 18 to October 6, 2000.

[2] Location indicated by township, range and section. The letters after the section number represent successive subdivisions of the section assigned in a counterclockwise direction beginning with 'A' in the northeast quarter. The first letter indicates a 160-acre area. Each successive letter indicates an area one-fourth the size of the area represented by the previous letter.

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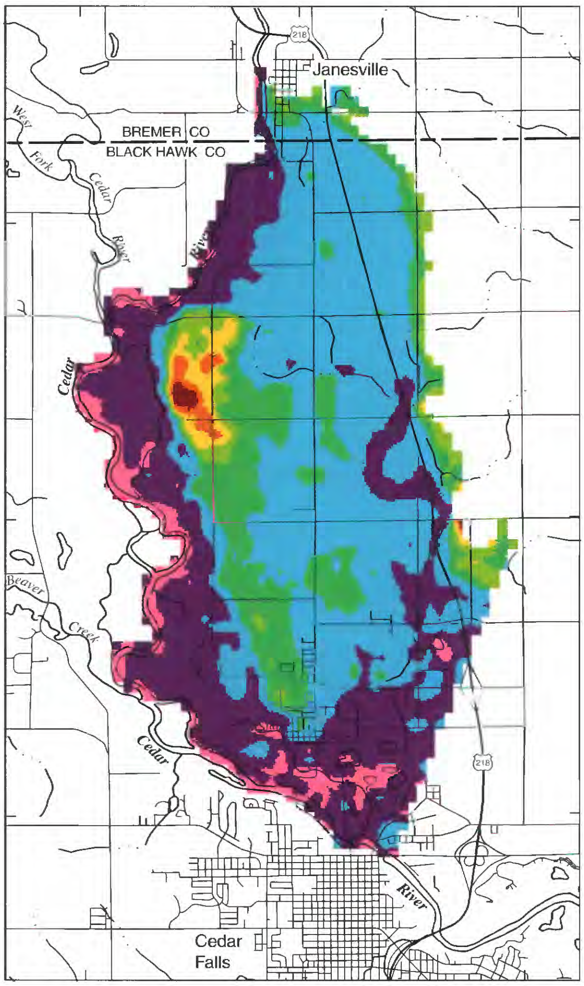
Water-Resources Investigations Report 03–4080



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

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Iowa City, Iowa
2003

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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)	3,785	cubic meters per day
foot squared per day (ft^2/d)	0.0929	meter squared per day

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), unless otherwise noted.

Simulation of Ground-Water Flow in the Cedar River Alluvium, Northwest Black Hawk County and Southwest Bremer County, Iowa

By Bryan D. Schaap, Mark E. Savoca, *and* Michael J. Turco

Abstract

Flooding and high ground-water levels after large or frequent rainstorms have occurred in an area of about 30 square miles along the eastern bank of the Cedar River from Cedar Falls in northwest Black Hawk County to Janesville in southwest Bremer County, Iowa. The U.S. Geological Survey, in cooperation with Black Hawk County, conducted a hydrologic study of the Cedar River alluvium in the northwest Black Hawk and southwest Bremer Counties, to improve understanding of the ground-water flow system and evaluate the effects of hypothetical variations in recharge and discharge conditions.

A steady-state ground-water flow model was constructed for the area using November 2001 hydrologic conditions. The model was discretized into an 83-row by 47-column grid of cells measuring approximately 500 feet by 500 feet. Two model layers, one for the alluvium and one for the underlying bedrock units, were used to represent flow in the area.

Precipitation during 2001 was similar to historical normals. Precipitation during 1999, especially during the summer when flooding occurred, was well above the historical normals. Borings in the unconsolidated deposits in the study area confirmed the presence of a bedrock valley dipping to the south in the central part of the study area. Water-level measurements in 2001 indicate that ground-water flow in much of the alluvial aquifer parallels the direction of flow in the Cedar River toward the south rather than following shorter flow paths to the west toward the Cedar River.

Under steady-state conditions and 2001 pumpage, primary sources of inflow to the ground-water flow system are the Cedar River (65.5 percent), recharge through infiltration of precipitation and upland runoff (31.4 percent), and subsurface flow across the lateral boundaries (3.1 percent). The primary components of outflow from the ground-water flow system are intermittent streams (56.0 percent) and the Cedar River (43.7 percent).

Two hypothetical scenarios were used to assess the potential effects of higher river levels and increased recharge compared to the steady-state conditions. For one scenario, river levels were set to bankfull conditions, and a recharge of 1.2 times the steady-state rate was applied. This simulation was used to evaluate the effects of wet conditions. This scenario led to increased water levels, in general, and large areas of shallow (0 to 10 feet) depths to water along the eastern part of the model area near Highway 218. For the second scenario, conditions were the same as for the first scenario, but streambed conductance of intermittent streams modeled as drains was increased to 10 times the steady-state value to simulate increased flow of water from the shallow ground-water flow system. The area with depth to water of 0 to 10 feet along the eastern part of the model area was substantially smaller than that of the first scenario.

In general, once high ground-water levels occur, either because of high Cedar River water

levels or above normal local precipitation or both, ground-water in the central part of the study area along Highway 218 flows toward the south rather than following shorter flow paths to the Cedar River. Intermittent streams in the study area discharge substantial amounts of water from the ground-water flow system.

INTRODUCTION

Flooding and high ground-water levels after large or frequent rainstorms have occurred in an area of about 30 mi^2 along the eastern bank of the Cedar River from Cedar Falls in northwest Black Hawk County to Janesville in southwest Bremer County, Iowa (fig. 1). The Cedar River alluvium underlies the river valley and consists primarily of fluvial and glaciofluvial sand and gravel deposits. Ground-water levels in these deposits are influenced by recharge from precipitation and intermittent stream losses, changing stage in the Cedar River, and nearby municipal supply-well withdrawals. An extensive natural or artificial surface-water drainage network has not developed in the area, and changes in land use may affect surface-water and ground-water movement. Protection of property and infrastructure in the area requires an assessment of the factors that affect the movement of water from areas of recharge to areas of discharge.

The U.S. Geological Survey (USGS), in cooperation with the Black Hawk County Board of Supervisors and the County Engineer's office, conducted a hydrologic study of the Cedar River alluvium in northwest Black Hawk County and a small part of southwest Bremer County to improve understanding of the ground-water flow system.

Purpose and Scope

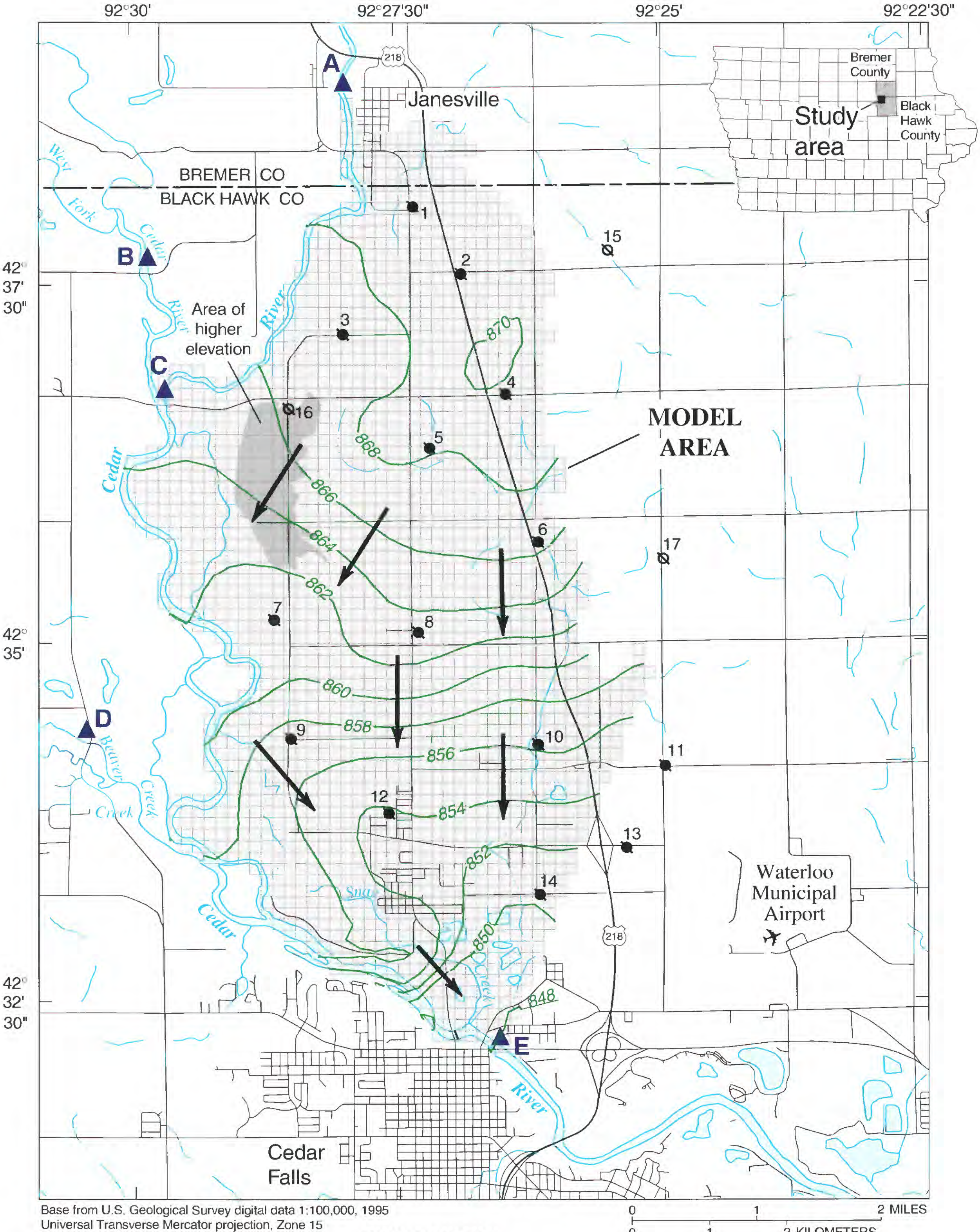
The purposes of this report are (1) to delineate and characterize the extent of unconsolidated deposits in the study area, (2) to describe hydrologic data used to facilitate analysis of surface-water and ground-water movement in the study area, and (3) to describe development of a ground-water flow model and the simulation of aquifer response to selected stresses.

This report describes the hydrogeology of a 30-mi^2 area in northwest Black Hawk County and extreme southwest Bremer County (model area, fig. 1). Model results are presented to evaluate simulated aquifer response to climatic and anthropogenic stresses. Hydrogeologic data were collected from October 2000 through November 2001.

Description of Study Area

The study area covers about 53 mi^2 along the Cedar River in northwest Black Hawk County and southwest Bremer County, Iowa, and contains a 30-mi^2 model area where ground-water flow was simulated (fig. 1). The area consists of a relatively flat alluvial valley bounded by low hills that separate the alluvial valley from upland areas. The Cedar River alluvium underlies the alluvial valley and consists primarily of fluvial and glaciofluvial sand and gravel deposits. The Cedar River alluvial aquifer is composed of the Cedar River alluvium. Upland areas consist primarily of glacial deposits (loess and till). Bedrock consisting of limestone and dolomite of Silurian and Devonian age underlies the alluvium and glacial deposits. The Silurian-Devonian aquifer is composed of the limestone and dolomite bedrock. Land-surface altitude in the river valley within the study area ranges between 850 and 890 ft above sea level and increases to 950 ft above sea level in the upland area. Within the alluvial valley, there is an isolated area with altitudes higher than 940 ft. Based on a small amount of test-hole data, this isolated area was assumed to consist of loess, glacial till, and bedrock. The south- to south-east-flowing Cedar River occupies the western edge of the alluvial valley, and several intermittent streams drain the upland area.

Land use in the study area is primarily agricultural; corn and soybeans are the principal crops. Forested areas are present along the Cedar River and along a few upland drainages. Rural residences are present throughout the study area; suburban and urban areas are located in and around Cedar Falls in the southern part of the study area. Active and formerly active sandpits are present in the southern part of the area. The City of Cedar Falls operates two municipal water-supply wells within the study area in northern Cedar Falls. These wells withdraw water from the Silurian-Devonian aquifer, which underlies the alluvial aquifer.



EXPLANATION

ACTIVE MODEL CELLS

–844– POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells. Contour interval 2 feet. Vertical datum is NAVD 88

GENERAL DIRECTION OF GROUND-WATER FLOW

13 OBSERVATION WELL—Number indicates site number

15 TEST HOLE—Number indicates site number

D STREAMFLOW MEASUREMENT—Letter indicates site identification (see table 1)

Figure 1. Location of study area, extent of digital model, location of data-collection sites, and measured potentiometric surface of the Cedar River alluvial aquifer, November 13–14, 2001.

Previous Studies

Ground water is an important resource in eastern Iowa and has been the subject of many studies in recent years. Several ground-water flow models have been developed for areas with similar geologic settings to this investigation.

For each of these models, flow in an alluvial aquifer and Silurian-Devonian aquifer was simulated for steady-state conditions. For some of the models, the Silurian-Devonian aquifer was represented by one layer and sometimes two layers. For the Muscatine (Lucey and others, 1995; Lucey, 1997; Savoca and others, 2002), Cedar Rapids (Schulmeyer and Schnoebelen, 1998), and Burlington (Boyd, 2001) models, calibration was accomplished by assuming that the system had reached steady-state conditions during a fall through winter period. Evapotranspiration was assumed to be minimal, and recharge was not simulated with the extreme variations associated with rapid snowmelt of spring or thunderstorms of summer.

The regional Cedar Falls model (Turco, 2002) was concerned primarily with the Silurian-Devonian aquifer. Calibration was to the mean water levels from April 1998 to February 1999, but water levels in most wells measured during this period had little variation (Turco, 2002, p. 10).

Concentrations and possible sources of nitrate in water from the Silurian-Devonian aquifer in Cedar Falls were studied by Schaap (1999). Water samples were collected from four wells that were located within the study area described in this report. Analysis of limited chlorofluorocarbon and isotope data indicated that water was moving along predominantly horizontal ground-water flow paths through the Silurian-Devonian aquifer.

Acknowledgments

The authors thank the private landowners, the City of Cedar Falls, and Black Hawk County for allowing the USGS to install and collect data from observation wells on private and public property in the study area. Water-supply well withdrawals for 2001 were provided by the City of Cedar Falls. Geologic information in the vicinity of Highway 218 was provided by the Iowa Department of Transportation. Observation-well altitudes and periodic water levels were measured by personnel from the Black Hawk County Engineer's office. Additional mapping and hydrologic data were provided by Black Hawk County through the Federal Emergency Management Agency's Cooperating Technical Communities program and the Rock Island District, U.S. Army Corps of Engineers Planning Assistance to States program, respectively. Ken Hedmark's (USGS) guidance and participation during well installation is greatly appreciated.

METHODS OF INVESTIGATION

Several types of data were collected and evaluated during the study to help define the hydrogeology of the Cedar River alluvium and to assist in the development of a ground-water flow model. The study included collection of precipitation, river stage and discharge measurements; construction of wells and measurement of ground-water levels, and determination of aquifer properties. Additional hydrogeologic data were obtained from the Iowa Department of Natural Resources–Geological Survey Bureau and Iowa Department of Transportation.

Precipitation Measurements

Precipitation measurements were used to determine relations between rainfall, ground-water levels, and river stage. Precipitation data were collected by a tipping-bucket recorder installed at the site of well 5 (fig. 1). Precipitation amounts were recorded every 15 minutes to the nearest 0.01 inch. Precipitation records also were obtained from the National Weather Service station at the Waterloo Municipal Airport located about 3 mi southeast from the center of the study area.

Figure 2 presents cumulative precipitation data collected at the Waterloo airport. From 1971 through 2000, the mean annual precipitation was 33.15 inches. During that 30-year period, the minimum annual total of 18.99 inches was recorded during 1988 and the maximum annual total of 53.07 inches was recorded during 1993 (National Oceanic and Atmospheric Administration, 2002). The difference of 34.08 inches between these two extremes indicates that for any specific year, precipitation can vary greatly from "normal" conditions.

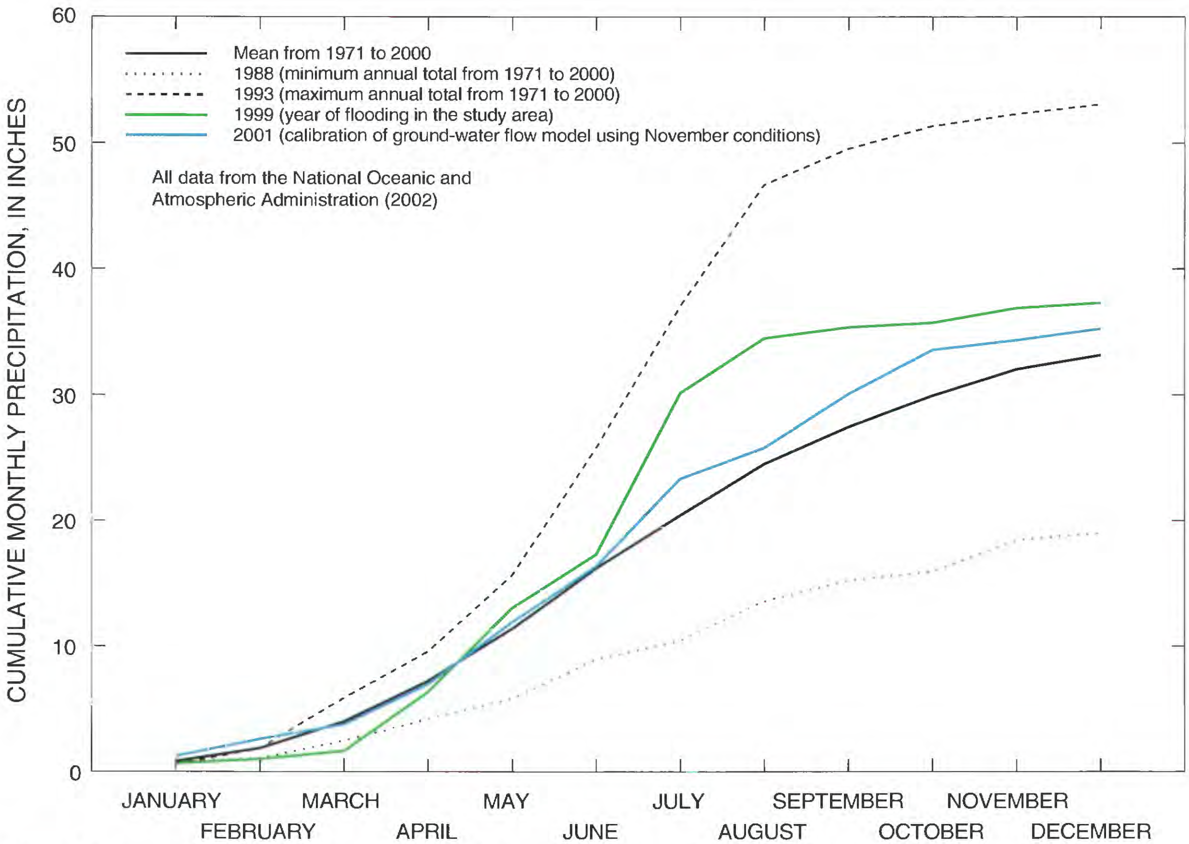


Figure 2. Cumulative precipitation at the Waterloo, Iowa, airport for selected years.

Surface-Water Stage and Streamflow Measurements

The Cedar River is the major surface-water feature in the area. Information about the stage and streamflow of the river is useful for understanding the ground-water flow in the Cedar River alluvium. For this study, stage information was collected in conjunction with streamflow information at selected points along the Cedar River and its tributaries (fig. 1).

Stage refers to the vertical distance between the river surface and a specific reference altitude. Streamflow is the amount of water moving through the river, and it is described in units of volume per time, such as cubic feet per second (ft^3/s). The relation between stage and streamflow is determined primarily by the river channel shape, which may be quite variable along the length of the river.

Stage

Stage is relatively easy to measure and comparisons can be made to water levels in aquifers to determine hydraulic gradients between the river and the aquifers. For this study, stage information for the Cedar River was collected at selected bridge crossings and at USGS streamflow-gaging sites (fig. 1).

Within the study area, the stage of the Cedar River varied by more than 15 ft during 1999 (Ballew and Eash, 2001) and also during 1961 (Schwob, 1963). During the 1999 flood, the gradient of the river surface between Janesville and the southern end of the study area was about 2.18 ft/mi. When the measurements were made for a 1999 low-flow water-surface profile and a November 13–14, 2001, water-surface profile, the gradients were about 2.38 ft/mi and 2.36 ft/mi, respectively. Figure 3 shows the gradient of the Cedar River in the study area for selected flow conditions.

Bankfull stages are defined by the National Weather Service for selected locations, typically those with gaging stations. For the Cedar River at Janesville gaging station, the altitude of the bankfull stage is 877.23 ft (National Weather Service, 2002a). For the Cedar River at Waterloo gaging station, the altitude of the bankfull stage is 833.58 ft (National Weather Service, 2002b). For selected locations along the

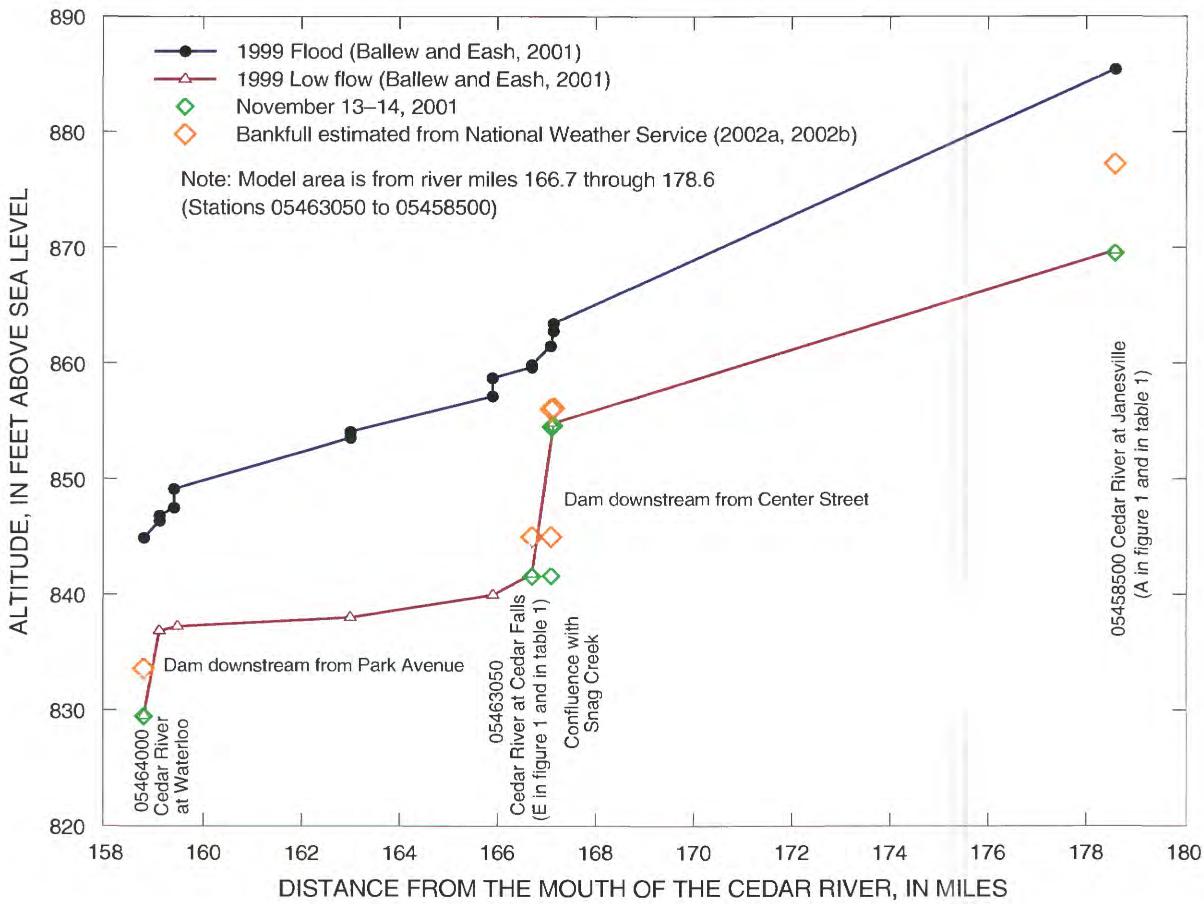


Figure 3. Cedar River stage in the study area for selected flow conditions.

Cedar River, stage was estimated by linear interpolation using the specified bankfull stages and historical stage information from earlier studies (Ballew and Eash, 2001; Schwob, 1963). For the southern extent of the Cedar River along the study area boundary, the altitude of the river stage during bankfull conditions was estimated as 844.98 ft, with a gradient of 2.71 ft/mi. Of the estimated 32.35 ft of fall from the upstream to the downstream end of the study area, about 11 ft occurs at the Cedar River dam between Center Street and the confluence with Snag Creek.

Streamflow

During November 13–14, 2001, streamflow measurements (table 1) were made at selected river sites in and near the study area (fig. 1) to investigate the interaction between the river and the ground-water system. Site selection was affected by several factors, including ease of access, so not all of the drainage area of the Cedar River is accounted for with these measurements. Streamflow measurements were made during November 2000 from a different set of sites at higher flow. The November 2000 measurements indicated that upstream from the West Fork Cedar River, the Cedar River was losing water to the ground-water system and downstream from the West Fork Cedar River to Waterloo, the Cedar River was gaining water from the ground-water system. However, the November 2001 streamflow measurements indicated that during these low-flow conditions, the losses or gains appear to be minimal and may be within the limits of measurement error.

Well Construction and Nomenclature

Test-hole and observation-well boring locations were selected to provide adequate spatial coverage of the study area (fig. 1). These borings provide information about the distribution of geologic materials and water levels in the Cedar River alluvium. This infor-

Table 1. Selected streamflow measurements in the Cedar River Basin on November 13–14, 2001

[ft^3s, cubic feet per second]

Site (fig. 1)	Station name	Streamflow (ft^3s)	Measurement type
A	05458500 Cedar River at Janesville	360	Recorded daily mean
B	05462300 West Fork Cedar River near Janesville	577	Wading
C	05462400 Confluence of the West Fork Cedar River and the Cedar River below Janesville	991	Wading
D	05463030 Beaver Creek near Cedar Falls	89	Wading
E	05463050 Cedar River at Cedar Falls	1,070	Wading
Not shown	05464000 Cedar River at Waterloo	1,170	Recorded daily mean

mation is used in the construction and calibration of the ground-water flow model. Test holes were drilled at three sites to characterize deposits underlying the upland area and to help define the eastern model boundary. Wells were not installed at test-hole locations. USGS personnel used a hand-held global positioning system (GPS) unit to determine the horizontal location (latitude and longitude) of test holes and observation wells.

Observation wells were installed at 14 sites in the Cedar River alluvium by using procedures described by Lapham and others (1995). Boreholes were drilled using 4.25-inch inside-diameter, continuous-flight, hollow-stem augers. Observation-well boreholes were drilled to bedrock or to the limits of the drill rig being used. Samples of auger cuttings were collected at major lithologic changes during drilling, and a description (driller's log) of alluvial materials encountered was recorded for each well (Appendix). The augers were left in place during well construction to prevent borehole collapse. Wells were constructed of 2-inch inside-diameter, flush-threaded, polyvinyl-chloride (PVC) pipe and 5 ft of 0.02-inch slotted PVC screen at the base of each well. Well depths ranged from about 17 to 47 ft below land surface. Alluvial material was allowed to fill the annular space around the screen during removal of the augers to form a natural filter pack extending about 2 ft above the top of the screen. An artificial sand-filter pack was emplaced around the screen in wells having fine-grained material adjacent to the screened interval (wells 2 and 4). A bentonite clay seal was placed above the filter pack, and the remainder of the borehole was backfilled with native material to within a few feet of land surface. A lockable, protective steel casing set in a cement pad was installed at land surface to protect the well casing and prevent infiltration of surface water down the borehole. Wells were developed after completion by pumping until the water was visually clear of sediment.

Maps depicting the thickness of unconsolidated deposits and the altitude of the Silurian-Devonian bedrock surface in the study area were constructed from available geologic information obtained from well and test-boring records of the Iowa Department of Natural Resources–Geological Survey Bureau, Iowa Department of Transportation, and USGS. A water-table surface map for the Cedar River alluvium was constructed from water-level altitudes measured at USGS observation wells and selected Cedar River sites on November 13–14, 2001 (fig. 1).

Table 2 lists the ground-water sites used for data collection in the study and includes well-construction data. Observation wells and test holes are designated by local site identifier (for example, 6) and USGS station identification number (for example, the USGS station identification number for site 6 is 423547092260901). The 15-digit station identification number contains site location information; the first six numbers describe latitude (degrees, minutes, seconds), the next seven numbers describe longitude (degrees, minutes, seconds), and the last two numbers sequentially differentiate between closely spaced sites.

Ground-Water-Level Measurements

Altitudes of measuring points on all wells were surveyed to sea-level datum and all water-level measurements were reported as altitudes above NGVD 88. Periodic ground-water-level measurements were

Table 2. Data-collection sites and observation-well construction data

[LSD, land-surface altitude in feet above NAVD 1988, North American Vertical Datum of 1988; MP, measuring-point altitude in feet above NAVD 1988; NA, no well installed, test hole]

Site name (fig. 1)	Station identification number	LSD	MP	Total well depth (feet below land surface)	Depth (in feet) of screened interval (top/bottom)
1	423808092271901	887.60	890.99	42	37/42
2	423740092265201	884.75	887.23	22.5	17.5/22.5
3	423715092275901	877.36	879.91	27.5	22.5/27.5
4	423650092262701	881.88	885.04	16.75	11.75/16.75
5	423627092271101	877.16	880.46	39	34/39
6	423547092260901	875.80	879.36	21	16/21
7	423515092283901	882.80	885.16	22.7	17.7/22.7
8	423510092271801	874.53	877.81	41	36/41
9	423426092283001	867.11	870.63	42	37/42
10	423423092261001	864.42	867.60	31.5	26.5/31.5
11	423414092245801	872.32	874.45	42.5	37.5/42.5
12	423354092273501	875.22	878.72	42	37/42
13	423339092252001	871.52	873.98	42	37/42
14	423320092261001	866.02	869.14	47	42/47
15	423743092252801	933.57	NA	NA	NA
16	423637092283001	906.71	NA	NA	NA
17	423533092245801	931.65	NA	NA	NA

obtained from 14 observation wells completed in the Cedar River alluvium and 3 domestic wells completed in the underlying Devonian-age limestone by using a calibrated electronic tape. Periodic measurements varied from twice a month during the winter to once a week during the remainder of the year when greater water-level fluctuations occur. Two observation wells (5 and 8) were equipped with continuous-data recorders and vented pressure transducers to collect hourly water levels. Periodic and continuous ground-water levels were recorded to the nearest 0.01 ft. Water levels were used to help conceptualize the ground-water flow system and calibrate the ground-water flow model.

Determination of Aquifer Properties

Slug tests were conducted in the 14 observation wells (table 3) completed in the Cedar River alluvium in northwestern Black Hawk County, Iowa, on May 14–17, 2001, and December 3, 2001. The slug tests were conducted to estimate horizontal hydraulic-conductivity values for the Cedar River alluvium. These values were used to estimate the distribution of horizontal hydraulic conductivity in the ground-water flow model prior to calibration. A slug constructed of a sand-filled, 1.25-inch outer-diameter PVC pipe was used to displace the static water level in observation wells. Water-level changes were measured with pressure transducers and data recorders. Slug-test results were analyzed using the Bouwer and Rice method for partially penetrating wells (Bouwer, 1989). The following assumptions are specified for the Bouwer and Rice method: (1) unconfined aquifer of "apparently" infinite extent; (2) homogeneous, isotropic aquifer of uniform thickness; (3) water table is horizontal prior to the test; (4) instantaneous change in head at start of test; (5) inertia of water column and non-linear well losses are negligible; (6) well storage is not negligible and is taken into account; (7) the flow to the well is in steady state; and (8) there is no flow above the water table.

The results of the slug tests (table 3) are affected by the degree to which conditions fail to match these assumptions. Even if all of the natural conditions are

Table 3. Horizontal hydraulic conductivity values estimated with slug tests and used in the ground-water flow model for the Cedar River alluvium in northwest Black Hawk County, Iowa, 2001

[NA, well is outside model area]

Site name (fig. 1)	Lithology near screened interval of well	Horizontal hydraulic conductivity	
		Estimate based on slug test (feet per day)	Value used in flow model cell (feet per day)
1	Coarse sand	18	63
2	Medium to coarse sand, silt, and clay with artificial sand pack	47	63
3	Coarse to medium sand	100	338
4	Fine to medium sand and clay with artificial sand pack	0.09	10
5	Very coarse sand and gravel	100	338
6	Medium sand	100	563
7	Medium to very coarse sand and gravel	20	338
8	Coarse to medium sand	200	938
9	Medium to fine sand	25	338
10	Medium to coarse sand and gravel	200	1,063
11	Very coarse sand and gravel	100	NA
12	Clay with medium to coarse natural sand pack	15	563
13	Medium to coarse sand	100	NA
14	Medium to very coarse sand	30	338

ideal, the alluvium is affected by the drilling of the well. The practical result of the slug test is an estimated hydraulic conductivity value for a small, disturbed portion of the alluvium, and this value may be much different than the hydraulic conductivity properties that affect the movement of ground water on a larger scale, such as the cell size used in the ground-water flow model.

Ground-Water Flow Model

Ground-water flow in the study area was simulated with MODFLOW, a computer program developed by McDonald and Harbaugh (1988). The program simulates flow in three dimensions by using a block-centered, finite-difference approach, which simultaneously solves a series of mathematical equations that describe saturated ground-water flow. The finite-difference equations were solved using the strongly implicit procedure.

HYDROGEOLOGY

The occurrence and movement of ground water in the study area is influenced by the distribution and physical properties of geologic materials. A description of the hydrogeology of the study area is given below. Detailed descriptions of the hydrogeology of the area are given by Anderson (1983), Horick (1984), Hansen (1975), Olcott (1992), and Witzke and others (1988).

Geology and Water-Bearing Characteristics

The Cedar River alluvium that underlies the river valley consists of unconsolidated deposits of sand, gravel, silt, and clay (table 4). The deposits are of fluvial and glaciofluvial origin and range in thickness from about 20 to 160 ft in the study area (fig. 4). Distinct zones in the alluvium are not defined; however, fining-upwards sequences were observed at several wells (Appendix). Upland areas adjacent to the alluvial valley are underlain by loess and glacial till

Table 4. Hydrogeologic units in the study area and their water-bearing characteristics

[gpm, gallons per minute]

Hydrogeologic unit[1]	Geologic unit	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	Cedar River alluvium, glacial deposits	20–250	Quaternary	Well yields variable, 3–25 gpm, not a widely used source of water.	Medium to coarse sand; fine sand and silt. Loess, silty clay and fine sand; till, clay, and some pebbles.	Layer 1
Silurian-Devonian aquifer	Undifferentiated	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, gypsum, 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 2
Confining unit	Maquoketa Formation	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.

(table 4). The unconsolidated silts and clays of the loess and glacial till range in thickness from about 20 to 160 ft in the study area. Isolated deposits of glacial till are present at the base of the alluvium within the valley. These glacial till deposits may represent erosional remnants of a once more continuous till cover in the area that was subsequently removed by Holocene-age fluvial erosion. Unconsolidated deposits are underlain by rocks of Devonian and Silurian age (fig. 5) that consist of limestone and dolomite with interbedded deposits of gypsum and shale (table 4). Devonian-age rocks are 75 to 100 ft thick and Silurian-age rocks are about 100 ft thick (Horick, 1984; Olcott, 1992). The underlying Ordovician-age Maquoketa Formation, a regional confining unit (table 4), consists predominantly of shale and is about 300 ft thick (Horick, 1984; Olcott, 1992). A buried bedrock valley, possibly formed by erosion from a paleochannel of the Cedar River, underlies the central part of the study area (fig. 5). This bedrock feature was initially depicted by Hansen (1975).

Surface Water

Studies done of high-flow and low-flow conditions along the Cedar River indicate that during 1999 flooding and low-flow conditions, the river stage steadily decreased from Janesville downstream to the dam at river mile 167.09 near Cedar Falls (fig. 3). During the 1999 flood, the maximum streamflow at Janesville was 42,200 ft^3/s and at Waterloo was 69,300 ft^3/s (Ballew and Eash, 2001).

Discharge of the Cedar River during the November 2001 measurements (table 1) was about 100 ft^3/s less than when the low-flow profile measurements of river surface were made during 1999 (Ballew and Eash, 2001).

Figure 6 shows the streamflow recorded at the USGS continuous-record gaging station 05458500 Cedar River at Janesville in the northern part of the study area. During 2001, streamflow varied during the spring and early summer but was fairly stable during the remainder of the year, including November, when the hydrologic system was assumed to be at steady-

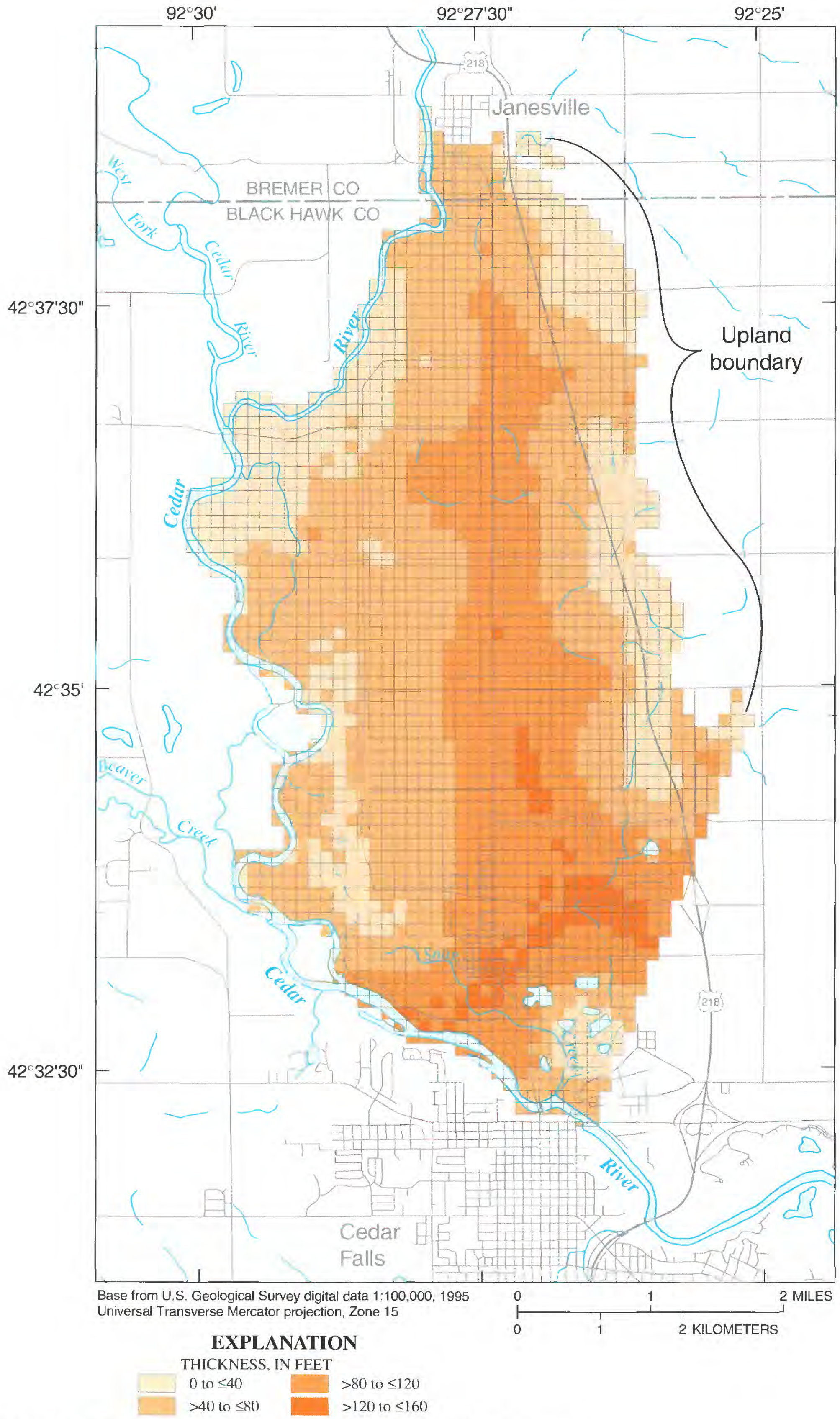


Figure 4. Thickness of unconsolidated materials in the study area.

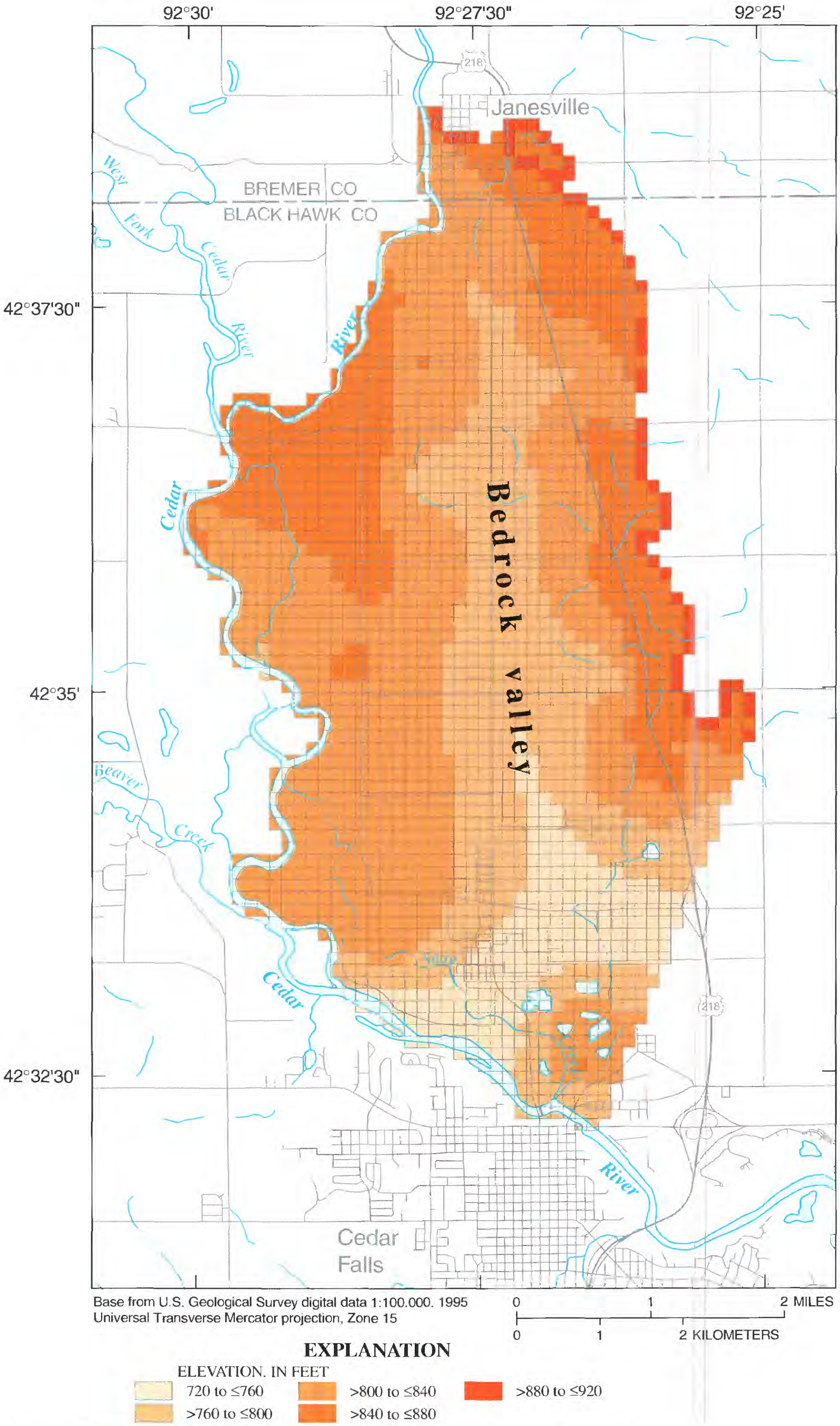


Figure 5. Altitude and configuration of the bedrock surface in the study area.

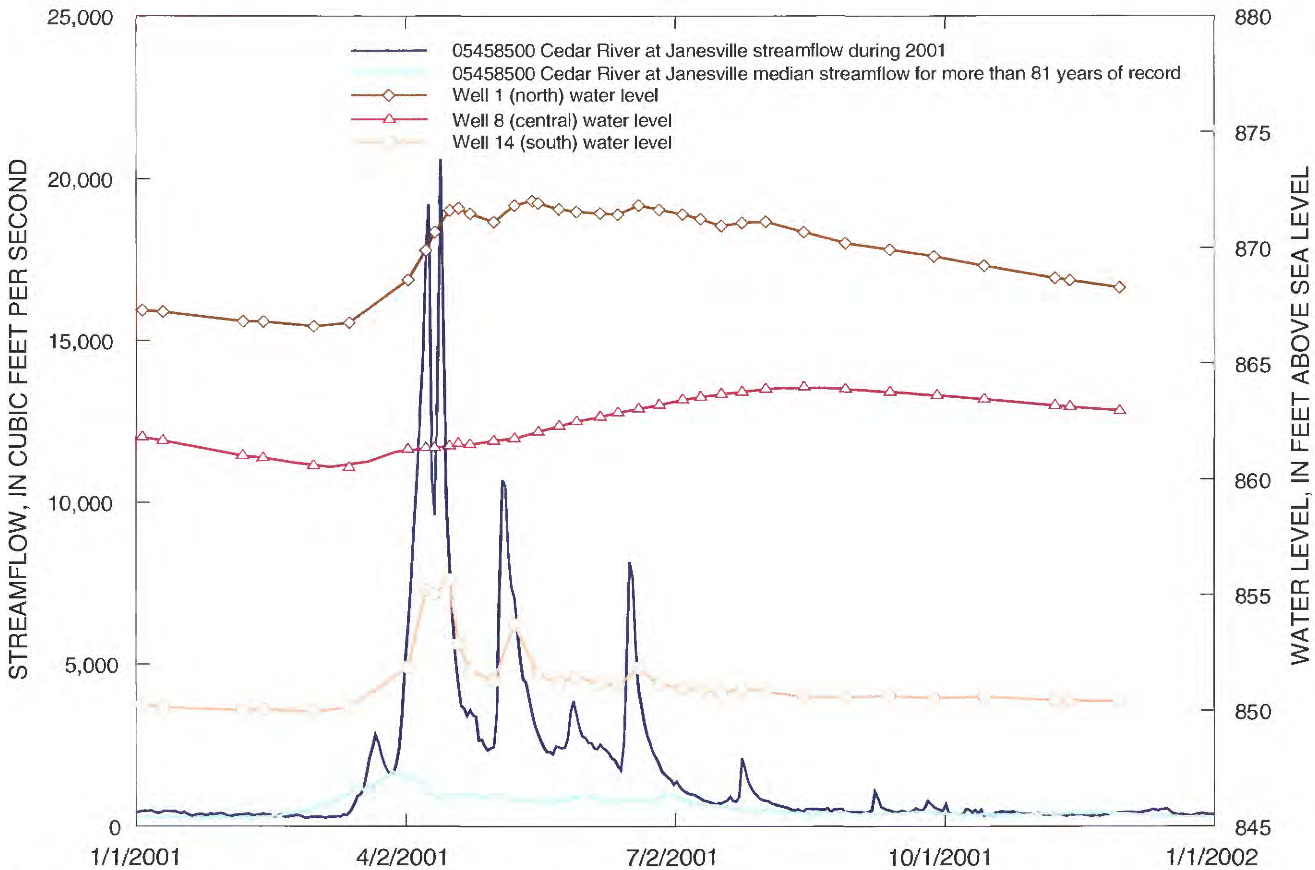


Figure 6. Cedar River at Janesville, Iowa, discharge and measured water levels in three wells in the study area.

state conditions for this report. Long-term records from this station indicate that the amount of streamflow during the fall of 2001 was similar to median streamflow during the Novembers of more than 81 years of record. Also, these long-term records indicate a similar pattern to that of 2001, with streamflow at a fairly stable level for much of the year including late fall.

Ground Water

Hydraulic conductivity describes the ability of geologic materials to transmit water. Hydraulic conductivity for unconsolidated materials such as the Cedar River alluvium generally varies with particle size. Clays and silts tend to have lesser hydraulic-conductivity values, whereas sands and gravels tend to have greater hydraulic-conductivity values (Todd, 1980). For this report, hydraulic conductivities in the Cedar River alluvium were estimated with slug-test analyses in 14 observation wells (table 3). Estimated hydraulic-conductivity values measured in the observation wells ranged over four orders of magnitude (table 3). The wide range of hydraulic-conductivity values reflects the natural heterogeneity of geologic materials. Hydraulic conductivities used in the calibrated flow model differed from the estimated slug-test values. Typically, the values used in the model described in this report are greater than the slug-test values, but they are often within an order of magnitude. The horizontal hydraulic-conductivity values used in the model ranged over three orders of magnitude (table 3).

Ground water in the alluvium is unconfined. Ground water in the underlying bedrock likely is confined in most parts of the model area, as described by Turco (2002). The direction of ground-water flow in the alluvium generally is from the upland areas toward the Cedar River. Figure 1 shows water levels in the Cedar River alluvium on November 13–14, 2001.

The direction of ground-water flow in the alluvium parallels the direction of flow in the Cedar River but occurs down the center of the alluvial valley coincident with the bedrock valley. This may indicate that ground water in the eastern and central part of the study area drains predominantly to the south toward the Cedar River rather than taking a shorter flow path westward to the Cedar River. The regional direction of ground-water flow in the underlying bedrock generally is from the northwest toward the southeast, but variations in the general regional direction of flow occur locally (Turco, 2002). Water levels measured in observation wells for this report are summarized in table 5 and listed in table 6. Water levels in the alluvium tended to be highest in spring, corresponding to high Cedar River stages, or later in the summer or fall corresponding with some time lag after increased rainfall from thunderstorms, depending on the location within the model area (figs. 1 and 6).

Sources of water (recharge) to the alluvium in the study area include precipitation, the river when river stages are greater than water levels in the alluvium, runoff from adjacent upland areas, ground water from the underlying bedrock, and subsurface flow from areas adjacent to the study area. Water in the alluvium may be removed (discharged) by well withdrawals, flow to rivers and drains, flow to the underlying bedrock, subsurface flow to areas adjacent to the study area, and evapotranspiration during the growing season.

Table 5. Ground-water levels measured in observation wells in northwest Black Hawk County, Iowa, on November 13–14, 2001, and values simulated by using the ground-water flow model

[All water levels in feet above North American Vertical Datum of 1988 (NAVD 88); NA, site not within model area]

Site name (fig. 1)	Water-level altitude (feet above NAVD 1988 level)	
	Measured on November 13–14, 2001	Simulated by flow model
1	868.60	869.02
2	869.37	868.27
3	867.28	866.70
4	869.70	866.27
5	868.08	864.81
6	866.26	863.13
7	860.54	861.68
8	863.15	861.06
9	857.26	859.14
10	856.16	858.14
11	854.28	NA
12	853.87	856.86
13	851.83	NA
14	850.43	852.97

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
1	10–12–00	18.86	868.74
	10–31–00	19.35	868.25
	11–14–00	19.50	868.10
	12–01–00	19.84	867.76
	12–14–00	20.05	867.55
	01–03–01	20.30	867.30
	01–10–01	20.36	867.24
	02–06–01	20.77	866.83
	02–13–01	20.79	866.81
	03–02–01	20.99	866.61
	03–14–01	20.84	866.76
	04–03–01	18.99	868.61
	04–09–01	17.71	869.89
	04–12–01	16.92	870.68
	04–17–01	15.98	871.62
	04–20–01	15.87	871.73
	04–24–01	16.11	871.49
	05–02–01	16.47	871.13
	05–09–01	15.75	871.85
	05–15–01	15.56	872.04
	05–17–01	15.66	871.94
	05–24–01	15.91	871.69
	05–30–01	16.03	871.57
	06–07–01	16.09	871.51
	06–13–01	16.14	871.46
	06–20–01	15.75	871.85
	06–27–01	15.94	871.66
	07–05–01	16.15	871.45
	07–11–01	16.35	871.25
	07–18–01	16.65	870.95
	07–25–01	16.52	871.08
	08–02–01	16.46	871.14
	08–15–01	16.91	870.69
	08–29–01	17.39	870.21
	09–13–01	17.67	869.93
	09–28–01	17.97	869.63
	10–15–01	18.37	869.23
	11–08–01	18.91	868.69
	11–13–01	19.00	868.60
	11–30–01	19.32	868.28
2	10–13–00	15.56	869.19
	10–31–00	16.23	868.52
	11–14–00	16.72	868.03
	12–01–00	17.27	867.48
	12–14–00	17.73	867.02
	01–03–01	18.16	866.59
	01–10–01	18.41	866.34
	02–06–01	19.17	865.58
	02–13–01	19.23	865.52
	03–02–01	19.49	865.26
	03–14–01	19.08	865.67
	04–03–01	16.74	868.01
	04–09–01	15.80	868.95
	04–12–01	15.61	869.14
	04–17–01	15.16	869.59
	04–20–01	15.02	869.73
	04–24–01	15.21	869.54
	05–02–01	15.26	869.49
	05–09–01	14.56	870.19
	05–16–01	14.17	870.58
	05–17–01	14.14	870.61
	05–24–01	14.15	870.60
	05–30–01	14.13	870.62
	06–07–01	13.81	870.94
	06–13–01	13.67	871.08
	06–20–01	13.43	871.32
	06–27–01	13.52	871.23
	07–05–01	13.43	871.32
	07–11–01	13.57	871.18
	07–18–01	ND	ND
	07–25–01	13.20	871.55
	08–02–01	ND	ND
	08–15–01	13.29	871.46
	08–29–01	13.68	871.07
	09–13–01	13.85	870.90
	09–28–01	13.68	871.07
	10–15–01	14.71	870.04
	11–08–01	15.31	869.44
	11–13–01	15.38	869.37
	11–30–01	15.85	868.90

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
3	10–13–00	10.17	867.19
	10–31–00	10.57	866.79
	11–14–00	10.71	866.65
	12–01–00	10.94	866.42
	12–14–00	11.16	866.20
	01–03–01	ND	ND
	01–10–01	11.44	865.92
	02–06–01	11.84	865.52
	02–13–01	11.89	865.47
	03–02–01	12.07	865.29
	03–14–01	11.95	865.41
	04–03–01	10.36	867.00
	04–09–01	2.84	874.52
	04–12–01	3.83	873.53
	04–17–01	4.11	873.25
	04–20–01	4.94	872.42
	04–24–01	5.91	871.45
	05–02–01	7.00	870.36
	05–09–01	5.54	871.82
	05–16–01	6.20	871.16
	05–17–01	6.37	870.99
	05–24–01	7.09	870.27
	05–30–01	7.31	870.05
	06–07–01	6.99	870.37
	06–13–01	7.19	870.17
	06–20–01	6.69	870.67
	06–27–01	7.06	870.30
	07–05–01	7.04	870.32
	07–11–01	7.54	869.82
	07–18–01	8.00	869.36
	07–25–01	7.60	869.76
	08–02–01	7.88	869.48
	08–15–01	8.44	868.92
	08–29–01	8.87	868.49
	09–13–01	8.92	868.44
	09–28–01	9.23	868.13
	10–15–01	9.61	867.75
	11–08–01	10.02	867.34
	11–13–01	10.08	867.28
	11–30–01	10.35	867.01
4	10–13–00	13.19	868.69
	10–31–00	13.73	868.15
	11–14–00	14.04	867.84
	12–01–00	14.75	867.13
	12–14–00	15.58	866.30
	01–03–01	16.25	865.63
	01–10–01	16.48	865.40
	02–06–01	16.86	865.02
	02–13–01	16.86	865.02
	03–02–01	17.07	864.81
	03–14–01	10.42	871.46
	04–03–01	11.45	870.43
	04–09–01	11.85	870.03
	04–12–01	12.02	869.86
	04–17–01	11.77	870.11
	04–20–01	11.77	870.11
	04–24–01	11.87	870.01
	05–02–01	12.01	869.87
	05–09–01	11.61	870.27
	05–16–01	11.08	870.80
	05–17–01	11.23	870.65
	05–24–01	11.65	870.23
	05–30–01	11.82	870.06
	06–07–01	10.73	871.15
	06–13–01	10.93	870.95
	06–20–01	11.13	870.75
	06–27–01	11.15	870.73
	07–05–01	10.57	871.31
	07–11–01	10.87	871.01
	07–18–01	11.02	870.86
	07–25–01	9.76	872.12
	08–02–01	10.40	871.48
	08–15–01	10.63	871.25
	08–29–01	10.89	870.99
	09–13–01	10.84	871.04
	09–28–01	11.26	870.62
	10–15–01	11.77	870.11
	11–08–01	12.17	869.71
	11–13–01	12.18	869.70
	11–30–01	12.57	869.31

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
5	10–12–00	9.27	867.89
	10–31–00	9.89	867.27
	11–14–00	10.26	866.90
	12–01–00	10.78	866.38
	12–14–00	11.15	866.01
	01–03–01	11.62	865.54
	01–10–01	11.80	865.36
	02–06–01	12.48	864.68
	02–13–01	12.62	864.54
	03–02–01	12.94	864.22
	03–14–01	12.88	864.28
	04–03–01	11.17	865.99
	04–09–01	10.83	866.33
	04–12–01	10.64	866.52
	04–17–01	10.22	866.94
	04–20–01	9.88	867.28
	04–24–01	9.75	867.41
	05–02–01	ND	ND
	05–09–01	9.15	868.01
	05–16–01	8.27	868.89
	05–17–01	8.22	868.94
	05–24–01	8.08	869.08
	05–30–01	8.07	869.09
	06–07–01	7.67	869.49
	06–13–01	7.42	869.74
	06–20–01	7.32	869.84
	06–27–01	7.32	869.84
	07–05–01	7.17	869.99
	07–11–01	7.26	869.90
	07–18–01	7.39	869.77
	07–25–01	6.95	870.21
	08–02–01	6.81	870.35
	08–15–01	7.10	870.06
	08–29–01	7.51	869.65
	09–13–01	7.70	869.46
	09–28–01	8.13	869.03
	10–15–01	8.58	868.58
	11–08–01	9.03	868.13
	11–13–01	9.08	868.08
	11–30–01	9.48	867.68

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
6	10–13–00	9.87	865.93
	10–31–00	10.42	865.38
	11–14–00	10.72	865.08
	12–01–00	11.26	864.54
	12–14–00	11.72	864.08
	01–03–01	12.28	863.52
	01–10–01	12.45	863.35
	02–06–01	13.18	862.62
	02–13–01	13.29	862.51
	03–02–01	13.62	862.18
	03–14–01	13.39	862.41
	04–03–01	11.39	864.41
	04–09–01	11.14	864.66
	04–12–01	11.00	864.80
	04–17–01	10.74	865.06
	04–20–01	10.52	865.28
	04–24–01	10.53	865.27
	05–02–01	10.42	865.38
	05–09–01	9.94	865.86
	05–16–01	8.50	867.30
	05–17–01	8.48	867.32
	05–24–01	8.59	867.21
	05–30–01	8.70	867.10
	06–07–01	7.65	868.15
	06–13–01	7.45	868.35
	06–20–01	7.59	868.21
	06–27–01	7.83	867.97
	07–05–01	7.54	868.26
	07–11–01	7.59	868.21
	07–18–01	7.90	867.90
	07–25–01	7.31	868.49
	08–02–01	6.79	869.01
	08–15–01	7.53	868.27
	08–29–01	8.11	867.69
	09–13–01	8.23	867.57
	09–28–01	8.66	867.14
	10–15–01	9.09	866.71
	11–08–01	9.45	866.35
	11–13–01	9.54	866.26
	11–30–01	9.97	865.83

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
7	10–12–00	21.57	861.23
	10–31–00	22.03	860.77
	11–14–00	22.25	860.55
	12–01–00	22.47	860.33
	12–14–00	22.65	860.15
	01–03–01	ND	ND
	01–10–01	ND	ND
	02–06–01	ND	ND
	02–13–01	ND	ND
	03–02–01	ND	ND
	03–14–01	ND	ND
	04–03–01	21.66	861.14
	04–09–01	18.96	863.84
	04–12–01	18.31	864.49
	04–17–01	17.47	865.33
	04–20–01	17.94	864.86
	04–24–01	18.44	864.36
	05–02–01	18.98	863.82
	05–09–01	17.99	864.81
	05–15–01	18.17	864.63
	05–17–01	18.30	864.50
	05–24–01	18.69	864.11
	05–30–01	18.73	864.07
	06–07–01	18.82	863.98
	06–13–01	18.89	863.91
	06–20–01	18.40	864.40
	06–27–01	18.71	864.09
	07–05–01	18.93	863.87
	07–11–01	19.09	863.71
	07–18–01	19.32	863.48
	07–25–01	19.50	863.30
	08–02–01	19.65	863.15
	08–15–01	20.02	862.78
	08–29–01	20.54	862.26
	09–13–01	20.93	861.87
	09–28–01	21.27	861.53
	10–15–01	21.71	861.09
	11–08–01	22.19	860.61
	11–13–01	22.26	860.54
	11–30–01	22.52	860.28

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
8	10–12–00	10.86	863.67
	10–31–00	11.26	863.27
	11–14–00	11.57	862.96
	12–01–00	11.91	862.62
	12–14–00	12.30	862.23
	01–03–01	12.70	861.83
	01–10–01	12.86	861.67
	02–06–01	13.50	861.03
	02–13–01	13.60	860.93
	03–02–01	13.94	860.59
	03–14–01	14.02	860.51
	04–03–01	13.23	861.30
	04–09–01	13.17	861.36
	04–12–01	13.17	861.36
	04–17–01	13.09	861.44
	04–20–01	12.97	861.56
	04–24–01	13.01	861.52
	05–02–01	12.86	861.67
	05–09–01	12.76	861.77
	05–16–01	12.53	862.00
	05–17–01	12.47	862.06
	05–24–01	12.22	862.31
	05–30–01	12.03	862.50
	06–07–01	11.82	862.71
	06–13–01	11.64	862.89
	06–20–01	11.47	863.06
	06–27–01	11.30	863.23
	07–05–01	11.09	863.44
	07–11–01	10.97	863.56
	07–18–01	10.85	863.68
	07–25–01	10.75	863.78
	08–02–01	10.63	863.90
	08–15–01	10.54	863.99
	08–29–01	10.63	863.90
	09–13–01	10.75	863.78
	09–28–01	10.90	863.63
	10–15–01	11.06	863.47
	11–08–01	11.35	863.18
	11–13–01	11.38	863.15
	11–30–01	11.58	862.95

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
9	10–12–00	9.51	857.60
	10–31–00	9.68	857.43
	11–14–00	9.64	857.47
	12–01–00	9.71	857.40
	12–14–00	9.88	857.23
	01–03–01	10.00	857.11
	01–10–01	10.02	857.09
	02–06–01	10.20	856.91
	02–13–01	10.22	856.89
	03–02–01	10.31	856.80
	03–14–01	10.00	857.11
	04–03–01	7.39	859.72
	04–09–01	4.38	862.73
	04–12–01	5.26	861.85
	04–17–01	4.77	862.34
	04–20–01	5.94	861.17
	04–24–01	6.81	860.30
	05–02–01	7.67	859.44
	05–09–01	5.78	861.33
	05–15–01	6.86	860.25
	05–17–01	7.17	859.94
	05–24–01	7.86	859.25
	05–30–01	7.60	859.51
	06–07–01	7.90	859.21
	06–13–01	8.08	859.03
	06–20–01	7.30	859.81
	06–27–01	7.93	859.18
	07–05–01	8.34	858.77
	07–11–01	8.59	858.52
	07–18–01	8.79	858.32
	07–25–01	8.48	858.63
	08–02–01	8.88	858.23
	08–15–01	9.17	857.94
	08–29–01	9.38	857.73
	09–13–01	9.37	857.74
	09–28–01	9.57	857.54
	10–15–01	9.67	857.44
	11–08–01	9.83	857.28
	11–13–01	9.85	857.26
	11–30–01	9.97	857.14
10	10–12–00	7.78	856.64
	10–31–00	8.27	856.15
	11–14–00	8.51	855.91
	12–01–00	8.90	855.52
	12–14–00	9.13	855.29
	01–03–01	9.50	854.92
	01–10–01	9.61	854.81
	02–06–01	10.11	854.31
	02–13–01	10.18	854.24
	03–02–01	10.46	853.96
	03–14–01	10.29	854.13
	04–03–01	9.27	855.15
	04–09–01	9.03	855.39
	04–12–01	8.89	855.53
	04–17–01	8.65	855.77
	04–20–01	8.47	855.95
	04–24–01	8.37	856.05
	05–02–01	8.21	856.21
	05–09–01	7.91	856.51
	05–15–01	7.63	856.79
	05–17–01	7.58	856.84
	05–24–01	7.45	856.97
	05–30–01	7.36	857.06
	06–07–01	6.88	857.54
	06–13–01	6.77	857.65
	06–20–01	6.53	857.89
	06–27–01	6.58	857.84
	07–05–01	6.05	858.37
	07–11–01	6.37	858.05
	07–18–01	6.76	857.66
	07–25–01	5.64	858.78
	08–02–01	5.87	858.55
	08–15–01	6.41	858.01
	08–29–01	6.89	857.53
	09–13–01	7.07	857.35
	09–28–01	7.58	856.84
	10–15–01	7.92	856.50
	11–08–01	8.20	856.22
	11–13–01	8.26	856.16
	11–30–01	8.47	855.95

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
11	10–12–00	17.75	854.57
	10–31–00	18.31	854.01
	11–14–00	18.59	853.73
	12–01–00	18.84	853.48
	12–14–00	19.07	853.25
	01–03–01	19.41	852.91
	01–10–01	19.51	852.81
	02–06–01	20.00	852.32
	02–13–01	20.08	852.24
	03–02–01	20.31	852.01
	03–14–01	19.99	852.33
	04–03–01	18.37	853.95
	04–09–01	18.47	853.85
	04–12–01	17.69	854.63
	04–17–01	17.29	855.03
	04–20–01	17.00	855.32
	04–24–01	16.98	855.34
	05–02–01	16.94	855.38
	05–09–01	16.72	855.60
	05–14–01	16.43	855.89
	05–17–01	16.32	856.00
	05–24–01	16.24	856.08
	05–30–01	16.21	856.11
	06–07–01	16.12	856.20
	06–13–01	16.08	856.24
	06–20–01	15.93	856.39
	06–27–01	15.81	856.51
	07–05–01	15.91	856.41
	07–11–01	16.02	856.30
	07–18–01	16.23	856.09
	07–25–01	16.22	856.10
	08–02–01	16.05	856.27
	08–15–01	16.40	855.92
	08–29–01	16.80	855.52
	09–13–01	17.21	855.11
	09–28–01	17.52	854.80
	10–15–01	17.90	854.42
	11–08–01	18.01	854.31
	11–13–01	18.04	854.28
	11–30–01	18.21	854.11
12	10–12–00	20.39	854.83
	10–31–00	20.80	854.42
	11–14–00	21.04	854.18
	12–01–00	21.26	853.96
	12–14–00	21.49	853.73
	01–03–01	21.80	853.42
	01–10–01	21.86	853.36
	02–06–01	22.23	852.99
	02–13–01	22.29	852.93
	03–02–01	22.51	852.71
	03–14–01	22.58	852.64
	04–03–01	21.87	853.35
	04–09–01	21.66	853.56
	04–12–01	21.56	853.66
	04–17–01	21.33	853.89
	04–20–01	21.14	854.08
	04–24–01	20.98	854.24
	05–02–01	20.58	854.64
	05–09–01	20.41	854.81
	05–15–01	20.19	855.03
	05–17–01	20.13	855.09
	05–24–01	19.99	855.23
	05–30–01	19.92	855.30
	06–07–01	19.83	855.39
	06–13–01	19.79	855.43
	06–20–01	19.76	855.46
	06–27–01	19.75	855.47
	07–05–01	19.79	855.43
	07–11–01	19.84	855.38
	07–18–01	19.93	855.29
	07–25–01	19.97	855.25
	08–02–01	20.04	855.18
	08–15–01	20.22	855.00
	08–29–01	20.43	854.79
	09–13–01	20.65	854.57
	09–28–01	20.84	854.38
	10–15–01	21.08	854.14
	11–08–01	21.33	853.89
	11–13–01	21.35	853.87
	11–30–01	21.49	853.73

Table 6. Ground-water levels measured in observation wells in the Cedar River alluvium in northwest Black Hawk County, Iowa, 2000–2001—Continued

[mm-dd-yy, month-day-year; bls, below land surface; NAVD 88, North American Vertical Datum of 1988; ND, no data]

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
13	10–12–00	19.44	852.08
	10–31–00	19.87	851.65
	11–14–00	19.99	851.53
	12–01–00	20.16	851.36
	12–14–00	20.31	851.21
	01–03–01	20.57	850.95
	01–10–01	20.66	850.86
	02–06–01	21.05	850.47
	02–13–01	21.10	850.42
	03–02–01	21.30	850.22
	03–14–01	21.21	850.31
	04–03–01	19.61	851.91
	04–09–01	18.91	852.61
	04–12–01	18.74	852.78
	04–17–01	18.05	853.47
	04–20–01	17.91	853.61
	04–24–01	17.98	853.54
	05–02–01	18.12	853.40
	05–09–01	17.78	853.74
	05–14–01	17.64	853.88
	05–17–01	17.64	853.88
	05–24–01	17.79	853.73
	05–30–01	17.74	853.78
	06–07–01	17.82	853.70
	06–13–01	17.84	853.68
	06–20–01	17.60	853.92
	06–27–01	17.61	853.91
	07–05–01	17.84	853.68
	07–11–01	18.00	853.52
	07–18–01	18.26	853.26
	07–25–01	18.37	853.15
	08–02–01	18.26	853.26
	08–15–01	18.56	852.96
	08–29–01	18.86	852.66
	09–13–01	19.12	852.40
	09–28–01	19.37	852.15
	10–15–01	19.70	851.82
	11–08–01	19.68	851.84
	11–13–01	19.69	851.83
	11–30–01	19.76	851.76

Site name (fig. 1)	Date (mm-dd-yy)	Water-level measurement	
		Depth to water (feet bls)	Altitude (feet above NAVD 88)
14	10–12–00	15.62	850.40
	10–31–00	15.71	850.31
	11–14–00	15.66	850.36
	12–01–00	15.78	850.24
	12–14–00	15.82	850.20
	01–03–01	15.77	850.25
	01–10–01	15.87	850.15
	02–06–01	16.00	850.02
	02–13–01	15.96	850.06
	03–02–01	16.07	849.95
	03–14–01	15.88	850.14
	04–03–01	14.15	851.87
	04–09–01	10.80	855.22
	04–12–01	10.97	855.05
	04–17–01	10.38	855.64
	04–20–01	13.16	852.86
	04–24–01	14.24	851.78
	05–02–01	14.73	851.29
	05–09–01	12.28	853.74
	05–15–01	14.25	851.77
	05–17–01	14.49	851.53
	05–24–01	14.78	851.24
	05–30–01	14.54	851.48
	06–07–01	14.85	851.17
	06–13–01	14.92	851.10
	06–20–01	14.17	851.85
	06–27–01	14.89	851.13
	07–05–01	15.04	850.98
	07–11–01	15.14	850.88
	07–18–01	15.26	850.76
	07–25–01	15.04	850.98
	08–02–01	15.19	850.83
	08–15–01	15.42	850.60
	08–29–01	15.42	850.60
	09–13–01	15.39	850.63
	09–28–01	15.48	850.54
	10–15–01	15.42	850.60
	11–08–01	15.57	850.45
	11–13–01	15.59	850.43
	11–30–01	15.60	850.42

SIMULATION OF GROUND-WATER FLOW

A ground-water flow model is a simplified mathematical approximation of the physical flow system. The flow model for this study was used to help understand the shallow ground-water flow system, identify sources of water to the Cedar River alluvium, and evaluate the potential effects of variations in recharge rates and discharge conditions. Onsite observations and hydrogeologic data were used to estimate hydraulic properties of the flow system. While adequate for the purposes of this report, the model likely is not suitable to conduct accurate predictive analyses because of the uncertainty associated with estimated hydraulic properties and other model limitations.

The flow model was constructed by assuming steady-state conditions. Steady-state conditions occur when the volume of water flowing into the system equals the volume of water flowing out of the system. Hydrologic conditions within the study area in November 2001 were considered to be a good approximation of steady-state conditions. Ground-water levels measured in observation wells in November 2001 were about the same as ground-water levels in October 2001 and December 2001 (table 6). Streamflow of the Cedar River was relatively constant (fig. 6) and there was relatively little rainfall during this time (fig. 2). Results of the ground-water flow model may not be valid when conditions are not steady state. Steady-state conditions do not occur when ground-water levels rapidly change such as during late spring and early summer when the Cedar River stage rapidly changes or after large amounts of rainfall.

The flow model was developed by conceptualizing the ground-water system on the basis of onsite observations and hydrogeologic data collected during the period of study and the results of a ground-water flow model constructed by Turco (2002) for a larger area of the Cedar River alluvium and underlying bedrock of Silurian and Devonian age, which includes the study area described in this report. Spatial limits of the model were established by using existing natural hydrologic boundaries and defining distant boundaries for areas without existing natural boundaries. The Maquoketa Formation, a regional confining unit underlying the study area, was used as a boundary beneath the study area. The upland areas bordering the alluvial valley were used as a lateral boundary on the east. The main channel of the Cedar River was used as a lateral boundary for the alluvium on the west and southwest. Distant boundaries were specified to account for subsurface flow in the bedrock from the northeast. Most ground-water flow in the unconsolidated deposits was assumed to occur in the alluvium rather than in adjacent, less permeable tills. The alluvium, bedrock, and rivers were assumed to be in hydraulic connection.

Model Description and Boundary Conditions

The model consists of two layers. Layer 1 represents the unconsolidated deposits and layer 2 represents the bedrock of Silurian and Devonian age. Flow in layer 1 is simulated as unconfined (water-table conditions) and flow in layer 2 is simulated as confined.

An 83-row by 47-column grid was used to discretize the area of study into a grid of approximately 500-ft by 500-ft cells for each of the model layers (figs. 7 and 8). The cell area was identical in each layer, but the vertical dimension varied with layer thickness. The active cells of layer 1 coincide with the area where the alluvium is present. The model code calculates the hydraulic head (ground-water-level altitude) at the center, or node, of each active cell and a ground-water flux across each cell face based on water-level gradients between adjacent active cell nodes. Cells are identified by a row, column, and layer designation.

The Cedar River is simulated by river cells (fig. 7) that allow movement of water through the river bottom to or from layer 1 based on riverbed conductance and the difference in hydraulic heads between the river and layer 1. Conductance is the product of the vertical hydraulic conductivity of the bed material, and the length and width of the reach in the cell, divided by bed-material thickness (McDonald and Harbaugh, 1988). No onsite measurements of bed-material thickness or hydraulic properties were made, so an estimated bed-material thickness of 1 ft was used for the river cells. The vertical hydraulic conductivity of bed materials was initially estimated on the basis of expected lithologies and modified during model calibration. A river cell will provide or receive as much water as the model requires to reach a mathematical solution. However, if the head in the cell that contains the river were to go dry, then the contribution of the

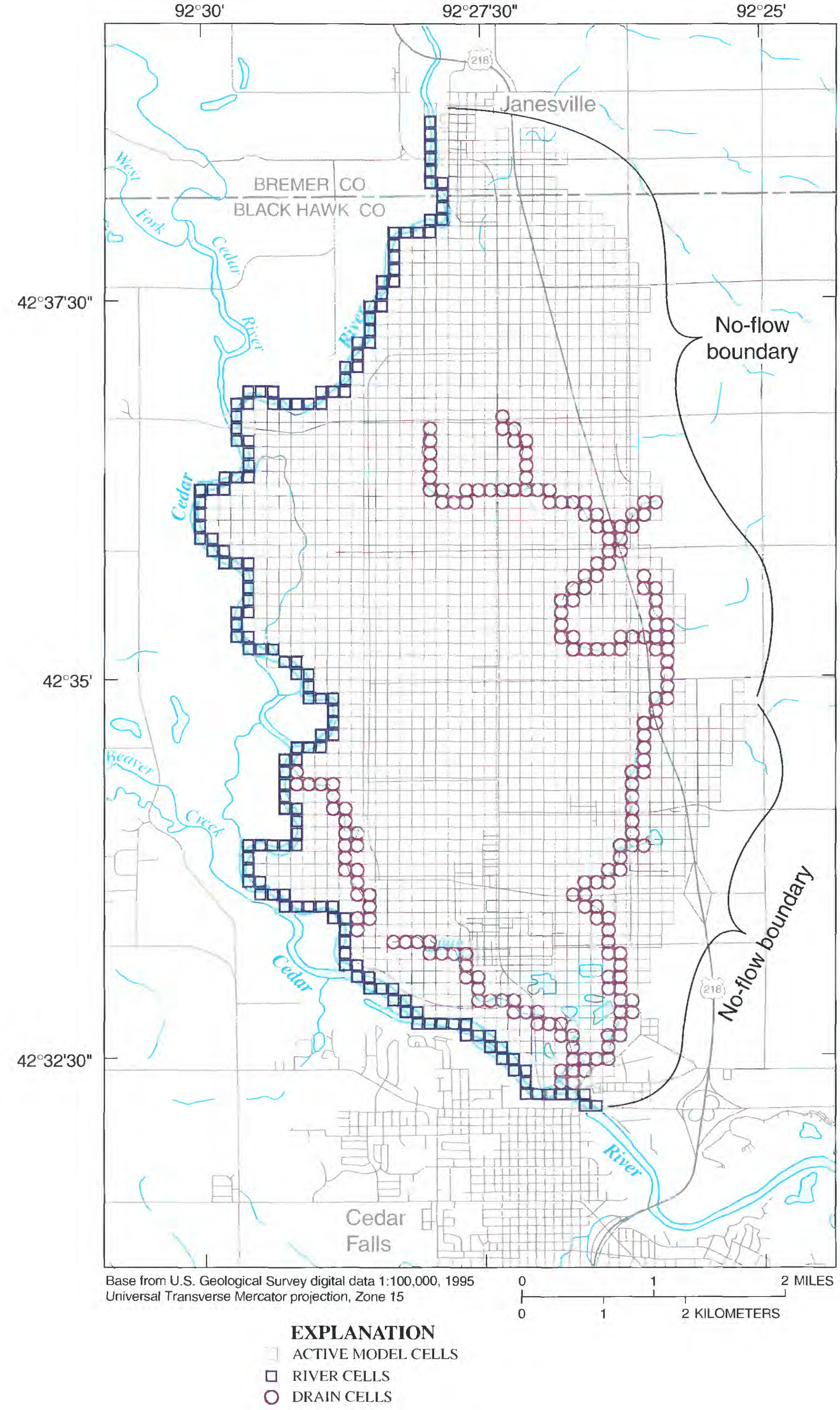


Figure 7. Orientation of model grid, grid discretization, and stress-related model parameters used in layer 1.

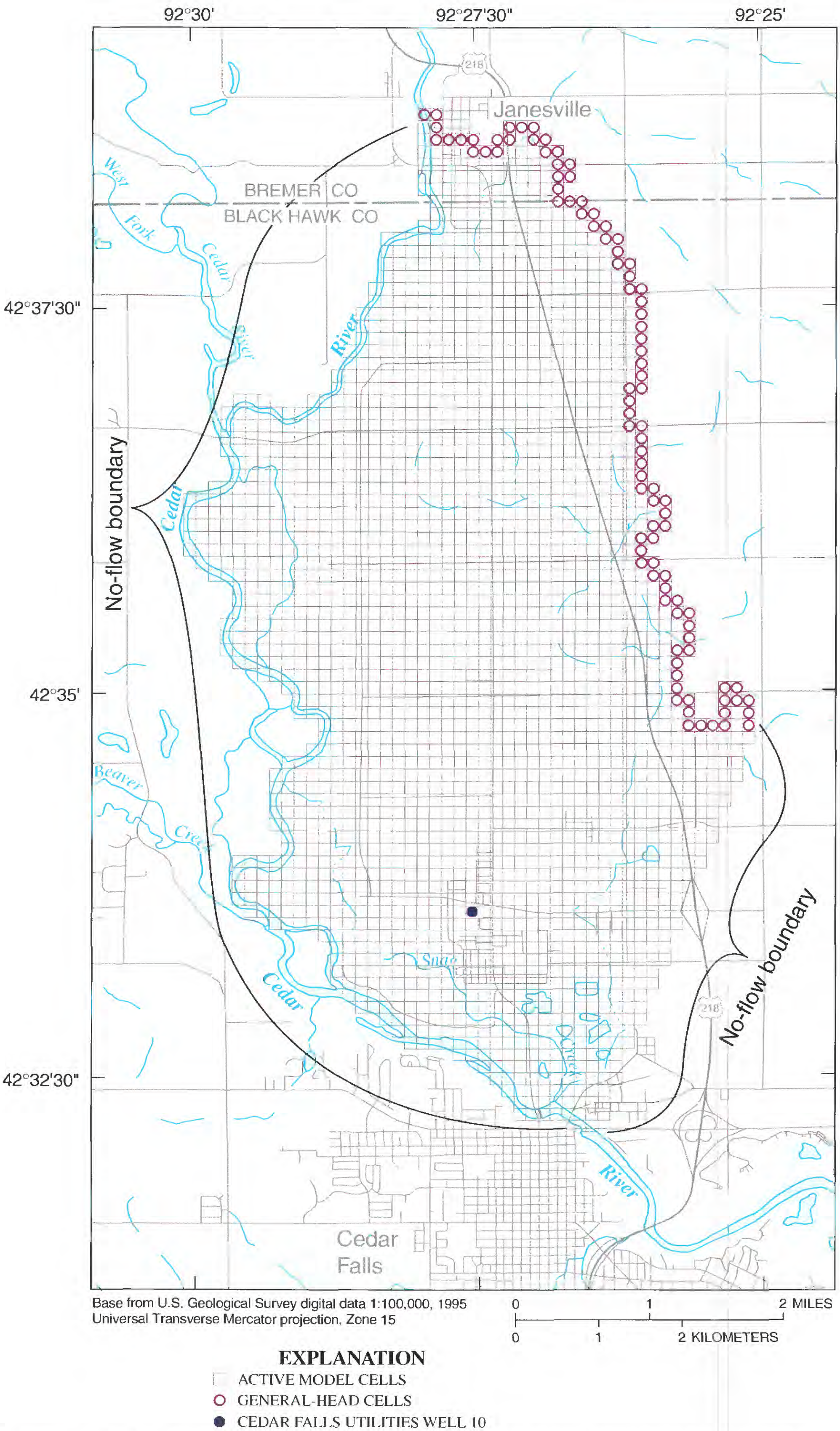


Figure 8. Orientation of model grid, grid discretization, and stress-related model parameters used in layer 2.

river in that cell would be negated. Long-term records for the Cedar River show that there was at least some streamflow during some of the extended drier periods of the 1900s, and it is unlikely that the river cells would go dry. The Cedar River serves as the western boundary of the model area. In the regional model developed by Turco (2002), aquifer properties and water movement were approximately symmetrical about the Cedar River. There are no major pumping centers to the west of the Cedar River in the study area to induce flow from the alluvium or bedrock in the model area.

Intermittent streams that contain water only during high water-table conditions can be simulated in MODFLOW with drains. Ground water can move into drains and is then removed from the ground-water system, but water cannot move from the drains into the ground-water system. Drain locations (fig. 7) were estimated from USGS 7.5-minute topographic maps and discussion with staff members of the Black Hawk County Engineering Department. Observations made in the study area during November 2001 noted there was no water in the intermittent streams at that time. No onsite measurements of intermittent stream widths or depths were made. A geometry of the drains was estimated that resulted in a uniform conductivity value that was assigned to all of the drains.

The upper boundary of the model area is a free surface that represents the water table. A specified-flux boundary is used to represent spatial recharge to layer 1. No-flow boundaries are used to simulate the limits of the model area where ground-water flow is assumed to be insignificant or in areas where aquifer material is absent. The bottom of the modeled system is the top of the relatively impermeable Maquoketa Formation and is represented by a no-flow boundary at the bottom of layer 2. The lateral hydrologic boundaries formed by the relatively impermeable glacial till adjacent to the alluvium (layer 1) establish logical hydrologic limits for modeling ground-water flow in the alluvium. These boundaries are modeled as no-flow boundaries.

General-head cells are used to simulate lateral model boundaries where ground water can enter or leave the system. Flow across the boundary is proportional to the differences between hydraulic head in the cells at the model boundary and hydraulic head assigned at a distance outside the model. General-head cells are used at the northeastern limits of layer 2 to simulate subsurface flow into and out of the model area through the bedrock of Silurian and Devonian age in proportion to relative hydraulic-head differences between the cells at the model boundary and the regional potentiometric surface outside the model area. The regional Cedar Falls model (Turco, 2000) indicates ground water generally flows north to south or northeast to southwest in the model area described in this report.

Model Parameters

Model parameters are variables assigned to individual cells in the model array and are used in the flow equations that simulate ground-water flow within the modeled area. Parameters assigned to the node of each active cell represent an average value for the entire cell. Parameters were used in the model to represent horizontal and vertical hydraulic conductivity, recharge by precipitation, and ground water pumped from the ground-water flow system.

Transmissivity (hydraulic conductivity multiplied by the saturated thickness) is used by the model to solve the ground-water flow equations. Hydraulic conductivity and thickness were specified for each cell in layers 1 and 2, and the model calculated the corresponding transmissivity.

In general, the spatial distribution of hydraulic conductivity for the layer 1 cells was based on the slug-test results (table 3) for the observation wells completed in the alluvium. The slug-test results were used to create computer-generated contours, and the areas between the contours were assigned values equal to the average of the bounding contour lines. Some adjustments were made to this distribution based on the geology of the study area. The isolated high-altitude area in the northern part of the model area was delineated using the 900-foot contour as a guide (fig. 1). Based on the assumption that this area might be an erosional remnant, the horizontal hydraulic-conductivity value of the underlying bedrock of layer 2 was assigned to this higher altitude area. The vertical hydraulic conductivity of the alluvium assigned for all cells in layer 1 was one-tenth of the horizontal hydraulic conductivity. That vertical hydraulic conductivity was about twice the value of the vertical hydraulic conductivity of the underlying bedrock. Initial hydraulic conductivity values were adjusted during the model calibration process. The area of large horizontal hydraulic conductivity in the southeastern part of the model area appeared to be associated with the bedrock valley, so the areas were adjusted in recognition that the bedrock valley continues to the southeast of the model area. Assigned horizontal hydraulic conductivity values were adjusted as part of the calibration process described later, but the basic geometry described above was maintained. Figure 9 shows the distribution of horizontal and hydraulic conductivity in layer 1 after the model was calibrated for steady-state conditions.

Hydraulic conductivity for the layer 2 cells was based on the distribution of hydraulic conductivity used for the development of the regional Cedar Falls model (Turco, 2002). The Cedar Falls model used two separate layers to represent the bedrock of Silurian and Devonian age (Turco, 2002). For the Devonian-age layer, horizontal and vertical hydraulic conductivity was greatest near the Cedar River and decreased with the distance from the Cedar River (Turco, 2002, p. 17). For the Silurian-age layer, horizontal and vertical hydraulic conductivity decreased from north to south (Turco, 2002, p. 18) in the area of interest for the model described in this report. Combining the information from the two layers in the Cedar Falls model produced five zones of different horizontal and vertical hydraulic conductivity for layer 2 of the model described in this report (fig. 10). The values were not adjusted as the model described in this report was calibrated to steady-state conditions.

A net recharge rate of 0.0022 ft/d was used in the model to account for precipitation infiltrating to the water table. During the 30 days of November 2001, 0.80 inch of precipitation was recorded at the Waterloo airport. Infiltration of runoff from upland areas to the east of the model area was accounted for by increasing the recharge at model cells along the eastern boundary to 0.022 ft/d.

Types of discharge from the flow system included in the model were ground-water pumpage, flow to the river and drains, and flow across general-head boundaries. For most of the period of data collection for this report, the City of Cedar Falls pumped only one of its two municipal wells (well 10, fig. 8) at a relatively constant rate of 12,450 ft^3/d (Jerald Lukensmeyer, City of Cedar Falls, oral commun., June 2001). Flow from the river and drains and flow across general-head boundaries were calculated by the model. Evapotranspiration was not considered as a significant form of discharge during late fall steady-state conditions.

Model Calibration

Model calibration is a process in which the differences between simulated ground-water levels and measured ground-water levels are minimized by adjusting model parameters. Ground-water levels measured on November 13–14, 2001, were used as a basis for calibration. Hydraulic conductivity, vertical leakance, drain and streambed conductance, and flow across model boundaries were varied iteratively until the differences between measured water levels and simulated water levels in respective corresponding model cells were within about 3 ft. Model calibration was further refined by continuing to vary model parameters until the average head difference (AVEH) and root-mean-squared error (RMSE) were minimized.

The AVEH is an indicator of systematic error and is the sum of the differences between measured and simulated water levels divided by the total number of measurements. It approaches zero when the sum of the differences between measured and simulated ground-water levels that are greater than zero equals the sum of the differences that are less than zero.

The RMSE is a measure of the magnitude of error between measured and simulated ground-water levels over the entire model area (Anderson and Woessner, 1992). Table 5 lists water levels measured in observation wells on November 13–14, 2001, and water levels simulated by the calibrated model. The AVEH for the calibrated model was 0.16 ft. The RMSE for the calibrated model was 2.30 ft. The discrepancy between measured and simulated water levels likely results from the fact that the model is a simplified representation of a complex ground-water system. For example, the model represents heterogeneous aquifer properties with discretized model parameters estimated from few onsite measurements.

The steady-state model was considered calibrated when the following criteria were met:

1. Incremental changes in model input parameters did not produce an AVEH closer to zero or a smaller RMSE for all layers in the model,
2. The RMSE represented a small percentage of the range of measured ground-water levels, and
3. Simulated lateral ground-water flow directions approximated flow directions interpreted from the water-table map in the alluvium constructed using water levels measured on November 13–14, 2001.

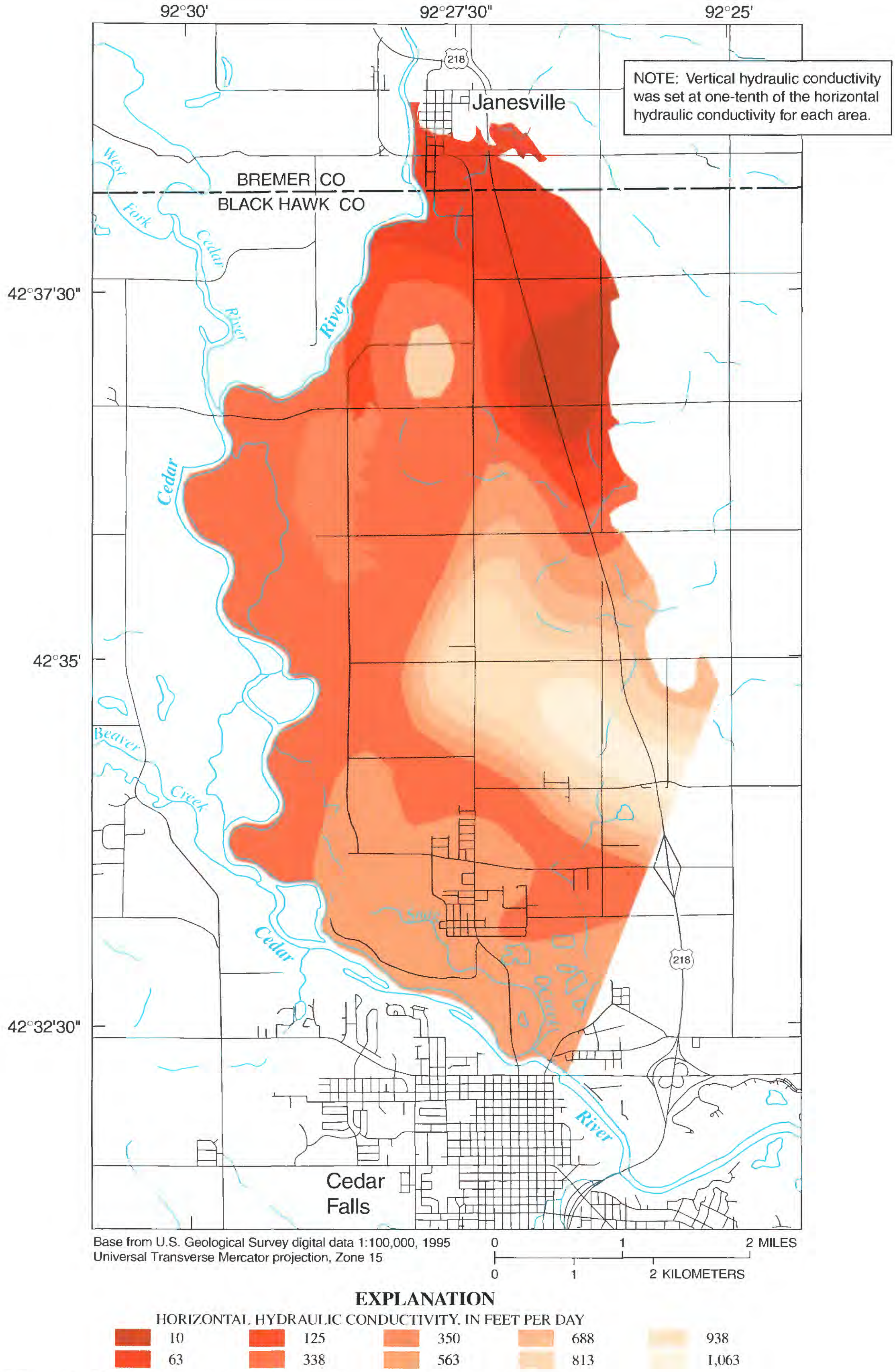
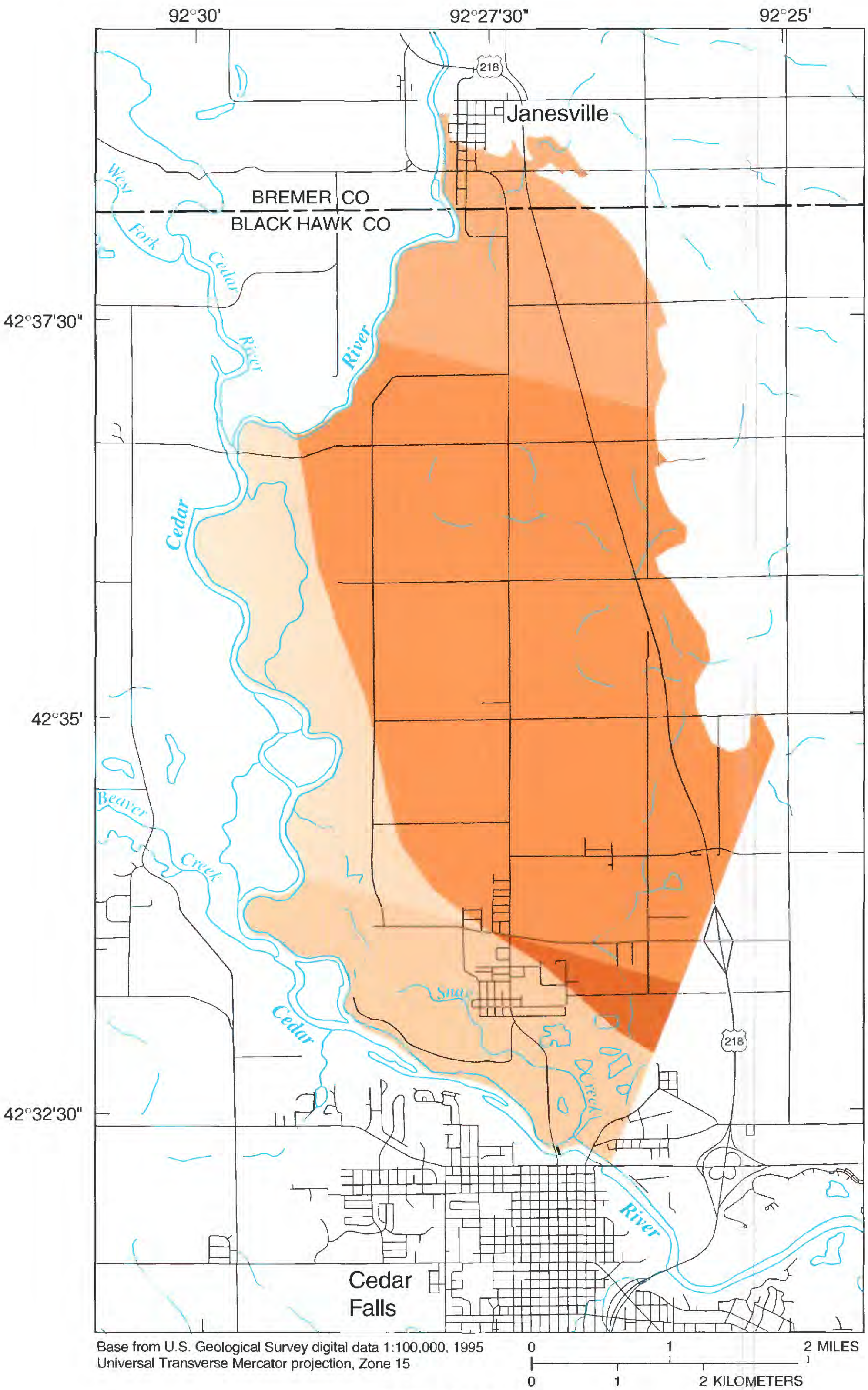


Figure 9. Distribution of horizontal hydraulic conductivity in layer 1.



EXPLANATION

HORIZONTAL/VERTICAL HYDRAULIC CONDUCTIVITY, IN FEET PER DAY

285/14
350/20
425/28
510/96
575/102

Figure 10. Distribution of horizontal and vertical hydraulic conductivity in layer 2.

Streamflow measurements were made in the Cedar River and selected tributaries during low-flow conditions in November 2001. Measured losses and gains were minimal and probably within limits of measurement error; therefore, the model was not calibrated to leakage to or from the Cedar River. During model calibration, drainbed conductivity was adjusted to 16.4 (ft^2/d)/ft, based on the distribution of the differences between the observed water levels and the simulated water levels in layer 1 and examination of the flow budget.

Sensitivity Analysis

The calibrated model is influenced by uncertainty resulting from limited knowledge of the spatial variation of parameter values and uncertainty associated with the definition of boundary conditions. A sensitivity analysis establishes the effect of parameter uncertainty on the calibrated model by documenting the response of the model-simulated water-level changes and flux to incremental changes in parameter values. The model is sensitive to a parameter when changes in the parameter value produce substantial changes in model response. If improvement in the model is desired, additional data collection could be directed toward improving the accuracy of the most sensitive parameters.

Simulated water-level response to incremental changes in selected input parameters is shown in figure 11. The RMSE is plotted against the multiplication factor used to vary the parameters. The calibrated model parameters are represented by a multiplication factor of 1. The multiplication factor was applied uniformly to the entire model for the indicated parameter and ranged from 0.1 to 10. The parameter being tested was adjusted while the remaining model param-

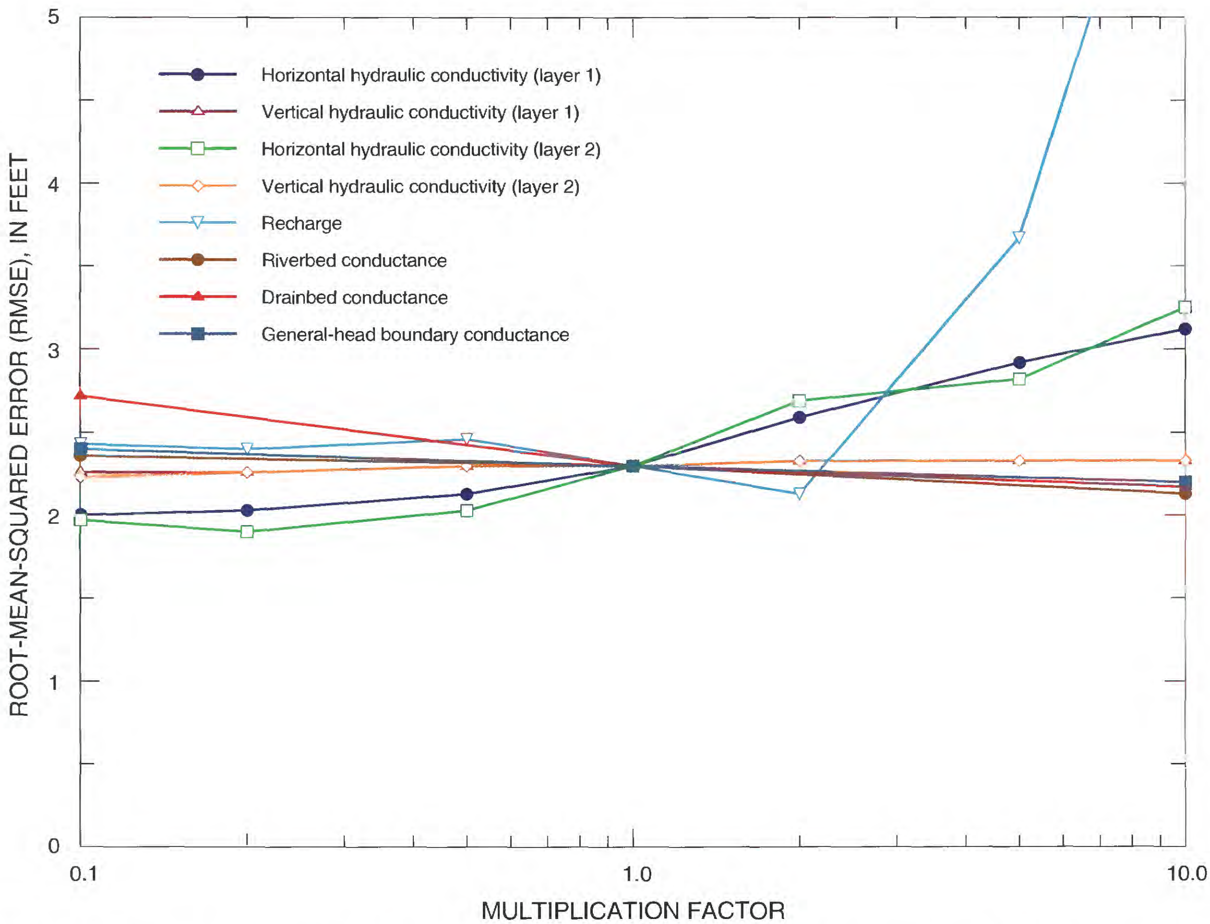


Figure 11. Sensitivity analysis of selected model parameters based on the root-mean-squared error in heads compared to observation wells in the alluvial aquifer.

eters were held at the calibrated values. Water levels were most sensitive to recharge and to horizontal hydraulic conductivity in layers 1 and 2. Water levels were insensitive to vertical hydraulic conductivity in layers 1 and 2 and the conductance of the riverbed, drainbed, and general-head boundary.

The sensitivity of simulated river leakage was evaluated by varying model input parameters and determining the proportion of simulated inflow to the ground-water flow system obtained from the Cedar River. River leakage was most sensitive to recharge and horizontal hydraulic conductivity in layer 2, whereas horizontal hydraulic conductivity in layer 1 and vertical hydraulic conductivity in layers 1 and 2 had less of an effect (fig. 12).

The calibrated model uses hydraulic conductivity that ranges from 1.97 ft/d (north) to 1.64 ft/d (south) for the general-head boundary, and flow entering the model from the general-head boundary is about 3.1 percent of the total. Increasing the hydraulic conductivity of the general-head boundary by a factor of 100 leads to a contribution from the bedrock of about 17.9 percent of the total flow. Decreasing the hydraulic conductivity of the general-head boundary by a factor of 100 of the calibrated model value leads to a contribution from the bedrock of much less than 1 percent.

Model Limitations

The ground-water flow model constructed for this report simulates the flow system under steady-state conditions. However, several model limitations should be considered. Model input parameters, such as horizontal and vertical hydraulic conductivity and recharge from precipitation, are specified at the node of each active cell and represent an average for the entire cell. The assumptions of uniformity for the entire cell introduce inaccuracies because of the heterogeneous nature of geologic materials and the variability of climatic conditions. The steady-state model assumes that inflows to the ground-water system equal outflows. If inflows were not equal to outflows in November 2001, the resultant change in ground-water storage would be a source of model error. For example, water levels could have been either rising or falling during the assumed equilibrium conditions.

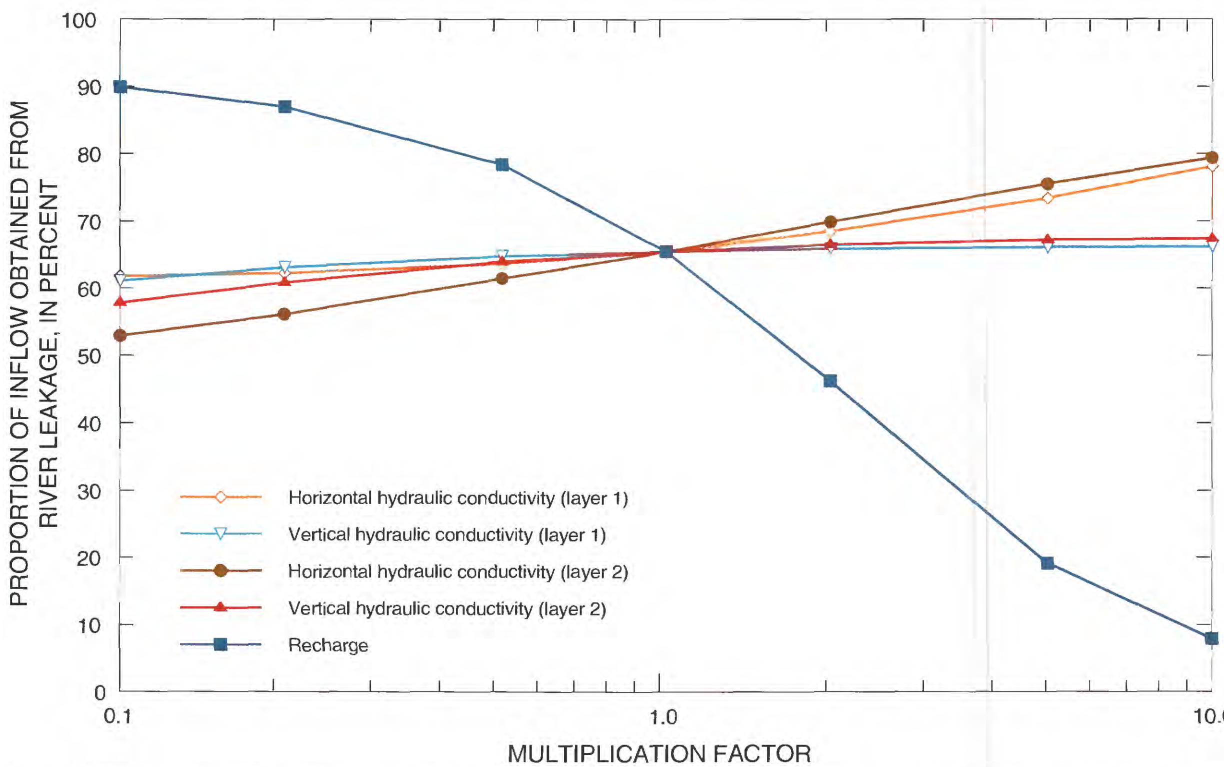


Figure 12. Proportion of simulated inflow from river leakage as a result of varying selected model parameters.

The steady-state flow model does not account for dynamic (transient) conditions (natural or anthropogenic). The steady-state model does not indicate the time needed to reach equilibrium conditions. Attaining equilibrium might take a substantial period of time and is complicated by varying climatic and hydrologic conditions and noncontinuous municipal pumping.

Simulation Results

The calibrated model was used to simulate steady-state conditions as approximated by hydrologic conditions during November 2001. The model calculates a ground-water-level altitude at the node of each cell from which a simulated water-table surface in the alluvium was constructed. The model also calculates a ground-water flux between cells from which a simulated water budget is computed. Ground-water flow directions derived from analysis of the simulated ground-water-level altitudes, and inflows and outflows quantified in the water budget, assist in developing an improved understanding of the ground-water flow system.

The simulated water-table surface for layer 1 is shown in figure 13. A comparison between simulated water levels at the observation well locations and water levels measured November 13–14, 2001, is shown in table 5. The simulated water levels show the general direction of ground-water flow in the alluvium to be toward the south, with little apparent preferential flow toward the Cedar River. Figure 14 shows the approximate depth to the top of the water table in the model area.

The sources of the water recharging the alluvium can be identified from an analysis of the water budget (table 7). Under assumed steady-state conditions and 2001 pumpage, the model calculated about 3.97 million ft^3/d of flow into and out of the ground-water system. The difference between the calculated inflow and outflow was less than 1 percent and was due to the model approximating a solution to the mathematical equations.

Primary sources of inflow to the model are the Cedar River (65.5 percent) and infiltration of precipitation and upland runoff (31.4 percent). All of these sources of inflow enter the ground-water system through the alluvium.

The primary components of outflow from the ground-water system are flow to the drains (56 percent) and the Cedar River (43.7 percent), which leaves the system through the alluvium. The pumpage from the bedrock and flow across the general-head boundaries of the model account for less than 1 percent of the total outflow.

Table 7. Simulated water budgets

[Inflow, water added to the ground-water system; ft^3/d, cubic feet per day; outflow, water removed from the ground-water system; pumpage—municipal, ground-water withdrawals by Cedar Falls Utilities]

Budget component	Steady state	Scenario 1	Scenario 2
Inflow (ft^3/d)			
Recharge from precipitation and upland runoff	1,244,718	1,493,662	1,493,662
Leakage—Cedar River	2,597,458	2,657,807	5,729131
Leakage—drains (intermittent streams)	0	0	0
Subsurface flow across outer boundaries	123,170	4,885	26,215
Pumpage—municipal	0	0	0
Total inflow	**3,965,360**	**4,156,356**	**7,248,976**
Outflow (ft^3/d)			
Recharge from precipitation and upland runoff	0	0	0
Leakage—Cedar River	1,733,658	1,000,159	198,845
Leakage—drains (intermittent streams)	2,219,276	2,994,001	6,916,031
Subsurface flow across outer boundaries	0	149,747	121,673
Pumpage—municipal	12,450	12,450	12,450
Total outflow	**3,965,395**	**4,156,356**	**7,248,976**

Scenario 1–Bankfull river conditions, recharge 1.2 times calibration conditions.

Scenario 2–Bankfull river conditions, recharge 1.2 times calibration conditions, and drainbed conductance 10 times calibration conditions.

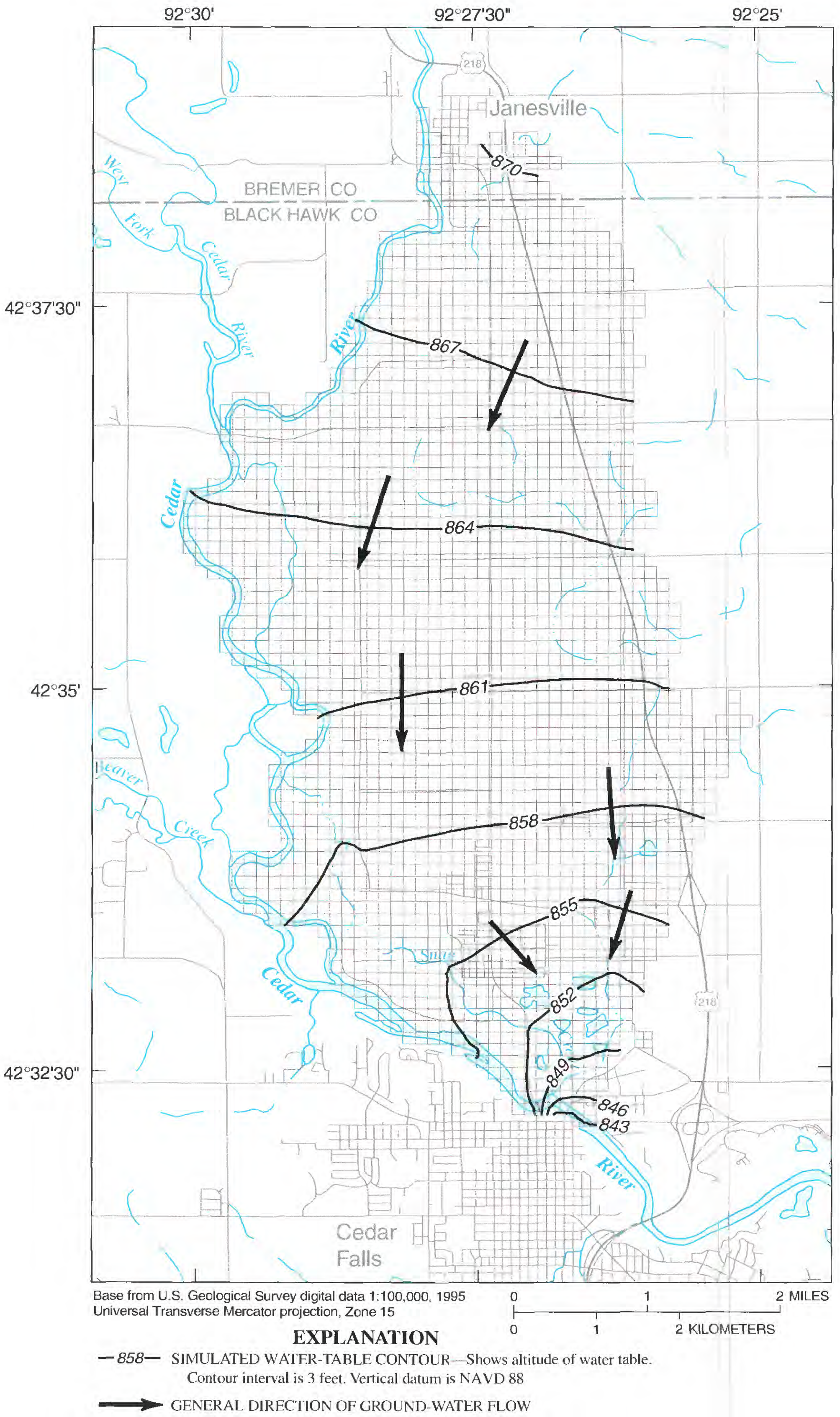


Figure 13. Simulated water-table surface in the Cedar River alluvium, November 13–14, 2001.

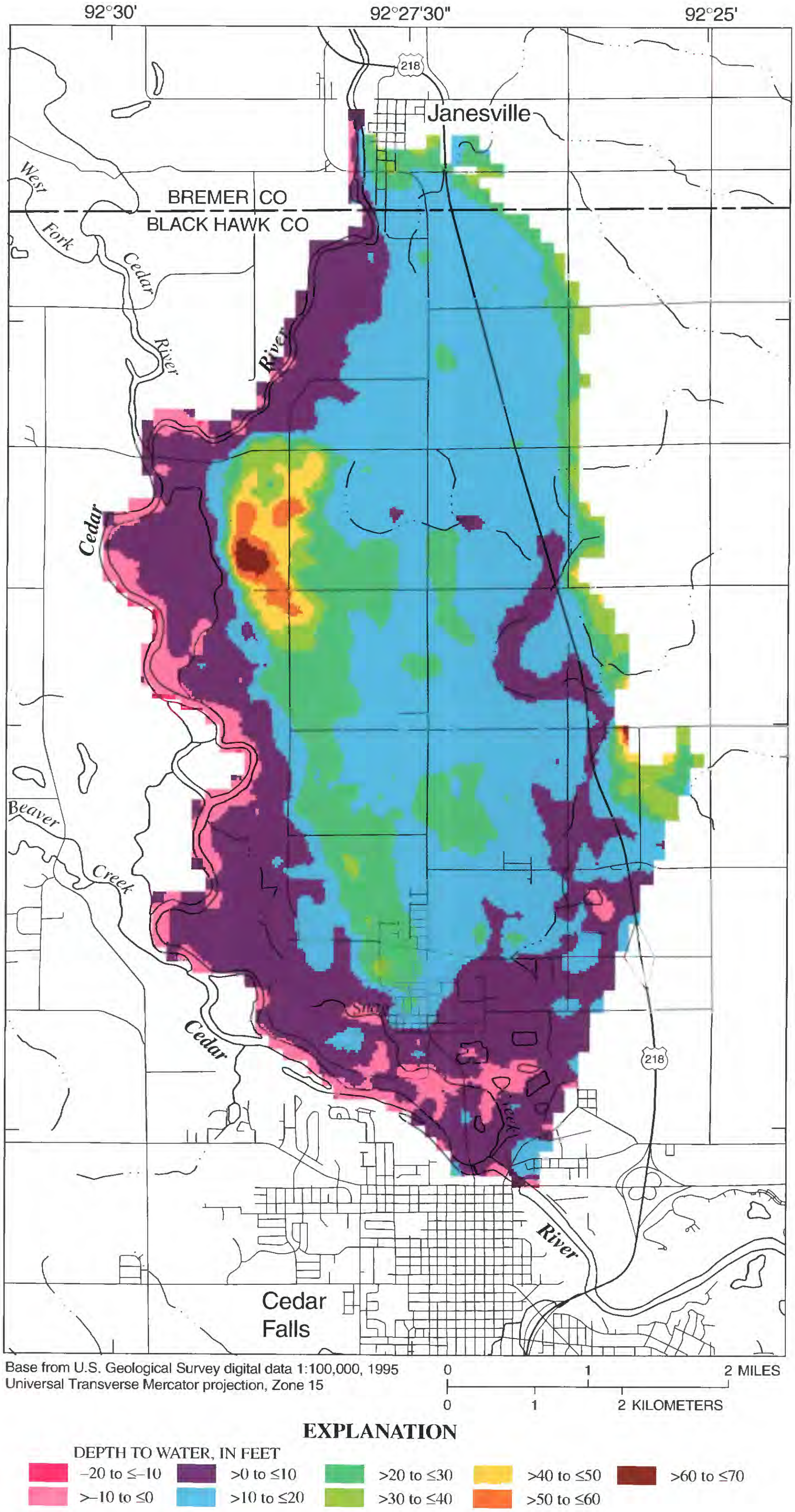


Figure 14. Depth to water table for steady-state calibrated model.

Results of the calibrated steady-state flow model support the interpretation that ground-water flow in the alluvium is primarily toward the south. This direction of flow is probably enhanced by the greater hydraulic conductivity of the unconsolidated materials in the southern and eastern parts of the study area and possibly by the lower Cedar River stage in the southern part of the study area. Shallow depths to the water table occur in areas near Highway 218. The intermittent streams simulated with drain cells remove more water from the ground-water flow system than does the Cedar River; however, the amount of time required to accomplish this removal is not known.

Two hypothetical scenarios were used to assess the potential effects of higher river levels and increased local recharge compared to the steady-state conditions. River levels higher than the steady-state model might be associated with a large recharge event, such as a large rainstorm that affects a large part of the drainage basin or snowmelt in the spring. The higher river levels for these scenarios were based on bankfull levels established by the National Weather Service for the Cedar River at Janesville (National Weather Service, 2002a) and Cedar River at Waterloo (National Weather Service, 2002b) gaging stations and estimating river levels between these two points by considering low-flow and flood-profile information collected during 1999 (Ballew and Eash, 2001). Recharge greater than the steady-state model might be associated with a greater than normal increase in precipitation in the study area.

For the first hypothetical scenario, river levels were set to bankfull conditions, and a recharge rate of 1.2 times the steady-state rate was applied to simulate wet conditions in the study area. This scenario led to increased water levels in general. Of particular interest are the large areas with shallow (0 to 10 ft) depths to water in the eastern part of the model area along Highway 218 (fig. 15). Also, there was a strikingly reduced (over 0.7 million ft^3/d) simulated discharge of the ground-water flow system to the Cedar River, probably due to the higher river stages that reduce or eliminate gradients favorable for ground-water discharge to the river. The result is that the intermittent streams (drains) in the study area are required to remove additional water.

For the second hypothetical scenario, conditions were the same as for the first, but drain conductance was increased to 10 times the value used in the calibrated steady-state model to simulate the effect of increasing the amount of drainage in the model area. The area with depth to water of 0 to 10 ft along the eastern part of the model area is substantially smaller than for the first hypothetical scenario (fig. 16) indicating that an increase in the ability to remove water from the alluvium through drains will result in lower water levels in the area near the drains. The flow budget for this scenario reflects the tenfold increase in discharge from the drain cells.

In general, it appears that once high ground-water levels in the central part of the study area develop, either because of high Cedar River water levels or above normal local precipitation, or both, ground-water flow from the central part of the study area near Highway 218 is toward the south rather than by shorter flow paths to the Cedar River to the west. The intermittent streams contribute significantly to discharging water from the ground-water flow system during wet conditions.

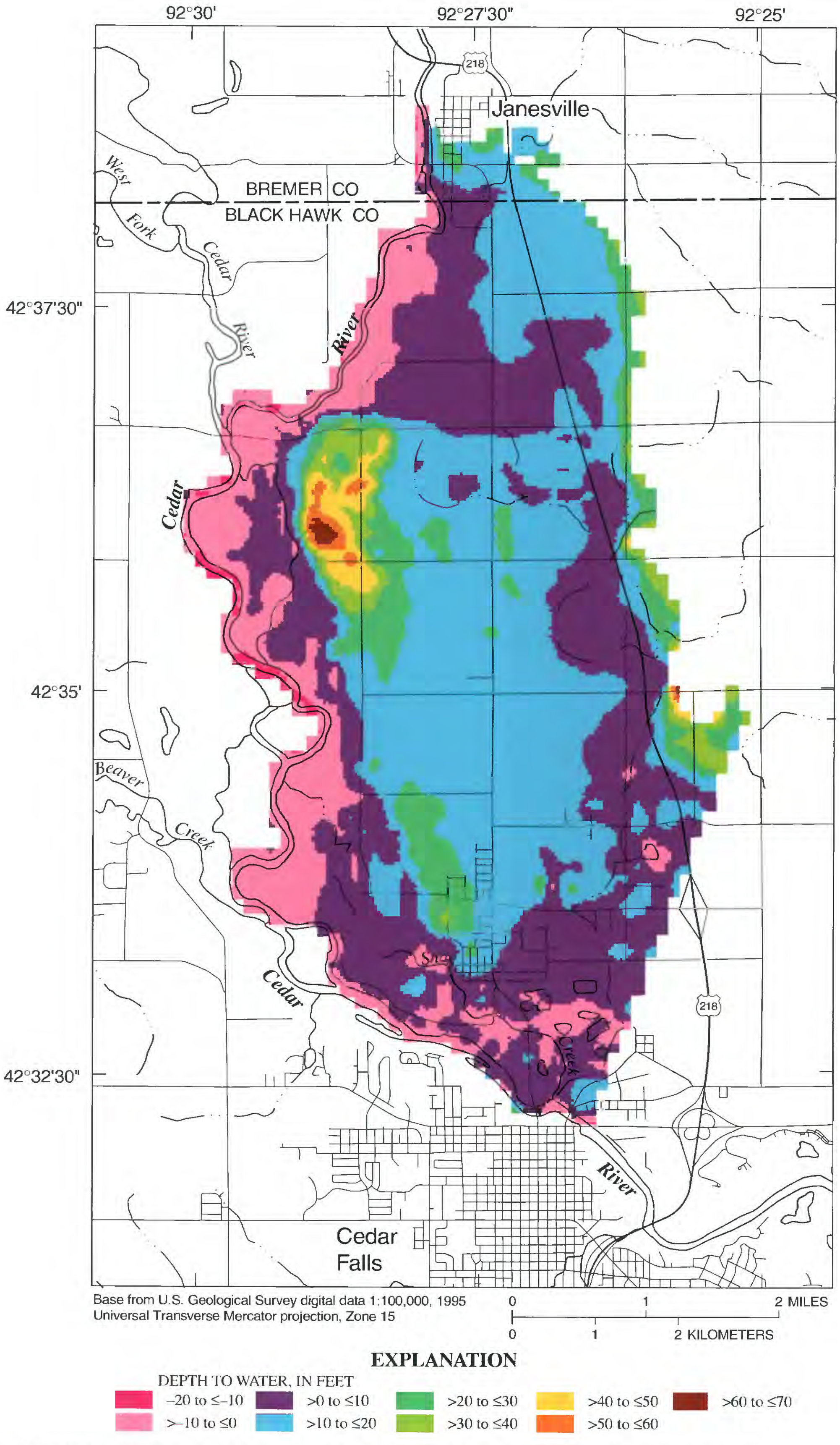


Figure 15. Depth to water table for the high-river, high-recharge, steady-state scenario.

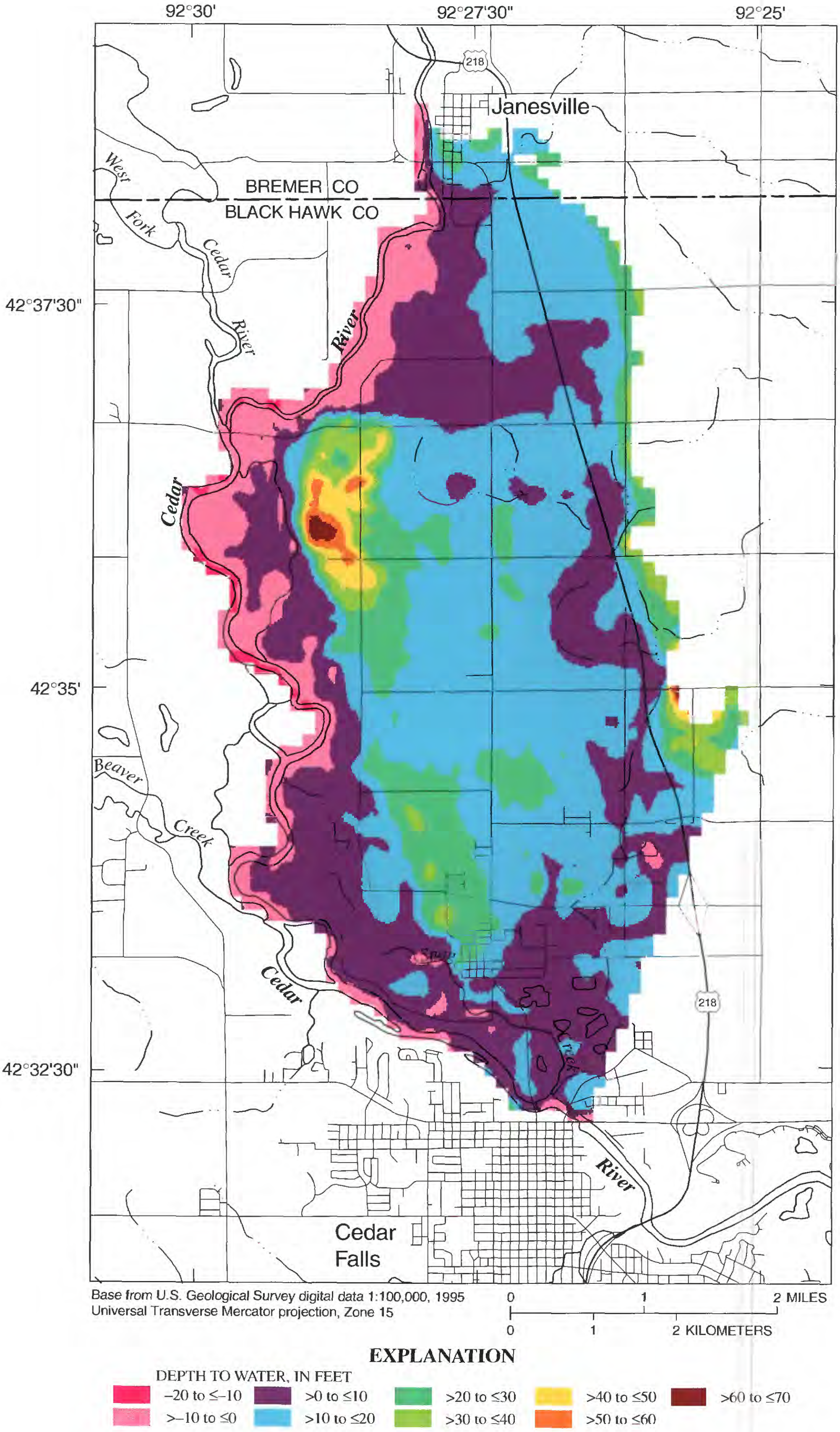


Figure 16. Depth to water table for the high-river, high-recharge, high-drain conductivity, steady-state scenario.

SUMMARY

The USGS, in cooperation with the Black Hawk County Board of Supervisors and the County Engineer's office, conducted a hydrologic study of the Cedar River alluvium in northwest Black Hawk and southwest Bremer Counties, Iowa, to improve understanding of the ground-water flow system, particularly during times of flooding and high ground-water levels. The purposes of this report are (1) to delineate and characterize the extent of unconsolidated deposits in the study area, (2) to describe hydrologic data used to facilitate analysis of surface-water and ground-water movement in the study area, and (3) to describe development of a ground-water flow model and the simulation of aquifer response to selected stresses.

Streamflow measurements made during November 2001 indicated that during these low-flow conditions, flow to and from the Cedar River to the ground-water system were within the limits of measurement error. A water-table surface map for the Cedar River alluvium was constructed from water-level measurements recorded at USGS observation wells and selected Cedar River sites on November 13–14, 2001, which shows the direction of ground-water flow in the alluvium is generally parallel to and east of the Cedar River. A bedrock valley, possibly formed by erosion from a paleochannel of the Cedar River, underlies the central part of the study area. Hydraulic conductivities in the Cedar River alluvium were estimated with slug-test analyses in 14 observation wells. The estimated hydraulic conductivity values in the observation wells ranged over four orders of magnitude, which is an indication of the natural heterogeneity of geologic materials, and are largest in the eastern and southeastern parts of the study area.

The ground-water flow model consists of two layers. In general, layer 1 represents the unconsolidated deposits and layer 2 represents the bedrock of Silurian and Devonian age. Flow in layer 1 is simulated as unconfined (water-table conditions) and flow in layer 2 is simulated as confined. An 83-row by 47-column grid was used to discretize part of the study area (model area) into a grid of approximately 500-ft by 500-ft cells. The active cells of layer 1 in the model coincide with the area where the alluvium is present.

Simulated water levels were most sensitive to recharge and to horizontal hydraulic conductivity in layers 1 and 2. Water levels were insensitive to vertical hydraulic conductivity in layers 1 and 2 and in the conductance of the riverbed, drainbed, and general-head boundary. River leakage was most sensitive to recharge and horizontal hydraulic conductivity in layer 2, whereas horizontal hydraulic conductivity in layer 1 and vertical hydraulic conductivity in layer 1 and 2 had less of an effect.

Primary sources of inflow to the ground-water flow system are Cedar River leakage (65.5 percent) and infiltration of precipitation and upland runoff (31.4 percent). All of these sources of inflow enter the system through the alluvium.

The primary components of outflow from the ground-water system are leakage to the drains (56 percent) and the Cedar River (43.7 percent), which leaves the system through the alluvium. Pumpage from the bedrock and flow across the general-head boundaries of the model account for less than 1 percent of the total ground-water outflow.

Two hypothetical scenarios were used to assess the potential effects of higher river levels and increased local recharge compared to the steady-state conditions. For the first hypothetical scenario, river levels were set to bankfull conditions and a recharge rate of 1.2 times the steady-state rate was applied to simulate wet conditions in the study area. This scenario led to increased water levels in general and a large area of shallow (0 to 10 ft) depths to water along the eastern part of the model area near Highway 218.

For the second hypothetical scenario, conditions were the same as for first, but drain conductance was increased to 10 times the value used in calibrated steady-state model to simulate the effect of increasing the amount of drainage in the model area. The area with depth to water of 0 to 10 ft along the eastern part of the model area is substantially smaller than for the first hypothetical scenario.

In general, it appears that once high ground-water levels develop, either because of high Cedar River water levels or above normal local precipitation or both, ground-water flow from the central part of the study area along Highway 218 is toward the south rather than shorter flow paths to the Cedar River. Intermittent streams play an important part in discharging water from the ground-water flow system.

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APPENDIX

Appendix. Description of drilled test holes and geologic information

[(lf), lithic fragments]

Test-hole identifier[1] (fig. 1)	Location land net [2]	Geologic unit	Drilled depth, feet below land surface	Driller's log/cuttings description
1	T90N–R14W–01BCCC (42°38′09″92°27′20″)	Quaternary-age alluvium	0–4	Soil, silty
			4–6	Clay, silty
			6–10	Sand, medium to fine
			10–26	Sand, medium with pebbles (lf)
			26–75	Sand, medium to coarse, with pebbles (lf)
2	T90N–R14W–12BAB (42°37′41″ 92°26′53″)	Quaternary-age alluvium	0–2	Soil, clayey
			2–5	Clay, silty
			5–10	Sand, fine with pebbles (lf)
			10–15	Sand, fine to medium with pebbles (lf)
			15–18	Sand, medium to coarse with pebbles (lf)
			18–23	Till, initially silty to clay
			23	Bedrock, no cuttings
3	T90N–R14W–11ACC (42°37′16″ 92°28′00″)	Quaternary-age alluvium	0–4	Soil, silty
			4–10	Sand, medium
			10–15	Sand, medium to coarse with pebbles (lf)
			15–28	Sand, coarse to medium with pebbles (lf)
4	T90N–R14W–12DDC (42°36′50″ 92°26′28″)	Quaternary-age alluvium	0–4	Soil, silty
			4–14	Sand, medium with pebbles (lf)
			14–17.5	Till, silty sandy clay
			17.5	Bedrock, no cuttings
5	T90N–R14W–13BCC (42°36′28″ 92°27′11″)	Quaternary-age alluvium	0–3	Soil, silty
			3–4	Sand, fine to medium with pebbles (lf)
			4–25	Sand, medium to coarse with pebbles (lf)
			25–35	Sand, very coarse with pebbles (lf)
			35–42.5	Sand and gravel, very coarse
6	T90N–R13W–19BBC (42°35′48″ 92°26′10″)	Quaternary-age alluvium	0–5	Soil, silty with pebbles (lf)
			5–21.5	Sand, medium with pebbles (lf)
7	T90N–R14W–22DDB (42°35′16″ 92°28′40″)	Quaternary-age alluvium	0–5	Soil, silty
			5–10	Sand, fine to medium
			10–20	Sand, medium to coarse with pebbles (lf)
			20–28.5	Sand and gravel, very coarse
			28.5	Bedrock, no cuttings
8	T90N–R14W–24CCC (42°35′11″ 92°27′18″)	Quaternary-age alluvium	0–2	Soil, silty
			2–4	Sand, medium with pebbles (lf)
			4–11	Sand, medium to coarse with pebbles (lf)
			11–42	Sand, coarse to medium with pebbles (lf)
9	T90N–R14W–26CBC (42°34′26″ 92°28′31″)	Quaternary-age alluvium	0–4	Soil, silty
			4–10	Sand, fine
			10–12	Sand, fine to medium with pebbles (lf)
			12–18	Sand, medium to coarse with pebbles (lf)
			18–30	Sand, coarse to medium with pebbles (lf)
			30–42	Sand, medium to fine with pebbles (lf)
10	T90N–R13W–30CCB (42°34′23″ 92°26′11″)	Quaternary-age alluvium	0–4	Soil, silty
			4–10	Sand, fine
			10–12	Sand, fine to medium with pebbles (lf)
			12–18	Sand, medium to coarse with pebbles (lf)
			18–30	Sand, coarse to medium with pebbles (lf)
			30–42	Sand, medium to fine with pebbles (lf)

Appendix. Description of drilled test holes and geologic information—Continued

[(lf), lithic fragments]

Test-hole identifier[1] (fig. 1)	Location land net [2]	Geologic unit	Drilled depth, feet below land surface	Driller's log/cuttings description
11	T90N–R13W–29CCC (42°34′14″ 92°24′58″)	Quaternary-age alluvium	0–4	Soil, silty sandy
			4–16	Sand, medium to coarse with pebbles (lf)
			16–17	Sand, medium to coarse
			17–25	Sand, medium to coarse with pebbles (lf)
			25–47	Sand and gravel, very coarse with pebbles (lf)
12	T90N–R14W–35ADB (42°33′55″ 92°27′36″)	Quaternary-age alluvium	0–3	Soil, silty clay
			3–6	Clay, silty
			6–15	Sand, medium to fine
			15–25	Sand, fine with few pebbles (lf)
			25–36	Sand, medium to coarse with pebbles (lf)
			36–42	Till, clay
13	T90N–R13W–31DBD (42°33′40″ 92°25′21″)	Quaternary-age alluvium	0–2	Soil, silty
			2–4	Silt, clayey
			4–25	Sand, medium to coarse with pebbles (lf)
			25–43	Sand, medium to coarse
14	T89N–R13W–06BBB (42°33′21″ 92°26′10″)	Quaternary-age alluvium	0–1	Soil, silty
			1–3	Sand, medium
			3–9	Sand, fine to medium with pebbles (lf)
			9–18	Sand, fine to medium, few pebbles
			18–25	Sand, medium to coarse, few pebbles
			25–45	Sand, very coarse grained
			45–65	Sand, medium to coarse with pebbles (lf)
			65–77.5	Till, clay
15	T90N–R13W–06DCC (42°37′43″ 92°25′28″)	Pleistocene-age loess and till	0–1	Soil, silty
			1–13	Sand, fine, silty
			13–15	Sand , fine, silty clay
			15–21	Loess, silty clay
			21–29	Till, clay
16	T90N–R14W–15AAD (42°36′38″ 92°28′30″)	Pleistocene-age loess and till	0–2	Soil, sandy
			2–7	Sand, fine to medium
			7–15	Sand, fine, silty with depth
			15–26	Till, silty clay with pebbles
17	T90N–R13W–20BCC (42°35′34″ 92°24′58″)	Pleistocene-age loess and till	0–2	Soil, silty
			2–10	Sand, fine, silty
			10–14	Loess, silty clay, some fine sand
			14–23	Till, clay
			23–37	Till, clay with some pebbles (lf)

[1] Sites 1 to 17 drilled by U.S. Geological Survey, September 18 to October 6, 2000.

[2] Location indicated by township, range and section. The letters after the section number represent successive subdivisions of the section assigned in a counterclockwise direction beginning with 'A' in the northeast quarter. The first letter indicates a 160-acre area. Each successive letter indicates an area one-fourth the size of the area represented by the previous letter.

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