

Prepared in cooperation with the Johnson County Board of Supervisors, Iowa

# Simulation of Groundwater Flow in the Silurian Aquifer, Eastern Iowa, 2020–45

Scientific Investigations Report 2026–5020

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

**Cover.** Photograph showing an outcrop of Silurian rocks by the Cedar River, taken at Cedar Valley Park in Cedar County, Iowa, on May 2, 2026, by Emilia Bristow, U.S. Geological Survey.

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By Emilia Bristow, John M. Gannon, and Andrew Williams

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**U.S. Geological Survey**

## U.S. Geological Survey, Reston, Virginia: 2026

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Iowa Geological Survey, 2022, GeoSam: Iowa Geological Survey database, <https://www.ihr.uiowa.edu/igs/GeoSam/home>.

Iowa Geological Survey, 2023, IGS Pump Test: Iowa Geological Survey database, <https://www.ihr.uiowa.edu/igs/pump-test/home>. [Also available at <https://igs.ihr.uiowa.edu/igs/pump-test/home>.]

U.S. Geological Survey, 2025, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, <https://doi.org/10.5066/F7P55KJN>.

Williams, A.M., and Gannon, J.M., 2026, Multi-well aquifer test characteristics for Johnson County, Iowa, 1943–2022: U.S. Geological Survey data release, <https://doi.org/10.3133/P9M0YR6M>.

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## Conversion Factors

U.S. customary units to International System of Units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
	Length	
foot (ft)	0.3048	meter (m)

International System of Units to U.S. customary units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m <sup>2</sup> )	0.0002471	acre
square meter (m <sup>2</sup> )	10.76	square foot (ft <sup>2</sup> )
square kilometer (km <sup>2</sup> )	0.3861	square mile (mi <sup>2</sup> )
	Flow rate	
square meter per day (m <sup>2</sup> /d)	10.76	square foot per day (ft <sup>2</sup> /d)
cubic meter per second (m <sup>3</sup> /s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m <sup>3</sup> /s)	35.31	cubic foot per second (ft <sup>3</sup> /s)
cubic meter per day (m <sup>3</sup> /d)	264.2	gallon per day (gal/d)
centimeter per year (cm/yr)	0.3937	inch per year (in/yr)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)

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

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

## Datums

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).

Elevation, as used in this report, refers to distance above the vertical datum.

## Supplemental Information

Specific storage (dimensionless) is given per meter ( $m^{-1}$ ).

## Abbreviations

~	about
CHB	Constant Head Boundary [package]
GHB	General Head Boundary [package]
PEST	parameter estimation
RMSE	root mean square error
USGS	U.S. Geological Survey

# Simulation of Groundwater Flow in the Silurian Aquifer, Eastern Iowa, 2020–45

By Emilia Bristow, John M. Gannon, and Andrew Williams

## Abstract

The Silurian aquifer is an important water source for municipalities, industry, and rural households and communities in eastern Iowa, including Johnson County. Increasing demand for groundwater from the aquifer indicated that analytical tools may be beneficial to quantify groundwater resources and inform water-management decisions for the aquifer. The U.S. Geological Survey, in cooperation with the Johnson County Board of Supervisors, developed conceptual and numerical groundwater models to simulate water levels in the Silurian aquifer, determine groundwater budgets, and forecast changes in groundwater levels through 2045. A MODFLOW numerical model was constructed to match water levels for 2020 through 2022. Model performance was assessed by comparing simulated and observed water-level hydrographs at several pumping and monitoring wells. Hydrograph comparison indicates that the model simulates water levels accurately at monitoring wells that are not near areas of pumping and generally overpredicts water levels near pumping wells, while accurately simulating the drawdown trend over time at pumping wells. This transient model framework was then used to predict water levels through 2045 in a scenario of moderate drought and increased groundwater withdrawals. Results from the predictive model indicate as much as 13 meters of additional drawdown in 2045 from 2020 water levels in the area of pumping wells.

## Plain Language Summary

Increasing demand for groundwater from the Silurian aquifer by municipalities, industry, and rural households and communities in eastern Iowa, including Johnson County, led to the U.S. Geological Survey, in cooperation with Johnson County Board of Supervisors, developing conceptual and numerical groundwater models to simulate water levels in the aquifer, determine groundwater budgets, and forecast changes in groundwater levels through 2045. The numerical model simulates water levels accurately at monitoring wells that are not near areas of pumping, and it generally overpredicts water levels near pumping wells but accurately simulates the

drawdown trend over time at pumping wells. Results of one version of the numerical model, the predictive model, indicate as much as 13 meters of additional drawdown in 2045 from 2020 water levels in the area of pumping wells.

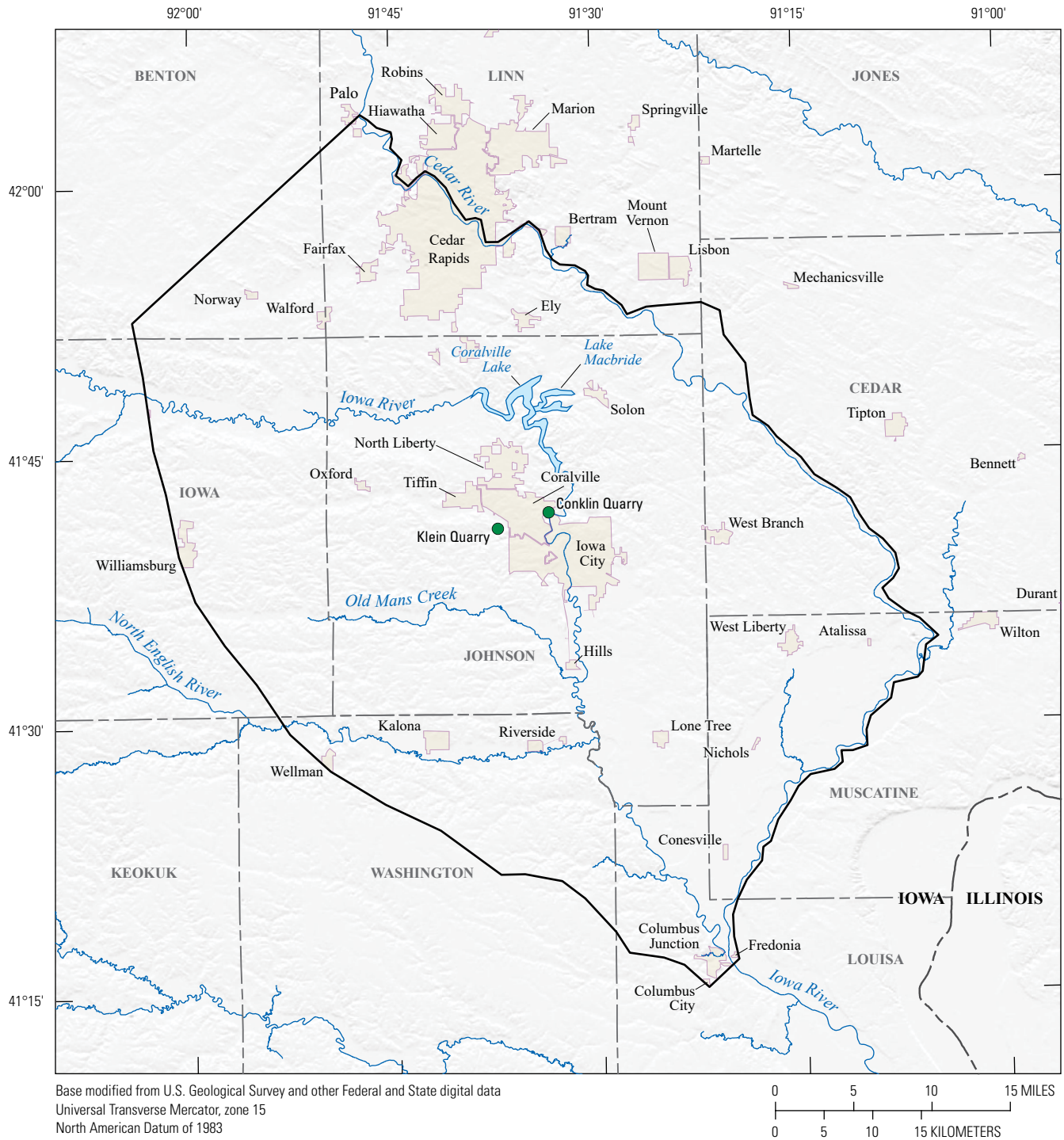
## Introduction

The Silurian aquifer is an important source of groundwater in eastern Iowa, including Johnson County (fig. 1; Prior and others, 2003). Wells completed in the Silurian aquifer supply groundwater to municipalities, industry, and rural households and communities (Gannon and others, 2011). From 2010 to 2021, the population in Johnson County increased by 18 percent, from 130,882 to 154,748 (U.S. Census Bureau, 2022). Simultaneously, total groundwater withdrawals from the Silurian aquifer in Johnson County increased from 0.12 cubic meter per second ( $\text{m}^3/\text{s}$ ) in 2010 to 0.15  $\text{m}^3/\text{s}$  in 2021, or about (~) 25 percent (Iowa Department of Natural Resources, 2023).

Because of the increase in water demand, analytical tools may be beneficial to quantify groundwater resources and to inform water-management decisions for the Silurian aquifer in Johnson County. In 2022, the U.S. Geological Survey (USGS), in cooperation with Johnson County Planning and Zoning, began developing these tools by collecting data about the hydrogeology of Johnson County and designing a groundwater-flow model to simulate water levels in the Silurian aquifer. The purpose of this study is to provide a quantitative assessment of groundwater in the Silurian aquifer system of Johnson County using a groundwater-flow model that also can be used by local governmental agencies as an analytical water-management tool.

This study included the construction of conceptual and numerical three-dimensional groundwater-flow models to characterize and simulate the Silurian aquifer within the model area. The numerical groundwater model was used for quantitative assessment to determine groundwater budgets, forecast changes in groundwater levels, and determine long-term (2025–45) decreases in aquifer storage. The model area included Johnson County and parts of Linn, Benton, Iowa, Washington, Louisa, Muscatine, and Cedar Counties (fig. 1). In addition to the Silurian aquifer, the model also included

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**Figure 1.** Map showing the extent of the groundwater model area in eastern Iowa.

the overlying Devonian strata as a confining unit and a source of recharge to the Silurian aquifer. This report describes the geology and hydrogeology of the Silurian aquifer system; documents the conceptualization, construction, and calibration of a groundwater-flow model of the aquifer systems; and provides estimates of the effects of anticipated future groundwater development and drought with simulations of groundwater flow.

## Previous Studies

Previous studies estimated water budgets for the Silurian aquifer using groundwater models. A two-layered groundwater-flow model, using the same boundaries as Johnson County, was constructed and calibrated by the USGS in 2006 (Tucci and McKay, 2006). In the Tucci and McKay (2006) model, the Silurian aquifer and the overlying Devonian aquifer were combined to form one hydraulically connected system. The model was calibrated to steady-state conditions and then used to forecast future drawdowns using projected 2025 groundwater pumping rates at existing and anticipated new wells. Groundwater levels projected by the forecast model were 0.3 to 3.3 meters (m) lower throughout the county than 2005 groundwater levels. When potential future drought conditions were incorporated into the forecast simulation, with a 25-percent reduction in recharge to the Silurian-Devonian aquifer system and a 25-percent increase in projected water use, simulated future groundwater levels were 1.5 to 9.1 m lower than 2005 groundwater levels.

In 2011, a three-layered groundwater-flow model was constructed by the Iowa Geological Survey for 12 counties in eastern Iowa, including Johnson County (Gannon and others, 2011). The model conceptualized the Silurian aquifer as a distinct hydrogeologic unit from the Devonian aquifer and was calibrated to steady-state and transient conditions. Forecasts using the groundwater model estimated that increasing pumping of the City of Coralville wells by 3 percent per year from 2012 to 2022 would result in 3.0–9.1 m of total drawdown within the Coralville wellfield.

## Purpose and Scope

The purpose of this report is to describe the conceptual and numerical groundwater-flow models for the Silurian aquifer system in the model area. Steady-state and transient numerical models were constructed and calibrated. The transient model was modified to forecast the effects of estimated future water use through 2045. The model detailed here simulates water levels in the Silurian aquifer in Johnson County and could be used to assess the sustainability of the aquifer and assist communities with decision making and planning for long-term (2025–45) water supplies.

## Model Area Description

The model area is in east-central Iowa (fig. 1) and covers an area of ~4,139 square kilometers. The model area includes all of Johnson County and parts of adjoining Linn, Benton, Iowa, Washington, Louisa, Muscatine, and Cedar Counties. Major cities in the model area include Cedar Rapids, with a population of ~136,000 in 2022, and Iowa City, with a population of ~75,000 in 2022 (U.S. Census Bureau, 2022). Other municipalities in the model area include the Cities of Coralville, North Liberty, Solon, and Tiffin (fig. 1).

The model area surficial landscape consists of incised valleys eroded into and through glacial deposits and bedrock, widely mantled by loess (Prior, 1991). Major river valleys in the model area are filled with alluvial sediment and have areas of bedrock outcroppings at the valley margins. Land surface elevations in the model area range from 176.5 m above the North American Vertical Datum of 1988 in northern Louisa County to 285 m in southeastern Benton County. Major rivers within the model area include the Iowa River (about a 154-kilometer [km] reach) and the Cedar River (about a 151-km reach; fig. 1). Two reservoirs, Coralville Lake and Lake Macbride, are in north-central Johnson County.

The model area is in a humid continental climate with hot and humid summers and cold winters. Average annual precipitation over the 30-year period from 1991 to 2020 was ~97.7 centimeters (cm) at Iowa City in the center of the model area (National Centers for Environmental Information, 2025). Annual precipitation from 2012 to 2023 ranged from 55.3 cm in 2023 to 121.9 cm in 2018. Mean monthly precipitation is generally lowest in January and February (~2.5 cm per month) and greatest in June (~12.7 cm). Monthly average high temperatures range from 0 degrees Celsius (°C) in January to 30.5 °C in July (National Centers for Environmental Information, 2025).

## Geology

The geology of the model area includes Quaternary unconsolidated deposits underlain by Paleozoic bedrock units. The geologic units discussed in this section use naming conventions from the Iowa Geological Survey (Gannon and others, 2011; fig. 2) and are presented from youngest to oldest, following the order of model hydrogeologic units from the land surface downward. Previous hydrologic investigations in eastern Iowa commonly grouped Silurian and overlying Middle Devonian strata into a single aquifer system called the “Silurian-Devonian aquifer” (Horick, 1984; Tucci and McKay, 2006). However, hydrologic separation and hydraulic head differences between these water-bearing Silurian and Devonian strata are evident in much of the model area (Gannon and others, 2011). This study conceptualizes the Devonian and Silurian aquifers as two distinct hydrogeologic units and focuses on the Silurian aquifer.

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Geologic era	Geologic period	Geologic units	Description	Hydrogeologic unit	Hydrostratigraphic unit (model layer)
Cenozoic	Quaternary	Quaternary undifferentiated	Glacial deposits, loess, sand and gravel, clay	Quaternary confining unit	Upper confining unit (layer 1)
Paleozoic	Pennsylvanian	Cherokee Group	Shale, sandstone	Cherokee confining unit	
	Mississippian	Early Mississippian Units (Kinderhookian)	Dolomite and limestone	Mississippian confining unit	
	Upper Devonian	Maple Mill Formation Sheffield Formation Lime Creek Formation	Shale with some dolostone	Upper Devonian shale confining unit	
	Middle Devonian	Cedar Valley Group: Lithograph City Formation Coralville Formation Little Cedar Formation	Limestone	Devonian aquifer	Devonian aquifer (layer 2)
	Lower Devonian	Wapsipinicon Group (continued): Pinicon Ridge Formation, Kenwood Member	Shale	Confining unit	Devonian confining layer (layer 3)
Lower Devonian		Wapsipinicon Group (continued): Otis Formation	Limestone and dolomite	Silurian aquifer	Silurian aquifer (layer 4)
	Silurian	Gower Formation Scotch Grove Formation Hopkinton Formation Blanding Formation	Dolostone, variably cherty		
Upper Ordovician	Maquoketa Formation	Shale with some dolostone	Maquoketa confining unit	Lower confining unit (layer 5)	

**Figure 2.** Diagram showing geologic and hydrogeologic information used to develop the five hydrogeologic layers in the model (geologic units follow terminology used by the Iowa Geological Survey [2004; 2010]).

## Quaternary Deposits

The unconsolidated Quaternary geologic materials from the land surface to the underlying bedrock units are known from well data and from exposures at the Klein and Conklin Quarries near the City of Coralville, Iowa (Kemmis and others, 1992). These deposits consist of a complex interlayered sequence of glacial till and intertill deposits, including paleosols and associated sediments, capped by loess or alluvium (Hallberg, 1980; Tassier-Surine and others, 2007). The thickness of these deposits varies across the model area from 0 m along segments of the Iowa and Cedar Rivers, where bedrock intersects the land surface, up to 141 m in southeastern and western Johnson County and parts of Cedar, Muscatine, and Louisa Counties, where bedrock valleys are located (fig. 3). The glacial till that forms the bulk of these Quaternary deposits consists primarily of clay with discontinuous lenses of silt, sand, and gravel (Schulmeyer and Schnoebelen, 1998). The upper part of the till is mostly oxidized and fractured, and the deeper unweathered till is unoxidized and unfractured (Schilling and Tassier-Surine, 2006). These deposits, particularly the unweathered till, generally have low permeability and are considered confining units that limit the vertical movement of groundwater. Where these deposits are present, recharge to the underlying bedrock is relatively lower. Where they are relatively thin or absent, recharge to the underlying bedrock is higher. Some private water wells are completed in the Quaternary deposits, mainly in the southern and western parts of Johnson County and usually in shallow alluvium or buried sand and gravel deposits. The City of Coralville has three production wells screened in a buried sand and gravel deposit, but these deposits seem to be isolated units within the glacial tills (Deb Tisor, River Products Company, Inc., written commun., January 2023).

## Devonian Stratigraphy

Devonian bedrock is the uppermost bedrock in most of the model area; Pennsylvanian- and Mississippian shales overlie Devonian bedrock in a small part of the model area, and Devonian bedrock has eroded along the Cedar River in the eastern part of the model area, exposing Silurian bedrock. Devonian System bedrock is divided into the Upper Devonian, Middle Devonian, and Lower Devonian Series (Hansen, 1970).

The Upper Devonian Series is the uppermost bedrock group in the southwestern half of Johnson County and is the first bedrock penetrated by wells near the Cities of North Liberty, Tiffin, and Hills (fig. 3). The Lime Creek Formation is the prevalent geologic unit in the Upper Devonian, but the overlying Sheffield and Maple Mill Formations

also are present in some areas. These units are composed predominantly of shale, although lesser carbonate interbeds are present. The thickness of the Upper Devonian Series ranges from 0 m in the northeastern part of the county to more than 100 m in the southwestern part of the county. Exposures of this unit are few in Johnson County but present in the Klein Quarry west of Iowa City, and small exposures are present along Coralville Lake. The Upper Devonian Series is a confining layer in the model.

The Middle Devonian Series in the model area consists of the Cedar Valley Group, a thick sequence of limestone present throughout Johnson County, except in the northeast, where Devonian units have eroded and Silurian units are present at the land surface (fig. 4). The Cedar Valley Group contains multiple formations, including from youngest to oldest, the Lithograph City Formation, the Coralville Formation, and the Little Cedar Formation. The Cedar Valley Group is exposed at the land surface along the Iowa River in Iowa City and upstream along Coralville Lake. The Cedar Valley Group is made up of relatively dense, pure limestone. The high calcite mineral content of the Cedar Valley limestones makes them susceptible to dissolution by groundwater, creating karst features such as caves and bedding plane voids. The dense and crystalline nature of the limestone imparts brittleness, and vertical and horizontal fractures are visible in some exposures. These fractures, some of which may be solution-enlarged, are the primary conduits for water movement through this unit (Witzke and others 1988). The Cedar Valley Group and the top part of the Lower Devonian, described in the following paragraph, form the Devonian aquifer, which serves as a source of water for some domestic wells in Johnson County. Where present, the aquifer typically ranges from 29 to 33 m thick.

The Lower Devonian Series in the model area is made up of the Wapsipinicon Group, which includes the Davenport, Spring Grove, and Kenwood Members of the Pinicon Ridge Formation, and the Otis Formation. The Davenport and Spring Grove Members, which consist of limestone and dolostone, make up the lower part of the Devonian aquifer. The Kenwood Member consists of 3.0–4.6 m of shale or shaly dolostone and is a confining unit underlying the Devonian aquifer, separating it from the underlying Silurian aquifer. The elevation of the top of the Devonian aquifer and the top of the shale of the Kenwood Member is shown in figures 5 and 6, respectively. The Otis Formation is a thin layer of fractured limestone and dolomite at the base of the Devonian System. The Otis Formation is hydrologically connected with the underlying Silurian bedrock and is part of the Silurian aquifer. Because the Otis Formation is thin, discontinuous, and not typically delineated in well logs, the elevation of the top of the Silurian aquifer used for this model is the elevation of the top of the Silurian rock.

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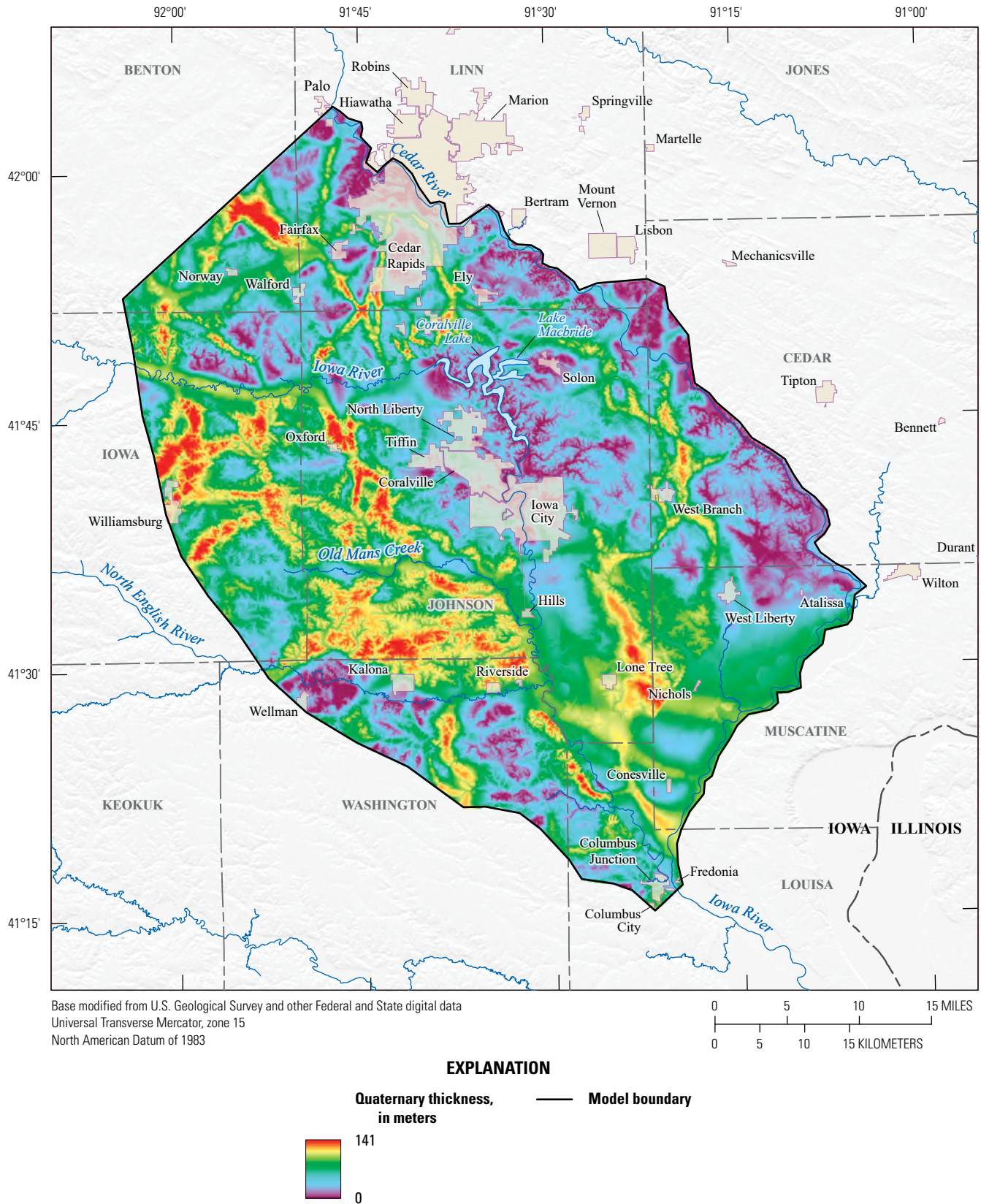


Figure 3. Map showing the Quaternary thickness, in meters, in the model area in eastern Iowa. Areas in red and orange identify bedrock valleys.

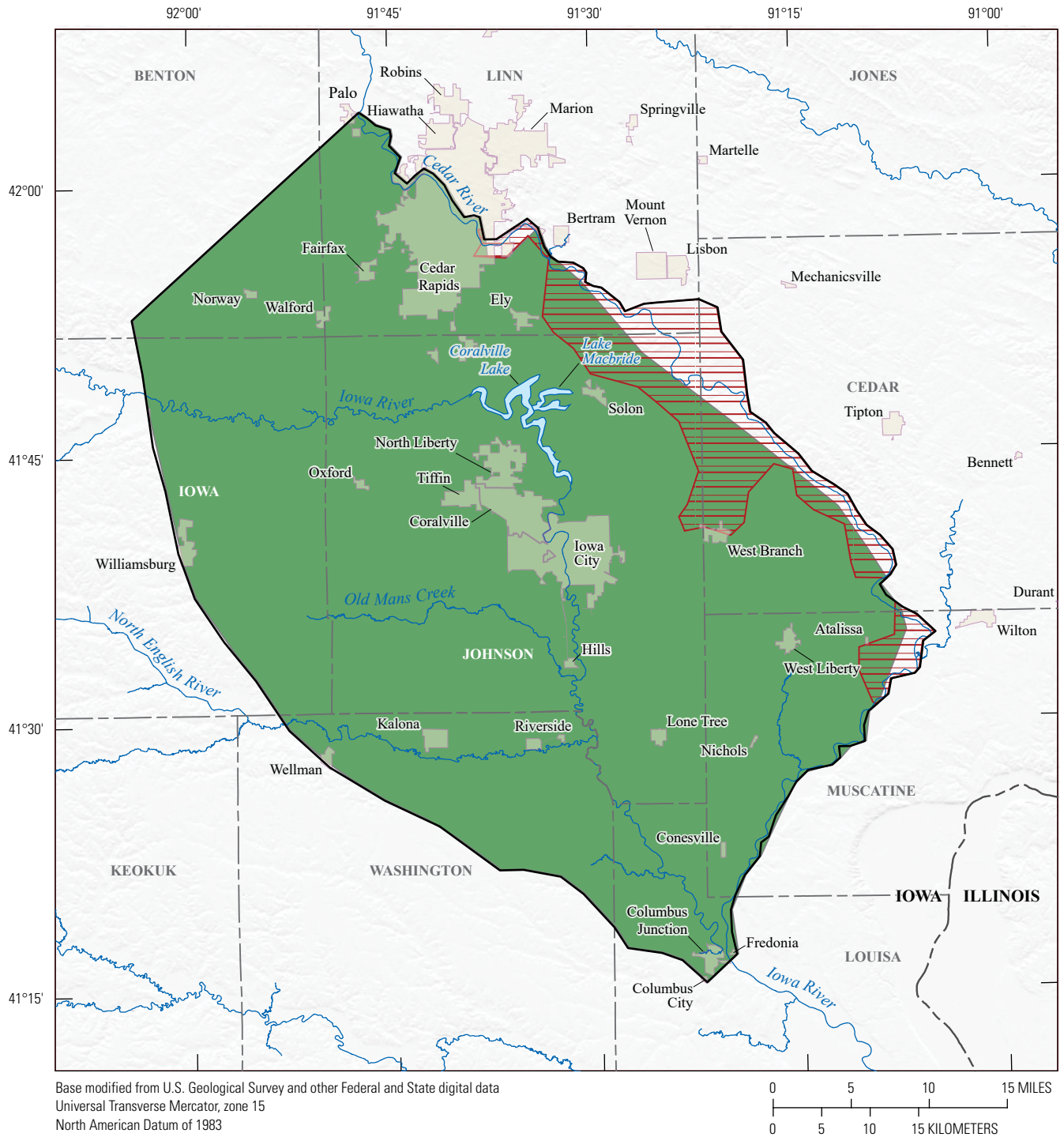


Figure 4. Map showing the Cedar Valley Group and Silurian units exposed at the surface in the model area in eastern Iowa.





## Silurian Stratigraphy

The Silurian bedrock in the model area consists of four geologic formations (from youngest to oldest): the Gower Formation, the Scotch Grove Formation, the Hopkinton Formation, and the Blanding Formation. The four formations are hydrologically connected and form one hydrogeologic unit called the Silurian aquifer. Witzke (1992) presented a detailed stratigraphy of these units from the Silurian outcrop belt of adjacent Linn and Jones Counties.

The Silurian units are a thick sequence of variably cherty dolostones and demonstrate lateral and vertical variation in texture, porosity, and fracture density (Gannon and others, 2011). Some of these variations are within the subsurface in the model area, but their effect on the hydraulic properties of the aquifer has not been investigated. Substantial variations in water yield have been recorded for many wells completed in the Silurian aquifer, likely related to changes in porosity and fracture density and the presence or absence of karst or solution features. Within the model area, the Silurian rocks composing the Silurian aquifer are mostly confined by overlying shales of the Kenwood Member and glacial till. The one known exception is along the Cedar River, where the Devonian units are absent and the glacial tills are relatively thin. In these areas, the uppermost bedrock is Silurian. The elevation of the top of the Silurian units and the points representing well logs used to define this surface (Iowa Geological Survey, 2022) are shown in [figure 7](#).

In the model area, the Silurian-age stratigraphy is thinnest (~3.0 m) in the southern part and thickest (~140 m) along the Linn and Johnson County boundary and in parts of Cedar County. In the Iowa City and City of North Liberty areas, the Silurian stratigraphy generally ranges in thickness from 61 to 76 m. Some variations in thickness are due to the uneven surface of the underlying Maquoketa Formation. Thinner areas of Silurian rock also are within bedrock valleys in the northern and southern parts of the model area, as shown on [figure 8](#).

## Maquoketa Formation

The Silurian rock is underlain by low-permeability shales of the Upper Ordovician Maquoketa Formation ([fig. 2](#); Gannon and others, 2011). The Maquoketa Formation is composed of shale strata with secondary dolomite units, especially in the lower and middle parts of the formation. The Maquoketa Formation is between 61 and 76 m thick in the model area. The thick shales form a regional confining unit that separates the overlying Silurian aquifer from the underlying Ordovician and Cambrian aquifers, which are not included in this model. The elevation of the top of the shales of the Maquoketa Formation, which was created using well information from GeoSam (Iowa Geological Survey, 2022), is shown in [figure 9](#).

## Conceptual Model

A conceptual model of the model area was constructed to represent the hydrogeology and water budget components of the study area. Hydrogeologic units in the study area were delineated using variations in lithology and hydrologic parameters to represent the groundwater-flow conditions in the model area. The conceptual model was used to construct the three-dimensional framework for the numerical model. This section describes the basic elements of the conceptual model, including the hydrogeologic units and water budget inflows and outflows.

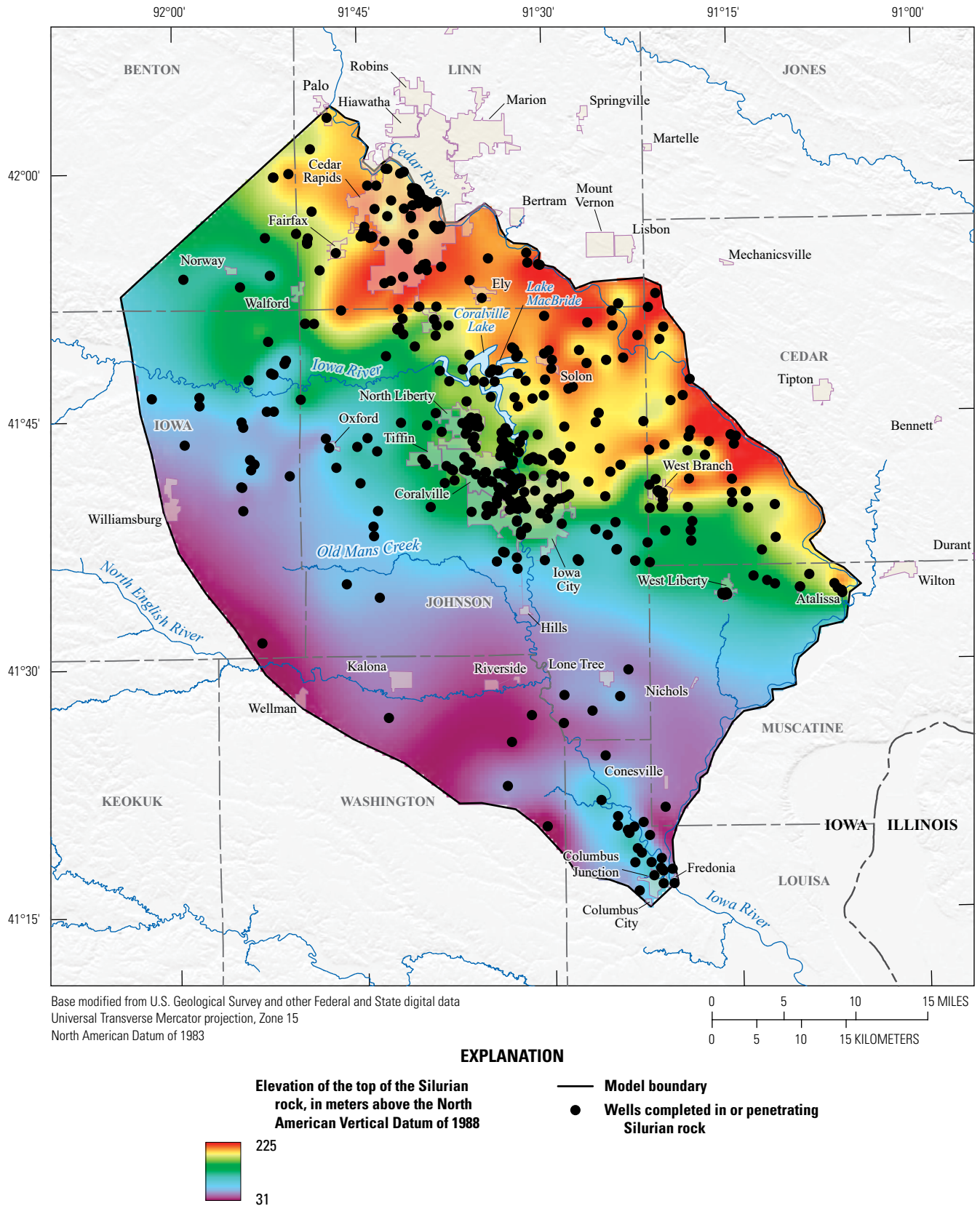
## Hydrogeologic Units

Five layered hydrogeologic units were defined for the conceptual model, each consisting of one or more geologic formations ([fig. 2](#)). Each hydrogeologic unit was conceptualized as either an aquifer or a confining unit. The conceptual model hydrogeologic units include, from top to bottom, (1) an upper confining layer consisting of surficial materials and some overlying bedrock, (2) the Devonian aquifer, (3) the Devonian confining layer, (4) the Silurian aquifer, and (5) the lower confining layer consisting of the Maquoketa Formation.

### Upper Confining Layer (Layer 1)

The uppermost hydrogeologic layer (model layer 1) included the following systems, groups, or formations combined into a single confining unit: the Quaternary System or undifferentiated deposits, Pennsylvanian System, Mississippian System (only present in a small part of the model area), and Upper Devonian System (western half of the model area). The top of layer 1 was defined as the land surface. The purpose of this layer was to provide a source of net recharge and to create confining conditions for model layer 2. The ground surface elevation was sampled at the model-cell scale from light detection and ranging digital elevation data (Iowa Geospatial Data, 2023).

Layer 1 varies in thickness from less than 7.6 m in parts of Cedar and northeastern Johnson Counties to more than 152 m in parts of Benton, Iowa, western Johnson, and Washington Counties. Layer 1 was conceptualized as a regional confining layer over most of the model area. Exceptions exist along parts of the Iowa and Cedar Rivers, where alluvial deposits are in direct contact with the Devonian and (or) Silurian aquifers. For most of layer 1, horizontal hydraulic conductivity values were uniformly assigned as 0.11 meter per day (m/d), and vertical hydraulic conductivity values were assigned as 0.011 m/d ([fig. 10](#)). Along the major river systems, Coralville Lake, and Lake Macbride ([fig. 1](#)), horizontal hydraulic conductivity values were uniformly



**Figure 7.** Map showing the elevation of the top of the Silurian units and wells used to define the top of the geologic surface in the model area in eastern Iowa.

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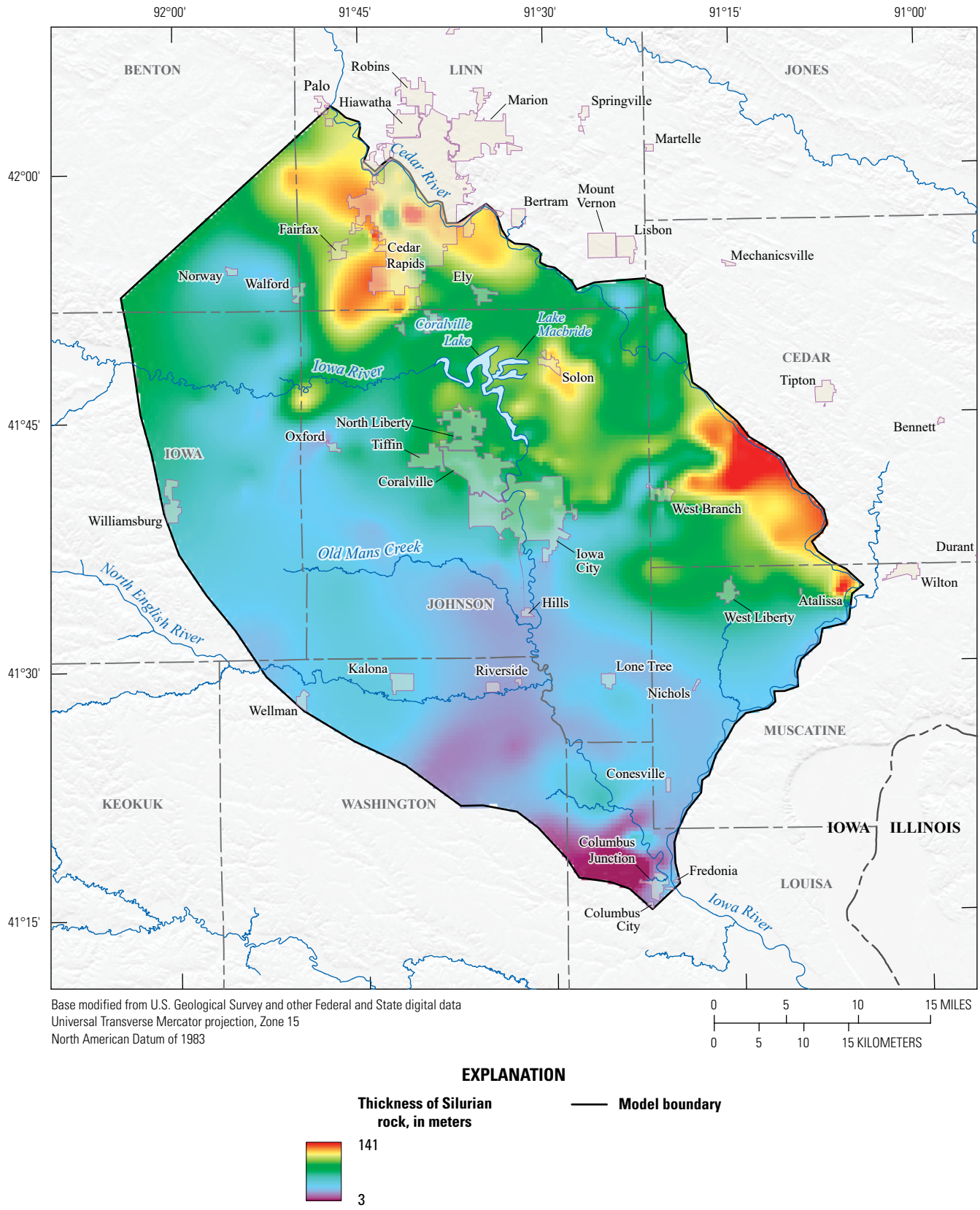


Figure 8. Map showing the thickness of the Silurian rock in the model area in eastern Iowa.

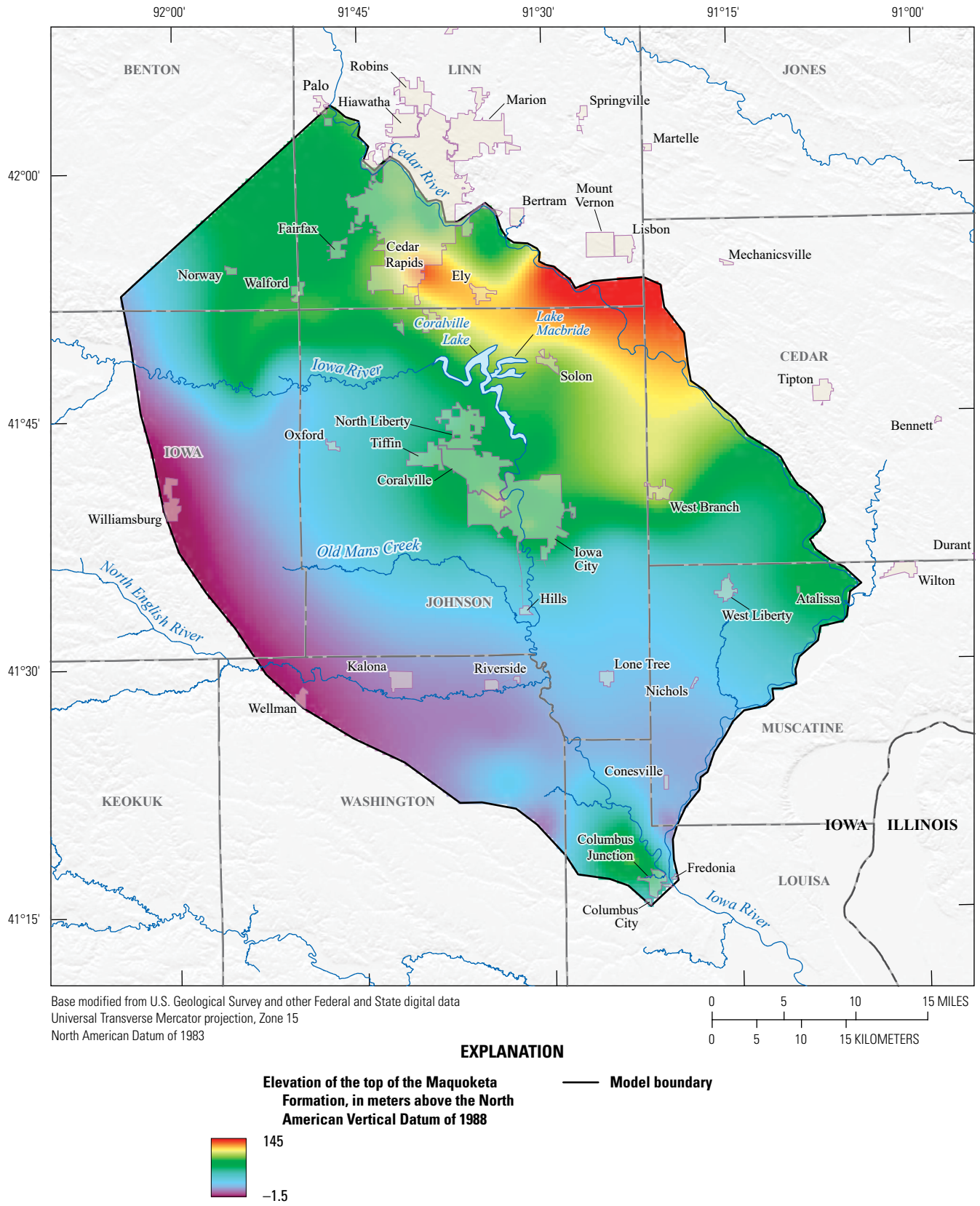


Figure 9. Map showing the elevation of the top of the Maquoketa Formation in the model area in eastern Iowa.

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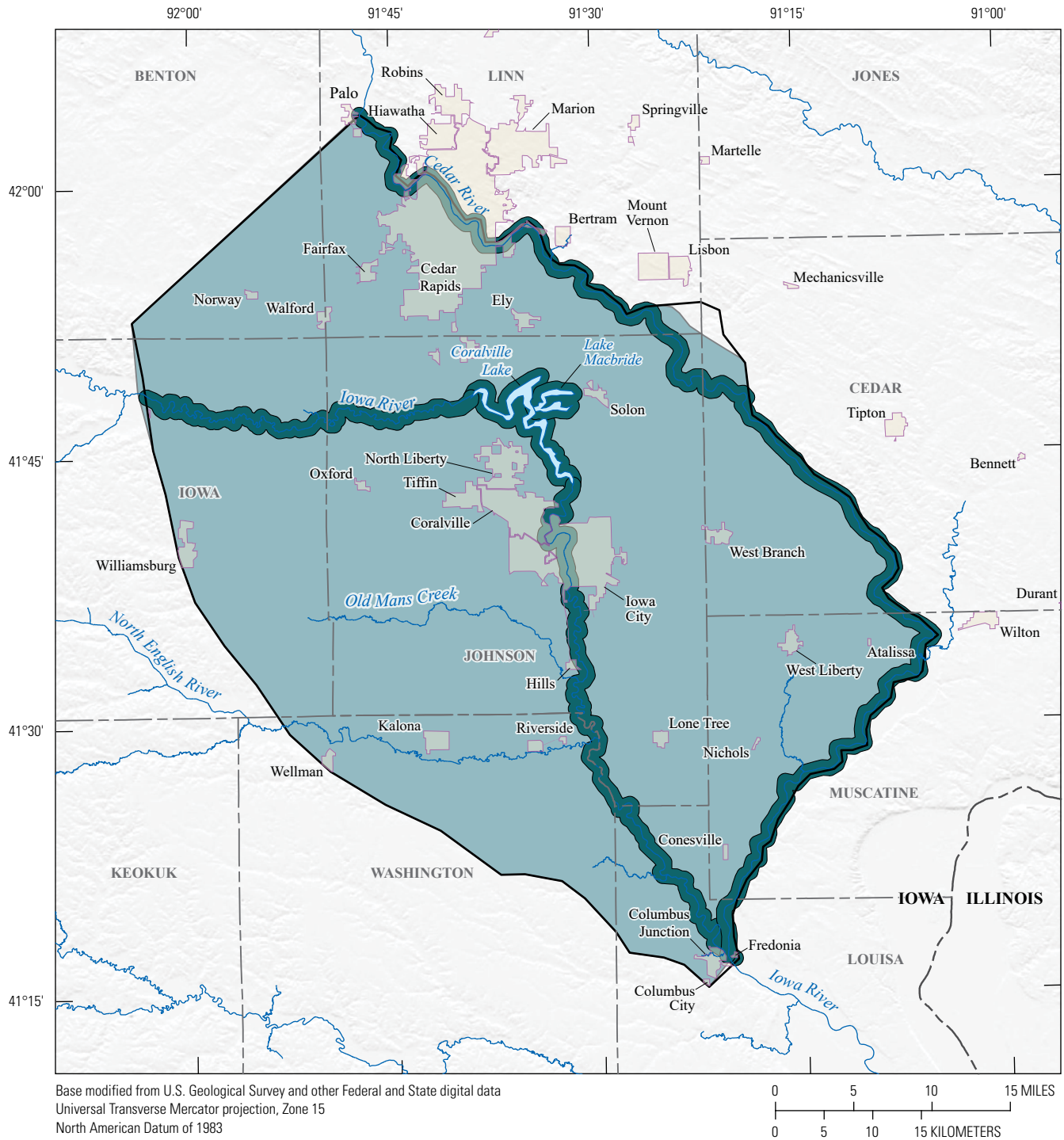


Figure 10. Map showing hydraulic conductivity, in meters per day, for hydrogeologic layer 1 (upper confining units) in the model area in eastern Iowa.

assigned as 0.18 m/d (fig. 10). Hydraulic conductivity values were based on drillers' lithologic descriptions and standard values from literature (Freeze and Cherry, 1979).

## Devonian Aquifer (Layer 2)

Layer 2 represents the Devonian aquifer and includes the Cedar Valley Group (Lithograph City Formation, Coralville Formation, and Little Cedar Formation), and the Spring Grove and Davenport Members of the Pinicon Ridge Formation. The Devonian aquifer crops out extensively along the Iowa River in Iowa City and upstream along Coralville Lake. The Devonian aquifer is mostly composed of dense, relatively pure limestone. Most of the permeability is related to secondary permeability, such as fractures, bedding plane voids, and solution cavities. Cedar Valley Group limestones are susceptible to dissolution by groundwater, which creates karst features such as caves and bedding plane voids. These karst features are the primary conduits for groundwater movement (Witzke, 1992; Ghasemizadeh and others, 2016; Cai and others, 2021).

The top elevation of the Cedar Valley Group rock, as well as the dip of the individual units and field mapping of exposed bedrock units (Gannon and others, 2011), was based on information compiled from well logs in GeoSam (Iowa Geological Survey, 2022). Hydraulic properties were determined from direct testing of the aquifer using controlled aquifer tests or aquifer pump tests on wells completed in the Devonian aquifer using known pumping rates, pumping duration, and water-level measurements (table 1; Iowa Geological Survey, 2023). The range of hydraulic conductivities derived from pump tests was 0.09–4.54 m/d but can be much higher because of karst features (table 1). A hydraulic conductivity of 5.12 m/d was defined for the city limits of the City of Coralville, 0.18 m/d along the major rivers, and 1.12 m/d for the rest of layer 2 within the model (fig. 11).

## Devonian Confining Layer (Layer 3)

Layer 3 represents the Kenwood Member of the lower Devonian Pinicon Ridge Formation and is a relatively low-permeability layer confining the underlying rock in most of the model area (fig. 12). The top of the shale of the Kenwood Member (where present) was generated by adding 10 feet to the top of the Silurian surface. The horizontal and vertical hydraulic conductivity of layer 3 was estimated based on the lithology in well logs. Most of layer 3 was assigned a horizontal hydraulic conductivity value of 0.11 m/d and a vertical hydraulic conductivity value of 0.011 m/d. Areas of layer 3 along the major rivers were assigned a hydraulic conductivity value of 0.18 m/d.

## Silurian Aquifer (Layer 4)

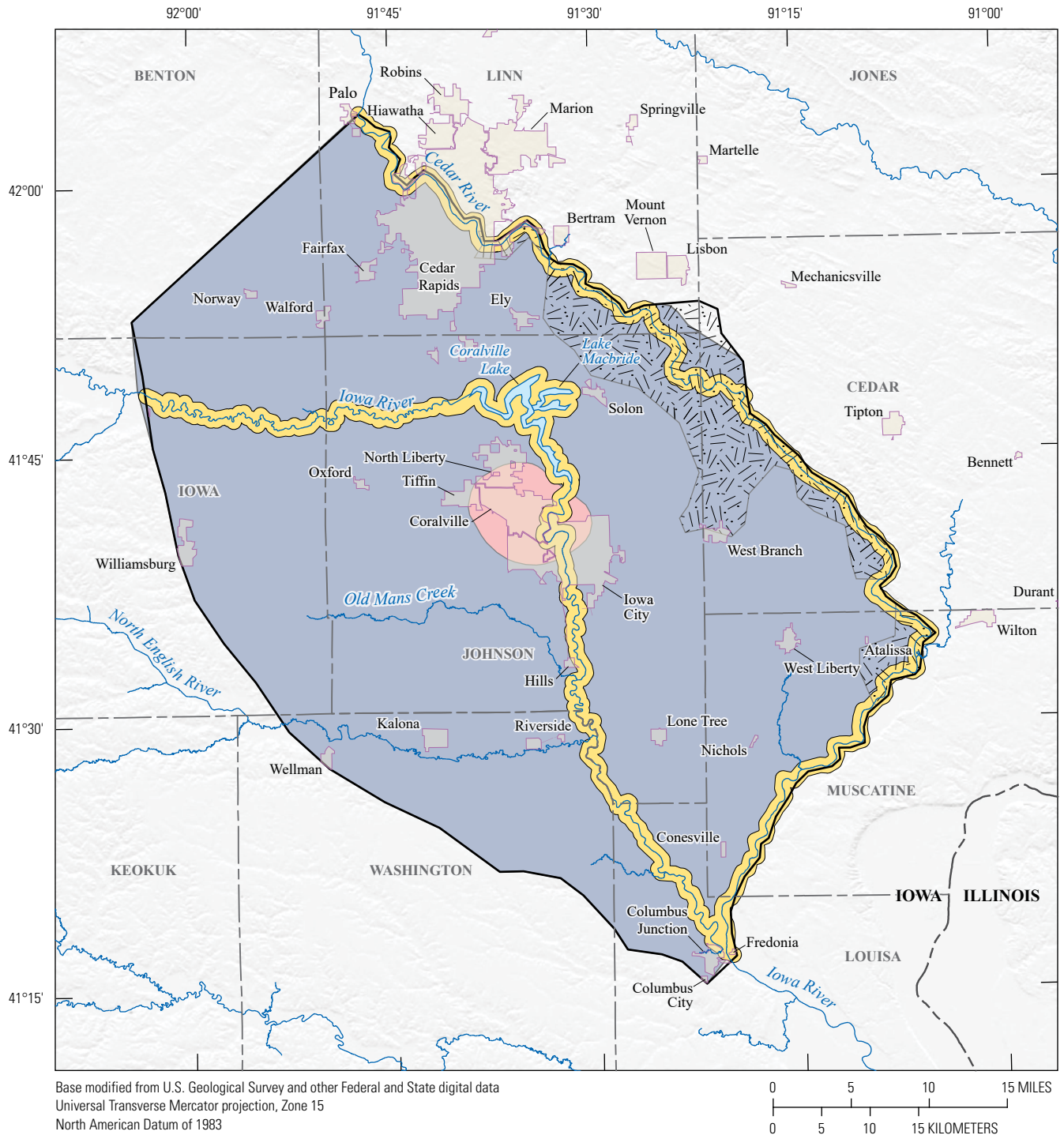
Layer 4 represents the Silurian aquifer and consists of rock from the Devonian Otis Formation and Silurian units. The Silurian aquifer is a thick sequence of dolostones and limestone. The top elevation of the Silurian rock surface, as well as the dip of the individual units and field mapping of exposed bedrock units (Gannon and others, 2011), was based on information compiled from well logs in GeoSam (Iowa Geological Survey, 2022). Silurian aquifer thickness was assumed to be the thickness of the Silurian units in the model; although the Silurian aquifer also includes the Devonian Otis Formation, this unit is relatively thin, is not distinguished in most well logs, and was not included in the thickness of the Silurian aquifer.

Data from 27 aquifer pump tests completed partly or entirely in the Silurian aquifer were used to hydraulically characterize the aquifer in the model area (Iowa Geological Survey, 2023). Of the tests, 16 were pump tests using 1 or more production wells and 1 or more observation wells, and 11 tests were recovery tests completed with only the production well (fig. 13; table 1; Williams and Gannon, 2026). Transmissivity estimates from pumping tests of the Silurian aquifer ranged from 8.44 to 346.06 square meters per day ( $\text{m}^2/\text{d}$ ; table 1). Williams and Gannon (2026) estimated the arithmetic mean transmissivity value for the aquifer was  $72.3 \text{ m}^2/\text{d}$  (Williams and Gannon, 2026). The variability in transmissivity is because of the secondary permeability in the Silurian aquifer from fractures and voids, especially in the Gower Formation. The fractures and voids have limited lateral extent and may not be representative of the regional permeability distribution; therefore, transmissivity in untested parts of the aquifer may be much higher than the values listed in table 1. Based on pump test results, hydraulic conductivity in the aquifer ranged from 0.091 to 4.54 m/d with an arithmetic mean of 0.91 m/d and standard deviation of 0.85 m/d (Williams and Gannon, 2026). These hydraulic conductivity values were averaged to zones in the model grid based on the spatial distribution of values observed in pump tests (fig. 14).

Hydraulic storage parameters (dimensionless) also were estimated for the Silurian aquifer from pumping test data. The storage coefficient, or storativity, was estimated for transient model construction and is equal to the volume of water released from a vertical column of the aquifer per unit surface area of the aquifer and unit decline in water level (Freeze and Cherry, 1979). Pumping test data for the storativity of the Silurian aquifer ranged from about  $1.0 \times 10^{-7}$  to  $7.9 \times 10^{-4}$ , and the arithmetic mean storativity value was  $1.5 \times 10^{-4}$  (Williams and Gannon, 2026). An average storativity value of  $1.0 \times 10^{-4}$  was used for the Silurian aquifer based on the pump test results (Williams and Gannon, 2026). For confined aquifers, specific storage can be estimated by dividing storativity by the aquifer saturated thickness (Freeze and Cherry, 1979). The specific storage distribution in the Silurian aquifer estimated using a uniform storativity value of  $1.0 \times 10^{-4}$  divided by the

**Table 1.** Hydraulic conductivity, storativity, transmissivity, and assigned aquifer from pump and recovery tests used in the model (Williams and Gannon, 2026).[K, hydraulic conductivity; m/d, meter per day; m<sup>2</sup>/d, square meter per day; NA, not applicable]

Observation well identifier	Well identifier	K (m/d)	Storativity (dimensionless)	Transmissivity (m <sup>2</sup> /d)	Aquifer
48274	48274	0.09	NA	8.44	Silurian
27802	27802	0.20	NA	20.93	Silurian-Devonian
13409	13409	0.27	NA	22.58	Silurian
12477	12477	0.27	NA	25.33	Silurian
13029	13029	0.34	1.00×10 <sup>-5</sup>	30.66	Silurian
28063	28866	0.43	2.90×10 <sup>-5</sup>	32.52	Silurian
53450	53450	0.38	NA	34.84	Silurian
73173	73173	0.52	NA	35.06	Silurian
55159	55159	0.52	NA	35.22	Silurian
96021	96022	0.76	9.00×10 <sup>-5</sup>	39.95	Silurian
2920	8284	0.61	4.10×10 <sup>-4</sup>	40.33	Silurian
75768	75768	0.90	NA	45.07	Silurian
16340	25832	0.76	3.70×10 <sup>-4</sup>	48.77	Silurian
27214	85880	0.58	7.30×10 <sup>-5</sup>	49.78	Silurian
28866	28063	0.68	1.50×10 <sup>-5</sup>	51.79	Silurian
12954	12953	0.58	1.00×10 <sup>-7</sup>	52.95	Silurian
18238	4 North Liberty wells	0.67	2.90×10 <sup>-4</sup>	57.64	Silurian-Devonian
22742	22742	1.13	NA	59.12	Silurian-Devonian
75586	75586	1.21	NA	60.70	Silurian
31377	27934	0.69	2.50×10 <sup>-4</sup>	63.75	Silurian
30000	107	1.10	2.50×10 <sup>-5</sup>	83.61	Silurian-Devonian
62329	4 North Liberty wells	1.19	5.30×10 <sup>-5</sup>	102.17	Silurian-Devonian
25590	11597	1.46	7.89×10 <sup>-4</sup>	117.04	Silurian
66477	66477	1.37	NA	125.42	Silurian-Devonian
11597	25590	1.94	3.80×10 <sup>-5</sup>	155.40	Silurian
73808	72137	1.65	2.70×10 <sup>-5</sup>	205.19	Silurian
33399	7899	4.54	5.40×10 <sup>-7</sup>	346.06	Silurian-Devonian



**Figure 11.** Map showing hydraulic conductivity distribution, in meters per day, for hydrogeologic layer 2 (Devonian aquifer) in the model area in eastern Iowa.

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**Figure 12.** Map showing hydraulic conductivity distribution, in meters per day, for hydrogeologic layer 3 (Kenwood Member) in the model area in eastern Iowa.

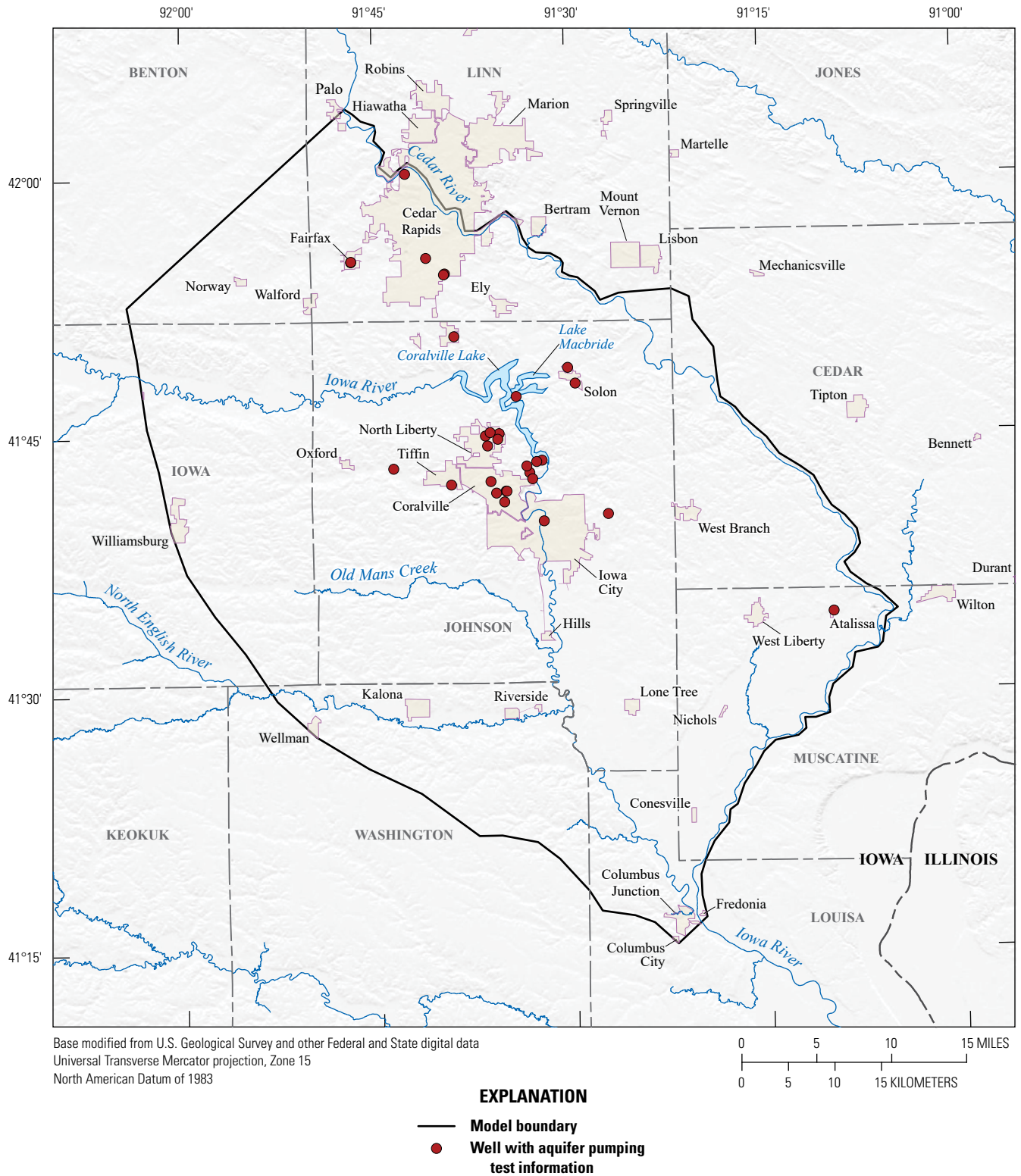
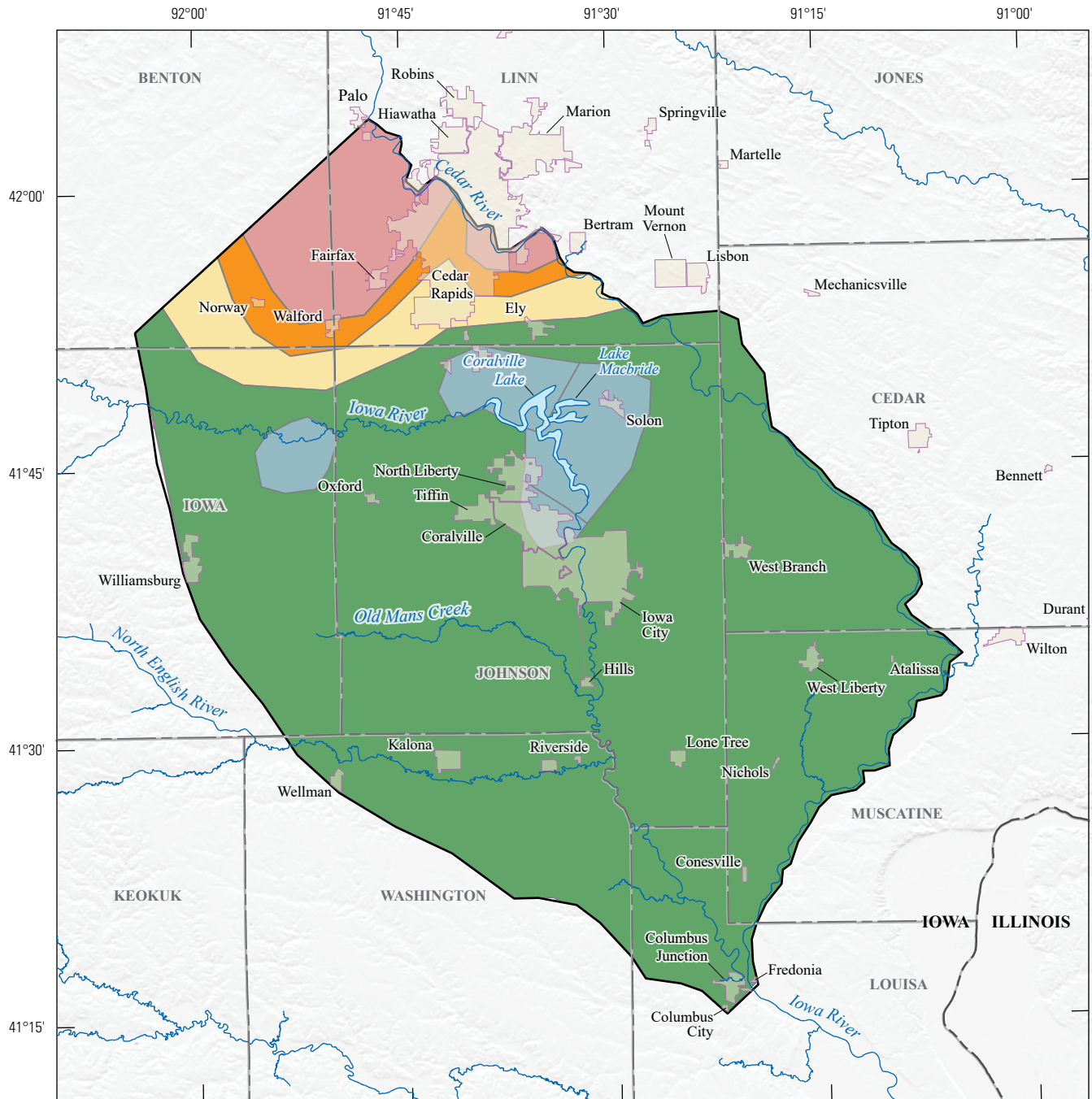
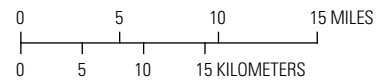


Figure 13. Map showing wells with aquifer pumping test information in the model area in eastern Iowa.

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Base modified from U.S. Geological Survey and other Federal and State digital data  
 Universal Transverse Mercator projection, Zone 15  
 North American Datum of 1983



**EXPLANATION**

**Average hydraulic conductivity from pump test, in meters per day**

	0.61		1.83		3.05
	1.22		2.44		

— **Model boundary**

**Figure 14.** Map showing the lateral distribution of averaged hydraulic conductivity in the Silurian aquifer, eastern Iowa, based on aquifer pumping tests.

isopach thickness of the Silurian aquifer (fig. 8) is shown in figure 15. Specific storage varied from  $2.5 \times 10^{-6}$  per meter across the northern parts of the model area to  $1.0 \times 10^{-5}$  per meter across the southern parts of the model area.

## Lower Confining Layer (Layer 5)

Layer 5 is the lowest model layer and represents the Maquoketa Formation, which is characterized as a low-permeability confining layer. The Maquoketa Formation is dominated by shale strata and averages ~61.0 m thick in the model area. This layer was conceptualized as a homogenous bottom confining unit for the model, and hydraulic conductivity for this layer was set uniformly at 0.11 m/d (0.011 m/d vertical hydraulic conductivity) based on published values for shale (Freeze and Cherry, 1979).

## Water Budget Components

The groundwater hydrology and water budget of the conceptual model were based on previously published groundwater maps and data on recharge and discharge from the aquifer system. This section describes the methods for estimating the initial potentiometric surface, lateral groundwater flow, and groundwater recharge and discharge within the Silurian aquifer.

## Potentiometric Surface and Groundwater Flow

An estimated steady-state potentiometric surface was interpolated from water-level measurements collected from known Silurian wells and average river stage elevation with the assumption that the water level in the Silurian aquifer approximately matches river stage at the location of major rivers (fig. 16; table 2). Steady-state conditions were defined using the river stage elevations and precipitation data for time intervals representing average or normal climatic conditions. Water-level data from 46 wells were used, including 39 static water levels from drillers' logs representing dates from 1899 to 2023 (most from 2000 and later) and averaged time-series data for 7 observation wells with multiple water-level measurements (table 2; Iowa Geological Survey, 2022; Iowa Department of Natural Resources, 2023). Average river stage (nondrought and nonflood) elevation data from 2000 to 2022 for nine USGS streamgages (fig. 17) in the model area also were used to define the groundwater potentiometric surface; the nine USGS streamgages were the Iowa River at Marengo (05453100), Iowa River below Coralville Dam near Coralville (05453520), Iowa River at Iowa City (05454500), Iowa River near Lone Tree (05455700), and Iowa River at Columbus Junction (05465100; USGS, 2023a, b, c, d, i) and Cedar River at Blairs Ferry Road at Palo (05464420), Cedar River at Cedar Rapids (05464500), Cedar River at Cedar Bluff (05464780), and Cedar River near Conesville (05465000) (USGS, 2023e, f, g, h). Measured groundwater levels and stream stage were

interpolated to model cells to generate the Silurian aquifer water table surface. Groundwater-flow direction in the Silurian aquifer was estimated by drawing lines perpendicular to equal head contours of the water table.

The regional groundwater head gradient in the model area is generally higher in the northwest and lower in the southeast. Rivers and quarries cause groundwater depressions in the water table (fig. 17). Groundwater depressions also are present at concentrated pumping areas in Johnson County, especially near the City of Coralville and Klein and Conklin Quarries. The water table gradient associated with the Johnson County cone of depression is steeper than the general regional gradient.

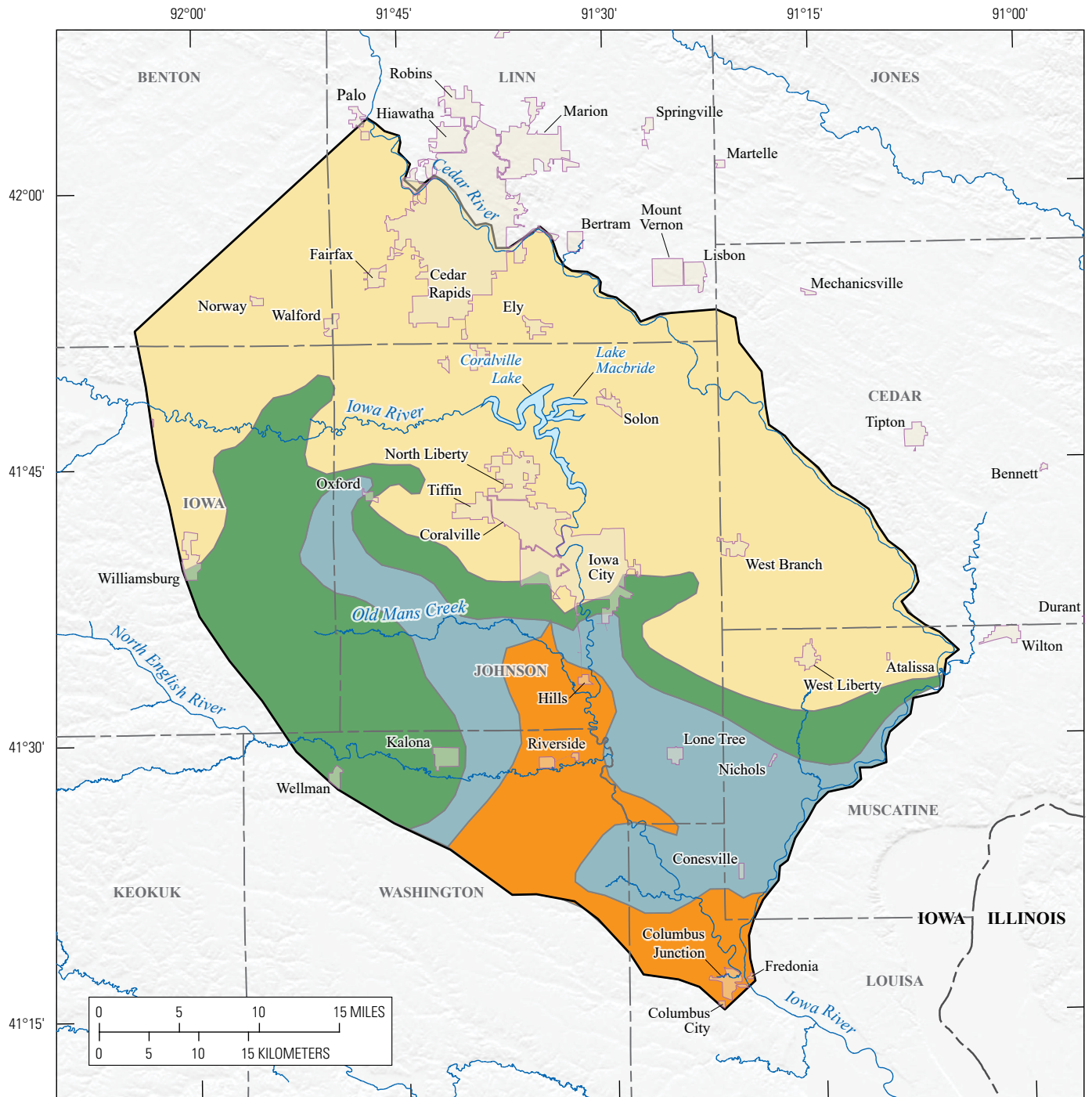
## Groundwater Recharge and Discharge

Recharge to the Silurian aquifer in the model area is mostly from precipitation and is assumed to be highest where the bedrock is at or near the land surface. Other inflow sources include seepage from the Iowa and Cedar Rivers into the aquifer, seepage from Lake Macbride and Coralville Lake (fig. 1), and groundwater inflow from outside the model area in Benton County and the northwestern part of Linn County. The primary aquifer outflows include withdrawals from wells, dewatering pumping from quarries, discharge to the Iowa and Cedar River systems, and groundwater outflow from the model area.

Net recharge is the amount of precipitation, minus evapotranspiration, that enters model aquifer layers from overlying confining and semiconfining beds. Net recharge to the Silurian aquifer in the northern part of Johnson County was estimated at ~0.30 centimeter per year (cm/yr; Hansen, 1970; Tucci and McKay, 2006). If that recharge rate is applied over the current model area (~3.72 billion square meters), the total volume of recharge per day would be ~0.031 million cubic meters per day ( $m^3/d$ ). The uniform recharge rate used by Tucci and McKay (2006) for the Silurian aquifer in Johnson County is not representative of the entire model area. Spatial variability in the vertical permeability and the thickness of the upper confining units in layer 1 results in a spatial variation of values for recharge or vertical leakage to the underlying aquifers. Because recharge was conceptualized as net recharge, evapotranspiration was not included separately in the model.

For the conceptual model, layer 1 was divided into several recharge zones to allow for spatial variation in recharge rates. Higher recharge values were assigned to areas in central and northeastern Johnson County where Silurian bedrock is within 7.62 m of the land surface (fig. 3). Lower recharge values were assigned to areas with thicker glacial tills (layer 1) and Devonian confining beds (layer 3). The interpolated potentiometric map also was used to delineate areas of higher and lower recharge outside of areas of heavy groundwater withdrawal (fig. 16), where areas with higher groundwater elevations were associated with zones of higher recharge and areas with lower groundwater elevations

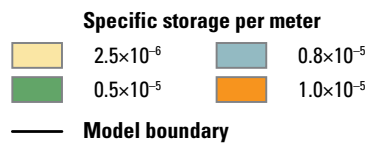
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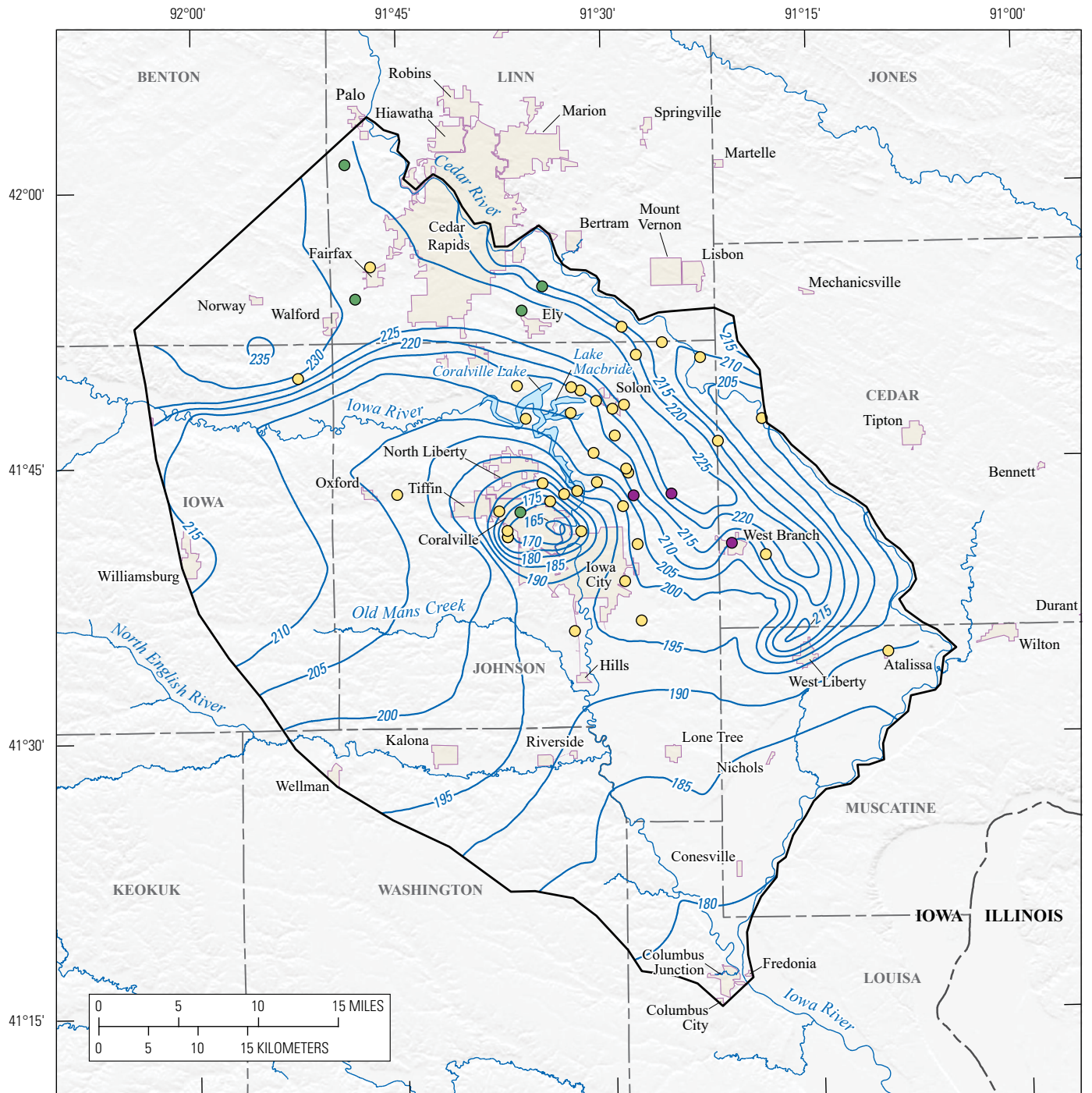
Base modified from U.S. Geological Survey and other Federal and State digital data  
 Universal Transverse Mercator projection, Zone 15  
 North American Datum of 1983

Data from Freeze and Cherry (1979) and Iowa Geological Survey (2022)

**EXPLANATION**



**Figure 15.** Map showing specific storage per meter for hydrogeologic layer 4 in the model area in eastern Iowa (Freeze and Cherry, 1979; Iowa Geological Survey, 2022).



Base modified from U.S. Geological Survey and other Federal and State digital data  
 Universal Transverse Mercator projection, Zone 15  
 North American Datum of 1983

Observed groundwater elevation data from  
 Iowa Geological Survey (2022),  
 Iowa Department of Natural Resources (2023), and  
 U.S. Geological Survey (2023 a, b, c, d, e, f, g, h, i)

**EXPLANATION**

- Model boundary**
- Steady-state potentiometric contours, in meters above the North American Vertical Datum of 1988**
- **Iowa Geological Survey GeoSam well**
- **U.S. Geological Survey/Iowa Geological Survey well**
- **U.S. Geological Survey well**

**Figure 16.** Map showing groundwater potentiometric contours based on observed groundwater elevation data in the Silurian aquifer, eastern Iowa, based on potentiometric controls from observed groundwater elevation data (1899–2023, Iowa Geological Survey, 2022; Iowa Department of Natural Resources, 2023; U.S. Geological Survey, 2023 a, b, c, d, e, f, g, h, i).

**Table 2.** Wells used to provide water-level data for the construction of a potentiometric map for the Silurian aquifer and for model calibration.

[DD, decimal degree; m, meter; ; USGS, U.S. Geological Survey; ID, identifier; IGS, Iowa Geological Survey; NA, not applicable; NW, Northwest; USGS/IGS, IGS under contract with the USGS; ODW, Oakdale well; Sil, Silurian, SW, Silurian well; PS, potentiometric surface; TC, transient calibration]

Well identifier <sup>a</sup>	Latitude (DD)	Longitude (DD)	Date/period of record <sup>b</sup>	Count	Head elevation (m)	Data source	Aquifer	Usage in model
12477	41.79919414	-91.49227069	10/20/1960	1	222.3	IGS GeoSam	Silurian	PS
17312	41.60653439	-91.46131592	8/31/1964	1	195.4	IGS GeoSam	Silurian	PS
18932	41.83048392	-91.873186	9/19/1966	1	227.1	IGS GeoSam	Silurian	PS
22976	41.70767308	-91.63155311	8/31/1964	1	182.6	IGS GeoSam	Devonian	PS/TC
25589	41.67550137	-91.3504128	3/25/1980–1/11/2016	14	208.2	USGS	Silurian	PS
25832	41.72505753	-91.53664987	8/16/1963	1	197.0	IGS GeoSam	Silurian	PS
28381	41.59799739	-91.54228405	11/30/1987	1	194.8	IGS GeoSam	Silurian-Devonian	PS
32142	41.57471397	-91.16381491	10/1/1990	1	189.6	IGS GeoSam	Silurian	PS
34554	41.71061547	-91.48149346	2/9/1994	1	199.7	IGS GeoSam	Silurian	PS
36023	41.64251058	-91.48047625	8/16/1963	1	197.9	IGS GeoSam	Silurian	PS
36026	41.72402712	-91.7548821	8/31/1964	1	202.4	IGS GeoSam	Silurian	PS
36027	41.6759309	-91.46458934	8/16/1963	1	202.7	IGS GeoSam	Silurian	PS
36036	41.81628623	-91.5309988	12/30/1899	1	218.3	IGS GeoSam	Silurian	PS
36817 (USGS ID 414313091280701)	41.72021436	-91.46842827	6/11/1997–11/3/2005	117	207.6	USGS	Silurian	PS
37159	41.66452206	-91.30950661	9/1/1966	1	214.6	IGS GeoSam	Silurian	PS
47050	41.82121295	-91.60764536	11/26/1998	1	212.2	IGS GeoSam	Silurian	PS
47797	41.73280095	-91.5126183	11/26/1998	1	205.5	IGS GeoSam	Silurian	PS
51746	41.68850092	-91.53256429	4/25/2000	1	175.9	IGS GeoSam	Silurian	PS/TC
52945	41.7960298	-91.54297993	10/19/2000	1	209.5	IGS GeoSam	Silurian-Devonian	PS
53844	41.76834406	-91.36503521	4/18/2001	1	215.9	IGS GeoSam	Silurian	PS
54227	41.85880475	-91.43080144	5/9/2001	1	210.4	IGS GeoSam	Silurian	PS
54260	41.77487276	-91.48995289	6/20/2001	1	216.8	IGS GeoSam	Silurian	PS
55158	41.73261728	-91.57850242	11/26/1998	1	182.6	IGS GeoSam	Silurian	PS/TC
57378	41.71607871	-91.56962282	5/7/2003	1	172.6	IGS GeoSam	Silurian	PS/TC
58173	41.79140524	-91.59763966	10/25/2003	1	207.9	IGS GeoSam	Silurian	PS
58428	41.74099148	-91.47441635	1/23/2004	1	212.2	IGS GeoSam	Silurian	PS
59205	41.78819964	-91.31123067	8/5/2004	1	196.3	IGS GeoSam	Silurian	PS
59225	41.74467155	-91.47685473	7/20/2004	1	213.1	IGS GeoSam	Silurian	PS
59232	41.75938777	-91.51602211	7/30/2004	1	210.7	IGS GeoSam	Silurian	PS
59571	41.87343616	-91.47935606	10/19/2004	1	216.8	IGS GeoSam	Silurian	PS

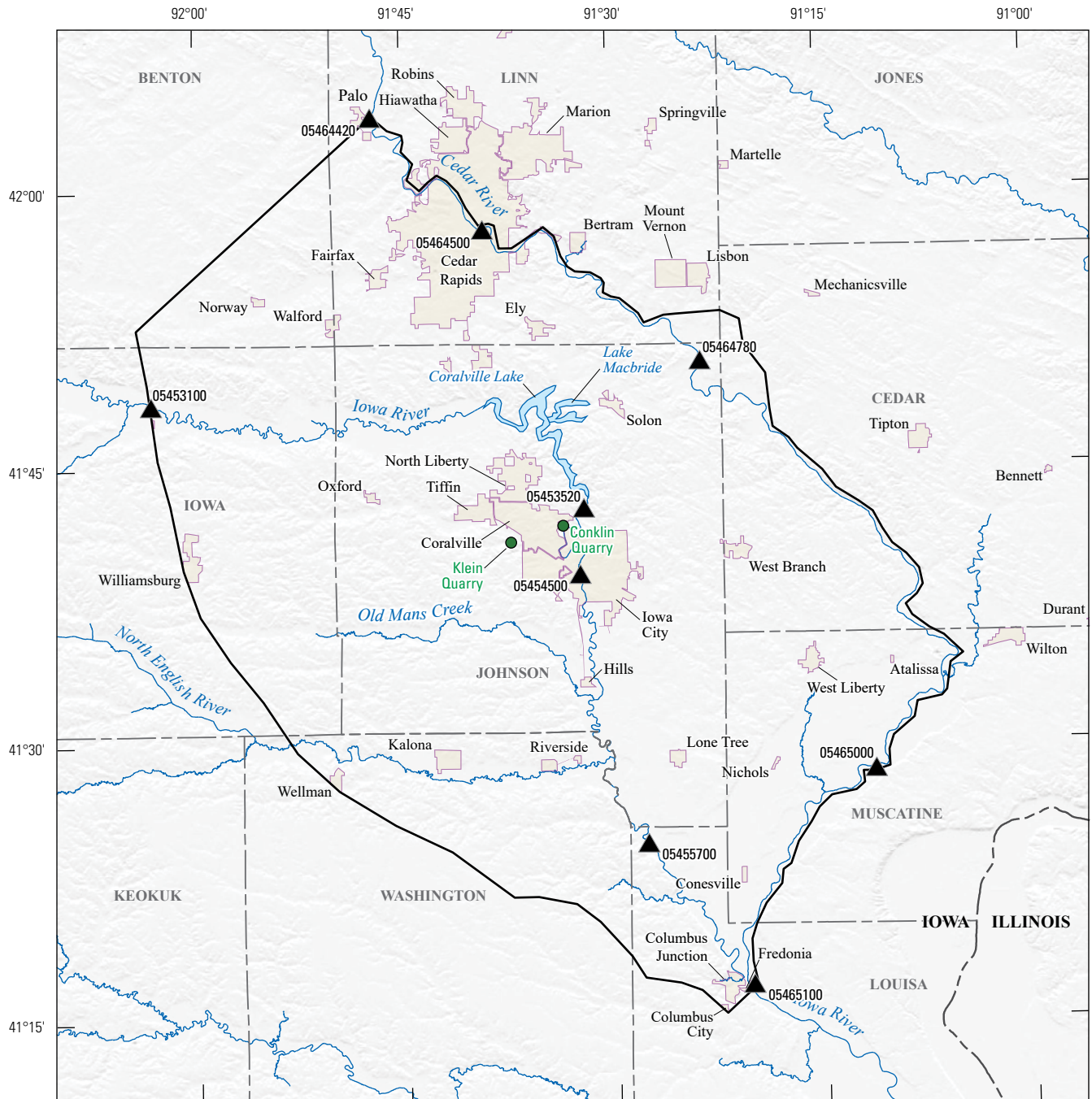
**Table 2.** Wells used to provide water-level data for the construction of a potentiometric map for the Silurian aquifer and for model calibration.—Continued

[DD, decimal degree; m, meter; ; USGS, U.S. Geological Survey; ID, identifier; IGS, Iowa Geological Survey; NA, not applicable; NW, Northwest; USGS/IGS, IGS under contract with the USGS; ODW, Oakdale well; Sil, Silurian, SW, Silurian well; PS, potentiometric surface; TC, transient calibration]

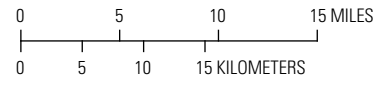
Well identifier <sup>a</sup>	Latitude (DD)	Longitude (DD)	Date/period of record <sup>b</sup>	Count	Head elevation (m)	Data source	Aquifer	Usage in model
59761	41.84789637	-91.46265163	12/20/2004	1	219.5	IGS GeoSam	Silurian	PS
60003	41.68409042	-91.62152779	3/16/2005	1	170.4	IGS GeoSam	Silurian	PS/TC
60004	41.68409042	-91.62152779	3/16/2005	1	172.3	IGS GeoSam	Silurian	PS
62628	41.84459256	-91.38469151	11/8/2005	1	210.7	IGS GeoSam	Silurian	PS
65041	41.72243073	-91.55254268	8/19/2009	1	186.6	IGS GeoSam	Devonian	PS/TC
68519	41.81939652	-91.54183622	12/21/2009	1	217.1	IGS GeoSam	Silurian	PS
73173	41.80659255	-91.51191154	10/18/2010	1	216.8	IGS GeoSam	Silurian	PS
83811	41.80269166	-91.47815338	12/30/1899	1	225.9	IGS GeoSam	Silurian	PS
89238	41.68981307	-91.62180214	4/19/2018	1	166.5	IGS GeoSam	Devonian	PS/TC
89605	41.93091574	-91.78389031	4/6/2017	1	226.2	IGS GeoSam	Silurian-Devonian	PS
Elmira Depot (USGS ID 414315091252002)	41.72128621	-91.42250323	10/24/1941–12/31/2022	890	226.2	USGS	Silurian	PS/TC
Ely North (USGS ID 415442091343101)	41.91134793	-91.57510983	4/29/1976–8/1/2013	466	218.0	USGS/IGS	Silurian	PS/TC
Ely NW (USGS ID 415343091360101)	41.88965723	-91.60049463	5/14/1976–8/1/2013	439	230.7	USGS/IGS	Silurian	PS/TC
Lincoln Church (USGS ID 420126091484701)	42.02402711	-91.81336563	10/11/1972–8/01/2013	292	226.0	USGS/IGS	Silurian-Devonian	PS/TC
ODW no. 1 (Sil) (USGS ID 414221091361101)	41.70654555	-91.60593996	4/16/1990–8/1/2013	219	170.7	USGS/IGS	Silurian	PS/TC
Stockpile (101036, USGS ID 415509091461801)	41.90183148	-91.8025504	12/15/2023	1	226.6	USGS/IGS	Silurian	PS/TC
Solon 4	41.806670	-91.511664	1/1/2020–12/31/2022	NA	NA	Solon Public Works	Silurian	TC
North Liberty 9	41.745883	-91.612933	1/1/2020–12/31/2022	NA	NA	North Liberty Water Department	Silurian	TC
Tiffin 3	41.705140	-91.663750	1/1/2020–12/31/2022	NA	NA	Tiffin Public Works	Silurian	TC
Coralville 14	41.693944	-91.596096	1/1/2020–12/31/2022	NA	NA	Coralville Public Works	Silurian	TC
Iowa City SW 4	41.671611	-91.555111	1/1/2020–12/31/2022	NA	NA	Iowa City Public Works	Silurian	TC

<sup>a</sup>USGS ID information from USGS (2025); Iowa Geological Survey well information from Iowa Geological Survey (2022).

<sup>b</sup>Dates are given in month/day/year format.



Base modified from U.S. Geological Survey and other Federal and State digital data  
 Universal Transverse Mercator projection, Zone 15  
 North American Datum of 1983



**EXPLANATION**

- Model boundary**
- Quarry**
- U.S. Geological Survey streamgage and identifier (U.S. Geological Survey, 2023a, b, c, d, e, f, g, h, i)**

**Figure 17.** Map showing U.S. Geological Survey streamgages on the Iowa and Cedar Rivers, eastern Iowa (U.S. Geological Survey, 2023a, b, c, d, e, f, g, h, i).

were associated with zones of lower recharge. The rate of groundwater lost or gained by various reaches of the Iowa and Cedar Rivers was generalized for the model area, and quantifying these values more precisely is outside the scope of the study.

## Numerical Model

A numerical model was developed to simulate groundwater levels in the Silurian aquifer and to evaluate groundwater availability and sustainability using historical water use (steady-state, 2000–22), current water use (transient, 2020–22), and future use (2025–45) scenarios. The future use scenarios used projected pumping rates provided by city staff from the Cities of Tiffin, North Liberty, Coralville, and Solon and Iowa City. Future well locations used in the predictive model also were provided by city personnel. Model files and documentation are available in the accompanying USGS data release (Bristow and Gannon, 2026).

## Model Construction and Boundary Conditions

Groundwater flow in the Silurian aquifer was simulated using MODFLOW 2005 (Niswonger and others, 2011) and MODFLOW 6 (Langevin and others, 2017). Visual MODFLOW Flex 9.0 (Waterloo Hydrogeologic, Inc., 2023) and the FloPy Python package (Bakker and others, 2016) were used to construct and evaluate the model. A steady-state MODFLOW 2005 version of the model was used for calibration of hydrologic parameters using the Visual MODFLOW Flex parameter estimation (PEST) calibration capability, which had not yet been implemented in the Visual MODFLOW Flex version of MODFLOW 6. Parameters from the MODFLOW 2005 version of the model were then incorporated into a transient MODFLOW 6 version, which was used to match observed conditions and predict future drawdowns.

The model was designed to represent the Silurian aquifer in Johnson County, and its spatial boundaries were extended into surrounding counties to capture areas that contribute groundwater flow into and out of Johnson County and to include all major water users within model boundaries. The model area was delineated using assumed hydrologic boundaries, including the Cedar River along the northeastern and southeastern edges of the model and topographic highs along the northwestern and southwestern edges. This model area was discretized spatially in a grid of rectangular cells. The steady-state model had 500 columns and 500 rows, and the standard grid size was 165.76 by 179.60 m. The grid size was reduced to 1 by 1 m around production wells used as observation wells in the 2020–22 transient model to more accurately simulate transient pumping water levels near wells (fig. 18). With added cells for grid refinement, the transient model had 630 rows and 630 columns. Each of the

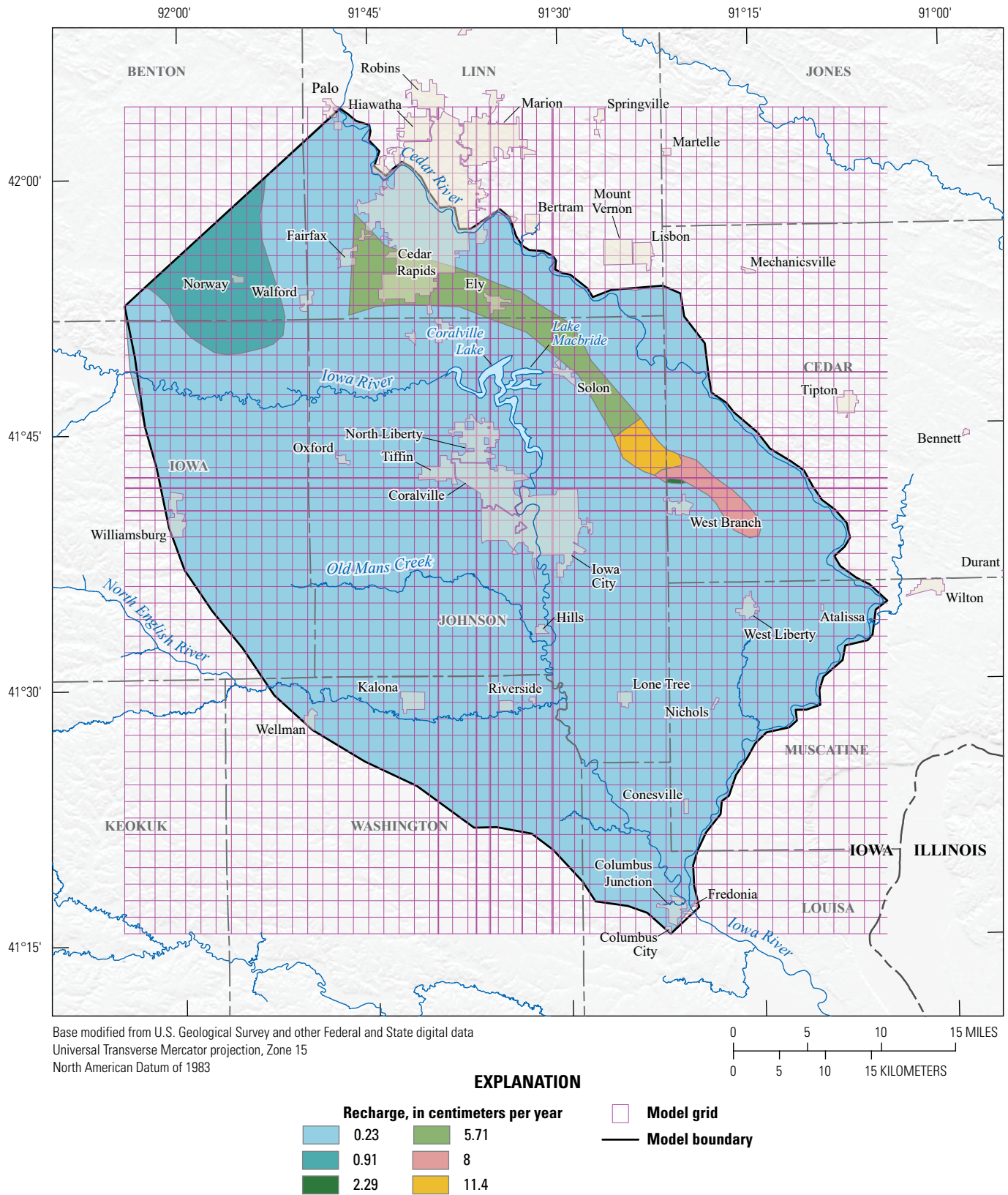
five conceptual model layers was included as a layer in the numerical model and discretized vertically by layer thickness for each grid cell. The use of the term “model” refers to the entire model, which contains five layers.

Boundary conditions were represented in the numerical model using various MODFLOW packages. The Constant Head Boundary (CHB) package was used to represent the groundwater-flow-through boundary along the model’s southwestern edge and water levels of the Klein and Conklin Quarry pools in layers 2 and 3 (Langevin and others, 2017). CHB model cells maintain a constant groundwater level specified during model construction. The groundwater head assigned to the CHB cells along the southwestern edge of the model was based on water table elevations from the Silurian aquifer potentiometric map and remained static for all model versions of the Silurian aquifer (fig. 16).

The water level at Klein and Conklin Quarries was represented using the General Head Boundary (GHB) package (Langevin and others, 2017). At a general-head boundary, flux into or out of the groundwater model varies linearly with the relation between calculated head in the cell and a specified reference head. These general-head boundaries were assigned to layer 4, and groundwater heads were set to a constant value for all stress periods and based on pool elevations obtained from River Products Company, Inc., which owns and manages both quarries (Bristow and Gannon, 2026). The two large reservoirs in the model area, Coralville Lake and Lake Macbride, also were represented with the GHB package and assigned to layer 1.

The MODFLOW Drain package was used to represent the secondary permeability in layer 2 (Devonian aquifer) from karst features (Langevin and others, 2017). The use of drains to model regional groundwater flow in a fractured or karst environment was modeled as documented by Quinn and others (1998). Drain elevation was 170 m, and conductance ranged from 17 to ~100,000 m<sup>2</sup>/d; variability in conductance is attributed to different cell sizes in areas of grid refinement.

The Cedar and Iowa Rivers were represented in the numerical model using MODFLOW’s River package (Langevin and others, 2017). The River package is a head-dependent flux package in which water moves into or out of the groundwater model at a rate dependent on the difference between groundwater head and river stage in each model cell with a river feature. USGS streamgage data were used to determine river stage for river boundaries (fig. 17; USGS, 2023a, b, c, d, e, f, g, h, i). The Cedar River boundary represented the eastern edge of the model area. Streambed vertical hydraulic conductivity was set at 0.305 m/d based on published values for silty sand (Freeze and Cherry, 1979), and streambed thickness was set at 1 m. River cells were assigned mostly to layer 1, but in areas where bedrock of layers 2, 3, or 4 crops out, river cells were assigned to these layers. Recharge was applied to the top layer of the numerical model using the Recharge package (Langevin and others, 2017). A base recharge value was determined based on previously published values and the Silurian aquifer top elevation depth. This value



**Figure 18.** Map showing calibrated steady-state net recharge distribution, in centimeters per year, and model grid (the model grid shown is a subsample of every 10th line of the grid for display purposes), eastern Iowa.

was calibrated using the steady-state version of the model. For the transient version of the model, a multiplier was applied to recharge for each stress period based on the deviation of recorded precipitation for that stress period from the average precipitation for the model period.

Wells were simulated using the Well package (Langevin and others, 2017). Well withdrawal data were provided by water managers at Iowa City and the Cities of Coralville, Solon, Tiffin, and North Liberty (Sam Fosse, Iowa City Public Works, written commun., 2023; Matt Gilmore, Coralville Public Works, written commun., 2023; Scott Kleppe, Solon Public Works, written commun., 2023; Brett Mehmen, Tiffin Public Works, written commun., 2023; Gregg Metternich, North Liberty Water Department, written commun., 2023), and annual water pumping volumes at other pumping wells in the model were obtained from the Iowa State water-use database (Iowa Department of Natural Resources, 2023). Annual water use was divided evenly into daily rates for each stress period. Monthly pumping withdrawal volume provided by the Cities of Solon, Tiffin, and Coralville and daily withdrawal volume provided by Iowa City were averaged into single daily stress period rates for each well. No water-use data were available for domestic wells, and the wells were not included in the model because they were assumed to be of negligible volume compared to municipal groundwater withdrawal volumes.

## Steady-State Groundwater Modeling

A steady-state numerical model was constructed to simulate average conditions in the Silurian aquifer between 2000 and 2022, to provide a model for PEST calibration of hydraulic conductivity, and to set initial conditions for the transient version of the model. Input data for this model included initial conditions from the steady-state potentiometric surface described in the “[Potentiometric Surface and Groundwater Flow](#)” section of this report, which represents conditions in the aquifer between 2000 and 2022 in periods without high or low streamflow; constant pool elevations of 170.7 m and 164 m at Klein and Conklin Quarries, respectively; and average groundwater withdrawals from 2012 to 2022 at production wells (Bristow and Gannon, 2026). Recharge values were adjusted manually. Recharge zones described in the “[Groundwater Recharge and Discharge](#)” section were not changed during simulations. Recharge rates were adjusted to match model-generated water levels with observed water levels only in the Silurian aquifer. The calibrated net recharge distribution is shown in [figure 18](#) and ranged from 0.23 cm/yr over the southwestern part of Johnson County to 11.4 cm/yr in eastern Johnson County.

## Calibration

Calibration is the process of adjusting model parameters to minimize the differences between numerical model outputs and hydrologic observations. The MODFLOW 2005 version of the steady-state model was calibrated manually and with

PEST calibration software. Calibrated values for recharge and hydraulic conductivity values were used as parameters for the MODFLOW 6 versions of the steady-state and transient models.

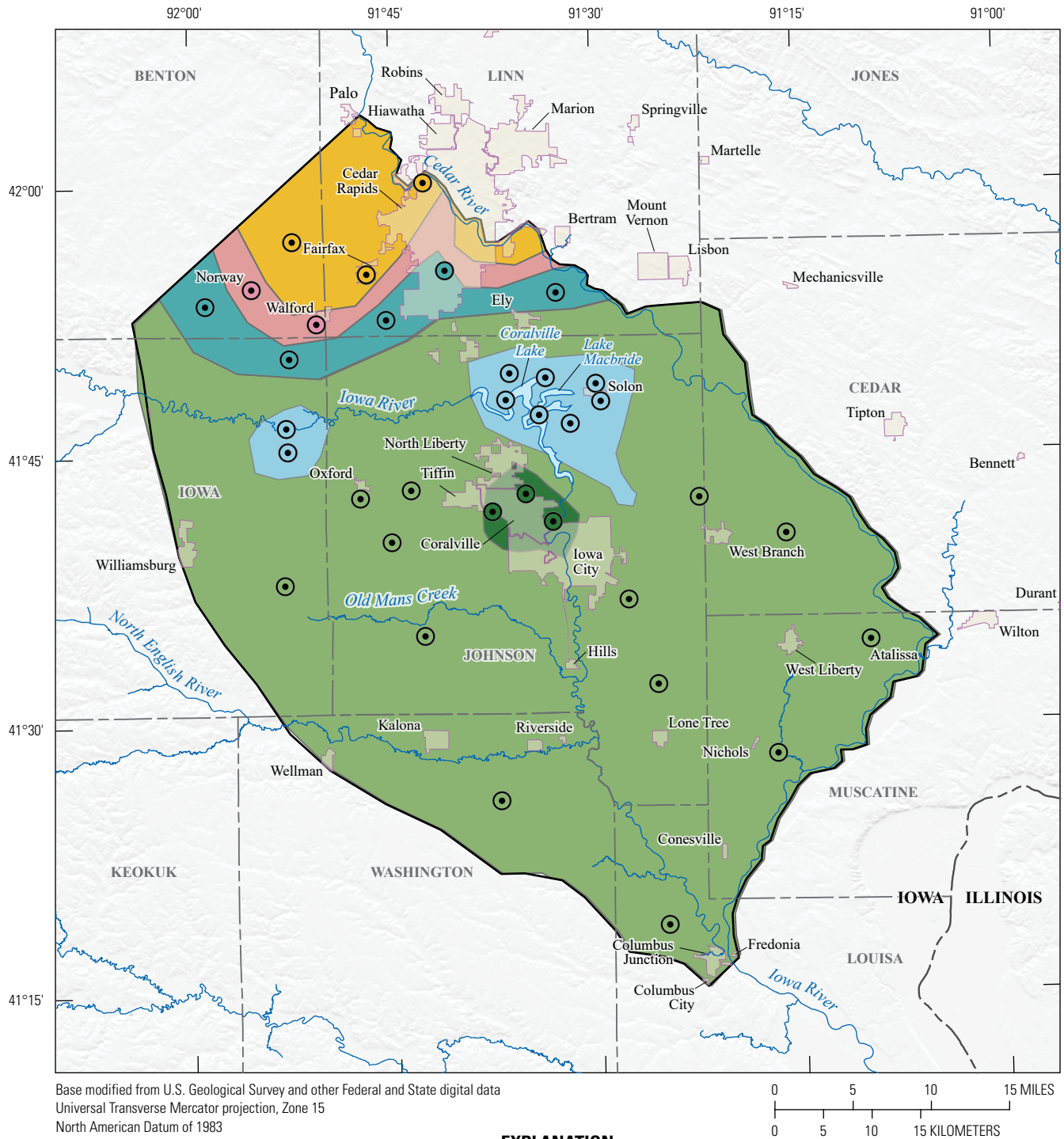
The hydraulic conductivity distribution in the Silurian aquifer (model layer 4) was calibrated using PEST calibration software version 12.3.1 (Doherty and Hunt, 2010; Doherty, 2018) included in Visual MODFLOW Flex (ver. 9.0). The PEST package adjusts hydraulic conductivity values for each zone in the Silurian aquifer (model layer 4) using an iterative approach to find a single set of model parameters that results in the lowest root mean square error (RMSE) between simulated and observed water levels.

Horizontal hydraulic conductivity values for layer 4 were generated from the PEST calibration of the steady-state model and ranged from 0.40 m/d over the northeastern third of Johnson County to 5.49 m/d around Cedar Rapids ([fig. 19](#)). Vertical hydraulic conductivity was not calibrated but was set to one-tenth of the horizontal hydraulic conductivity value for each zone.

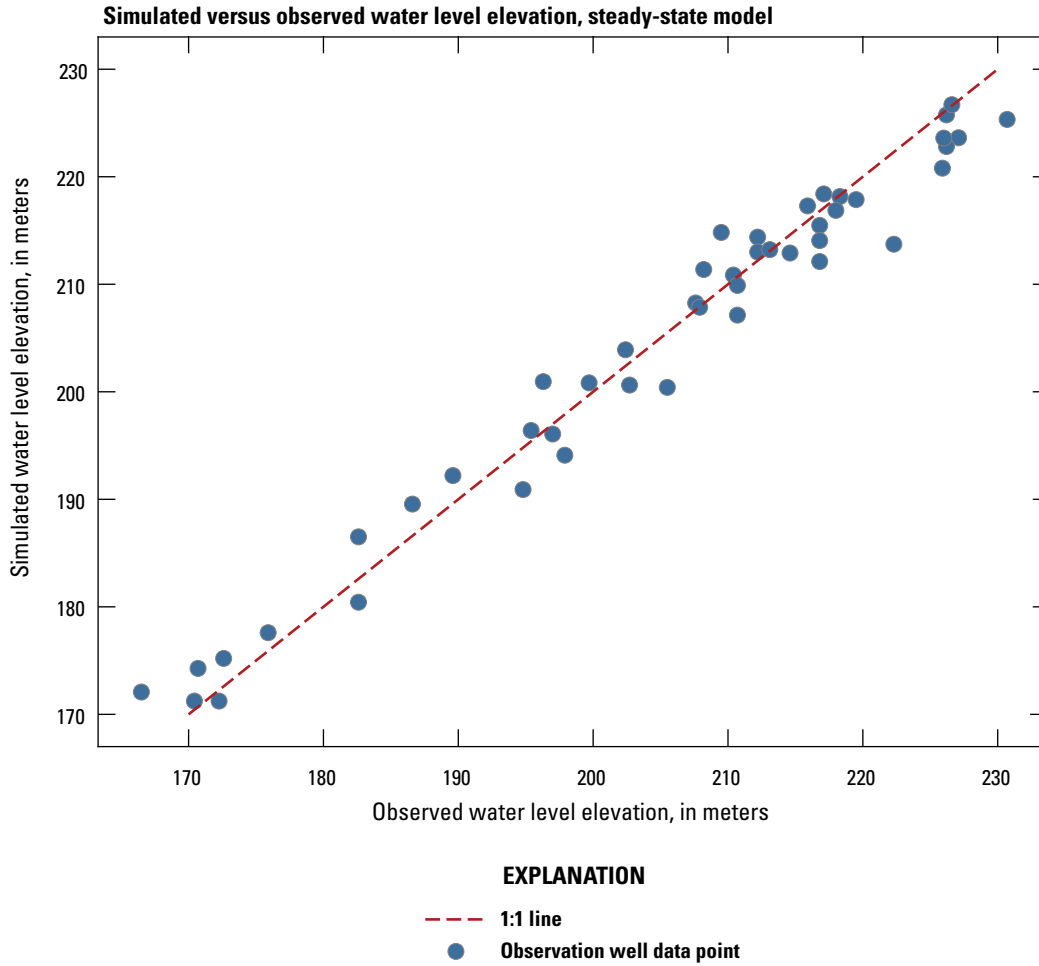
The lowest value for the RMSE during the steady-state calibration was 2.84 m. This error is relatively small compared to the size of the model boundary. By comparison, in the Tucci and McKay (2006) model, the RMSE for the Johnson County Silurian-Devonian aquifer system was 4.15 m, and in the Gannon and others (2011) model, the RMSE for the East-Central Iowa Silurian aquifer was 5.24 m. The average absolute value error in simulated water levels was 2.35 m. Of the 46 measured observed water levels used to compare to simulated water levels, 23 were lower than simulated values, and 23 were higher than simulated values ([fig. 20](#)). The range of errors between observed and simulated water levels was 0.009–6.08 m and can be attributed to fluctuations in precipitation recharge, river and streamgage elevation changes, and varying pumping rates from nearby wells.

## Sensitivity Analysis

Sensitivity analysis was completed to determine the effect on the RMSE from adjusting one parameter and holding the other parameters constant. The method used for the steady-state model was to vary one parameter by a certain percentage from the calibrated values and evaluate the resulting RMSE. The changes in RMSE for varying recharge and hydraulic conductivity based on this approach are listed in [table 3](#). The steady-state model was more sensitive to changes in hydraulic conductivity when smaller percentages of change were used and was more sensitive to recharge when larger percentages of change were used. This result is reasonable because the design of other boundary conditions, such as river cells and general-head boundaries used in lakes and quarries, means that as groundwater heads simulated by the model change, more or less water enters the model from these boundary condition features. This design numerically compensates for changed recharge values in the water balance, especially when these changes are small.



**Figure 19.** Map showing pilot points used in the parameter estimation (PEST) module in the model to refine the hydraulic conductivity of layer 4 (Silurian aquifer), eastern Iowa. Distribution of calibrated hydraulic conductivity, in meters per day, is also shown.



**Figure 20.** Graph showing steady-state model output showing simulated versus observed water-level elevations for the 46 observation wells, eastern Iowa.

**Table 3.** Sensitivity analysis results for steady-state model calibration for hydraulic conductivity and recharge.

[%, percent; m, meter; RMSE, root mean square error]

Statistic	Change (%)						
	0	+10	+20	+50	-10	-20	-50
Hydraulic conductivity							
Absolute residual mean (m)	2.38	2.77	2.90	3.64	2.8	2.74	8.13
Standard error	0.42	0.44	0.46	0.50	0.42	0.42	0.62
RMSE (m)	2.84	3.31	3.55	3.64	3.44	4.07	9.89
Residual mean (m)	-0.08	0.33	-0.21	-1.45	1.77	2.74	7.81
RMSE (%)	4.42	5.16	5.53	6.97	5.35	6.34	15.41
Correlation	0.99	0.98	0.98	0.98	0.99	0.99	0.97
Recharge							
Absolute residual mean (m)	2.38	2.83	3.25	5.64	2.80	3.20	5.12 <sup>a</sup>
Standard error	0.42	0.42	0.44	0.49	0.45	0.48	0.57 <sup>a</sup>
RMSE (m)	2.84	3.48	4.05	6.68	3.38	3.88	6.19 <sup>a</sup>
Residual mean (m)	-0.08	1.85	2.72	5.29	0.11	-0.76	-3.17 <sup>a</sup>
RMSE (%)	4.42	5.42	6.31	10.4	5.26	6.04	9.64 <sup>a</sup>
Correlation	0.99	0.99	0.99	0.98	0.98	0.98	0.97 <sup>a</sup>

<sup>a</sup>A run error was detected when the recharge was reduced by 50 percent.

## Transient Groundwater Model

A transient groundwater model of the Silurian aquifer was constructed from the calibrated steady-state model to simulate groundwater levels from 2020 through 2022. The period of 2020–22 was selected for the transient model because this represents the timespan of the pumping records available for the project. The transient model was divided into periods, called stress periods, and used hydrologic input data representative of average conditions during each stress period. The transient model was divided temporally into 12 3-month stress periods. The transient model incorporated calibrated parameter values from the steady-state model and added pumping water-level elevations from production wells along with pumping rates from 2020 to 2022. This approach used active production wells for the Cities of Coralville, North Liberty, Solon, and Tiffin and Iowa City as observation points. The cities provided water-use data and observed water levels for 2020, 2021, and 2022 (Sam Fosse, Iowa City Public Works, written commun., 2023; Matt Gilmore, Coralville Public Works, written commun., 2023; Scott Kleppe, Solon Public Works, written commun., 2023; Brett Mehmen, Tiffin Public Works, written commun., 2023; Gregg Metternich, North Liberty Water Department, written commun., 2023; [fig. 21](#)). To accommodate this approach and better capture groundwater variation near the pumping wells, the grid size was reduced to 1 m by 1 m at the production wells.

## Model Calibration for the 2020–22 Transient Model

The transient model was manually calibrated to 132 observed groundwater levels, including the pumping water levels provided by city staff. In this calibration process, horizontal hydraulic conductivity in layer 4 was adjusted to best match model output water levels to calibration observations. In addition to the production wells, 6 USGS and cooperative USGS and IGS observation wells with more than 20 years of groundwater-level data and 7 wells from GeoSam with groundwater-level data also were used for calibration observations ([fig. 21](#); Bristow and Gannon, 2026). As a result of this process, the layer 4 horizontal hydraulic conductivity values in the refined grid area around the City of North Liberty and Iowa City well fields were adjusted from 1.12 m/d to 0.62 m/d and 0.40 m/d, respectively; the calibrated hydraulic conductivity values from the steady-state model were otherwise retained in the transient model.

Observed and simulated water-level hydrographs for years 2020 through 2022 for 5 groundwater observation wells are shown in [figure 22A–E](#), and 3 production wells are shown in [figure 22F–H](#)). The observation well hydrographs (Elmira Depot, Ely North, Ely Northwest, Stockpile, and Lincoln Church) indicate that the model simulated the water table within a few meters of the observed values at these wells but did not capture small-scale water-level fluctuation in areas that

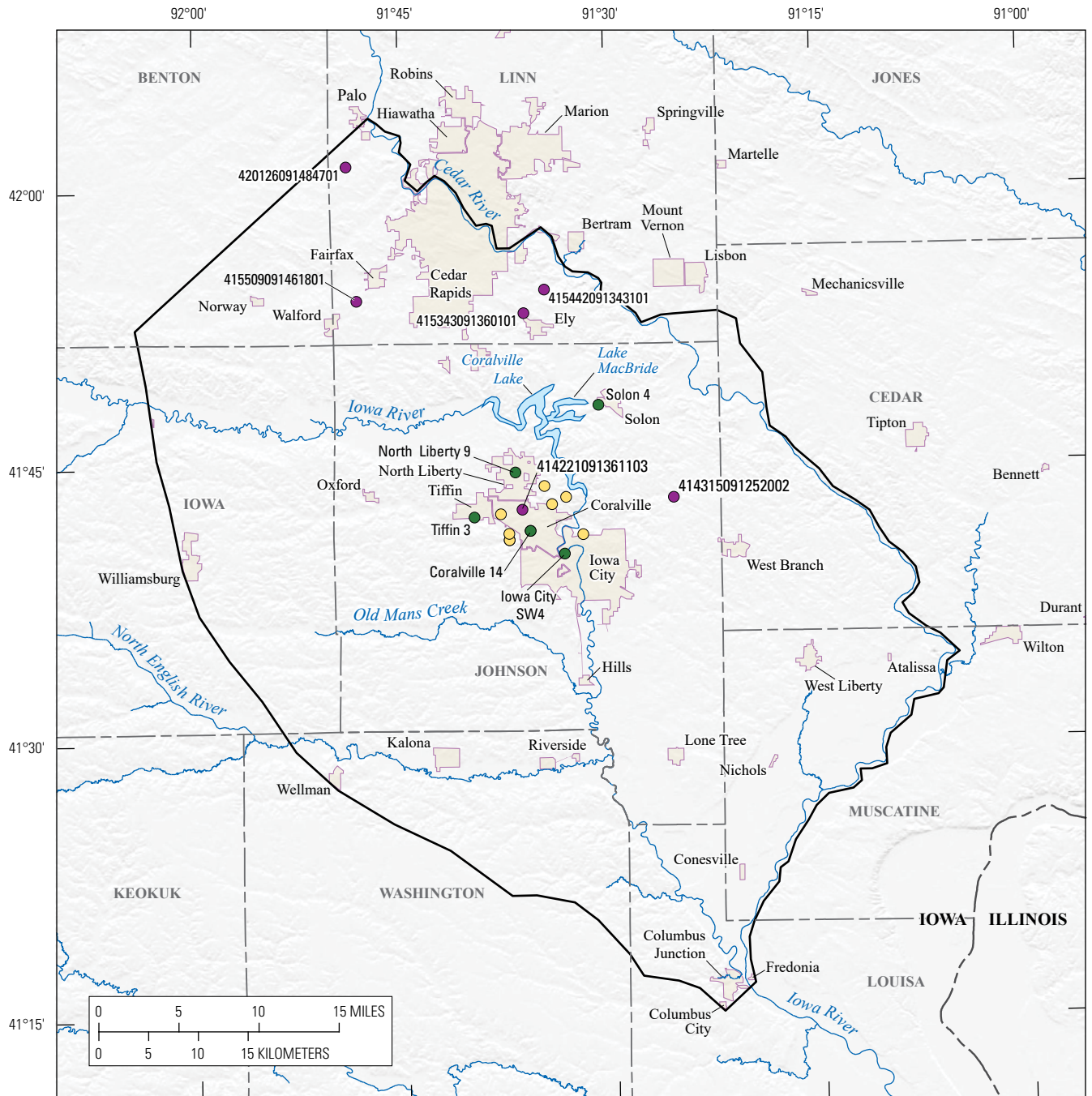
are not affected by pumping. The average residual for these five sites ranged from  $-1.8$  to  $3.4$  m. The hydrographs from production wells have higher errors in water level and indicate more fluctuation over time. The average water-level residual at Solon 4 was  $-5.6$  m, and the simulated water level was lower than observed for most stress periods. Average residuals at Coralville 14 and Iowa City SW4 were 8.2 m and 22.4 m, respectively. Simulated water level at the Iowa City SW4 well was consistently around 22 m too high, but the model accurately simulated water-level fluctuations at this well over time. Iowa City SW4 was the only production well with daily pumping records and daily water-level records. Other cities provided monthly or annual totals rather than daily, which is likely a contributing factor to the higher accuracy of the Iowa City hydrograph because a water-level measurement made once monthly is less representative of the average daily value over that month than a water-level measurement made daily. The higher accuracy of the Iowa City hydrograph indicates that although the model overestimates water levels in some areas of heavy pumping, it still reliably represents drawdowns (changes in water level) over time because of pumping.

A simulated potentiometric map for the final (October–December 2022) stress period of the transient model is shown in [figure 23](#). Lower water-level elevations are in the City of Coralville area near dewatering areas for the quarry and City of Coralville wells.

## Water Budget Analyses for Steady-State and Transient Models

Water budgets quantifying fluxes into and out of the entire model area were calculated for the steady-state and transient models using software tools available in Visual MODFLOW Flex 9.0. Model water budgets were estimated for steady-state flow and transient flow for 2020 through 2022, and a zone budget water balance indicating fluxes between model layers and at model boundaries was calculated near the Klein and Conklin Quarries.

The water budget for the steady-state model included net recharge, groundwater, surface water, and leakage from lakes and quarries into and out of the model area and the pumping of wells. Net recharge into the model was 0.0681 million  $\text{m}^3/\text{d}$ . Groundwater flow at the southwestern flow-through boundary and flux through the quarries is the difference between the constant head in (CHD in) and constant head out (CHD out), or a 0.0357-million- $\text{m}^3/\text{d}$  loss from the model area. Surface water flowing into the aquifer through streambeds is the difference between river in versus river out, or a 0.0117-million- $\text{m}^3/\text{d}$  net flux into the model area. Leakage into the aquifer from Coralville Lake and Lake Macbride and into layer 4 at the quarries is the difference between general head boundary in (GHB in) and general head boundary out (GHB out), or a 0.00076-million- $\text{m}^3/\text{d}$  net flux into the model.



Base modified from U.S. Geological Survey and other Federal and State digital data  
 Universal Transverse Mercator projection, Zone 15  
 North American Datum of 1983

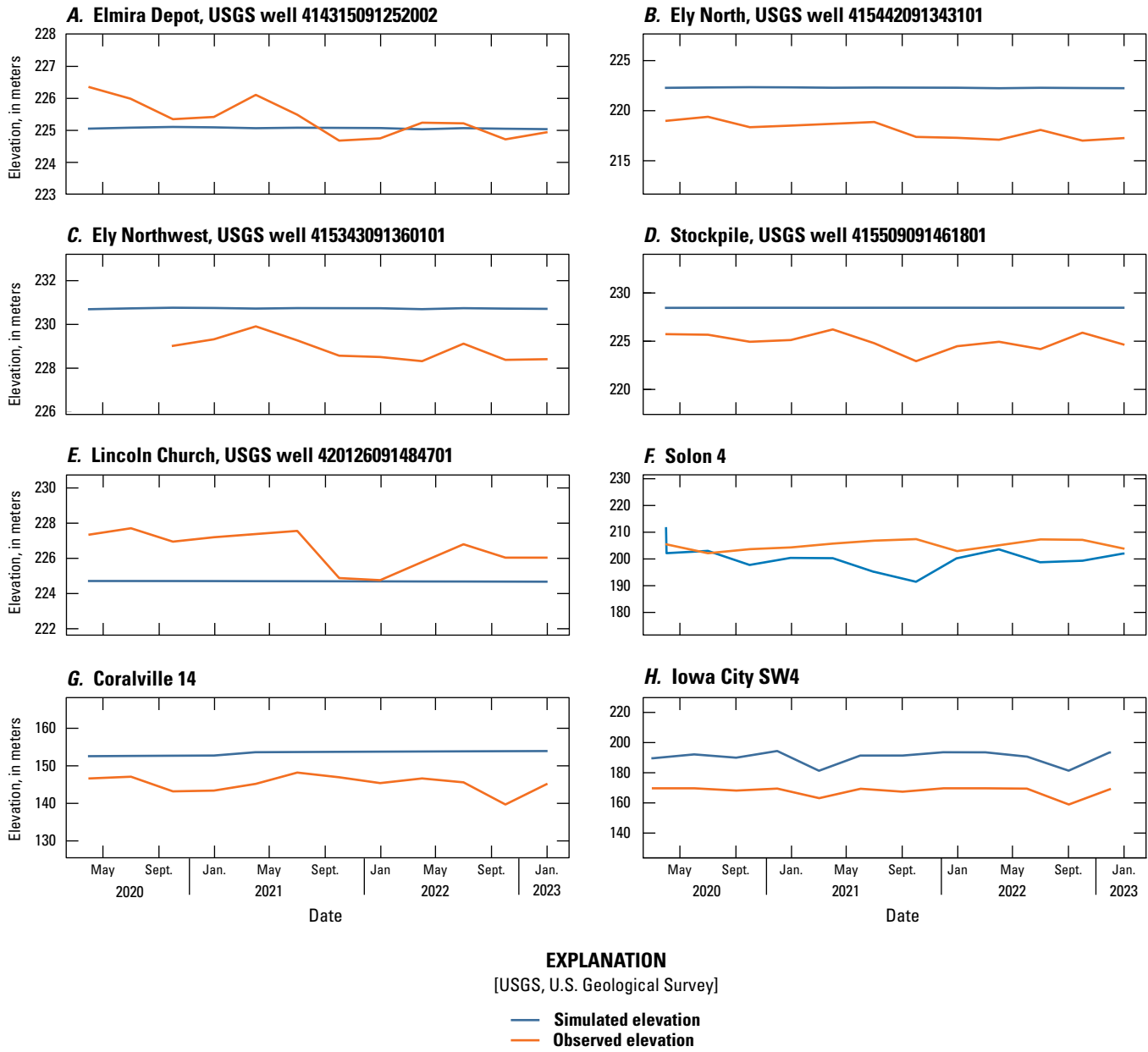
U.S. Geological Survey National Water Information System data from U.S. Geological Survey (2025)

**EXPLANATION**

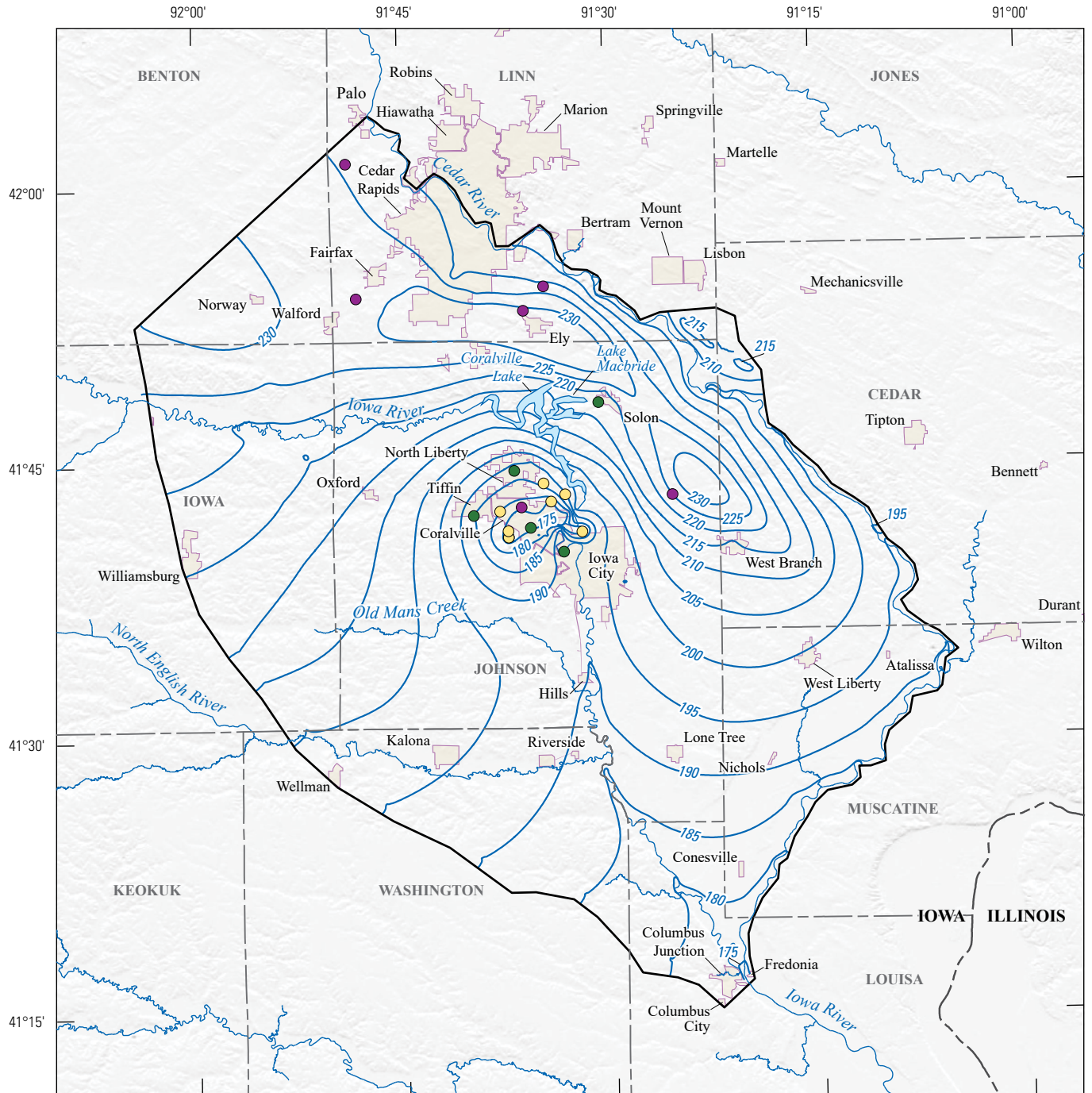
- Model boundary**
- Solon 4 Production well and identifier**
- 420126091484701 Observation well with U.S. Geological Survey National Water Information System identifier**
- Well log with water level from GeoSam**

**Figure 21.** Map showing the observation wells used to calibrate the transient 2020–22 model, eastern Iowa.

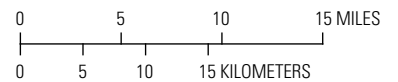
34 Simulation of Groundwater Flow in the Silurian Aquifer, Eastern Iowa, 2020–45



**Figure 22.** Hydrographs showing simulated and observed groundwater elevations for (A–E) U.S. Geological Survey and Iowa Geological Survey observation wells and (F–H) production wells from 2020 through 2022, eastern Iowa.



Base modified from U.S. Geological Survey and other Federal and State digital data  
 Universal Transverse Mercator projection, Zone 15  
 North American Datum of 1983



**EXPLANATION**

- Model boundary**
- Simulated potentiometric contours for October–December 2022, in meters above the North American Vertical Datum of 1988**
- Observation well**
- Well log with water level from GeoSam**
- Production well**

**Figure 23.** Map showing model-simulated potentiometric contours for the Silurian aquifer, eastern Iowa, based on October–December 2022 stress period condition results.

The pumping of wells and groundwater drained from karst features within the Silurian aquifer account for losses of 0.0163 million m<sup>3</sup>/d and 0.0287 million m<sup>3</sup>/d, respectively.

The water budget for the transient model over the prediction period of 2020–22 is shown in figure 24. Water entered the model area primarily from rivers, recharge, and storage over the prediction period listed in the order of most to least cubic meters per day. Water left the model area primarily to rivers, drains, wells, and storage over the prediction period listed in the order of most to least cubic meters per day. The amount of water leaving the model to rivers could, in part, be attributed to the dry conditions observed over the period of prediction. The water leaving the model through drains represents the karst features that exist in the Devonian aquifer in layer 2. Overall, storage from and to the model area decreases over the prediction period.

## Forecast Groundwater Level and Budget Components

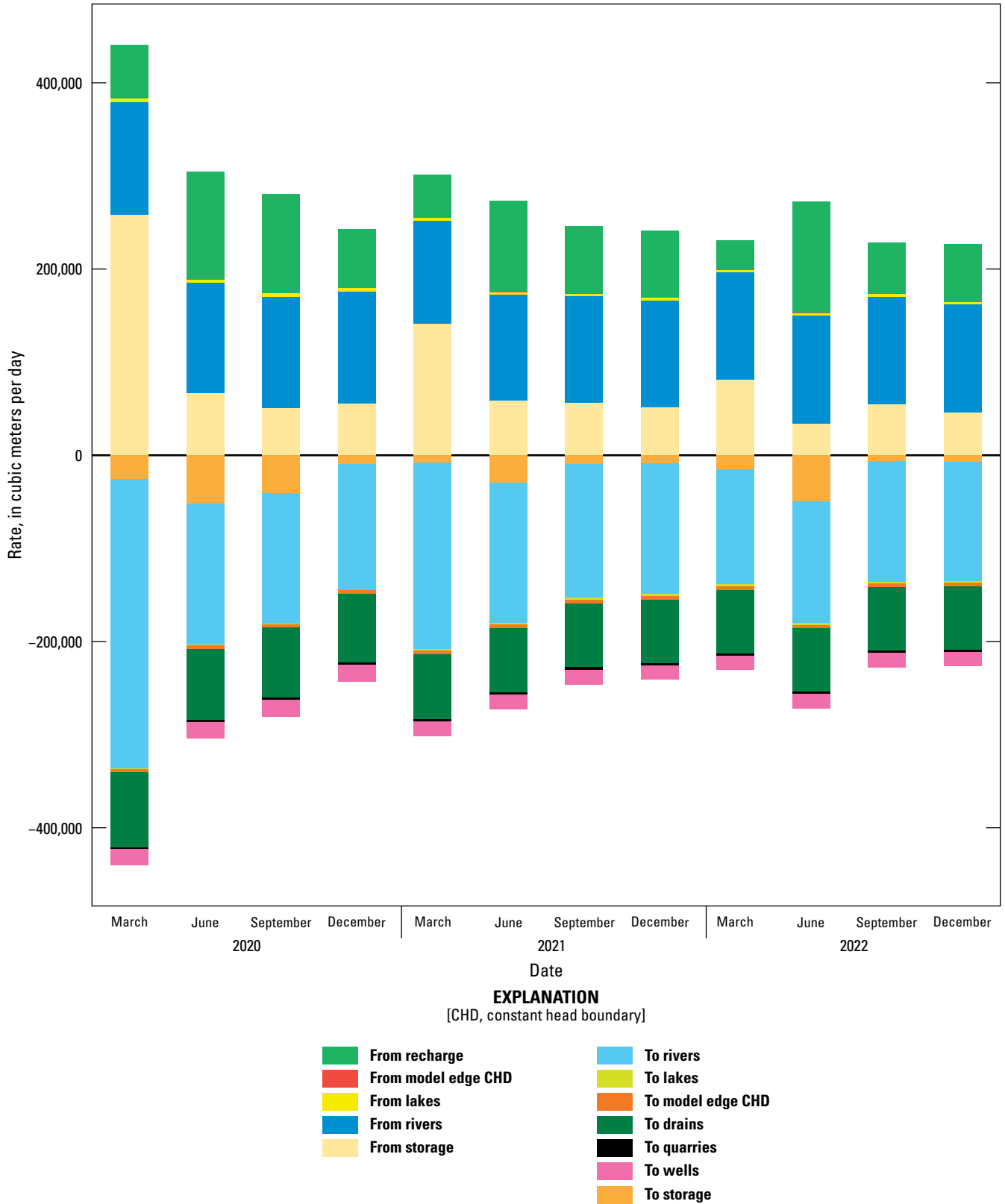
The transient (2020 through 2022) Silurian aquifer groundwater-flow model was modified to forecast effects on the aquifer from anticipated pumping scenarios for 2025–45. Public water supply staff provided estimates of future growth and water usage from 2025 to 2045 (Sam Fosse, Iowa City Public Works, written commun., 2023; Matt Gilmore, Coralville Public Works, written commun., 2023; Scott Kleppe, Solon Public Works, written commun., 2023; Brett Mehmen, Tiffin Public Works, written commun., 2023; Gregg Metternich, North Liberty Water Department, written commun., 2023). Increases in annual water use range from 0 percent per year in the Iowa City well field to 5 percent per year for the City of Tiffin. Future wells are likely to be near current well fields because industry and population growth are likely to be in these areas. Iowa City currently has three Silurian production wells but only uses the Silurian aquifer as an emergency supply.

The predictive model also assumed a moderate to severe drought about every 10 years. The 10th percentiles were used for river stage elevations, and recharge was reduced by 25 percent from steady-state recharge values to simulate drought conditions. The predictive model included 12 3-month stress periods representing 2020 through 2022 and 23 1-year stress periods representing 2023 through 2045.

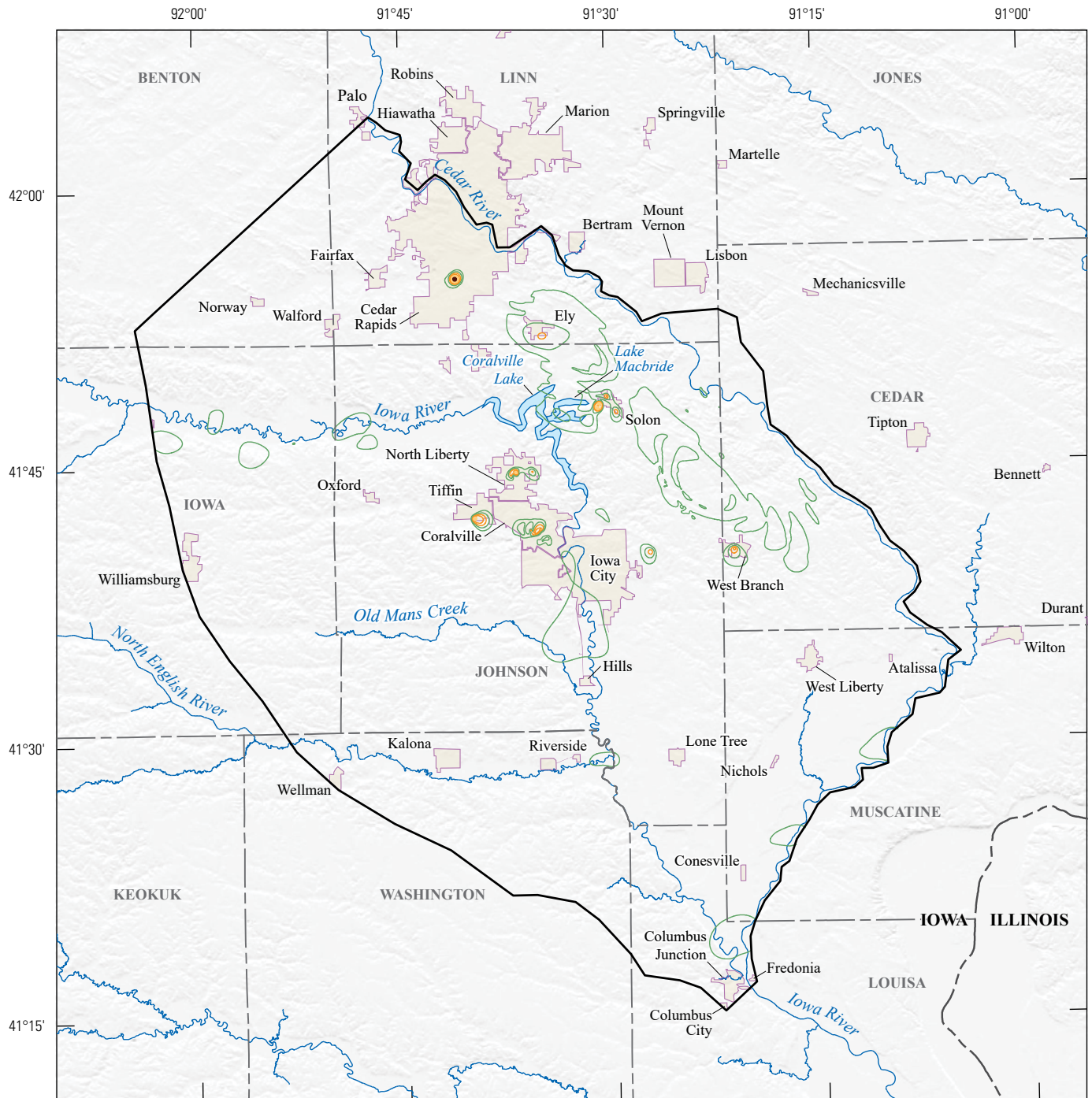
The water table drawdown from 2022 levels to 2045 levels based on projected pumping rates, moderate drought conditions, and existing (as of 2022) infrastructure are shown in figure 25. Less than 1 m of drawdown is predicted in most areas of the model without heavy water users. Drawdown ranges from less than 1 to 13 m, and the highest drawdowns are concentrated spatially (fig. 25), especially around the locations of production wells.

Output from the predictive model was used to calculate water budgets for four spatial zones within the model area for 2020–45. Although the overall water budget for each stress period is balanced within the entire model area, inflows and outflows within each individual subset zone do not necessarily balance because water moving into model cells outside the zone is not included in the zone budget. The zone budget regions (hereafter referred to as “zones”) used in this evaluation of the predictive model are shown in figure 26. Zone 2 includes the Iowa City metropolitan area (Iowa City and the Cities of Coralville, Tiffin, and North Liberty), zone 3 includes rural areas on the south side of Coralville Lake, zone 4 includes rural areas to the north and east of Coralville Lake, and zone 5 includes the Fairfax and Cedar Rapids areas (fig. 1). Zone 1 was used to designate the remainder of the model area outside the four target zones, and the budget for zone 1 is not shown.

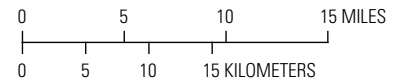
The changes in water budget components in each of the zones over the prediction period are shown in figure 27. Water entering the model area within each zone is given in positive rates in cubic meters per day, and water leaving the model area from each zone is given in negative rates in cubic meters per day. In zone 2, representing the Iowa City area, most of the water entering the model was as seepage from rivers (~40,000–50,000 m<sup>3</sup>/d), and water leaving the model was as losses to drains (~50,000–60,000 m<sup>3</sup>/d). Model outflows because of pumping moderately increased from ~6,000–8,000 m<sup>3</sup>/d (fig. 27). In zone 3, representing the rural areas to the south of Coralville Lake, the water budget indicated the largest source of model inflows was seepage from lakes and rivers with ~3,000 and ~7,000 m<sup>3</sup>/d entering the model area, respectively, and little change in this value over time. Input from storage generally decreased from ~1,500 to ~500 m<sup>3</sup>/d, and pumping moderately increased from ~300 to ~500 m<sup>3</sup>/d. In zone 4, representing the rural areas to the north and east of Coralville Lake, ~2,000–5,000 m<sup>3</sup>/d of recharge and ~500–3,000 m<sup>3</sup>/d from storage are entering the zone. The changes in storage in the water budget in zone 4 indicate that water coming out of storage into the model area increases over time. Water leaving the model area in this zone from well pumping increased over the prediction period from ~2,500 to ~4,500 m<sup>3</sup>/d. In zone 5, representing the Fairfax and Cedar Rapids areas, most of the water entering the model area in all stress periods was recharge from precipitation (~5,000–9,000 m<sup>3</sup>/d), and most of the water leaving the model area was from well pumping (~2,500–7,500 m<sup>3</sup>/d). As in zone 4, the amount of water from storage entering the model in this zone increased over time from ~200 to ~1,200 m<sup>3</sup>/d, but the amount of water leaving the model to storage decreased from ~3,700 to 0 m<sup>3</sup>/d.



**Figure 24.** Graph showing transient water balance, in cubic meters per day, for the Silurian aquifer model for 2020–22 in eastern Iowa.



Base modified from U.S. Geological Survey and other Federal and State digital data  
 Universal Transverse Mercator projection, Zone 15  
 North American Datum of 1983



**EXPLANATION**

**Drawdown contour from 2022 to 2045, in meters**

- 1
- 2
- 4
- 8
- **Model boundary**

**Figure 25.** Map showing the predicted drawdown from 2022 to 2045, in meters, based on the 2020–22 transient and predictive models, eastern Iowa.

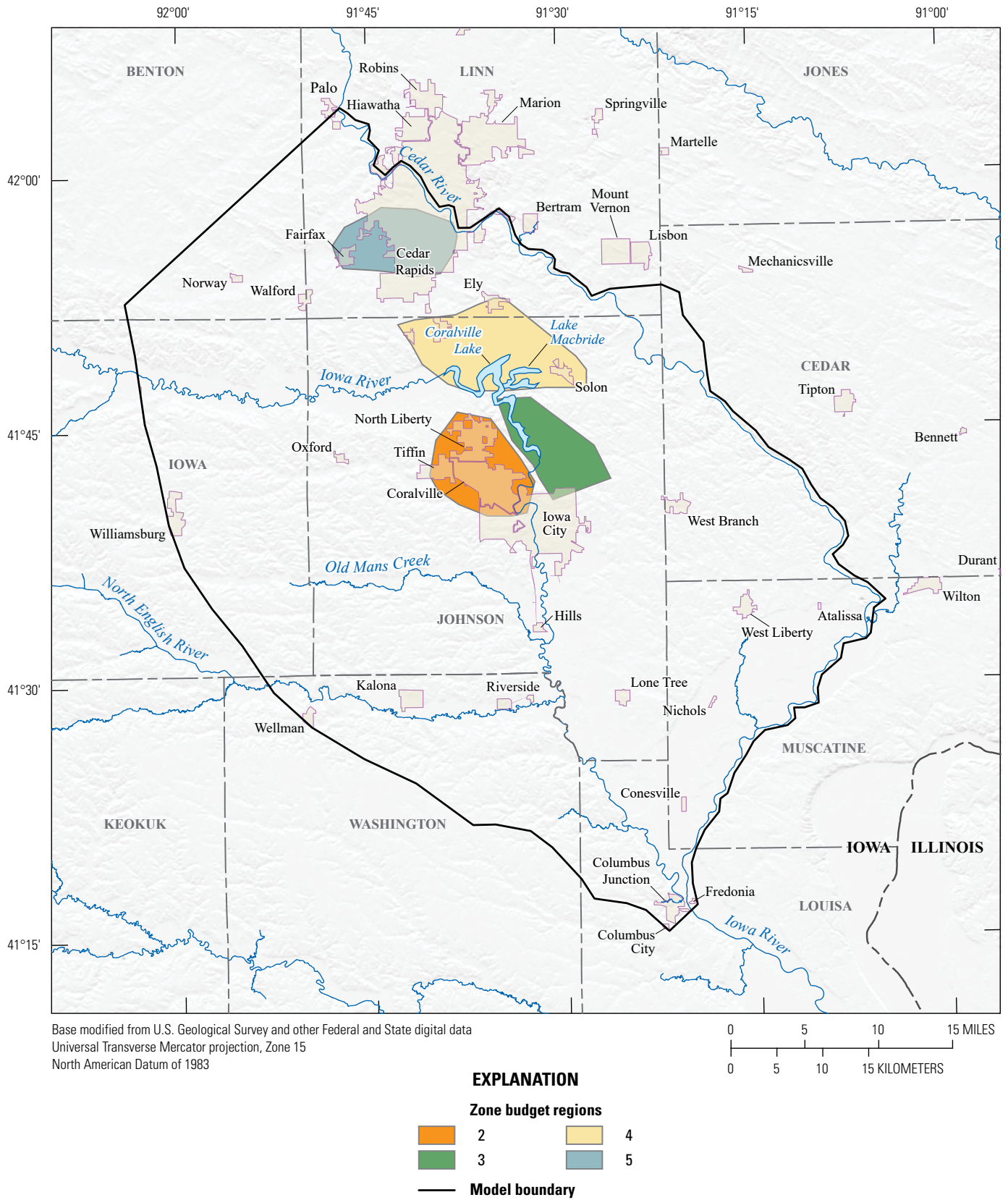
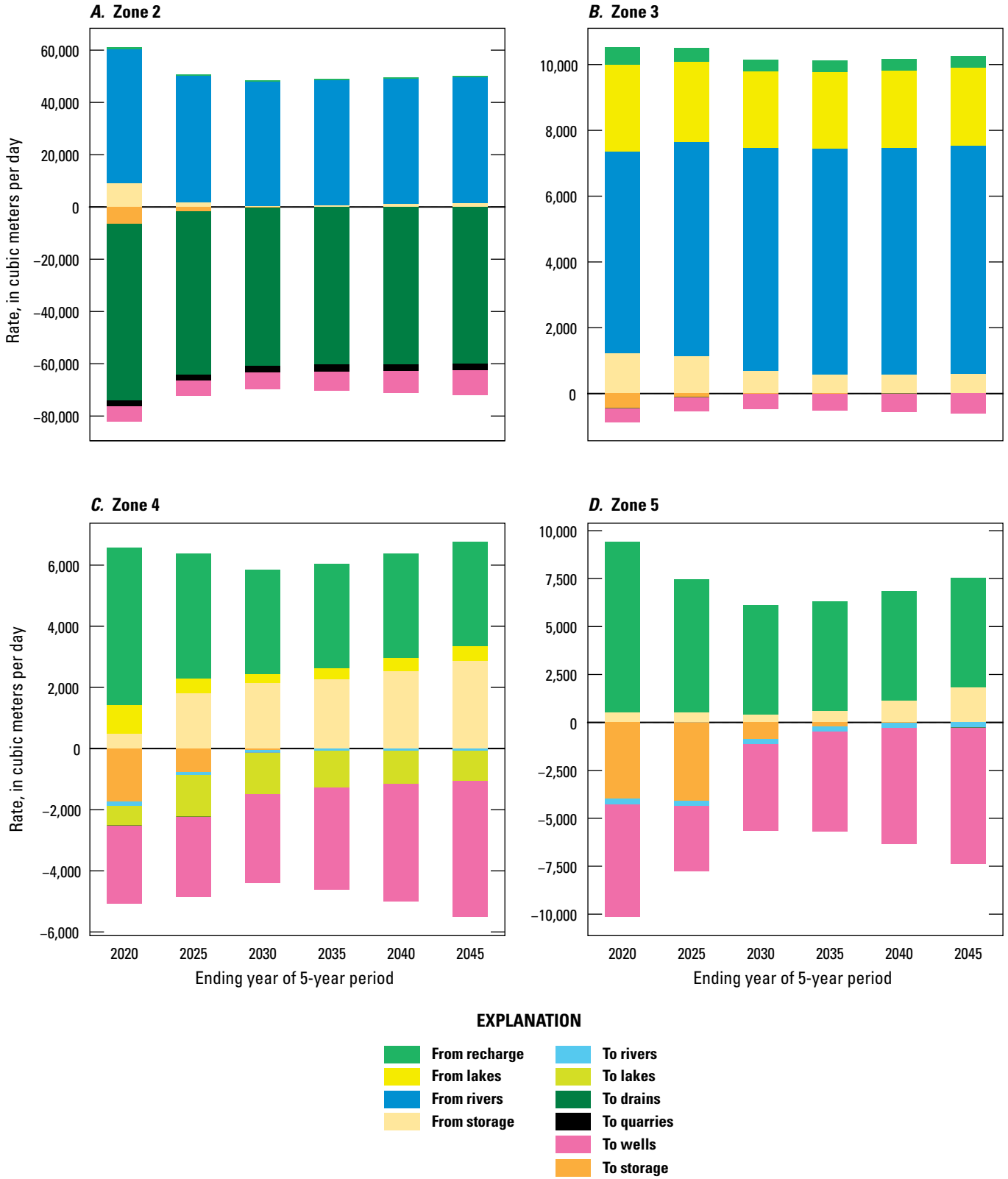


Figure 26. Map showing the zone budget regions, eastern Iowa.



**Figure 27.** Graph showing water budgets for zone budget regions (A) 2, (B) 3, (C) 4, and (D) 5, eastern Iowa, from 2020 to 2045 based on the 2020–22 transient model.

## Model Limitations

Numerical groundwater-flow models are simplified mathematical representations of complex natural systems, and as such, they are constructed with assumptions and generalizations that lead to limitations on model use and uncertainty in model results. Several model generalizations caused uncertainty in the results. Input datasets were interpolated and spatially averaged into model cells, which means that complexity within each cell may not be represented. Aquifer properties, which can be highly heterogeneous, were assumed to be homogeneous within hydrogeologic units or hydraulic conductivity zones in the aquifer. These parameters were often calculated from spatially distributed pump test results and are therefore averaged spatially. This simplification can introduce inaccuracies in aquifer volume and groundwater flux, especially at scales smaller than the grid size. Time-series inputs including river stage and groundwater pumping data were temporally averaged into stress periods of months or years, which limits the ability of the model to simulate shorter time intervals. Head values near flow-through boundaries may not accurately represent observed values because observation data were not available at all of these locations. General-head boundaries were used to minimize this error.

The nature and extent of available data, especially pumping and water-level data, also led to some limitations in this model. A few of the production wells used in the model are open in the Devonian and Silurian aquifers. No attempt was made to divide these withdrawals into separate aquifers. When the number of city wells and their locations were known but the allocation of withdrawals among the individual wells was unknown, pumping rates were equally divided among the active wells. For the transient model, water levels and pumping rates were averaged into 3-month stress periods, which means that fluctuations at the scale of days or single months were not represented by the model. Groundwater levels at pumping wells may be affected by pump operations and well conditions like siltation and are less reliable than groundwater levels measured at monitoring wells. Additional time-series groundwater-level measurements at monitoring wells would improve transient model calibration and reduce the uncertainty in predictive model results. Uncertainty in projected pumping rates contributes to uncertainty in the results of a predictive simulation (Konikow, 1986). Model error related to inaccuracies in how pumping is allocated among multiple wells is compounded if the projection of total future pumping is not accurate (Dutton and others, 2001).

## Summary

The Silurian aquifer is an important water source for municipalities, industry, and rural households and communities in eastern Iowa, including Johnson County. Regional population and economic growth have increased the demand for groundwater from the Silurian aquifer, indicating the benefit of analytical tools to quantify groundwater resources and to inform water-management decisions for the aquifer in Johnson County. The U.S. Geological Survey, in cooperation with Johnson County Planning and Zoning, developed conceptual and numerical groundwater models to simulate water levels in the Silurian aquifer, determine groundwater budgets, and forecast changes in groundwater levels through 2045. The model includes all of Johnson County and parts of neighboring counties, incorporating regional aquifer flow and major recharge sources and Silurian groundwater users within the model boundary.

A conceptual model of the model area was constructed to represent the hydrogeology and water budget components of the study area. The conceptual model included five layered hydrogeologic units: (1) an upper confining layer consisting of surficial materials and some overlying bedrock, (2) the Devonian aquifer, (3) the Devonian confining layer, (4) the Silurian aquifer, and (5) the lower confining layer consisting of the Maquoketa Formation. An initial potentiometric surface of the Silurian aquifer was interpolated from measured groundwater levels and river stage. Inflows to the aquifer include recharge from precipitation, seepage from rivers and lakes, and groundwater inflow from outside the model area. Outflows from the aquifer include withdrawals from wells, dewatering pumping from quarries, discharge to rivers, and groundwater outflow from the model area.

A numerical model was constructed in Visual MODFLOW Flex modeling software using MODFLOW 2005 and MODFLOW 6. Three versions of the model were constructed, including an initial steady-state version that calculated initial conditions for the other versions, a transient version simulating water levels from 2020 through 2022, and a predictive version that used the transient model framework to simulate water levels through 2045 using projected well withdrawals. Horizontal hydraulic conductivity was calibrated for the steady-state version of the model using parameter estimation calibration software within Visual MODFLOW Flex. The transient version of the model included smaller grid spacing around production wells to better simulate drawdowns in those areas and simulated 3-month stress periods. Hydraulic conductivity was further calibrated in the transient model using manual parameter adjustment to better match water-level observations.

Model performance was assessed by comparing simulated and observed water-level hydrographs at several pumping and monitoring wells. Hydrograph comparison indicates that the model simulates water levels accurately

at monitoring wells that are not near areas of pumping and generally overpredicts water levels near pumping wells, while accurately simulating the drawdown trend over time at pumping wells. This transient model framework was then used to predict water levels through 2045 in a scenario of moderate drought and increased groundwater withdrawals. Results from the predictive model indicate as much as 13 meters of additional drawdown in 2045 from 2022 water levels in the area of pumping wells.

Analysis of simulated groundwater budgets from the transient model indicates that inflow from rivers and recharge were the greatest inputs into the model area, along with the removal of water from storage, and seepage to rivers and drains (used to model karst and fractures) were the highest losses from the model area, followed by withdrawal from wells and removal to storage. Water tables simulated by the predictive model indicated increased drawdown around production wells by 2045. Water budgets for the predictive model were examined by zones, which were smaller subsets of the model area. Inflows and outflows were varied among the zones, and the water budget for each individual zone was dependent on the geology and landscape features of the zone, as well as the amount of groundwater pumping.

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