Hydrogeology and Simulation of Ground-Water Flow in the Silurian-Devonian Aquifer System, Johnson County, Iowa

By Patrick Tucci (U.S. Geological Survey) and Robert M. McKay (Iowa Department of Natural Resources, Iowa Geological Survey)

Prepared in cooperation with
The Iowa Department of Natural Resources – Water Supply Bureau
City of Iowa City
Johnson County Board of Supervisors
City of Coralville
The University of Iowa
City of North Liberty
City of Solon

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Conversion Factors and Datum

Multiply	By	To obtain
inch	2.54	centimeter (cm)
inch	25.4	millimeter (mm)
foot	0.3048	meter (m)
mile(mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]

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

$$°C = (°F-32)/1.8$$

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

Altitude, as used in this report, refers to distance above or below NAVD 88. NAVD 88 can be converted to National Geodetic Vertical Datum of 1929 (NGVD 29) by using the National Geodetic Survey conversion utility available at this URL:

http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html

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

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By Patrick Tucci and Robert M. McKay

Abstract

Bedrock of Silurian and Devonian age (termed the "Silurian-Devonian aquifer system") is the primary source of ground water for Johnson County in east-central Iowa. Population growth within municipal and suburban areas of the county has resulted in increased amounts of water withdrawn from this aquifer and water-level declines in some areas. A 3-year study of the hydrogeology of the Silurian-Devonian aquifer system in Johnson County was undertaken to provide a quantitative assessment of ground water resources and to construct a ground-water flow model that can be used by local governmental agencies as a management tool.

Johnson County is underlain by unconsolidated deposits of Quaternary age and Paleozoic-age bedrock units. The bulk of the Quaternary deposits consists of weathered and unweathered glacial till; however, shallow alluvium and buried sand and gravel deposits also are present. Six bedrock hydrogeologic units are present in Johnson County (oldest to youngest): Maquoketa confining unit, Silurian aquifer, Wapsipinicon Group (aquifer and confining unit), Cedar Valley aquifer, Upper Devonian shale confining unit, and Cherokee confining unit. Although separate aquifers and confining units are described, the Silurian- and Devonian-age units are considered as a single aquifer system. The top of the Silurian-Devonian aquifer system is considered as the top of the Cedar Valley aquifer, where present, and the base of the aquifer system is considered as the top of the Maquoketa confining unit.

The hydraulic properties of the rocks that comprise the Silurian-Devonian aquifer system are highly variable as a result of the variable composition of the rocks and the presence of solution features in some of the carbonate-rock units. For the combined Silurian-Devonian aquifer system, specific capacity averages 2.1 gallons per minute per foot of drawdown, transmissivity averages about 580 feet squared per day, and hydraulic conductivity averages 8.3 feet per day.

Recharge to the Silurian-Devonian aquifer system in Johnson County is predominantly from infiltration of precipitation to the bedrock. Discharge from the aquifer is primarily to municipal, industrial, and private-development wells. Reliable measurements of the amount of recharge to or discharge from the ground-water system in Johnson County, however, are not available.

Altitude of the 1996 potentiometric surface ranged from more than 750 feet above the North American Vertical Datum of 1988 (NAVD88) in northern Johnson County to less than 575 feet above NAVD88 in the central part of the county. A large cone of depression within the potentiometric surface is present in the central part of the county, between Coralville and Iowa City. A large limestone quarry is located near the center of this cone of depression. Ground water generally flows from the northern and western parts of Johnson County either toward the cone of depression in the center of the county or south out of the county. Ground water also flows toward the Cedar River in the northeastern part of the county. A ground-water divide in the northeastern part of the county roughly approximates the surface-water divide between the Iowa River and Cedar River drainages.

A numerical ground-water-flow model of the Silurian-Devonian aquifer system in Johnson County was used to test concepts of ground-water flow, to assess the need for additional data, and to evaluate the potential effects of anticipated increased ground-water development and drought. The 1-layer model was calibrated to average 1996 ground-water conditions, which were assumed to approximate steady-state flow conditions. The model also was used to simulate steady-state conditions for 2004, steady-state conditions using anticipated pumping rates for 2025, and potential future drought conditions.

The simulated potentiometric surface generally replicated the potentiometric surface for 1996 and 2004 conditions. The calculated root mean squared error values for the 1996 and 2004 simulations were 13.6 and 18.6 feet, respectively. The mean absolute differences between measured and simulated water levels for the 1996 and 2004 simulations were about 11 and 14 feet, respectively.

Total model-calculated inflow to the ground-water system for the 1996 simulation was 19.6 million gallons per day (Mgal/d), and the largest model-calculated inflow component was areal recharge (15.1 Mgal/d). Total model-calculated outflow from the ground-water system was 19.7 Mgal/d, and the largest outflow component was discharge to wells (10.5 Mgal/d). Model-calculated water-budget components for the 2004 simulation were similar to the 1996 components.

Potential future steady-state conditions were simulated using anticipated 2025 pumping rates. Pumpage both for existing wells and for assumed new wells, based on antici-

pated population growth in the northern part of the county and for the nearby municipalities, was included in the model. Simulated 2025 pumpage was about 1.5 Mgal/d greater than simulated 2004 pumpage. Simulated steady-state ground-water levels, using anticipated 2025 pumping rates, were lower than 2004 simulated levels throughout the county, and simulated water-level declines ranged from less than 1 foot near the county boundaries to about 11 feet.

Potential future drought conditions were simulated by assuming that recharge to the Silurian-Devonian aquifer system is reduced by a factor of 0.75 and that water-supply pumpage is increased by a factor of 1.25 over the anticipated 2025 pumping rates. Overall, simulated water levels for future drought conditions were greater than 5 feet lower than simulated 2004 conditions and were a maximum of about 30 feet lower in the northeastern part of the county.

The greatest limitation to the model is the lack of measured or estimated water-budget components for comparison to simulated water-budget components. Because the model is only calibrated to measured water levels, and not to water-budget components, the model results are nonunique. Other model limitations include the relatively coarse grid scale, lack of detailed information on pumpage from the quarry and from private developments and domestic wells, and the lack of separate water-level data for the Silurian- and Devonian-age rocks.

Introduction

Ground water is used for public and private water supplies in Johnson County in southeastern Iowa (fig. 1). Bedrock of Silurian and Devonian age (herein termed the “Silurian-Devonian aquifer system”) is the primary source of ground water in the northern part of Johnson County, locally known as the North Corridor (fig. 1). Population growth within municipal and suburban areas of the county has resulted in increased amounts of water withdrawn from this aquifer and water-level declines in parts of the county. From 1990 to 2000, the population in Johnson County increased by 15 percent, from about 96,000 to about 111,000 (U.S. Census Bureau, 2005). The population in the North Corridor area is projected to increase by about 15,000 by 2025 (Dan Swartzendruber, Johnson County Planning and Zoning Department, written commun., 2005).

Increasing demand for water has required communities to drill additional supply wells. Total ground-water withdrawals in the county increased by about 50 percent from 1990 to 2000 (E.E. Fischer, U.S. Geological Survey, written commun., 2005). Water levels have reportedly dropped in some wells, and some well owners have had submersible pumps burn out as water levels drop below pump intakes (R.C. Buchmiller, U.S. Geological Survey, written commun., 2003).

Because of the increased water demand, information is needed to quantify the ground-water resources in the Silurian-Devonian aquifer system and to aid in water-management decisions. To meet these needs, the U.S. Geological Survey (USGS), in cooperation with the Iowa Department of Natural Resources (IDNR) Water Supply Bureau, City of Iowa City, Johnson County Board of Supervisors, City of Coralville, the University of Iowa, City of North Liberty, and the City of Solon, began an assessment of the hydrogeology of Johnson County in late 2002. The Iowa Geological Survey (IGS), which is a part of the IDNR, provided maps of various hydrogeologic units, geologic and hydrogeologic analyses, and estimates of hydraulic conductivity for the aquifer.

The purpose of the 3-year study was to provide a quantitative assessment of ground water in the Silurian-Devonian aquifer system of Johnson County and to construct a ground-water flow model that can be used by local governmental agencies as a management tool. Only available data were used; additional information, such as hydraulic conductivity of the aquifer and the bedrock surface, was developed from the available data. A network of about 40 wells in the Silurian-Devonian aquifer system (fig. 2) was routinely monitored by the USGS for ground-water levels between 1995 and 2004, and these wells form the core data for the study.

The study included the following tasks:

- collect, compile, and analyze available geologic and hydrologic data;
- collect, compile, and estimate the location and amount of substantial ground-water withdrawals within the study area;
- construct and calibrate, to the extent possible, a ground-water flow model for the Silurian-Devonian aquifer system;
- simulate the potential effects of anticipated increased ground-water development and drought; and
- document the data used and the model simulations.

This report describes the hydrogeology of the Silurian-Devonian aquifer system, documents the construction and calibration of a ground-water flow model of the aquifer system, and provides estimates of the potential effects of anticipated future development and droughts through simulations of ground-water flow. Well-construction information and measured water levels in selected observation wells completed in the Silurian-Devonian aquifer system are included in the Appendix. Information about water levels used for model calibration and methods for obtaining the water levels also is included in the Appendix.

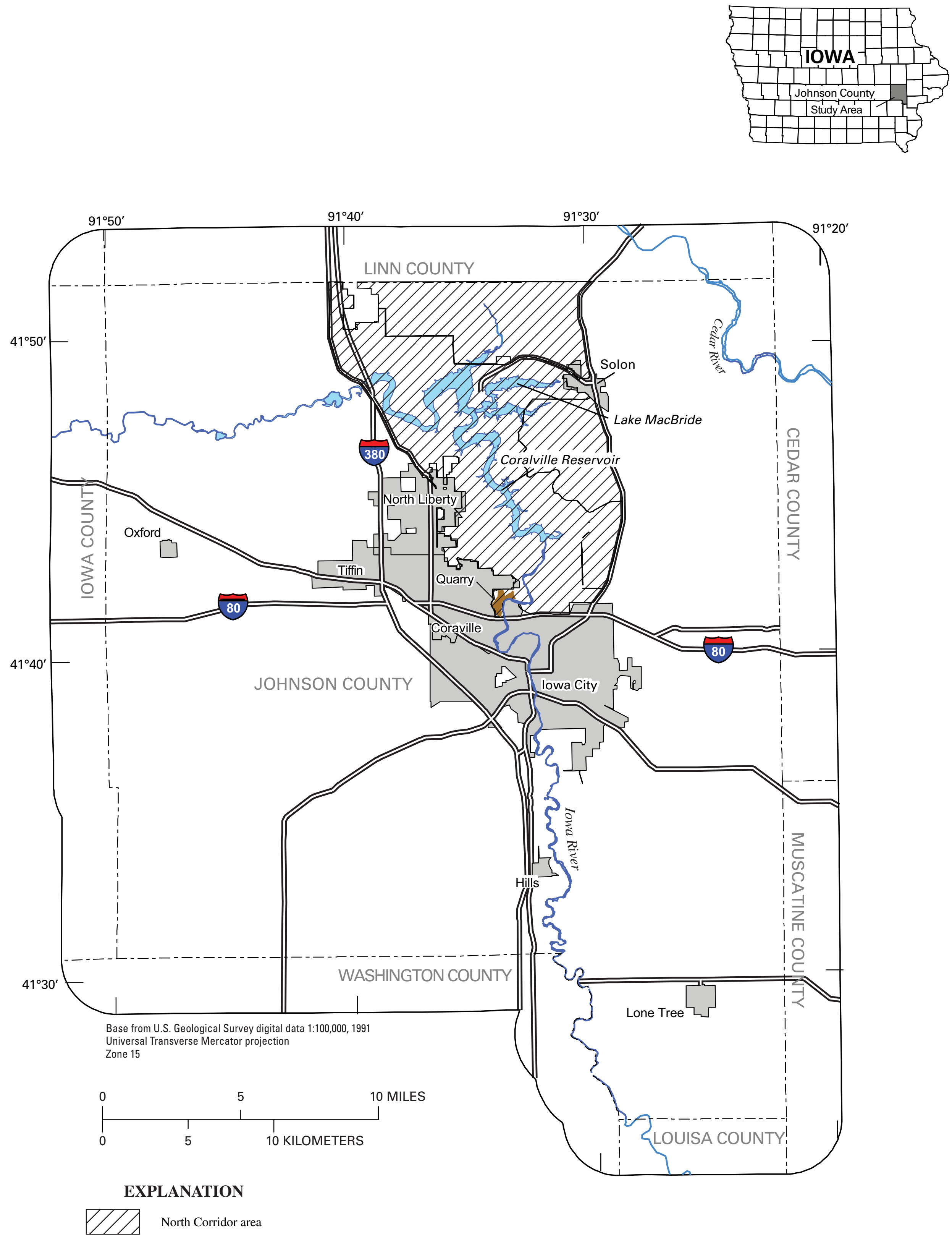


Figure 1. Location of study area and the North Corridor area of Johnson County.

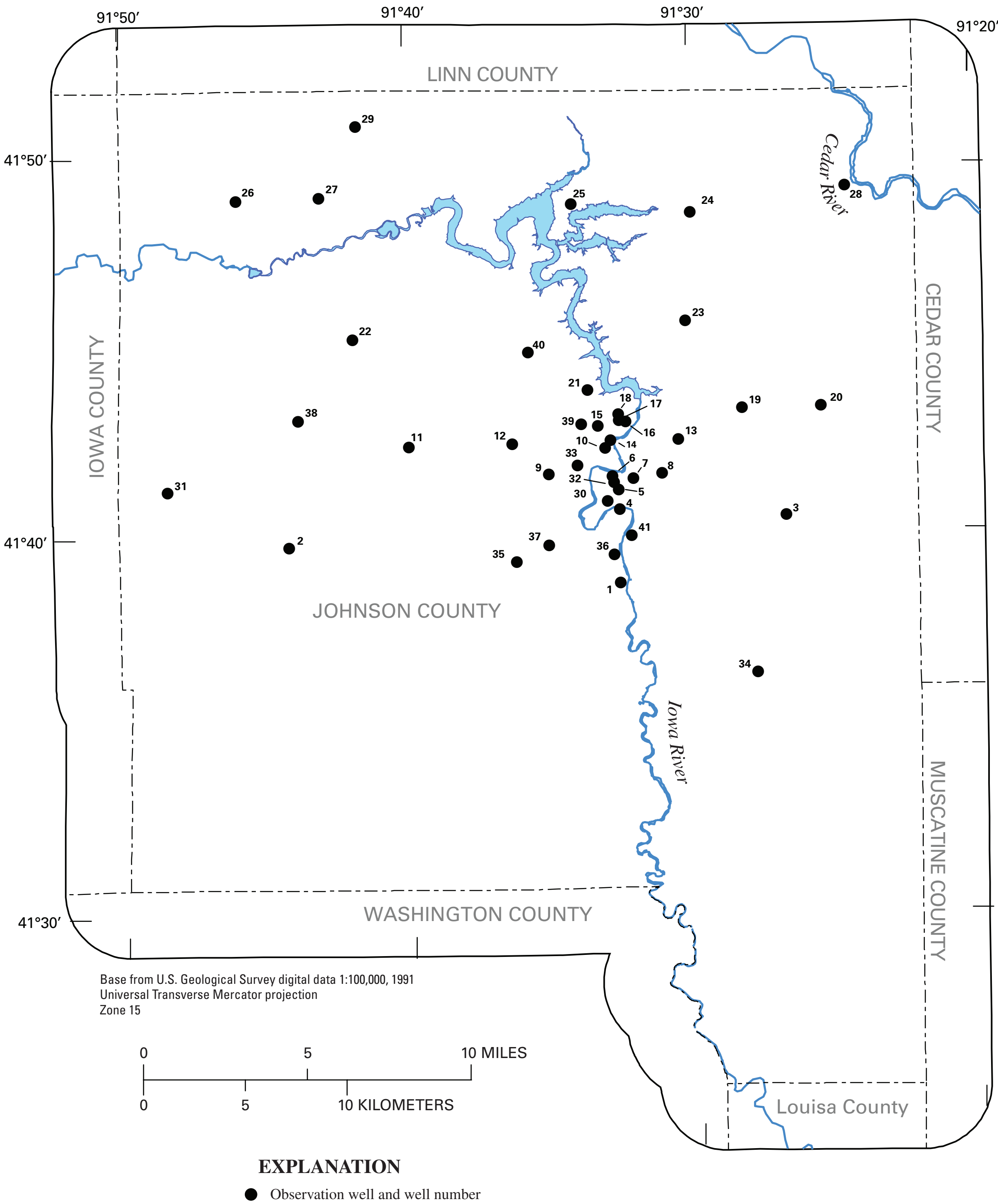


Figure 2. Location of observation wells used for comparison to model results.

Previous Studies

Although Johnson County has not previously been the subject of a hydrogeologic assessment, other regional studies that included Johnson County have been conducted.

Wahl and others (1978) compiled an atlas of the water resources of east-central Iowa that included discussions of surface-water and ground-water resources, water quality of those resources, water levels, well yields, and water use. They considered the Silurian- and Devonian-age rocks as comprising separate aquifers and showed maps of the aquifer depths, thickness, potentiometric surface, possible yields, and dissolved-solids concentrations of each of the aquifers in the region. Estimates of possible well yields in Johnson County ranged from less than 50 to 300 gal/min in the Devonian aquifer and from less than 100 to 500 gal/min in the Silurian aquifer (Wahl and others, 1978, p. 62-63).

Horick (1984) compiled a series of maps for the "Silurian-Devonian" aquifer of Iowa. Features such as areal extent and altitude of the top of the aquifer, thickness of individual rock units within the aquifer, potentiometric surface of the aquifer, location of municipal centers of pumping, and various water-quality characteristics of the aquifer were shown in these maps.

The northwestern corner of Johnson County was included in a study by Wahl and Bunker (1986) of the hydrology of the carbonate aquifers of parts of four counties. This study also considered the Silurian- and Devonian-age rocks as comprising separate aquifers, although the study focused on the Silurian-age rocks. The study produced maps of the extent and thickness of the aquifers, altitude of the bedrock units, potentiometric surfaces of the aquifers, and general water-quality characteristics. Wahl and Bunker (1986) also discussed hydrogeologic conditions such as recharge and well yields.

Two studies conducted in the Cedar Rapids area, just north of Johnson County, also provide information and insights to the Silurian-Devonian aquifer system. Schulmeyer and Schnoebelen (1998) evaluated the hydrogeology and water quality of the area and constructed a ground-water-flow model of the Cedar Rapids area. Although their study focused on the alluvial aquifer system, the hydrogeology of the Silurian- and Devonian-age rocks also was evaluated and included in the model. Turco and Buchmiller (2004) updated the flow model for Cedar Rapids and also included the Silurian-Devonian aquifer system as part of the updated model.

Physical Setting and Climate

Johnson County is in east-central Iowa (fig. 1), covering an area of about 600 mi^2. The topography is generally flat to hilly, and land-surface altitude ranges from about 850 ft in the northwestern part of the county to about 600 ft in the southeastern part of the county. Iowa City is the largest city in the county, with a population of about 62,000 in 2000 (U.S. Census Bureau, 2005). Other municipalities include Coralville, Tiffin, North Liberty, and Solon (fig. 1). The majority of the county, however, is suburban and rural.

Johnson County straddles three major landform regions in eastern Iowa: the Iowan Surface, the Southern Iowa Drift Plain, and the Mississippi Valley Alluvial Plain (Prior, 1991). The main distinction between these landform regions is reflected in the land-surface topography in combination with the underlying unconsolidated materials. The bulk of the county, including the central part, is within the Southern Iowa Drift Plain, a landform of moderately to deeply incised valleys that have been eroded into and through glacial deposits and bedrock units (Prior, 1991). This eroded surface is widely mantled by wind-blown loess and alluvial sediments and hosts a belt of rock outcroppings along the Iowa River corridor. Areas in the northern part of the county lie within the Iowan Surface, a region extending into northern Iowa that is distinguished by minimal thickness of loess deposits lying atop eroded glacial deposits (Prior, 1991). The Iowa River corridor in the southern part of the county comprises a northern extension of broad, low-relief alluvial deposits that dominate the landscape of the Mississippi Valley Alluvial Plain in southern Iowa.

The major drainage feature is the Iowa River, which enters the northwestern part of the county and flows east and south out of the county (fig. 1). Two constructed reservoirs, Coralville Reservoir and Lake MacBride, are in the north-central part of the county (fig. 1). Coralville Reservoir was built by the U.S. Army Corps of Engineers in 1958 (U.S. Army Corps of Engineers, 2005). Average lake stage from 1958 through 2002 was about an altitude of 682 ft; however, from 1995 through 2002, the average lake stage was about 685 ft (U.S. Army Corps of Engineers, 2005) (fig. 3). Lake MacBride is located adjacent to the northeast side of Coralville Reservoir and was constructed in 1937. The stage of Lake MacBride is usually kept close to the top of the spillway, at an altitude of 712 ft (S.M. Linhart, U.S. Geological Survey, oral commun., 2005). The Cedar River flows across the northeast corner of Johnson County (fig. 1).

Several large limestone quarries are present within Johnson County, and they provided valuable information on the subsurface geology of the county. Of particular note for this study is a limestone quarry adjacent to the Iowa River on the north side of Coralville (fig. 1). The bottom of the quarry extends into basal Devonian-age dolomite at an altitude of about 524 ft, well below the average stage of the Iowa River (about 648 ft) in that area.

Average annual precipitation at Iowa City for the period 1931-2004 (exclusive of 1947-51) is about 35 inches (National Climatic Data Center, 2005). Annual precipitation ranged from about 22 inches to about 63 inches (National Climatic Data Center, 2005) (fig. 4). Precipitation tends to be lowest in January and February (about 1 inch) and greatest in the summer months (generally more than 4 inches each month). Average monthly temperature ranges from 22ºF in January to 75ºF in July, although temperature extremes range from a record low

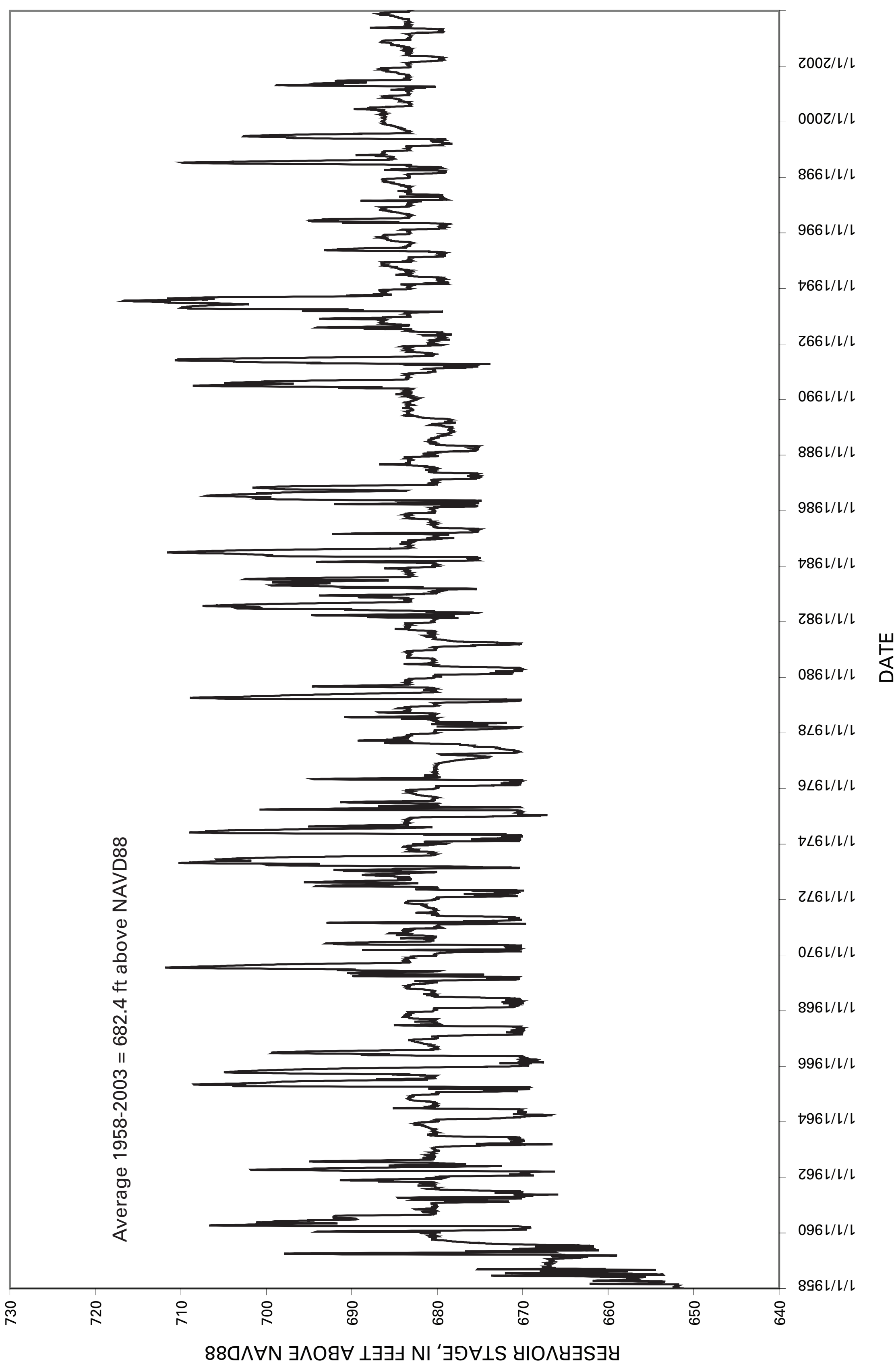


Figure 3. Altitude of the surface of Coralville Reservoir, 1958-2003 (U.S. Army Corps of Engineers, 2005).

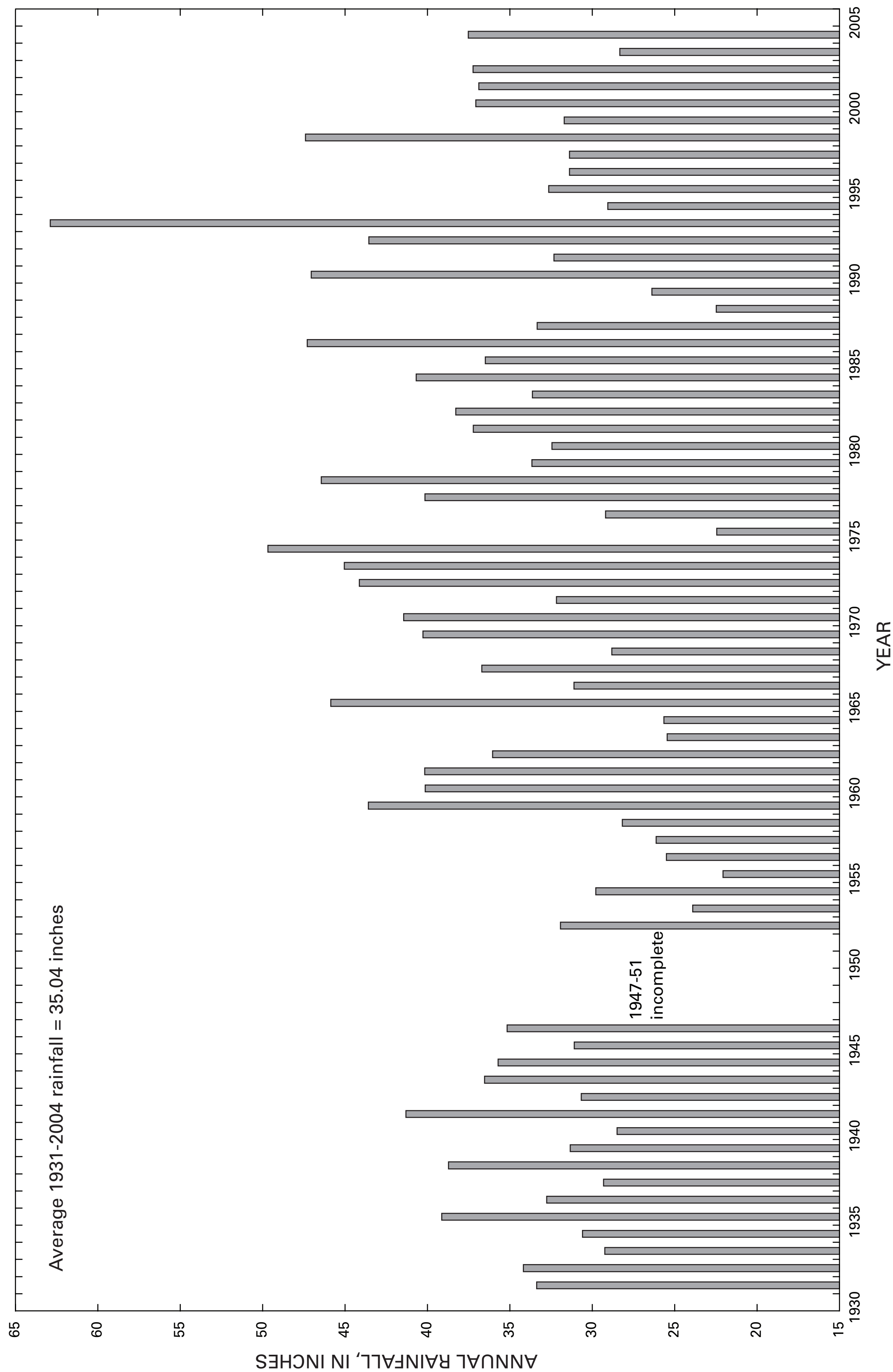


Figure 4 Annual rainfall for Iowa City, 1931-2004 (National Climatic Data Center, 2005).

of –26ºF in February 1996 to a record high of 104ºF in July 1988 (Weather.com, 2003).

Water Use

Ground water is the primary source of water for Johnson County, although Iowa City and the University of Iowa historically have also used water withdrawn directly from the Iowa River. Since installation and operation of collector wells completed in the alluvium beneath and adjacent to the Iowa River in 2004, Iowa City has greatly reduced the use of surface water obtained directly from the river (Edward Moreno, City of Iowa City, oral commun., 2005). Although some domestic and public-supply wells obtain ground water from unconsolidated deposits and some water is withdrawn from deeper aquifers, most ground water is obtained from the Silurian-Devonian aquifer system.

Total estimated ground-water withdrawals for Johnson County increased from 5.2 Mgal/d in 1990 to 7.1 Mgal/d in 1995 and to 7.8 Mgal/d in 2000 (E.E. Fischer, U.S. Geological Survey, written commun., 2005). Most ground-water withdrawals in 2000 were for public supply (2.9 Mgal/d), commercial use (2.5 Mgal/d), and domestic supply (1.5 Mgal/d). Ground-water withdrawals in 2000 for industrial uses, livestock, and irrigation were less than 1 Mgal/d. These values include withdrawals from the Silurian-Devonian aquifer system as well as approximately 2 Mgal/d from other aquifers in the county (R.C. Buchmiller, U.S. Geological Survey, written commun., 2003). The locations of 85 pumping wells for municipal and other uses, which are simulated in the model, are shown in figure 5.

Acknowledgments

Michael Gannon, IGS, analyzed more than 250 specific-capacity tests contained in the IGS files and provided hydraulic-conductivity values for the Silurian- and Devonian-age rocks. William Bunker, IGS, provided an updated bedrock geologic map of Johnson County and provided insights to the detailed geology of the county. Daniel Christiansen, USGS, provided GIS support to aid in converting the conceptual flow model to digital model input and in preparing figures for the report. Michael Turco, USGS, provided valuable support in construction of the digital model. Robert Buchmiller, USGS, provided logistical support and coordination for the study and answered innumerable questions regarding the hydrogeology and water budget of the study area.

Hydrogeologic setting

Johnson County is underlain by unconsolidated deposits of Quaternary age and Paleozoic-age bedrock units. This layered sequence of geologic units forms the framework of the ground-water-flow system of the county.

Hydrogeologic Units

The deposits and rocks that underlie Johnson County are grouped into hydrogeologic units in this report. A hydrogeologic unit is one that has a large areal extent and distinct hydrologic properties. Several adjacent geologic units that have similar water-transmitting characteristics may be combined into a single hydrogeologic unit.

The geologic and hydrogeologic units discussed in this section are listed in table 1. The geologic units discussed in this section follow terminology used by the Iowa Geological Survey (2005). Although separate aquifers and confining units are described here, the Silurian- and Devonian-age units are considered as a single aquifer system, termed the “Silurian-Devonian aquifer system” in this report.

Quaternary Deposits

The unconsolidated geologic materials of Quaternary age that lie between land surface and bedrock are known both from drillhole data and from large exposures at a quarry near Coralville (Kemmis and others, 1992). These materials consist of a complex inter-layered sequence of glacial till and intertill deposits, such as paleosols and associated sediments, capped by loess or alluvium. Thickness of these deposits varies across the county from zero feet along segments of the Iowa River and its tributaries, where bedrock is at or very close to the land surface, to more than 300 ft in the southeast part of the county, where bedrock valleys coincide with high land-surface altitudes. Some domestic water wells, typically in the southern and western parts of the county, are completed within the Quaternary deposits, usually in shallow alluvium or deeper, buried sand and gravel deposits.

The bulk of the Quaternary deposits consists of weathered and unweathered glacial till. The till 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, but the deeper (more than 25 ft) unweathered till is unoxidized and unfractured. These deposits, particularly the unweathered till, generally have low permeability and are considered as a confining unit that limits vertical movement of ground water to the underlying bedrock units. Where these deposits are present, recharge to the underlying bedrock may be minimal; where they are thin or absent, recharge to the underlying bedrock may be significant.

Bedrock Topography

Maps of land-surface altitude, combined with surface geology, define the landform regions and give us an understanding of the overall surface geology; however, visualization

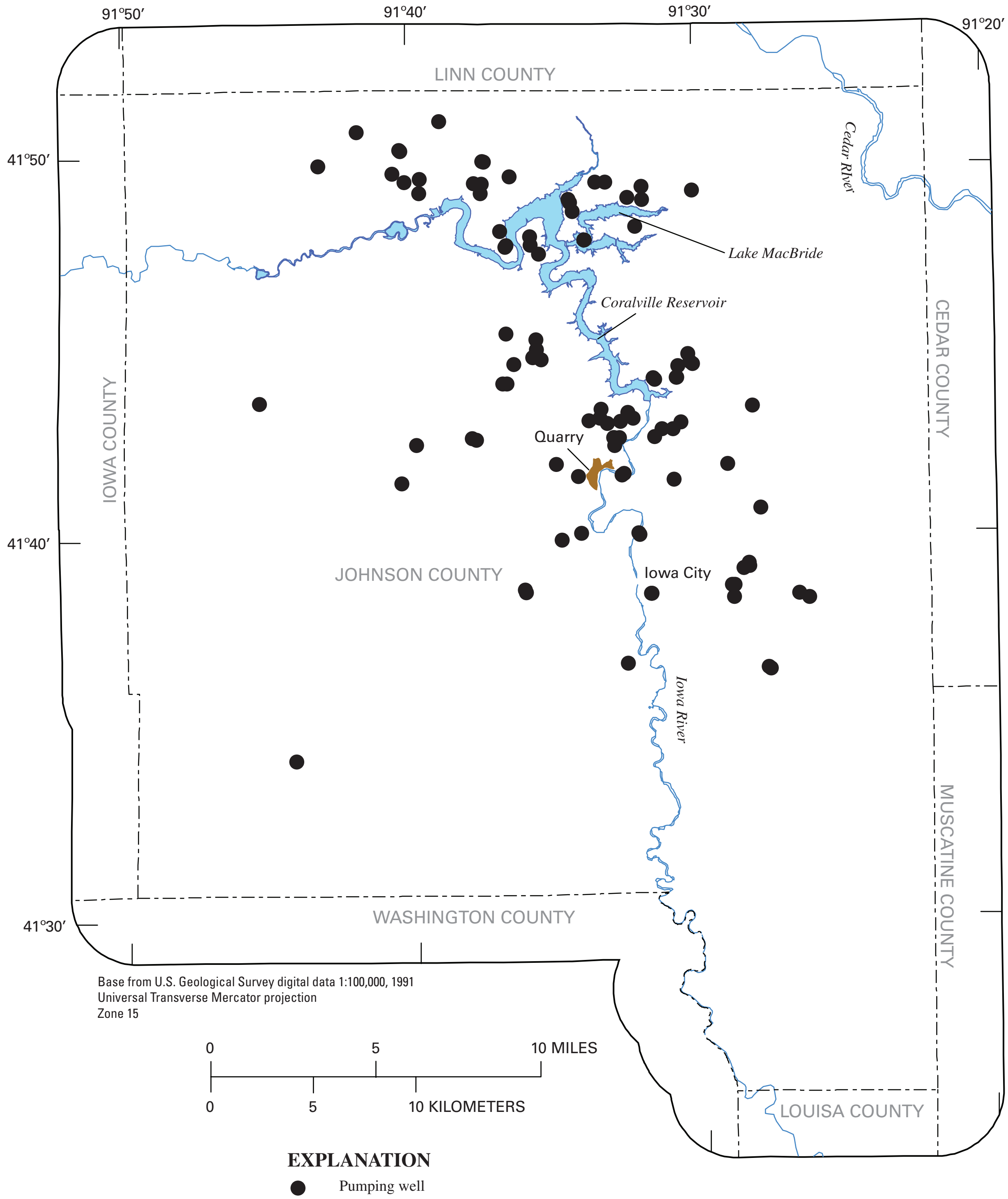


Figure 5. Location of pumping wells used in the 1996 steady-state simulation.

Table 1. Hydrogeologic and geologic units in Johnson County, Iowa.

[Geologic units follow terminology used by the Iowa Geological Survey (2005)]

Geologic System	Hydrogeologic Unit		Geologic Units	Principle Composition
Quaternary	Quaternary confining unit		Quaternary undifferentiated	Glacial deposits, loess, sand and gravel, clay.
Pennsylvanian	Cherokee confining unit		Cherokee Group	Shale, sandstone.
Devonian	Upper Devonian shale confining unit		Maple Mill Formation Sheffield Formation Lime Creek Formation	Shale with some dolostone.
	Cedar Valley aquifer	Silurian-Devonian aquifer system	Cedar Valley Group Lithograph City Formation Coralville Formation Little Cedar Formation	Limestone.
	Wapsipinicon Group (aquifer and confining unit)	Silurian-Devonian aquifer system	Wapsipinicon Group Davenport Member Spring Grove Member Kenwood Member	Limestone, dolostone.
	Silurian aquifer	Silurian-Devonian aquifer system	Otis Member	Limestone.
Silurian	Silurian aquifer	Silurian-Devonian aquifer system	Gower Formation Scotch Grove Formation Hopkinton Formation Blanding Formation	Dolostone, variably cherty.
Ordovician	Maquoketa confining unit		Maquoketa Formation	Shale with some dolostone.

of other geologic surfaces that lie at depth within the county is important in understanding the hydrogeology. These buried surfaces define the altitudes of the upper and lower surfaces of distinct geologic layers including unconsolidated materials such as loess, alluvium and glacial deposits, and the various bedrock formations. Figure 6 shows the altitude of the top of the bedrock that underlies the Quaternary deposits. The top of bedrock and the tops of the underlying hydrogeologic units are based on information compiled from drillers' and geologic logs on file with the IGS, as well as the projected dip of the individual units and field mapping of exposed bedrock units.

Bedrock attains the highest altitudes in the northern one-half of the county along the Iowa River, Coralville Reservoir, the Solon area, and near the county's northwest corner. The extensive outcrops of Devonian-age rock along the Iowa River corridor from Iowa City on the south to Lake MacBride on the north coincide with the river corridor's low surface altitudes. The lower altitudes on the bedrock surface are in the buried bedrock valleys. Two principal bedrock valleys dominate the bedrock surface (fig. 6). The largest valley enters the county from the north and trends south to Oxford, and then southeast (fig. 6). A lesser bedrock valley runs from Iowa City south to join the larger valley near Lone Tree (figs. 1 and 6). Another small bedrock valley trends west to east, north of Solon toward Cedar County (fig. 6). Two of these buried bedrock valleys are shown in a generalized southwest-northeast hydrogeologic section shown in figure 7.

Bedrock Hydrogeologic Units

From the uppermost surface of the bedrock to varying depths lie bedrock formations that are characterized as either aquifers or confining units. The distribution of these rock units at the bedrock surface are illustrated in a bedrock hydogeologic map of the county (fig. 8). Six bedrock hydrogeologic units are present in Johnson County (oldest to youngest): Maquoketa confining unit, Silurian aquifer, Wapsipinicon Group (aquifer and confining unit), Cedar Valley aquifer, Upper Devonian shale confining unit, and Cherokee confining unit.

Maquoketa Confining Unit

The lower boundary of the Silurian-Devonian aquifer system is defined by the top of the Ordovician-age Maquoketa confining unit. The distribution and upper surface of this unit are shown in figure 9. The Maquoketa is a 200-ft-thick, dense

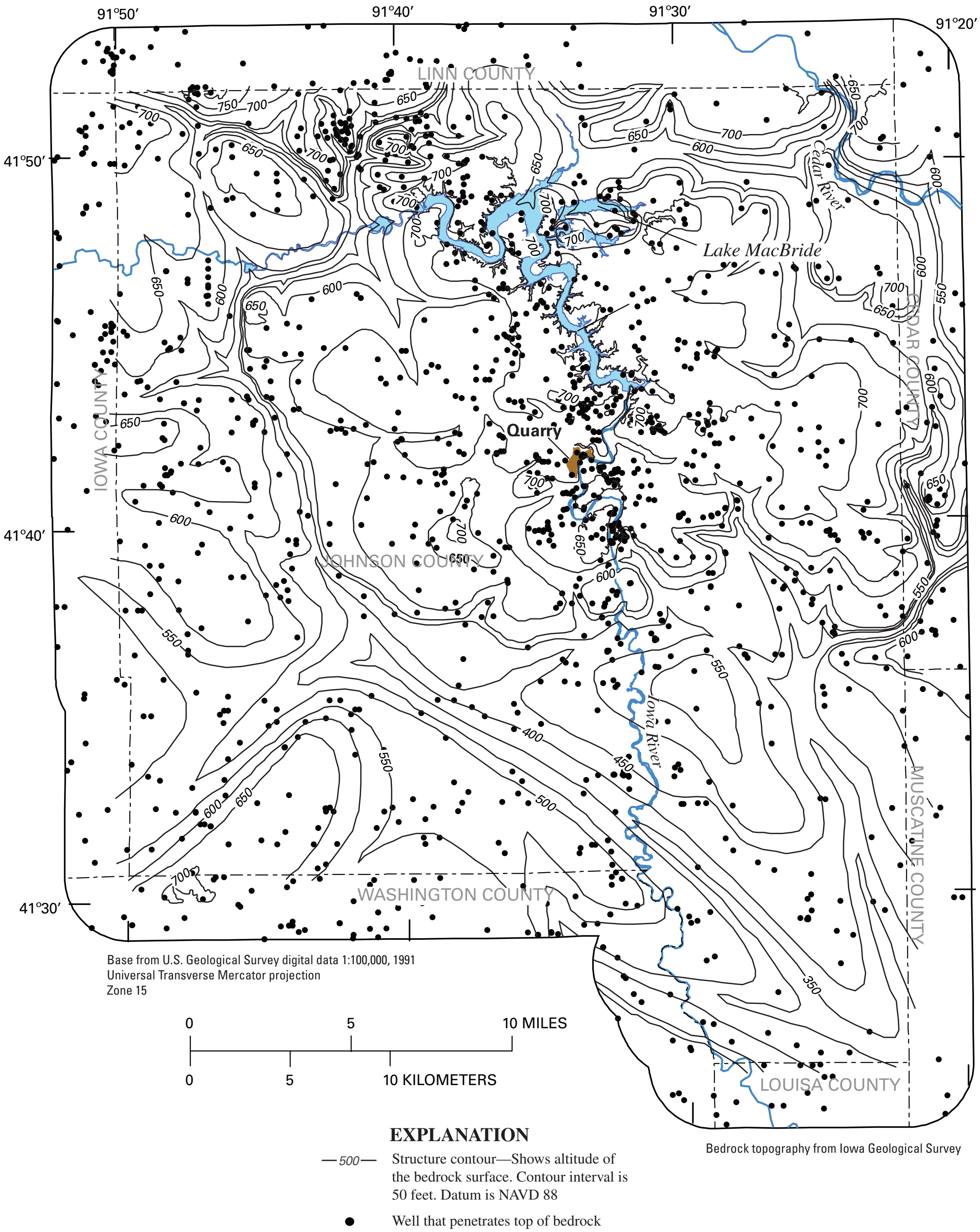


Figure 6. Bedrock topography.

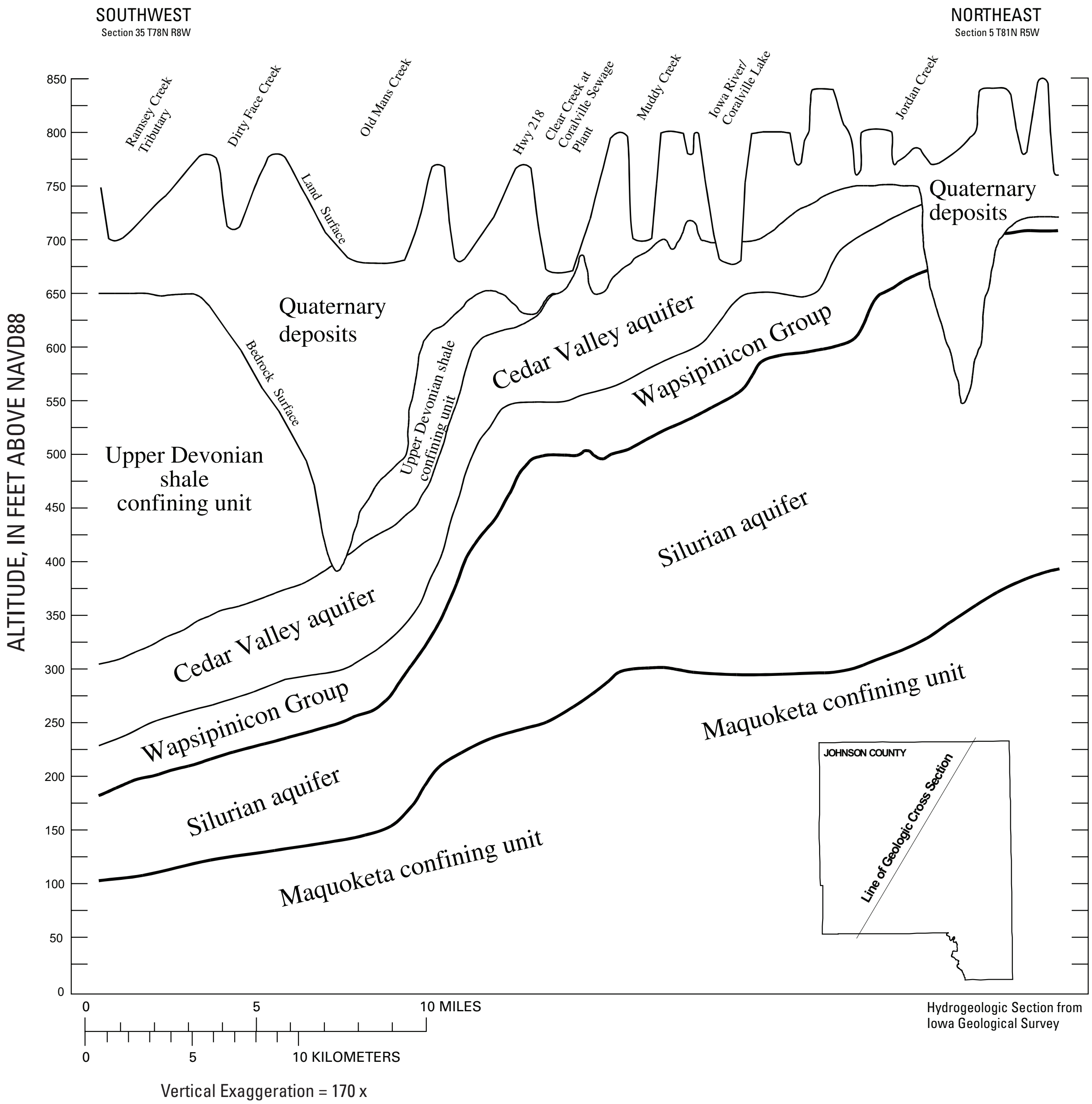


Figure 7. Southwest-northeast hydrogeologic section of Johnson County, Iowa.

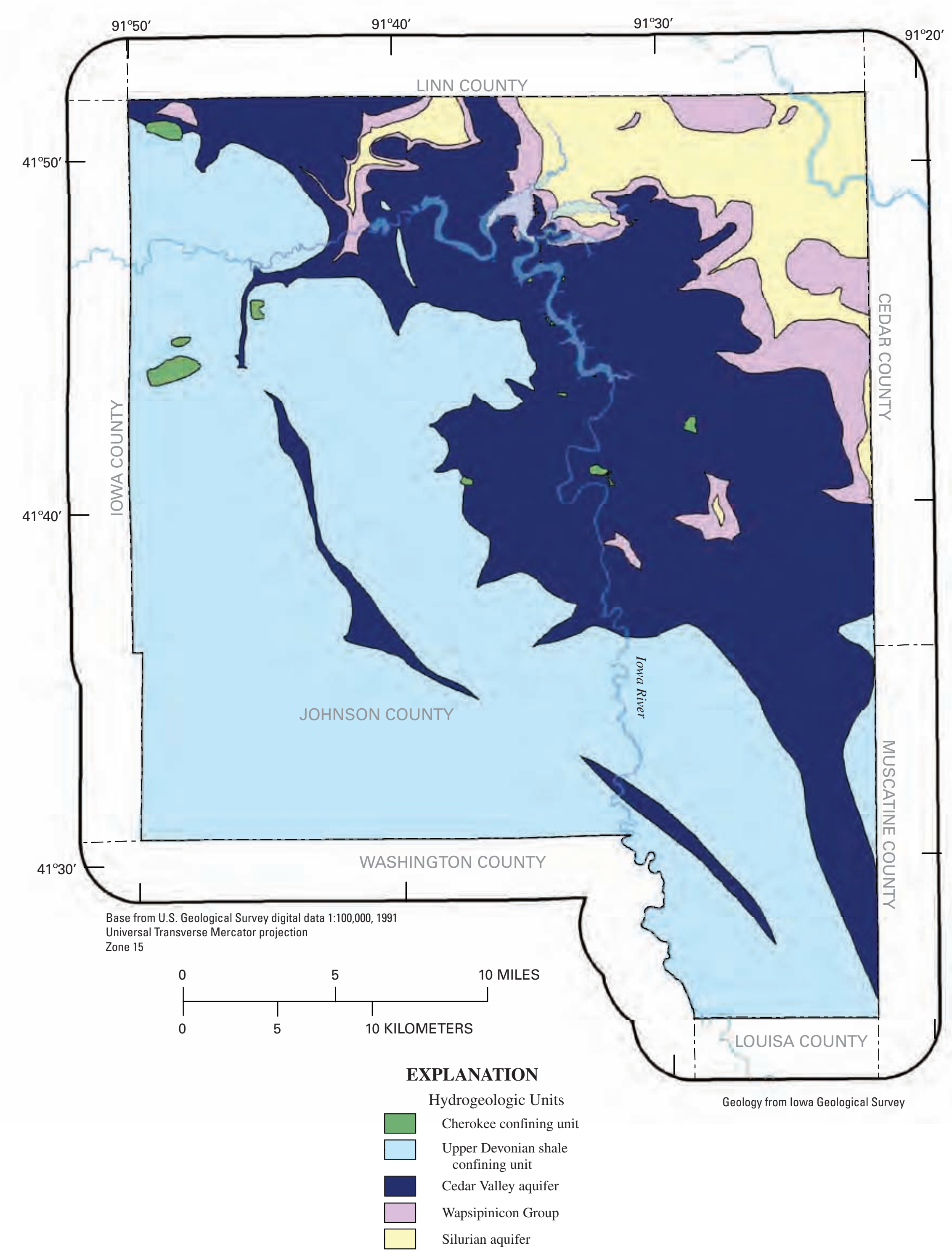
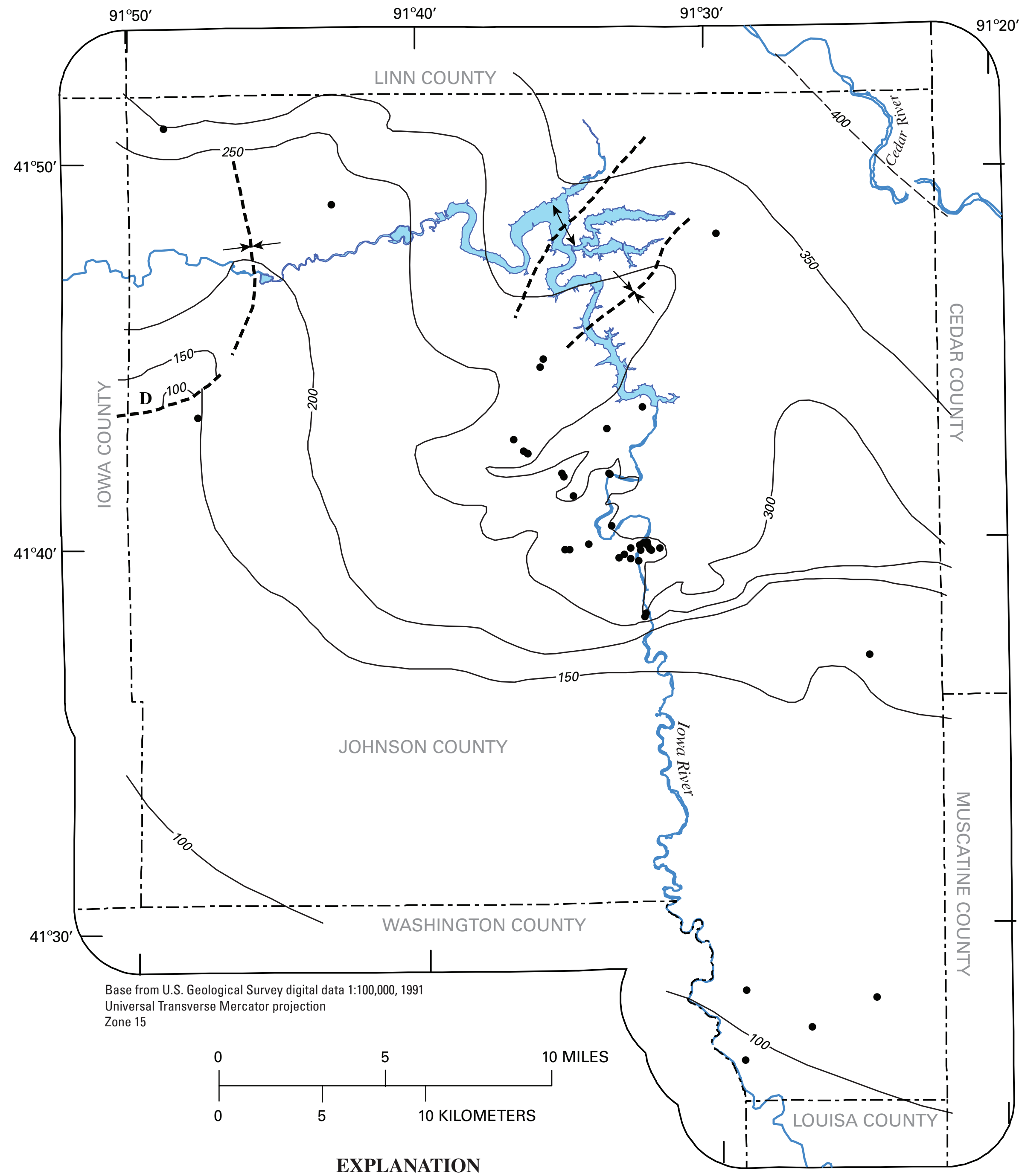


Figure 8. Generalized bedrock hydrogeology of Johnson County, Iowa.



EXPLANATION

—500— Structure contour—Shows altitude of the top of the Maquoketa confining unit. Contour interval is 50 feet. Datum is NAVD 88. Contours are approximately located where well control is lacking

D Fault, approximately located, **D**, downthrown side

• Well that penetrates top of the Maquoketa confining unit

Anticline, approximately located, showing trace of crestal plane

Syncline, approximately located, showing trace of trough plane

Figure 9. Top of the Maquoketa confining unit.

and compact shale and dolostone unit that forms an effective hydrologic separation of the Silurian aquifer from older and deeper Cambrian and Ordovician rock units. The unit has very low permeability.

Silurian Aquifer

The rock formations of Silurian age in Johnson County are typically grouped into one undifferentiated rock sequence and collectively referred to as the Silurian aquifer. The primary reason for this “lumping” approach lies in the fact that the formations, while not homogeneous, are all composed of relatively pure dolostone with varying quantities of chert, and appear to respond to water production as one hydrogeologic unit.

The Silurian aquifer consists of four geologic formations (from oldest to youngest): Blanding Formation, Hopkinton Formation, Scotch Grove Formation, and Gower Formation, (table 1). Witzke’s (1988) discussion of the detailed stratigraphy and geologic characteristics of these units from the Silurian outcrop belt of adjacent Linn and Jones Counties provides a more thorough description of these formations where they are exposed at the land surface. The Silurian aquifer is a thick sequence of variably cherty dolostones; however, detailed studies from the outcrop belt where thick sections have been carefully examined show that the sequence exhibits substantial lateral and vertical variation in texture and porosity. Some of these variations certainly occur within the subsurface in Johnson County, but their effect on the hydraulic properties of the aquifer has not been investigated. Substantial variations in water yield have been recorded for some Silurian aquifer wells, and these variations may be related to poorly defined texture and porosity trends in the subsurface or the presence or absence of solution features. In addition, some areas of the upper part of the aquifer contain clay-rich paleokarst deposits that fill voids and fractures; these localized paleokarst fills may cause lower yields in some wells.

Within Johnson County the rocks of the Silurian aquifer are confined almost exclusively to the subsurface. The one known exception is a bluff exposure of the upper part of the Gower Formation along the Cedar River in the northeastern part of the county. Figure 10 shows the altitude of the top of the Silurian aquifer. In some isolated parts of the county, the uppermost 15 to 20 ft of rocks that were mapped as the Silurian aquifer may in fact not be Silurian in age, but may actually be a porous and sporadically distributed Devonian-age unit below the Kenwood Member of the overlying Wapsipinicon Group. This unit, called the Otis Member, has been included within the Silurian aquifer because of its similarity in composition and porosity to the underlying Silurian-age rocks and its distinctly different character from the overlying Kenwood Member. The Silurian aquifer underlies the entire county, and across most of the county it is overlain by the Wapsipinicon Group. Exceptions to this are in the northern part of the county where deep bedrock valleys have been incised into the upper part of the Silurian-age rocks (fig. 6). In these areas the Silurian aquifer is the uppermost bedrock unit and well records indicate that this unit is typically overlain by glacial deposits.

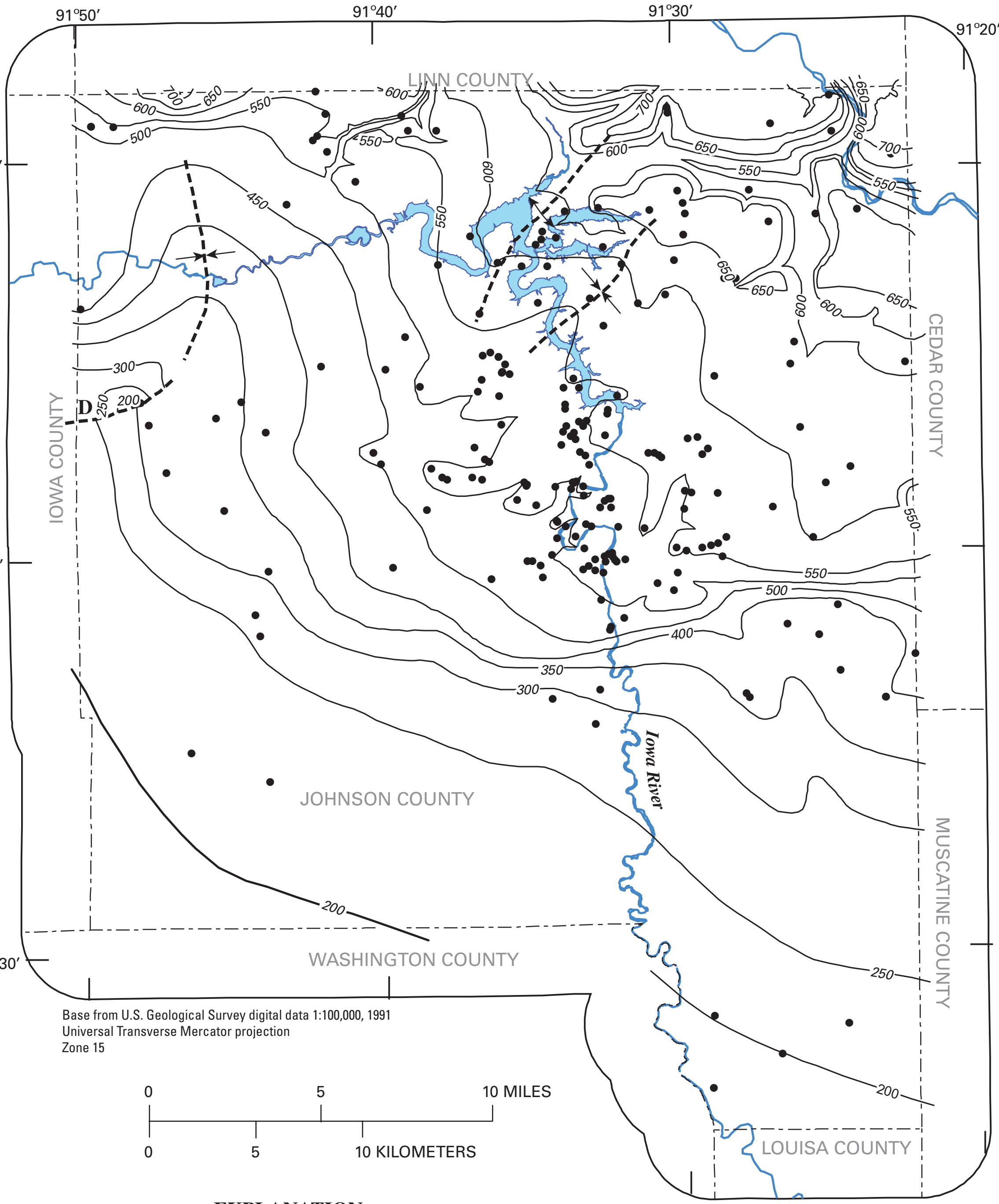
The thickness of the Silurian aquifer varies widely across the county. The aquifer is thinnest (approximately 80 ft) in the southern part of the county. It attains maximum thickness (about 380 ft) along the northern county boundary. In the Iowa City and North Liberty areas, the aquifer ranges in thickness from 200 to 250 ft. This large thickness variation is primarily attributable to regional thickness trends affecting the entire Silurian system, where the sequence thickens into east-central Iowa and thins to zero feet south of Johnson County. Localized thickness variations also occur. Some variations are due to the uneven unconformable surface on the Maquoketa Formation upon which the Silurian-age rocks were originally deposited and to the unconformable surface at the top of the sequence that the Devonian rocks overlie. More substantial thickness variations occur within bedrock valleys in the northern part of the county where the sequence was subjected to erosion before burial by glacial deposits.

Wapsipinicon Group

The Wapsipinicon Group, another carbonate-rock-dominated hydrogeologic unit, overlies the Silurian aquifer. The Wapsipinicon Group consists of multiple Lower-Devonian-age geologic units but for this study is considered as one hydrogeologic unit. The Wapsipinicon Group is more heterogenous in composition than the Silurian aquifer. It consists of shaly dolostone in the lower part (Kenwood Member), porous brown-colored dolostone in the middle (Spring Grove Member), and very pure, high-calcite limestone in its upper portion (Davenport Member). Fracture porosity dominates water movement pathways in the Wapsipinicon Group.

The lowermost member unit of the Wapsipinicon (Kenwood Member) is generally considered a confining unit, although its hydrogeologic properties and its role as a confining unit has not been specifically investigated. The Kenwood Member generally ranges from 10 to 20 ft thick, and is composed of dense, shaly dolostone. The Kenwood Member probably acts as an imperfect barrier to vertical flow between the underlying Silurian aquifer and the combined Cedar Valley and upper Wapsipinicon aquifers. The upper part (Spring Grove and Davenport members) of the Wapsipinicon Group is considered to be in hydrologic connection with the overlying Cedar Valley aquifer.

Figure 11 illustrates the altitude of the top of the Wapsipinicon Group where it is present. Thickness of this unit generally averages 50 ft but may be as much as 75 ft thick in some wells and thins to zero due to erosion in parts of north and northeast Johnson County. The upper part of the unit outcrops along Coralville Reservoir upstream from the Lake MacBride dam, and it is quarried for high-quality crushed stone in the deeper levels of some rock quarries. In past years the upper part of the Wapsipinicon Group commonly was drilled and left open to water production, along with the bulk of the Cedar



EXPLANATION

—500— Structure contour—Shows altitude of the top of the Silurian aquifer. Contour interval is 50 feet. Datum is NAVD 88. Contours are approximately located where well control is lacking

D Fault, approximately located, **D**, downthrown side

• Well that penetrates top of the Silurian aquifer

Anticline, approximately located, showing trace of crestal plane

Syncline, approximately located, showing trace of trough plane

Figure 10. Top of the Silurian aquifer.

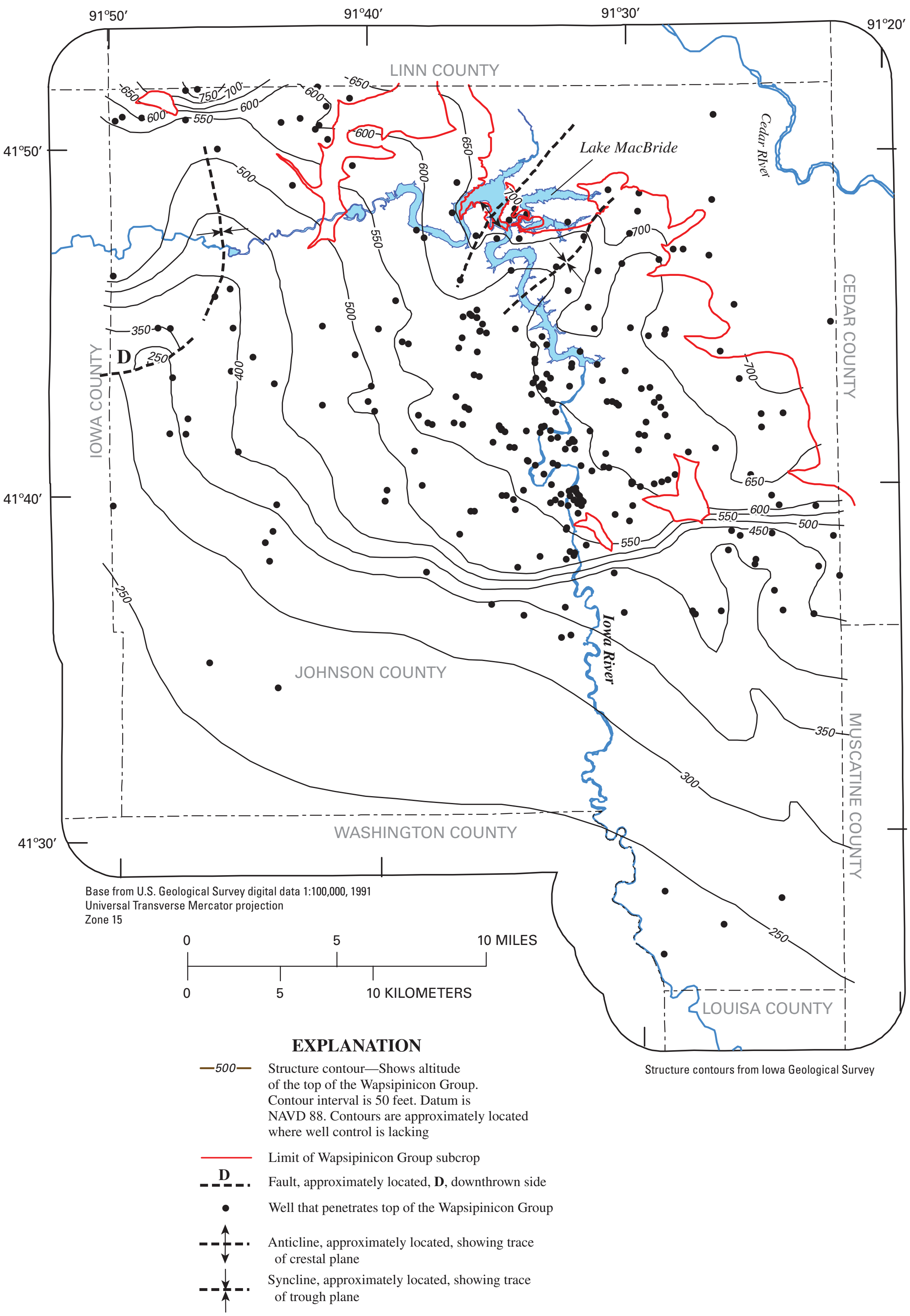


Figure 11. Top of the Wapsipinicon Group.

Valley aquifer, for low-yield domestic wells; however, the generally unsuitable water quality of these units, as compared to the underlying Silurian aquifer, has led to almost complete discontinuation of that practice.

Cedar Valley Aquifer

The Cedar Valley aquifer is a thick sequence of Middle-Devonian age limestone (Cedar Valley Group, table 1), which is present throughout the county except for the northeast part where it has been eroded (fig. 12). In the bedrock stratigraphic succession, it lies above the Wapsipinicon Group (fig. 7). The Cedar Valley aquifer contains multiple geologic subdivisions, including from oldest to youngest, Little Cedar Formation, Coralville Formation, and Lithograph City Formation; however, for aquifer-characterization purposes it was mapped as one undifferentiated hydrogeologic unit. The Cedar Valley aquifer outcrops extensively along the Iowa River in Iowa City and upstream along Coralville Reservoir. The Cedar Valley Group is the principal rock that is quarried for crushed stone resources, and it serves as a source of water for some older and shallower domestic wells.

The Cedar Valley aquifer is mainly composed of dense, relatively pure limestone that exhibits mudstone to grainstone texture; chert and very minor shale layers also may occur within the unit. Some subdivisions within the Cedar Valley aquifer contain conspicuous marine fossils, and locality names such as Coralville and Devonian Fossil Gorge (just below Coralville Dam) reflect the local prominence of these fossiliferous horizons. The aquifer typically ranges from 95 to 110 ft thick where it is overlain by upper Devonian shale. In the area where the Cedar Valley outcrops or is overlain by Quaternary deposits or the Cherokee Group, it is thinner. The altitude of the top of the Cedar Valley aquifer is shown in figure 12. This surface is considered as the top of the Silurian-Devonian aquifer system.

The high calcite mineral content of the Cedar Valley limestones makes it susceptible to dissolution by ground water, and small karst features are known from the outcrop belt although no major karst features such as caves have been recognized in Johnson County. The dense and crystalline nature of the limestone imparts brittleness, and both vertical and horizontal fractures are visible in some exposures and probably are present in the subsurface. These fractures, some of which may be solution enlarged (fig. 13), are the primary conduits for water movement through this unit. A more detailed discussion of the stratigraphy and geology of the Cedar Valley Group is in Day and Bunker (1992) and Witzke and others (1988).

Upper Devonian Shale Confining Unit

The next youngest hydrogeologic unit is referred to as the Upper Devonian shale confining unit. For mapping and aquifer-characterization purposes, several Devonian-age bedrock units were combined into this one hydrogeologic unit by virtue of their compositional and hydrologic property similarities. The geologic units that have been combined into this hydrogeologic unit are the the Lime Creek Formation, the Sheffield Formation, and the Maple Mill Formation (table 1). These units are all predominantly shale, although lesser carbonate interbeds are present.

The Upper Devonian shale confining unit comprises the uppermost bedrock unit over the southwest one-half of the county (fig. 8), and is the first bedrock penetrated by wells in North Liberty, Tiffin, and Hills (fig. 1). The thickness of the Upper Devonian shale confining unit ranges from zero in the northeast one-half of the county to almost 350 ft in the southwest (fig. 7). There are few exposures of this unit in the county, but it is present in a rock quarry west of Iowa City, and small exposures are present along Coralville Reservoir. Because this unit is shale dominated and is believed to be relatively impermeable, it is considered as the upper confining unit of the Silurian-Devonian aquifer system.

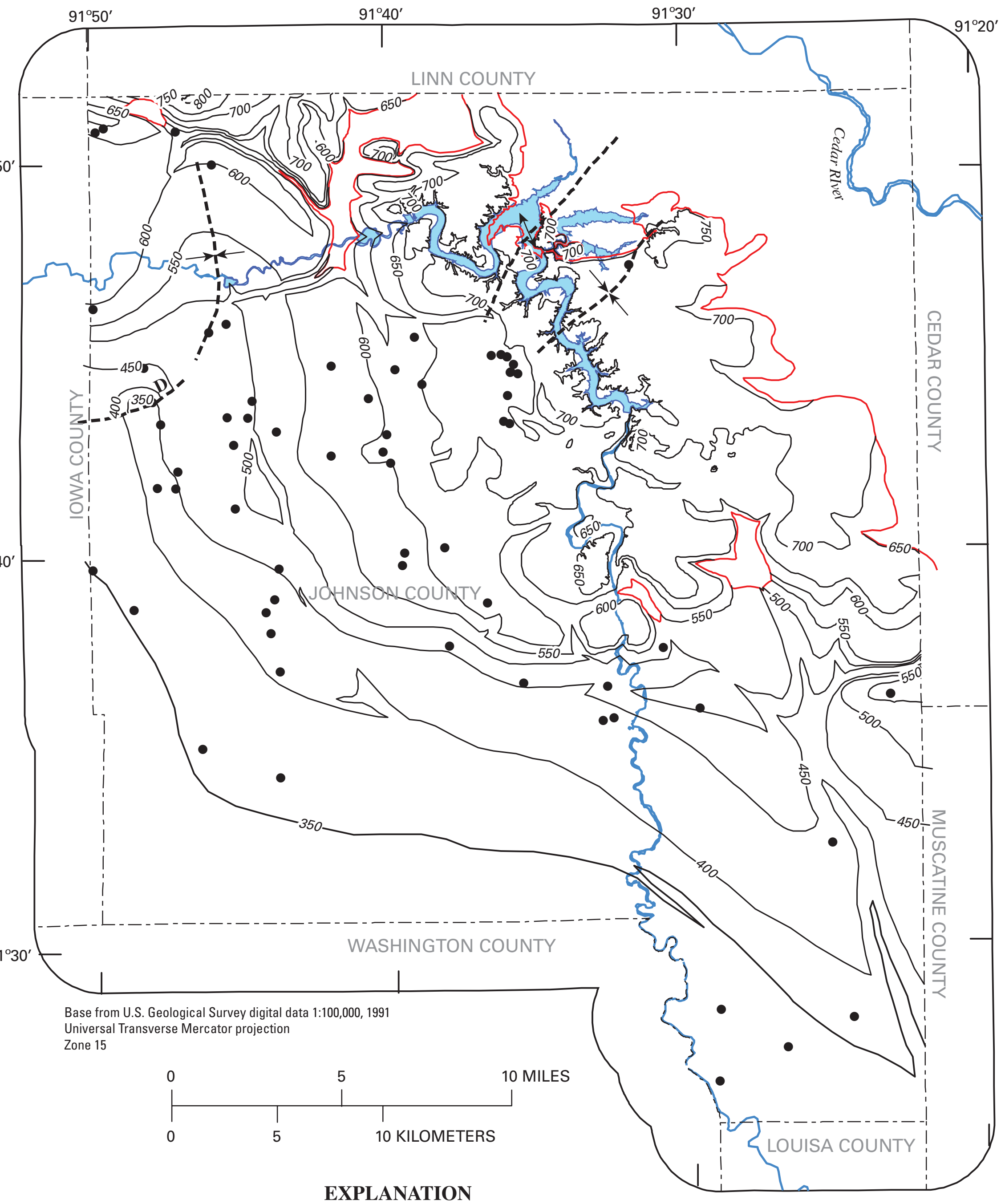
Cherokee Confining Unit

The youngest and uppermost hydrogeologic unit is that of the Pennsylvanian-age Cherokee confining unit. This unit is composed of interbedded fine-grained sandstones and shale of the Cherokee Group. Its distribution is very limited (fig. 8), and it generally is less than 70 ft thick. The Cherokee confining unit rests unconformably on Devonian-age shale and carbonate units. The best exposures of this unit are in the Iowa City area at the University of Iowa Mayflower dormitory. This unit is occasionally encountered in drillholes, and may be present as isolated, low–permeability clay fill within carbonate rock units. Because of its very limited areal extent, the Cherokee confining unit is not included as part of the Silurian-Devonian aquifer system.

Geologic Structure

Geologic structure commonly refers to folds, flexures, and faults. These features, where mapped, delineate where rock units have been deformed by bending, tilting, or fracturing. In addition, the structure describes the regional attitude or generalized tilt of the entire rock section. The series of hydrogeologic unit altitude maps (figs. 9-12) and the hydrogeologic section (fig. 7) compiled for this study illustrate not only the altitude of each bedrock surface but highlight the tilt and attitude of those units in the subsurface across the county.

Although most observers looking at almost any rock exposure in the county would consider the rock to lie flat, the general tilt of the entire rock sequence across the county is slightly to the southwest. This tilt, or dip, averages between 18 to 30 ft/mi to the southwest, and it is similar to the regional dip across much of eastern Iowa. Some gentle anticlinal and synclinal flexures are in the area between North Liberty and Solon and in the western part of the county (figs. 9-12). These



EXPLANATION

—500— Structure contour—Shows altitude of the top of the Cedar Valley aquifer. Contour interval is 50 feet. Datum is NAVD 88. Contours are approximately located where well control is lacking

Limit of Cedar Valley aquifer

D Fault, approximately located, **D**, downthrown side

Well that penetrates top of the Cedar Valley aquifer

Anticline, approximately located, showing trace of crestal plane

Syncline, approximately located, showing trace of trough plane

Figure 12. Top of the Cedar Valley aquifer.

Figure 13. Solution features in Devonian-age limestone near Coralville Dam.

features are defined on the basis of outcrop measurements of strike and dip, and on subsurface geologic information obtained from drillers' and geologic logs of wells.

More pronounced structure appears to be defined in several areas from the mapping. In the northwest part of the county, geologic-surface altitude mapping indicates a steepening of the dip to approximately 200 ft/mi. Previous structure mapping in this area and north into Linn County by Wahl and Bunker (1986) suggested that one or more faults with total offset of 150 ft might be present.

Another area of anomalous structure lies in a linear zone that crosses the southern part of Iowa City and extends east toward the boundary between Johnson and Cedar counties, where the dip is as much as 160 ft/mi to the south. Both the magnitude and direction of the dip depart from regional conditions. The dip of rock units along this linear trend is interpreted in this study as a steep flexure dipping to the south, but it also could be interpreted as a faulted flexure trend with relative movement down to the south.

A small fault, with approximately 100 ft of offset, also was mapped just to the northwest of Oxford (figs. 9–12). The fault was defined by offset of the top of the Cedar Valley aquifer in nearby wells (fig. 12). An earthquake of Mercalli Intensity IV that was felt and reported by residents on April 20, 1948 (Docekal, 1970) also was used as evidence for the estimated position of the fault. The fault is assumed to penetrate the other underlying hydrogeologic units (figs. 9–12).

Hydraulic Characteristics

The hydraulic properties of the rocks that compose the Silurian-Devonian aquifer system are highly variable. This variability is caused by the heterogeneous distribution of fractures, variation in bedrock porosity, and the presence of solution features in the carbonate-rock units (fig. 13). Parts of the aquifer that contain thick intervals of shale or that lack solution features generally have less water-transmitting ability than parts of the aquifer that have less shale and contain solution features. Unless otherwise specified, all descriptions of hydraulic conductivity in this report refer to horizontal hydraulic conductivity.

The relative productivity of a well may be expressed in terms of specific capacity, which is defined as the well discharge rate divided by the drawdown in the well (Theis and others, 1963). Values of transmissivity and hydraulic conductivity derived from specific-capacity test data, however, must be considered as estimates because factors such as well construction and test duration may greatly affect the specific capacity. Despite these limitations, estimates of transmissivity and hydraulic conductivity based on specific-capacity data should be reasonably reliable (Theis and others, 1963, p. 331).

Specific-capacity data on file with the IGS were used to provide information on transmissivity and hydraulic conductivity of the aquifer. The specific-capacity value was multiplied by 270 to estimate the transmissivity value (McClymonds and Franke, 1972, p. 11). The transmissivity value was then divided by the saturated thickness of the aquifer at the well to estimate the hydraulic-conductivity value.

Specific-capacity data were available for 117 wells completed in Devonian bedrock and for 144 wells completed in Silurian bedrock (fig. 14). Specific-capacity values for the Devonian-age rocks range from about 0.1 to 57 gal/min per foot of drawdown, and average 2.7 gal/min per foot of drawdown (table 2). Specific-capacity values for the Silurian-age rocks range from about 0.1 to 30 gal/min per foot of drawdown, and average 1.7 gal/min per foot of drawdown (table 2).

Estimated transmissivity values for the Devonian-age rocks range from 31 to about 15,300 ft^2/d and average about 720 ft^2/d. Hydraulic conductivity values calculated from these values range from 0.1 to 225 ft/d and average about 12 ft/d. Estimated transmissivity values for the Silurian-age rocks range from 31 to 8,100 ft^2/d and average 465 ft^2/d. Hydraulic conductivity values calculated from these values range from 0.1 to 135 ft/d, and average about 5 ft/d. For the combined Silurian-Devonian aquifer system, specific capacity averages 2.1 gal/min per foot of drawdown, transmissivity averages about 580 ft^2/d, and hydraulic conductivity averages 8.3 ft/d.

The hydraulic conductivity values for the Silurian- and Devonian-age rocks, calculated from the specific-capacity data, are similar to those used in the flow model of the Cedar Rapids area. Schulmeyer and Schnoebelen (1998, p. 30) used hydraulic-conductivity values of 7.0 ft/d for the Devonian-age rocks, and 8.7 ft/d for the Silurian-age rocks. The hydraulic-conductivity values also are similar to those used by Turco and Buchmiller (2004, p. 19–21) in the updated Cedar Rapids model for unweathered Devonian-age rocks (9 ft/d) and for weathered Silurian-age rocks (10 ft/d); however, the values used in this study are much less than the values used in the updated Cedar Rapids model to simulate slightly weathered (44 ft/d) and highly weathered (350 ft/d) Devonian-age rocks.

Recharge and Discharge

Recharge to the Silurian-Devonian aquifer system in Johnson County is from precipitation infiltrating bedrock outcrops, leakage to the aquifer from Coralville Reservoir and the Iowa River where they directly overlie bedrock, downward flow through the overlying glacial deposits, and lateral underflow from outside the county. Discharge from the aquifer is to pumping wells, discharge to Coralville Reservoir, and lateral underflow to surrounding counties.

Reliable measurements of the amount of recharge and discharge from the Silurian-Devonian aquifer system are difficult to obtain and generally are not available for Johnson County. These types of estimates may be obtained by evaluation of low-flow data of streams; however, in Johnson County, most of the rivers and streams flow within the glacial deposits that overlie the Silurian-Devonian aquifer system. Only a segment of the Iowa River, from Coralville Reservoir through Iowa City, flows over the Devonian-age rocks, which makes

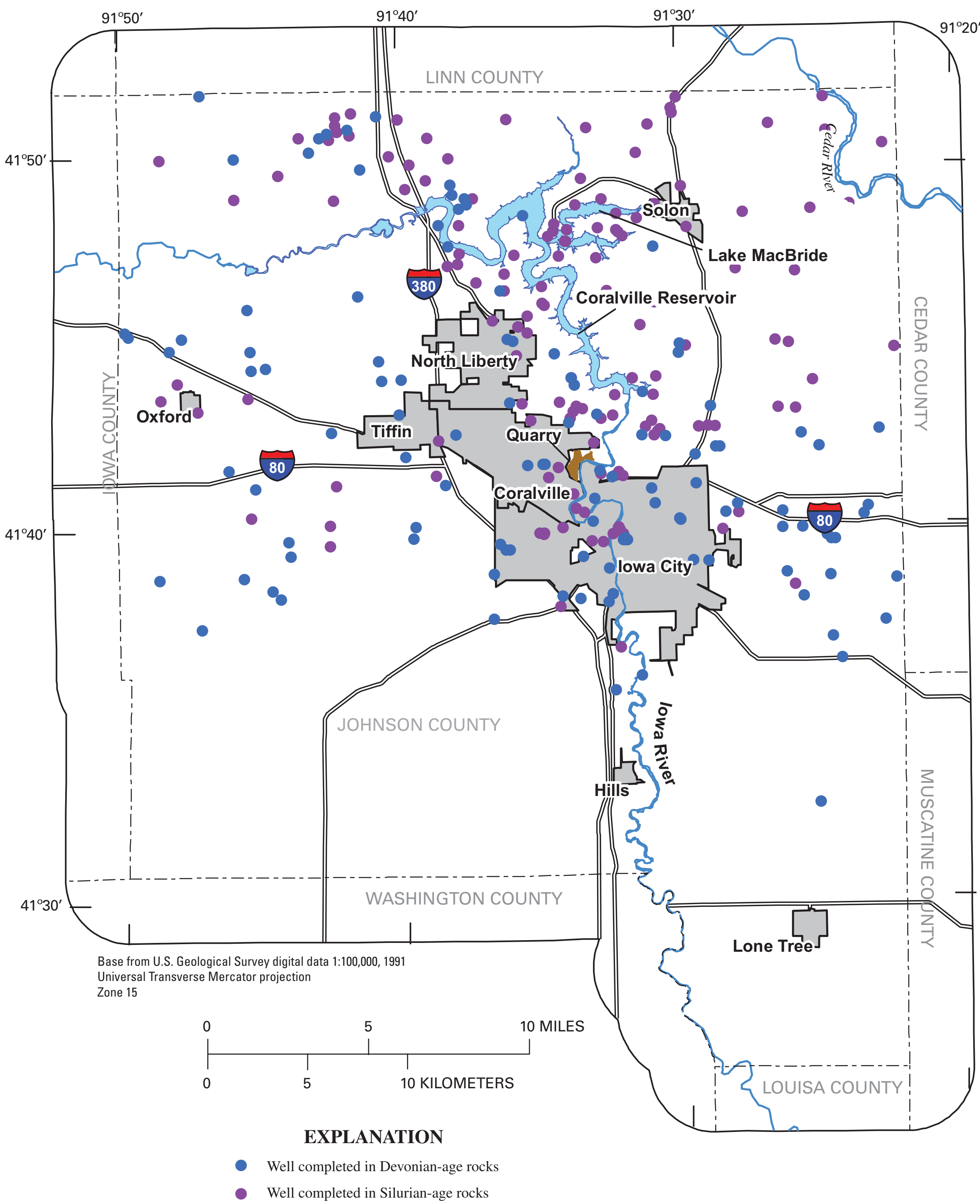


Figure 14. Wells completed in Silurian- and Devonian-age rocks that have specific-capacity test data.

Table 2. Summary of hydraulic characteristics of Silurian- and Devonian-age rocks in Johnson County, Iowa.

[Data from Iowa Geological Survey; (gal/min)/ft = gallons per minute per foot of drawdown; ft^2/d = feet squared per day; ft/d = feet per day]

	Number of tests	Specific capacity range [(gal/min)/ft]	Specific capacity average [(gal/min)/ft]	Transmissivity range (ft^2/d)	Transmissivity average (ft^2/d)	Hydraulic conductivity range (ft/d)	Hydraulic conductivity average (ft/d)
Devonian	117	0.1 - 57	2.7	31 - 15,300	720	0.1 - 225	12
Silurian	144	0.1 - 30	1.7	31 - 8,100	465	0.1 - 135	5.0
Combine Devonian-Silurian	261	0.1 - 57	2.1	31 - 15,300	580	0.1 - 225	8.3

using these methods to estimate recharge or discharge for the entire county inappropriate. Streamflow measurements were made by the USGS along this segment of the Iowa River during low-flow conditions in October 2003. Flow in the river decreased from 154 ft^3/s downstream from Coralville Dam to 128 ft^3/s at the Benton Street Bridge in Iowa City. These measurements indicated a net loss of streamflow of about 26 ft^3/s (about 16.8 Mgal/d) over an approximate 8-mi reach of the river at that time. Withdrawals from the river by the University of Iowa and Iowa City may account for some of the loss. Iowa City typically withdraws only about 6.5 Mgal/d from the river in October, and average withdrawals from the river by the University of Iowa for October 2003 were about 2.5 Mgal/d (David McClain, University of Iowa, oral commun., 2005). If these amounts of surface-water withdrawal are assumed, then about 7.8 Mgal/d was lost from the river to the ground-water system during the low-flow measurements. This amount is close to the limits of the accuracy of the streamflow measurements.

Hansen (1970) estimated recharge through the overlying glacial deposits to the Silurian-Devonian aquifer system in Linn County, immediately to the north of Johnson County, to be 0.0089 $(ft^3/s)/mi^2$. Applying this value to the 600-mi^2 area of Johnson County results in a recharge to the aquifer of about 5.3 ft^3/s or about 3.4 Mgal/d.

Additional recharge to the aquifer system may occur by seepage from Coralville Reservoir and (or) Lake MacBride. Because the lakes are several decades old, accumulation of fine-grained sediments on the lake bottoms may restrict this recharge; however, outcrops of Devonian-age rocks along the margins of the lakes may provide pathways for inflow of lake water to the aquifer. Because of the accumulated fine-grained sediments on the lake bottom, the amount of seepage from the lakes is believed to be relatively small. No water-balance calculations have been done for the lakes, so any potential recharge to the Silurian-Devonian aquifer system from the lakes is unknown at this time.

Discharge from the Silurian-Devonian aquifer system is primarily to wells and as ground-water outflow to the surrounding areas. Total discharge by pumping wells is not known because of the unknown amount of water pumped by the thousands of individual domestic wells in the county and because ground-water use by nonmunicipal wells is not routinely measured or reported. Pumping from wells for operation of the limestone quarry near Coralville was reported to be about 42,000 gal/d in 2005 (Deborah Tisor, River Products Corporation, written commun., 2005); however, total ground-water discharge to the quarry is not known.

Total pumpage by public-supply wells (municipal and private developments) is estimated to be about 5.0 Mgal/d in 1996 based on data provided to the USGS by the IDNR, Iowa City, Coralville, North Liberty, Solon, and Tiffin. Although monthly and (or) annual pumpage values are available for most of the municipal wells, annual pumpage values are available for only nine wells operated by private developments (subdivisions that provide their own water supply). An average of the available pumpage values for the private-development wells is 46,000 gal/d (data from Iowa Department of Natural Resources, written commun., 2004). This rate was then applied to other private-development wells for which pumpage data were not available.

Ground-water discharge to Coralville Reservoir and Lake MacBride may occur along the north sides of these surface-water bodies, where ground-water levels are higher than lake levels. The amount of ground-water discharge to the lakes is unknown at this time because water-balance calculations for the lakes are not available.

Ground-water outflow to surrounding areas occurs in northeastern Johnson County and possibly discharges to the Cedar River, which may act as a regional drain. The Cedar River generally gains ground water in this area (R.C. Buchmiller, U.S. Geological Survey, written commun., 2005); however, the portion of this gain from the Quaternary deposits and the portion from the Silurian-Devonian aquifer system is not known. Ground-water outflow also is believed to occur in the eastern, western, and southern parts of the county. The amount of this outflow to the surrounding counties, however, is not known.

Ground-Water Occurrence and Movement

A potentiometric-surface map for the Silurian-Devonian aquifer system (fig. 15) was constructed for average 1996 conditions, and water-level data for a few wells for other periods close to this time were used to help fill in data gaps in the areal distribution of water-level data. Water levels used to construct this map are listed and shown graphically in the Appendix.

Altitude of the potentiometric surface ranges from more than 750 ft in northern Johnson County to less than 575 ft in the central part of the county (fig. 15). The potentiometric surface at the southern county boundary may be controlled by the Iowa River and is estimated to be at an altitude of less than 600 ft (Horick, 1984, sheet 3, fig. 1). A large cone of depression within the potentiometric surface (defined by the 625-, 600-, and 575-ft contour lines, fig. 15) is present in the central part of the county, within Coralville and Iowa City. This area includes municipal pumping centers for those cities, but the cone of depression is not centered on either of their well fields. The quarry north of Coralville, however, is close to the center of the cone of depression and may contribute to this feature. Hydraulic gradients range from less than 4 ft/mi in the southwestern part of the county to about 160 ft/mi southwest of Coralville Reservoir (fig. 15).

Because information on the screened or open intervals is missing for some wells (Appendix), some uncertainty exists for the potentiometric contours shown in figure 15. Some wells may be completed only in Devonian- or Silurian-age rocks, and because large differences in water levels may exist between these rock units, using those wells to construct the potentiometric surface may introduce some error in the placement and shape of the contours.

Ground water occurs under confined conditions (potentiometric levels above the top of the Silurian-Devonian aquifer system) over most of Johnson County. Within the cone of depression in the central part of the county, however, potentiometric levels are more than 100 ft below the top of the aquifer, indicating unconfined conditions within the Devonian-age rocks in this area. Unconfined conditions also occur in a few isolated areas where the Devonian-age rocks are close to land surface.

Potentiometric levels in the Silurian-Devonian aquifer system fluctuate in response to seasonal pumping and variations in recharge (Appendix). Fluctuations in potentiometric levels in the 41 monitored wells in Johnson County range from less than 10 ft to more than 200 ft, and average 44.5 ft. The largest fluctuations are in response to pumping during the summer months.

Ground water generally flows from the northern and western parts of Johnson County toward either the large cone of depression in the center of the county or south out of the county. Ground water also flows toward the Cedar River in the northeastern part of the county. A ground-water divide in the northeastern part of the county roughly approximates the surface-water divide between the Iowa River and Cedar River basins. Because ground-water-level data are sparse in the western and southern parts of the county, there is some uncertainty as to directions of ground-water flow in those areas. Earlier, regional potentiometric-surface maps of the aquifer (Wahl and others, 1978; Horick, 1984) support the concept of ground-water inflow from the west and ground-water outflow to the south.

Ground-water levels in the glacial deposits generally are higher than in the Silurian-Devonian aquifer system, so downward ground-water flow from the glacial deposits may provide a source of recharge to some parts of the aquifer. Vertical flow probably occurs within the Silurian-Devonian aquifer system; however, data to support this concept are sparse. Many wells in the county are completed with large open intervals that span both the Silurian- and Devonian-age rocks; for many other wells, well-construction information is not available. Ground-water levels in a three-well cluster on the north side of Coralville, which are completed in glacial deposits, Devonian-age rocks, and Silurian-age rocks, indicate a substantial downward vertical gradient. These wells are located at the location of well number 12, which is shown in figure 2. Water levels in the glacial deposits (USGS Site ID 41422109361103) are about 85 ft higher than water levels in the Devonian-age rocks (USGS Site ID 41422109361102), which are in turn about 15 ft higher than in the Silurian-age rocks (USGS Site ID 41422109361101, well number 12) (fig. 16). Because this location is within the large cone of depression in the center of the county, it is not known whether or not similar vertical gradients are present throughout the county. The shale-rich Wapsipinicon Formation probably acts as a confining unit between the upper part of the Devonian-age rocks and the Silurian-age rocks; however, because of past erosion this unit is not present everywhere within the county (fig. 11).

Wahl and others (1978, p. 55) report that in most places in east-central Iowa, where the Silurian- and Devonian-age rocks both are present, the potentiometric surface in the Devonian-age rocks is higher than in the Silurian-age rocks. Wahl and Bunker (1986, p. 42) report that water levels in the Devonian-age rocks range from “being equivalent to greater than 40 feet higher” than heads in the Silurian-age rocks in southwestern Linn County and adjacent counties. Because of thick shale beds within the Maquoketa confining unit that underlies the Silurian-Devonian aquifer system, vertical movement of ground water to or from underlying aquifers is probably minimal.

Simulation of Ground-Water Flow

A numerical model of the Silurian-Devonian aquifer system in Johnson County was used to test concepts of ground-

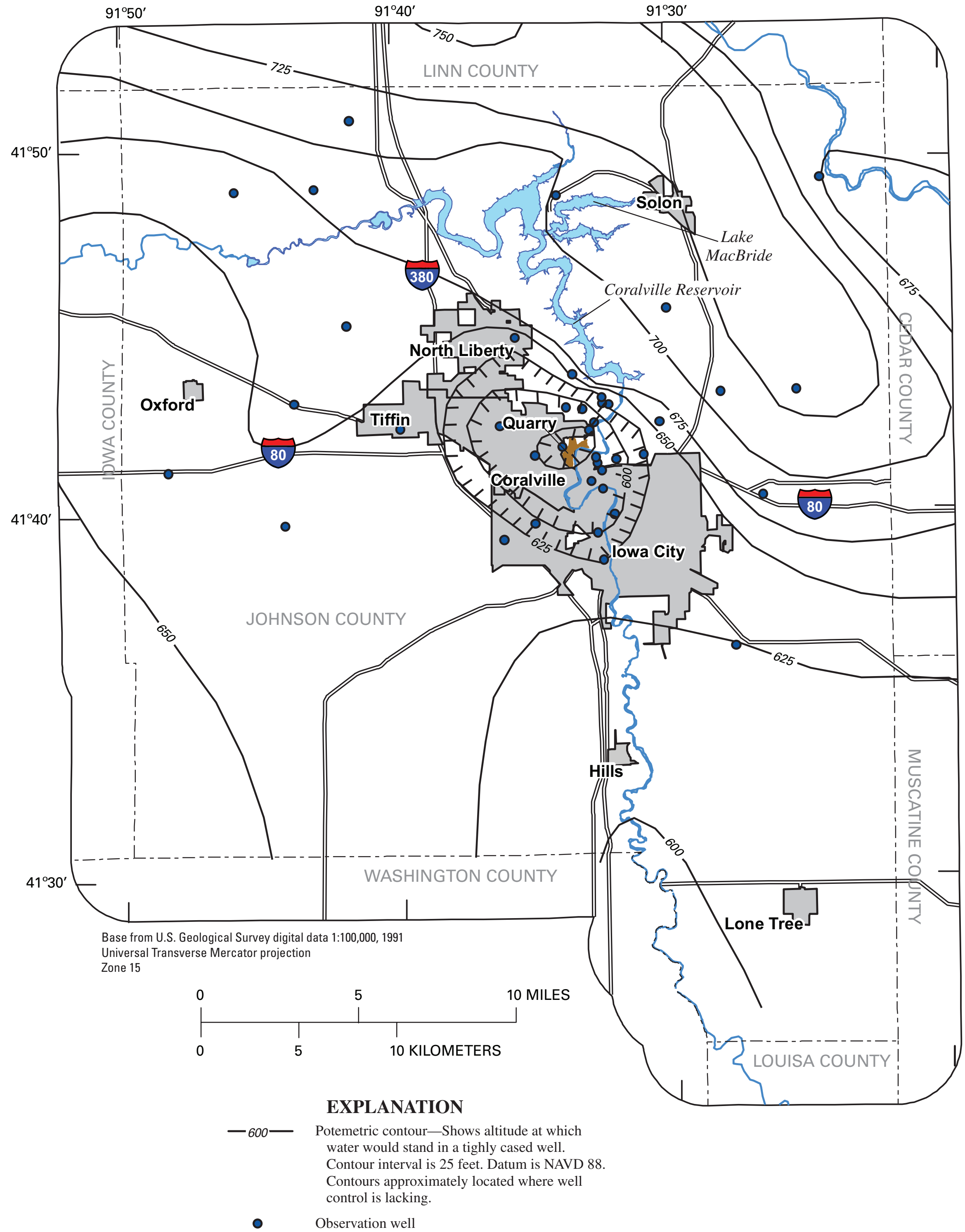


Figure 15. Potentiometric surface of the Silurian-Devonian aquifer system, Johnson County, Iowa, for average 1996 conditions.

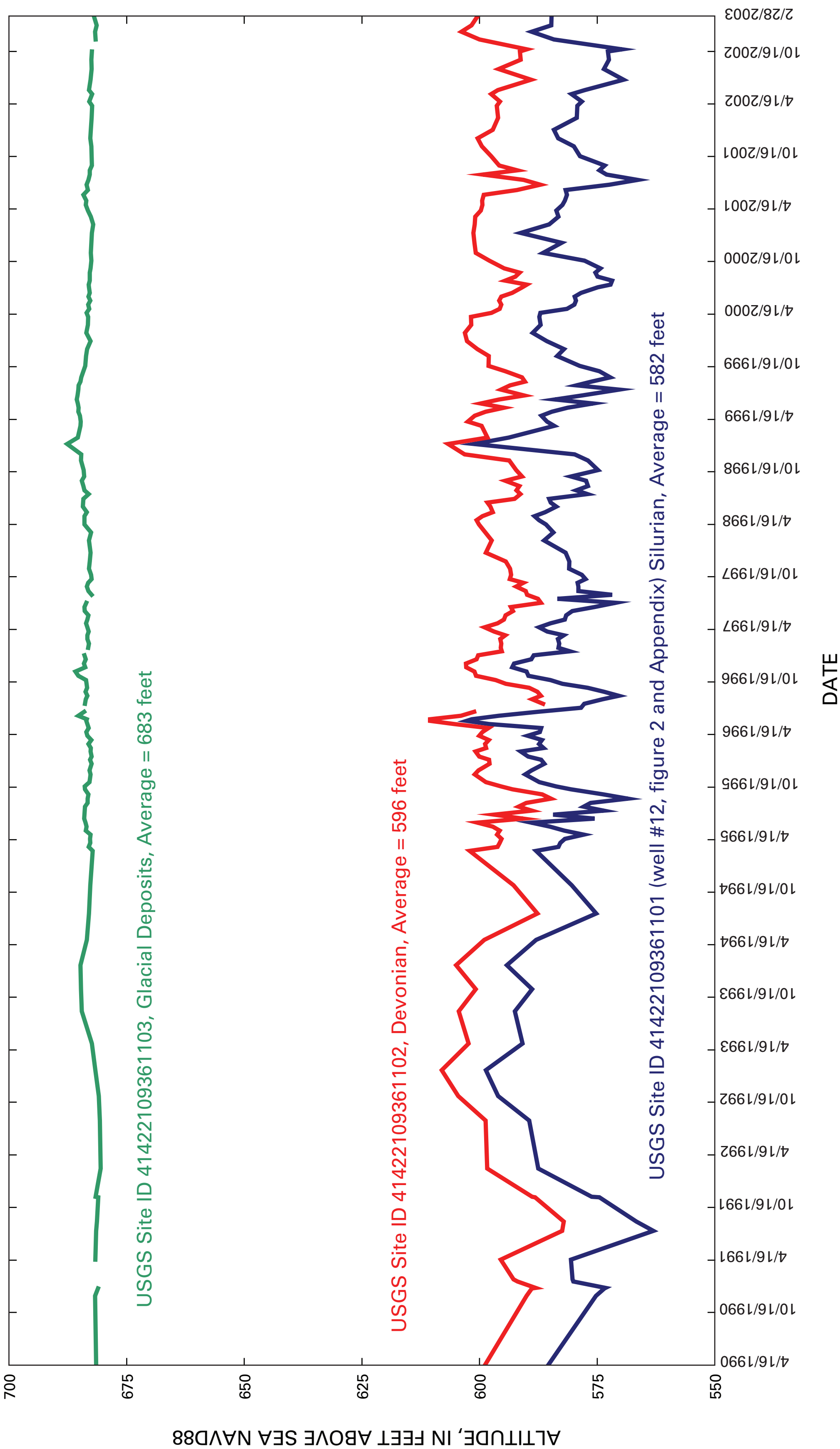


Figure 16. Ground-water levels in glacial deposits and Silurian- and Devonian-age rocks near Coralville, Iowa, April 1990 through February 2003

water flow, to assess the need for additional data, and to provide a preliminary evaluation of the effects of potential future ground-water development. Numerical models are useful tools for these purposes because they integrate all major ground-water flow components, and they allow for the evaluation of the interaction of the various components.

Ground-water flow in the Silurian-Devonian aquifer system of Johnson County was simulated using the USGS finite-difference ground-water-flow model, MODFLOW-2000 (Harbaugh and others, 2000; Hill and others, 2000). A basic assumption of this model is that ground-water flow through fractures and solution openings in the Silurian-Devonian aquifer system can be approximated as flow through a porous medium. Because of the regional (countywide) scale of the model, such an assumption is justified. Flow through individual fractures or solution features, which might affect ground-water movement locally on a scale of tens to hundreds of feet, is not simulated in this model.

The model was calibrated to average 1996 ground-water conditions, which were assumed to approximate steady-state flow conditions. In reality, the ground-water system is almost always in a state of change. Water levels fluctuate throughout the year in response to recharge from rainfall and nearby pumping. To try to duplicate these many short-term changes in a model would be impractical and beyond the scope of this study. Most wells had a complete year of water-level data in 1996, although about 25 percent of the wells had only partial or no data for 1996. If a well did not have a complete year of water-level data for 1996, then 1997 or 1998 water-level data were used. Ground-water levels in 1996 were at about long-term average levels in most wells not affected by pumping.

Precipitation in 1996 was 31.4 inches, about 4 inches less than the normal precipitation of about 35 inches at Iowa City (fig. 4). The average stage of Coralville Reservoir was at an altitude of about 684 ft in 1996, slightly higher than the 1958–2003 average stage of 682.4 ft (fig. 3). Municipal pumpage in 1996 was variable. Pumpage from the Silurian-Devonian aquifer system for Coralville and Iowa City was less than 1993–2002 average pumpage, but pumpage for Solon was about equal to the average 1992–2002 pumpage. Average pumpage data for North Liberty and Tiffin during these periods are not available.

Following the calibration process, the model also was used to simulate ground-water conditions in 2004 in order to provide a baseline for simulations of the potential effects of future development and drought on the ground-water system. These additional simulations are described in more detail in subsequent sections of this report.

Model Construction and Boundary Conditions

The area of the model extends approximately 2 mi beyond the Johnson County line on the north, west, and east sides and corresponds to the boundary between Johnson and Washington Counties between townships 78 N. and 77 N. on the south (fig. 17). The northeast corner of the model corresponds to the approximate location of the Cedar River. The model grid consists of 33 rows and 37 columns. Grid spacing is variable, ranging from 0.5 to 1.0 mi on a side. The smaller grid cells are located near the center of the model to better approximate the steep hydraulic gradients around the central cone of depression (fig. 17).

The Silurian-Devonian aquifer system is simulated as a single model layer, so that vertical flow between the Silurian- and Devonian-age rocks or the overlying unconsolidated deposits are not simulated. The top of the Cedar Valley Limestone, where present, is the top of the model. Where the Devonian-age rocks are missing, the top of the Silurian-age rocks represents the top of the model. The bottom of the model corresponds to the top of the Maquoketa Formation, and this model boundary is assumed to be a no-flow boundary.

The northern boundary is simulated as a constant-head boundary (fig. 17) in order to simulate ground-water inflow and outflow in this area. The northeastern boundary of the model also is simulated as a constant-head boundary to represent the Cedar River as a regional drain and to simulate ground-water outflow along the boundary. The southern part of the eastern model boundary is simulated as a no-flow boundary because this part of the boundary is approximately along a ground-water flow line. The northern part of the eastern boundary is simulated as a constant-head boundary to simulate ground-water outflow in this area. The western model boundary is primarily simulated as a no-flow boundary; however, four model cells along this boundary (rows 11–14, column 1) are simulated as a constant-head boundary to allow some ground-water inflow or outflow along the boundary. The southern boundary also is primarily simulated as a no-flow boundary; however, six cells (row 33, columns 21–26) near the Iowa River are simulated as a constant-head boundary to allow ground-water outflow along this boundary.

The upper model boundary represents recharge to the top of the Silurian-Devonian aquifer system that occurs through the overlying unconsolidated deposits. Recharge is simulated as a constant rate applied uniformly over each model cell to represent steady climate conditions. Several different zones of equal recharge rates were tested using the MODFLOW-2000 parameter-estimation process (Hill and others, 2000) during model calibration. Figure 18 shows the final distribution of recharge used for the steady-state model simulation. This distribution is discussed further in a subsequent section.

The model cells representing the Iowa River, from Coralville Dam through Iowa City where the river is assumed to be in direct hydraulic contact with the Devonian-age bedrock, were simulated as “river cells” (Harbaugh and others, 2000) (fig. 17). The Iowa River was not simulated in the northwestern and southern parts of the county, where it flows on unconsolidated glacial or alluvial deposits and is assumed to be hydraulically isolated from the Silurian-Devonian aquifer system. Ground-water inflow to, or outflow from, the river is simulated as a head-dependent flux boundary. Simulated ground-water flow to or from the river is a function of the river

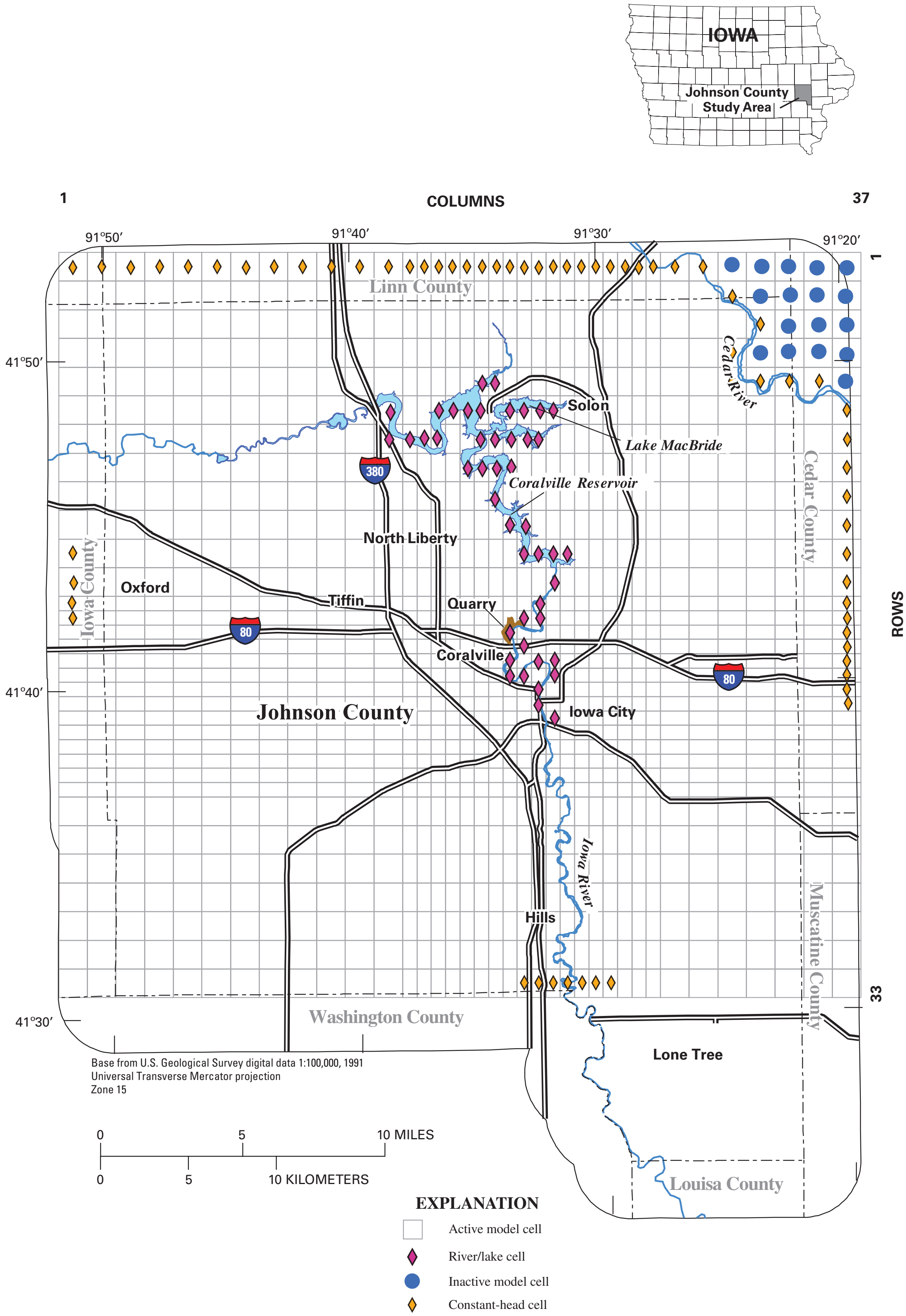


Figure 17. Model grid and boundary conditions.

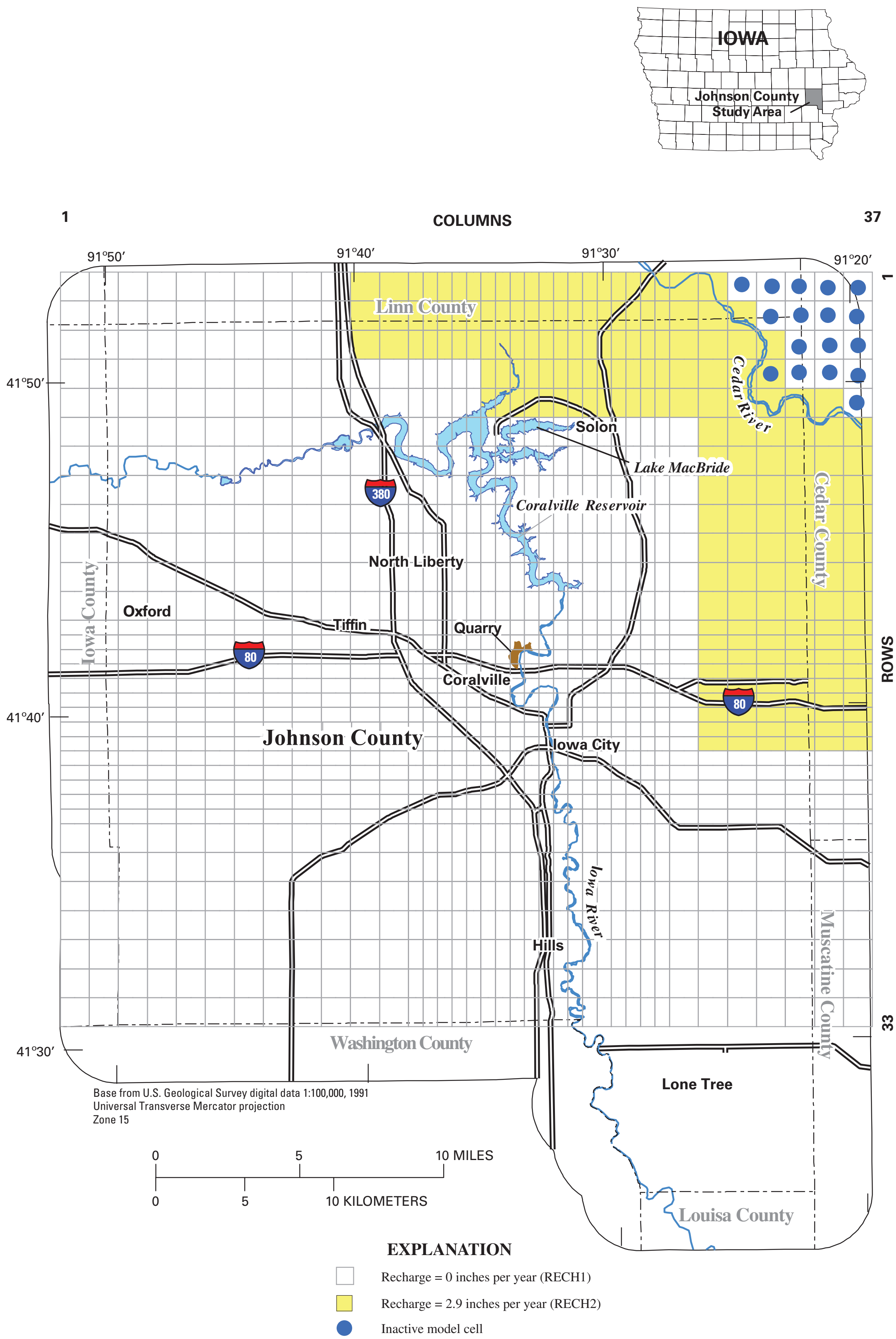


Figure 18. Final distribution of recharge for the 1996 steady-state simulation.

stage, the head in the underlying aquifer, and the riverbed conductance at each cell. Riverbed conductance (Harbaugh and others, 2000) is calculated as the vertical hydraulic conductivity of the riverbed materials (initially assumed to be one-tenth of the horizontal hydraulic conductivity) times the area of the riverbed (estimated from topographic maps), divided by the thickness of the riverbed materials (assumed to be 1 ft thick). Riverbed-conductance values were tested during model calibration using the MODFLOW-2000 parameter-estimation process. Coralville Reservoir and Lake MacBride, also are assumed to be in direct hydraulic connection with the Silurian-Devonian aquifer system and were simulated as river cells (fig. 17). As stated previously, the Cedar River was simulated as a constant-head boundary across the northeastern corner of the model. Other smaller streams in the county flow only over glacial deposits, and were not simulated.

Ground-water withdrawals from 104 municipal and private-development wells were simulated as wells in 85 cells in the model. Table 3 lists the model cells and the reported or assumed average pumping rates for 1996 used in the model to simulate steady-state ground-water conditions. Withdrawals from individual domestic wells were not simulated in the model because data on the number of wells and the pumping rates of those wells were not available.

The hydraulic conductivity of the Silurian-Devonian aquifer system was simulated using zones of similar hydraulic-conductivity values. The initial zones were estimated using hydraulic conductivities that were provided by IGS and based on specific-capacity data. The number of zones, their areal extent, and the hydraulic conductivity of each zone were evaluated during model calibration by using the MODFLOW-2000 parameter-estimation process. Figure 19 shows the final distribution of hydraulic conductivity used in the steady-state model simulation.

1996 Steady-State Calibration and Simulation

Steady-state conditions were assumed for 1996 for the simulation of ground-water flow in the Silurian-Devonian aquifer system. Although steady-state conditions may not have occurred in the entire study area at this time, the errors introduced by the assumption are believed to be small. The simulated potentiometric surface (fig. 20) generally replicates the potentiometric surface for 1996 conditions (fig. 15).

Model Calibration

Forty-one wells completed in the Silurian-Devonian aquifer system had water levels available for the 1996 period or times close to it (average monthly measured water levels for 1996 or 1997-98), and these water levels were compared to simulated water levels for model calibration. In order to evaluate model results, the root mean squared error (RMSE) of the residual between the measured and simulated water levels was calculated according to the equation:

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

where

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

The smaller the RMSE value, the closer the overall match is between the simulated and measured water levels. The calibration scheme was to adjust model-input parameters, within hydrologically justifiable limits, to minimize the RMSE value.

The parameter-estimation capability of MODFLOW-2000 (Hill and others, 2000) was used during model calibration to provide values for model parameters that produced the closest match between measured and simulated water levels. Parameters were defined for hydraulic conductivity, recharge, riverbed conductance, lakebed conductance, and pumpage from the quarry.

Several configurations of the areal distribution of hydraulic conductivity (zones of equal hydraulic conductivity), based on the analysis of specific-capacity test data by IGS, were evaluated during the calibration process. Although four hydraulic-conductivity zones were initially included in the model, the final distribution of two zones (parameters K1 and K2) (fig. 19) produced the best match between measured and simulated water levels. The final estimated values were 5.6 ft/d for parameter K1 and 18.7 ft/d for parameter K2. The average hydraulic conductivity of 8.7 ft/d for the Silurian- and Devonian-age rocks, based on the specific-capacity tests, is within the final estimated values for K1 and K2.

Several configurations of the distribution of areal recharge (zones of equal recharge rates) were evaluated during the calibration process. These configurations were based on different concepts of recharge to the ground-water system in the county. Initial model simulations used the uniform recharge rate of 3.4 Mgal/d based on Hansen's (1970) estimated rates; however, simulated water levels were too low in the northeastern part of the model and too high in the southern and western parts of the model. The final distribution included two zones (parameters RECH1 and RECH2) of uniform recharge rate (fig. 18). The zone for parameter RECH1 covers about three-fourths of the county (fig. 18). Parameter RECH1 represents a zone of no recharge and was based on the concepts that in this area recharge to the Silurian-Devonian aquifer system is inhibited by the Upper Devonian shale confining unit and by thick, low-permeability glacial till, and that pumping in the center of the county intercepts any recharge to the system. The initial concept for parameter RECH1 was that it was a zone of low recharge rate; however, during the calibration process the model consistently estimated

Table 3. Simulated pumping rates from wells for 1996 steady-state conditions, Silurian-Devonian aquifer system, Johnson County, Iowa.

[Pumping rates have been rounded]

Row	Column	Pumping rate (gallons per day)	Row	Column	Pumping rate (gallons per day)
3	9	46,000	12	7	21,000
3	12	46,000	12	20	46,000
4	3	50,000	12	20	46,000
4	8	46,000	12	20	46,000
4	10	92,000	12	21	46,000
4	13	92,000	12	21	46,000
5	10	46,000	12	22	46,000
5	10	46,000	12	22	46,000
5	11	46,000	12	22	46,000
5	11	46,000	12	22	46,000
5	13	46,000	12	25	46,000
5	13	92,000	12	26	101,000
5	15	46,000	12	29	46,000
5	18	46,000	13	13	50,000
5	20	46,000	13	21	46,000
5	20	40,000	13	21	3,000
5	22	46,000	13	21	55,000
5	23	46,000	13	23	46,000
5	23	46,000	14	11	40,000
6	14	46,000	14	28	46,000
6	18	46,000	15	11	22,000
6	19	46,000	15	18	246,000
6	22	46,000	15	19	5,550,000
6	23	21,000	15	24	125,000
6	26	93,000	15	25	50,000
6	26	6,600	16	22	46,000
6	29	42,000	16	24	46,000
7	14	92,000	17	30	40,000
7	16	92,000	18	19	40,000
7	17	46,000	19	18	156,000
7	19	92,000	19	23	198,000
9	15	46,000	20	29	46,000
10	16	42,000	21	29	40,000
10	16	42,000	21	31	84,000
10	17	42,000	22	16	92,000
10	25	46,000	22	23	92,000
10	26	138,000	22	28	46,000
11	15	113,000	22	28	92,000
11	22	700	22	31	92,000
11	23	11,000	27	21	48,000
11	24	1,400	27	30	92,000
11	25	92,000	29	7	46,000
11	25	27,000			

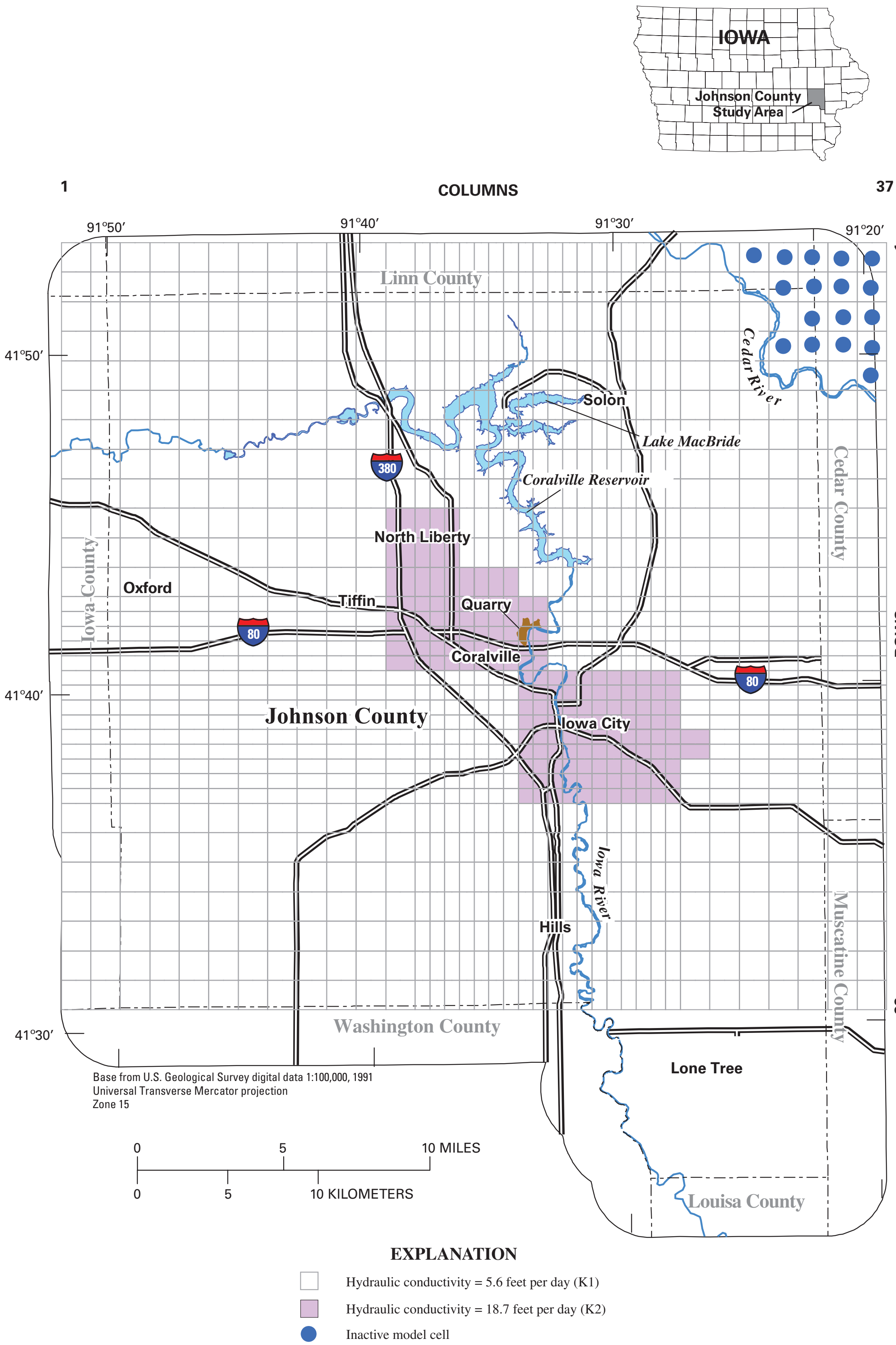


Figure 19. Final distribution of hydraulic conductivity for the 1996 steady-state simulation.

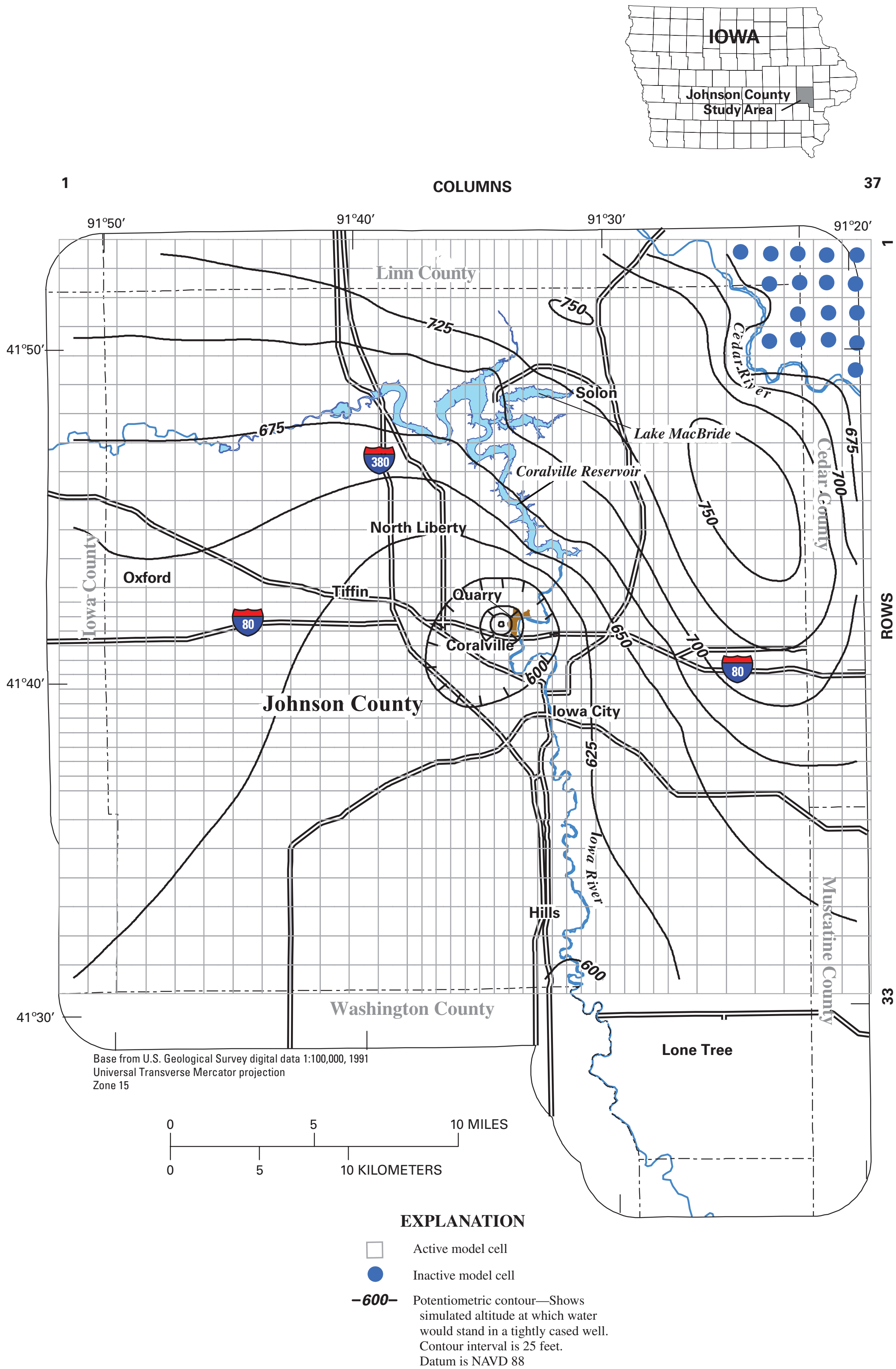


Figure 20. Simulated potentiometric surface for 1996 steady-state conditions.

negative recharge rates (discharge from the ground-water system) for this parameter. The negative estimated recharge rate for RECH1 may indicate that pumpage rates for wells in this area may be underestimated. Recharge rates for RECH1 were, therefore set equal to zero for the remainder of the calibration process. The zone for parameter RECH2 covers about one-fourth of the model area in the northern and northeastern parts of the county (fig. 18), corresponding to the high potentiometric levels that form a ground-water divide in those areas (fig. 15). The final estimated recharge rate for RECH2 was about 2.9 in/yr and is based on the concept that the recharge rate is larger in this area because the aquifer is closer to the surface and much of the Upper Devonian shale confining unit has been removed by erosion.

Riverbed conductance values, rather than values for vertical hydraulic conductivity, riverbed and lakebed area, and riverbed and lakebed thickness, were adjusted during model calibration. The riverbed conductance value (parameter RIV1) required for model calibration was 5.4 (ft^3/d)/ft. During the calibration process, the value for parameter RIV1 was consistently close to this value, and the model did not appear to be sensitive to the value of this parameter. The riverbed conductance was therefore fixed at this value for the remainder of the calibration process. The lakebed conductance value (parameter LAKE) required for model calibration was 2,045 (ft^3/d)/ft. These conductance values are both quite small and indicate that the Iowa River and the lakes are not hydraulically well connected to the ground-water system. Despite the presence of carbonate rocks at or near the surface beneath these surface-water bodies, accumulated fine-grained, low-permeability deposits along the river and lake bottoms and the low ground-water levels along the Iowa River apparently are restricting ground-water/surface-water interactions.

Pumping from the quarry near Coralville was not included in the model early in the calibration process. As model calibration proceeded, however, it became evident that the cone of depression in the potentiometric surface could not be reproduced without simulation of discharge from the quarry. Initial estimates for a pumping rate from the quarry were obtained by setting the water level in the quarry at a constant altitude of 524 ft, which is approximately equal to the altitude of the bottom of the quarry. The model then calculated the amount of discharge from that model cell required to keep the water level at that altitude. This discharge value was then used as an initial rate for use in the parameter-estimation process. The final estimated value for this parameter (WELL1) is about 5.6 Mgal/d, which is much greater than the reported pumping rate of about 0.04 Mgal/d for 2005. The reason for this large discrepancy is not known but may be due, in part, to the lack of vertical resolution in the model. The discrepancy is discussed further in the “Model Limitations and Additional Data Needs” section.

Simulation Results

The RMSE value for the 1996 model calibration is 13.6 ft. This value is about 30 percent of the average historical fluctuation in potentiometric levels in the 41 wells used for comparison to simulated levels. About 30 percent of the simulated water levels are within ± 5 ft of measured levels, about 60 percent of the simulated water levels are within ± 10 ft of measured levels, and 90 percent of the simulated water levels are within ± 20 ft of measured levels (fig. 21). The areal distribution of model residuals (fig. 21) indicates a generally random distribution, although there are some areas of generally low and high residuals (fig. 21). Some model cells with simulated water levels higher than measured levels are located among model cells with simulated water levels lower than measured levels.

Overall, simulated water levels were neither substantially higher nor lower than measured levels (fig. 22). Of the 41 measured water levels used for comparison to simulated water levels, 21 were lower than simulated and 20 were higher than simulated. Absolute differences between simulated and measured water levels ranged from less than 1 ft to about 35 ft. The mean absolute difference was 10.9 ft. The mean absolute difference between simulated and measured water levels may be within the range of differences between water levels in the Silurian- and Devonian-age rock units.

Although the model calculates components of the water budget for the ground-water system, few observed or estimated water-budget components were available for the calibration period to compare to model results. This lack of water-budget data is discussed further in the “Model Limitations and Additional Data Needs” section.

Model-calculated inflow to the ground-water system includes boundary inflow from surrounding areas, leakage from lakes (Coralville Reservoir and Lake MacBride), river leakage from the Iowa River, and areal recharge. Model-calculated outflow from the ground-water system includes boundary outflow to surrounding areas, discharge to wells, and leakage to lakes (Coralville Reservoir and Lake MacBride).

Model-calculated water-budget components are listed in table 4. The first part of table 4 lists the total flow components, based on calculated flow to or from each model cell. The second part of the table lists the net flow into or out of the model along the northern, northeastern (Cedar River), eastern, southern, and western model boundaries. This net flow is the sum of any inflow and outflow along each boundary segment. Although table 4 lists a net inflow of 0.6 Mgal/d (1996) along the northern boundary, this value is the sum of 1.6 Mgal/d of inflow and -1.0 Mgal/d of outflow along this boundary. Similarly, along the western boundary the net outflow is - 0.2 Mgal/d, which is the sum of 0.1 Mgal/d of inflow and -0.3 Mgal/d of outflow. All other boundary segments only have outflow components.

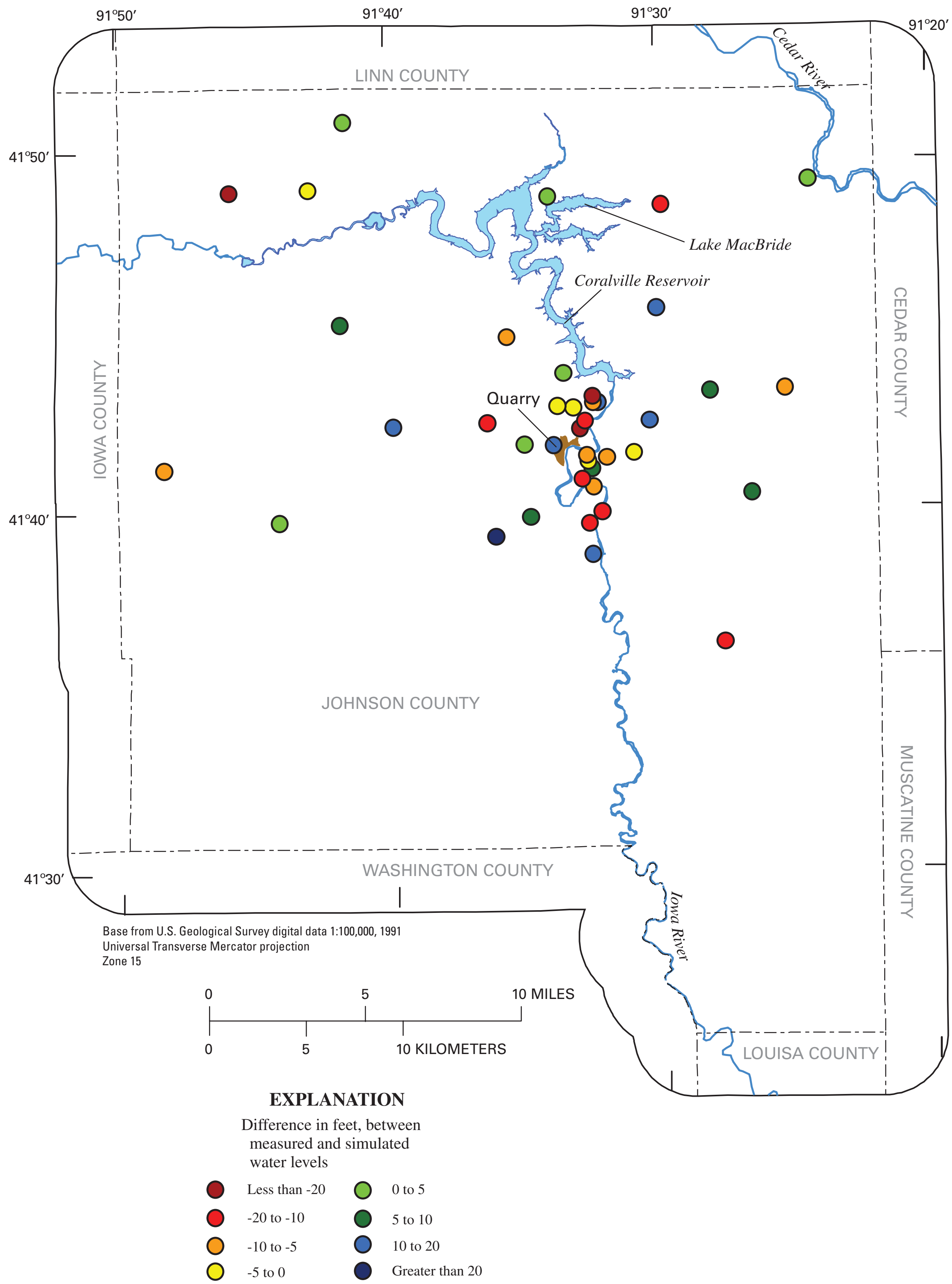


Figure 21. Difference between measured and simulated water levels.

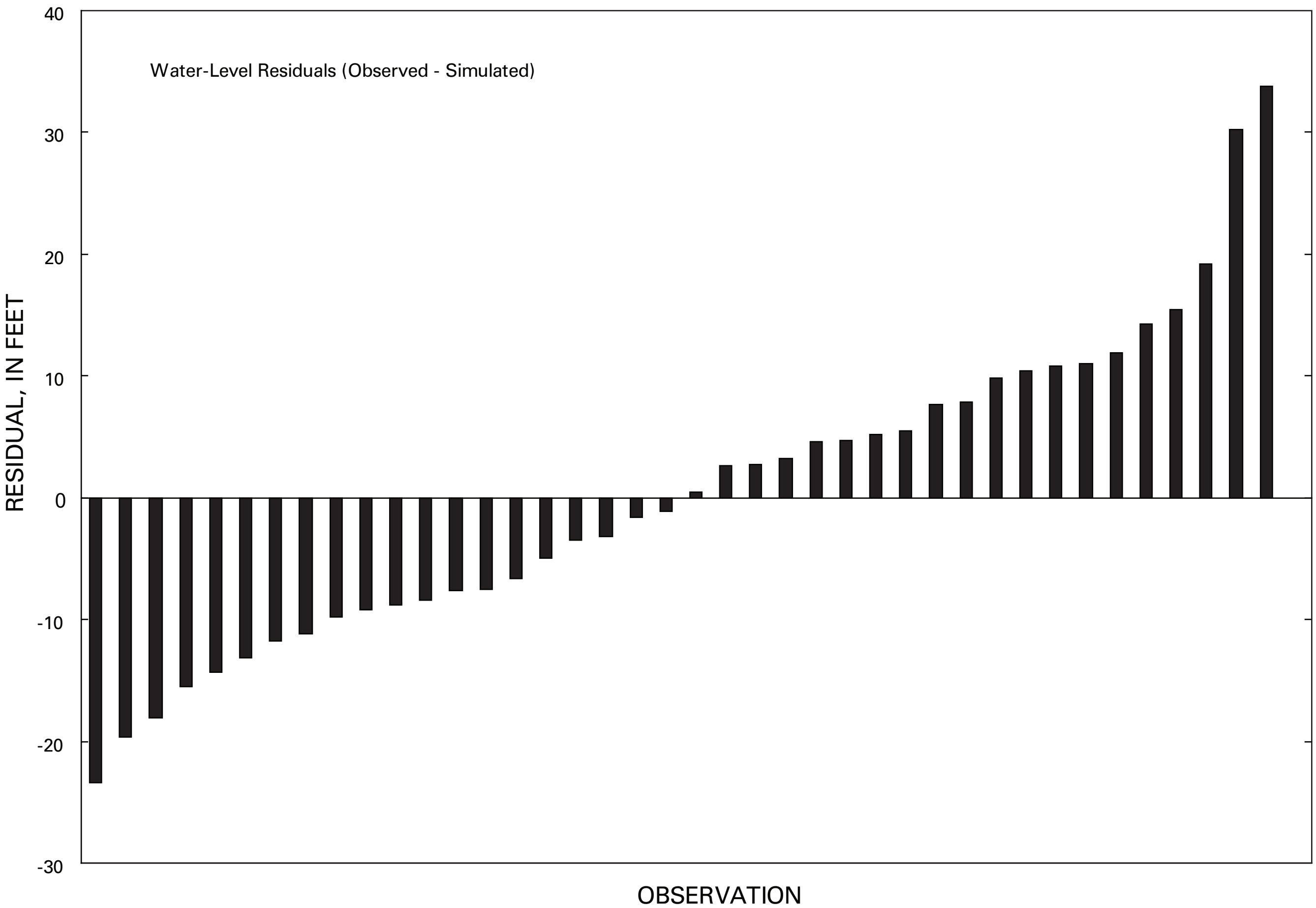


Figure 22. Distribution of 1996 water-level residuals.

Total model-calculated inflow to the ground-water system for 1996 was 19.6 Mgal/d (table 4), and the largest model-calculated inflow component was areal recharge (15.1 Mgal/d). This recharge rate is much greater than the estimated recharge of 3.4 Mgal/d for Johnson County, based on recharge rates for the Silurian-Devonian aquifer system in Linn County reported by Hansen (1970). Ground-water inflow from surrounding areas (1.7 Mgal/d total) occurred along parts of the northern and western model boundaries. Ground-water inflow from Coralville Reservoir and Lake MacBride of about 2.8 Mgal/d was simulated along the southern shores of the lakes. Ground-water inflow from the Iowa River was less than 0.1 Mgal/d, which is much less than the losses from the river (7.8 Mgal/d) measured in October 2003. The reason for this discrepancy is not known; however, the loss from the river during that time was within the limits of the accuracy of the streamflow measurements. Water levels in the Silurian-Devonian aquifer system are well below the bottom of the river along most of the reach of the Iowa River that flows on bedrock in Johnson County. These low water levels indicate that the river is not well connected to the ground-water system in that area, and this lack of direct connection may limit leakage from the river to the ground-water system.

Total model-calculated outflow from the ground-water system was 19.7 Mgal/d (table 4), and the largest outflow component was discharge to wells (10.5 Mgal/d). About one-half of this discharge (5.6 Mgal/d) was simulated as discharge from the quarry, and the remainder (4.9 Mgal/d) was simulated as discharge from municipal and private development wells. Ground-water outflow to surrounding areas (8.1 Mgal/d total) occurred along the northeastern, southern, and western model boundaries. Ground-water outflow to Coralville Reservoir and Lake MacBride was about 1.1 Mgal/d.

An alternate simulation for 1996 conditions, which included the reported pumping rate of 0.04 Mgal/d for the quarry, was conducted in order to investigate the discrepancy between the reported and simulated discharge from the quarry. This simulation, however, could not reproduce the low water levels in the center of the county, and the calculated RMSE was 17.1 ft, which is somewhat higher than the 1996 calibration value of 13.6 ft. The water-level altitude at the quarry simulated using the lower pumping rate was 582 ft, which is 58 ft higher than the bottom of the quarry.

Table 4. Model-calculated water-budget components.

[Mgal/d, million gallons per day; <, less than; negative values (-) indicate flow out of the model]

Budget Component	Inflow (Mgal/d)				Outflow (Mgal/d)			
	1996 Steady state	2004 Steady state	2025 Steady state	2025 Drought	1996 Steady state	2004 Steady state	2025 Steady state	2025 Drought
Total boundary flow	1.7	1.8	1.8	2.2	–8.1	–8.1	–7.7	–4.9
Areal recharge	15.1	15.1	15.1	11.3				
River	<0.1	<0.1	<0.1	<0.1				
Lakes	2.8	2.9	3.5	4.7	–1.1	–1.0	–0.8	–0.5
Public-supply wells					–4.9	–5.7	–7.2	–8.9
Quarry well					–5.6	–5.1	–4.7	–3.9
TOTAL	19.6	19.8	20.4	18.2	–19.7	–19.8	–20.4	–18.2

NET BOUNDARY FLOW

Boundary	1996 Steady state (Mgal/d)	2004 Steady state (Mgal/d)	2025 Steady state (Mgal/d)	2025 Drought (Mgal/d)
Northern	0.6	0.7	0.8	1.6
Northeastern	–3.3	–3.2	–3.2	–2.3
Eastern	–2.9	–2.9	–2.8	–1.6
Southern	–0.6	–0.6	–0.5	–.30
Western	–0.2	–0.2	–0.1	<–0.1

Model Sensitivity

The sensitivity process capability of MODFLOW-2000 (Hill and others, 2000) was used to determine the sensitivity of the model to the various estimated parameter values. The results of this evaluation provide an indication as to which parameters have the most influence on the model results. In other words, for parameters with large calculated sensitivities, small changes in the value of those parameters may result in large changes to simulated water levels and model-calculated water-budget components. The calculated sensitivities, when scaled properly, can be used to compare the importance of different observations to the estimation of a single parameter or the importance of different parameters to the simulation of an observed value (Hill, 1998, p. 15). Three types of statistics were evaluated for the sensitivity analysis: (1) dimensionless scaled sensitivity, (2) composite scaled sensitivity, and (3) parameter correlation coefficient.

Dimensionless scaled sensitivity (DSS) is used as an indicator of the importance of an observation to the estimation of a single parameter. A parameter having a large DSS value for one observation and small values for other observations is essentially defined by that one observation. An error in that one observation will result in an error in the parameter that it influences.

DSS values indicated that three parameters may be strongly influenced by water-level observations in two wells. One water-level observation (well #33), at the center of the measured cone of depression (figs. 2 and 20), had relatively large DSS values for parameters K1 and WELL1 compared with other observations. One water-level observation in the northeastern part of the model (well #20) had the largest DSS value for parameter RECH2. Well-construction information for wells #20 and #33 are not available except for total depth of the wells (Appendix). Well #20 is relatively shallow (83 ft deep) and may be completed only in the Devonian-age rocks. If water levels in these rocks are substantially higher than those in the combined Silurian-Devonian aquifer system rocks, then the relatively high water level in well #20 may cause parameter RECH2 to be too large. Similarly, well #33 (350 ft deep) may be completed only in Silurian-age rocks. If water levels in these rocks are substantially lower than in the combined Silurian-Devonian aquifer system rocks, then the low water level in well #33 may cause parameters K1 and WELL1 to be in error.

The measured losses from the Iowa River for October 2003 were initially used as an observation in the calibration process, despite the uncertainty of the amount of the measured loss. This observation had no apparent effect on the model results, probably because simulated water levels were well below the river bottom, and the observation was not used in later simulations.

Composite scaled sensitivity (CSS) is used to evaluate the overall sensitivity of a parameter. The relative size of CSS values also can be used to assess whether additional parameters should be included in the parameter-estimation process. A relatively large CSS value indicates that the model is sensitive to that parameter. A large CSS value also indicates that the parameter also may be subdivided into two or more separate parameters to reduce the model sensitivity. Such a subdivision would be advisable if one parameter has a CSS value much greater than the values for all other parameters. A relatively small CSS value (about two orders of magnitude less than the largest CSS value) indicates that the model is insensitive to that parameter and that observations provide insufficient information with which to estimate the parameter. Parameters with small CSS values generally were not included in the parameter-estimation process and were assigned a fixed value during the calibration process.

The model was most sensitive (largest CSS value) to the simulated pumping from the quarry (parameter WELL1; fig. 23). The CSS for this parameter was 36.5. The model also was sensitive to parameters K2 and RECH2. Composite scaled sensitivities for these parameters were 24.8 and 22.5, respectively (fig. 23). The model was much less sensitive to parameter K1 (CSS =11.4) and was relatively insensitive to parameter LAKE (CSS = 3.7) (fig. 23). Parameters RECH1 and RIV1 were assigned a fixed value during the later stages of model calibration because they had low CSS values.

Parameter correlation coefficients are calculated for each parameter pair and are used to evaluate whether parameter values can be uniquely estimated. A correlation coefficient having an absolute value close to 1.00 indicates that the two matched parameters cannot be estimated uniquely. Most of the estimated parameters for the model are highly correlated (table 5). The cause for this nonuniqueness of the parameters is the lack of any flow measurements to use as observations for model calibration.

Simulation of Potential Future Withdrawals

One of the objectives of the study was to simulate the potential effects of increased ground-water development. In order to provide a more current baseline than that provided by the simulation of 1996 conditions for such an assessement, 2004 ground-water conditions also were simulated. The output from the simulation of 2004 conditions was then used as starting conditions for simulation of anticipated pumpage 20 years

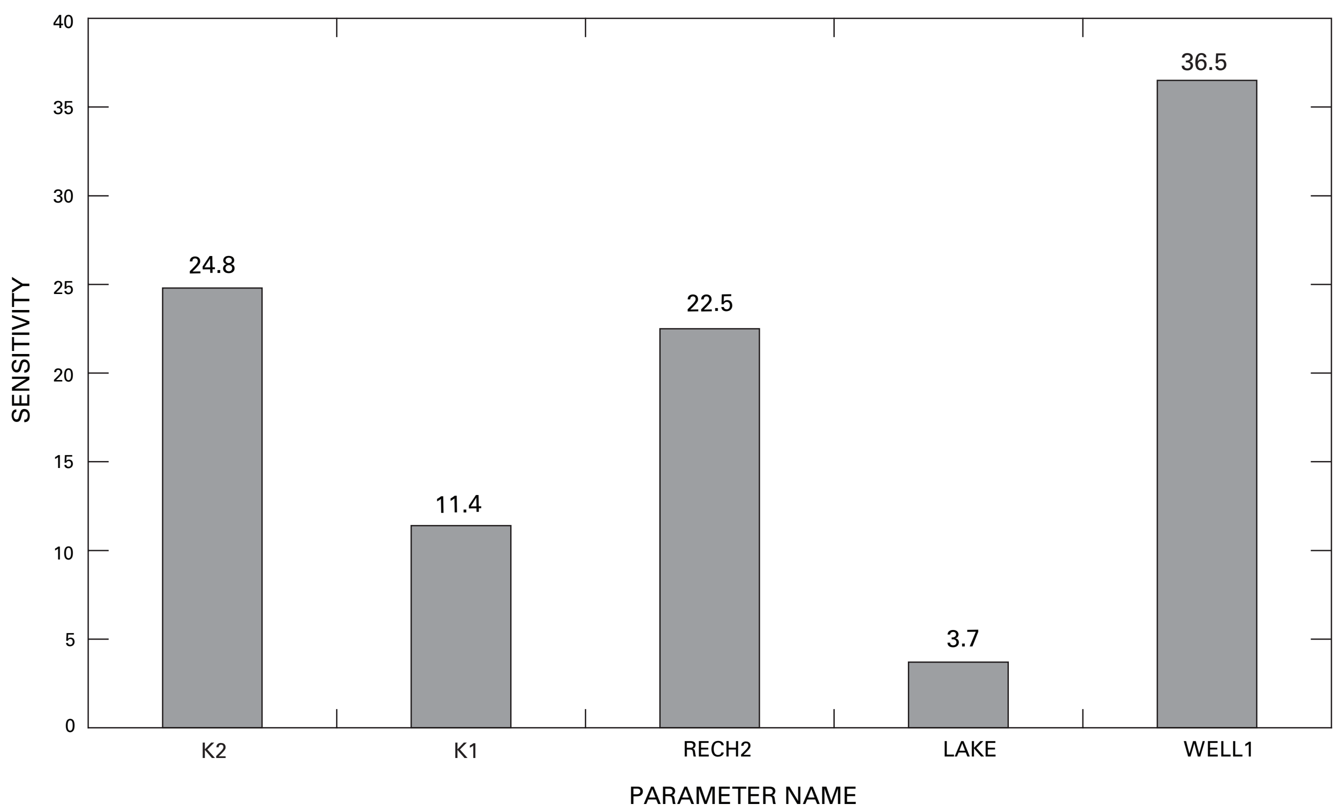


Figure 23. Composite scaled sensitivities of estimated model parameters.

Table 5. Correlation matrix for estimated model parameters.

Parameter	K2	K1	RECH2	LAKE	WELL1
K2	1.00	0.94	0.99	0.32	–0.98
K1	0.94	1.00	0.96	0.48	–0.98
RECH2	0.99	0.96	1.00	0.33	–0.98
LAKE	0.32	0.48	0.33	1.00	–0.46
WELL1	–0.98	–0.98	–0.98	–0.46	1.00

into the future (2025). Simulated water levels and water-budget components both for expected average steady-state conditions and for potential drought conditions, using anticipated pumping rates for 2025, were compared to 2004 simulated water levels and water-budget components.

Simulation of 2004 Conditions

Simulation of 2004 conditions required a few changes to model-input files used for the simulation of 1996 conditions. Changes included using average ground-water levels for 36 available wells for water year 2004 (October 2003 through September 2004) for comparison to simulated water levels, and using estimated 2004 pumping rates for municipal wells. Pumping was not specified at the quarry, but rather the water level was held constant at a level close to the bottom of the quarry (524 ft). The model then calculated the discharge from the quarry on the basis of that level. Using the 1996 simulated pumping rate for the quarry would be inappropriate because discharge to the quarry is dependent on existing ground-water conditions. Ground-water conditions and water levels in 2004 or other years could result in simulated water levels at the quarry that might be substantially higher or lower than the bottom of the quarry if the 1996 simulated pumping rate is used.

All other model inputs and boundary conditions were the same as those for the 1996 simulation. The model only simulated steady-state ground-water conditions because information on the storage properties of the Silurian-Devonian aquifer system is not available.

Overall, measured ground-water levels were an average of about 8 ft lower in 2004 than in 1996, and the change in ground-water levels ranged from about 9 ft higher to almost 40 ft lower than 1996 levels. Total pumpage for all of the municipal wells is estimated to have increased from 1996 to 2004 by about 0.8 Mgal/d. Pumping rates for private-development wells were assumed to be the same as 1996 rates, and no new wells were added to the simulation.

Simulated ground-water levels (fig. 24) ranged from less than 1 ft to about 46 ft different than measured 2004 water levels, and the absolute mean difference between simulated and measured water levels was about 14 ft. Simulated ground-water levels were lower than measured levels at 15 wells and were higher than measured levels at 21 wells. This small model bias toward higher water levels suggests that either the pumpage was underestimated or that the recharge was overestimated for this simulation. Despite the reported population growth and new construction between 1996 and 2004, no new private-development wells were added to the simulation; so it is likely that the pumpage was underestimated. The calculated RMSE was 18.6 ft, which is somewhat higher than the RMSE for the 1996 simulation (13.6 ft) and is about 42 percent of the average historical water-level fluctuations in the observation wells used for comparison to simulated water levels. The overall shape of the simulated 2004 potentiometric surface (fig. 24), however, was similar to the 1996 potentiometric surface (fig. 15).

Overall, the simulated water-budget components for 2004 were similar to simulated 1996 water-budget components (table 4). The largest changes were for outflow components, in which municipal well pumpage increased by about 0.8 Mgal/d; but simulated boundary outflow decreased by about 0.1 Mgal/d, and simulated outflow to the lakes decreased by about 0.1 Mgal/d. Additionally, model-calculated discharge from the quarry was about 0.5 Mgal/d less than the simulated pumping rate for the 1996 simulation. Total boundary inflow from adjacent areas and from the lakes both increased by 0.1 Mgal/d.

Simulation of Potential 2025 Steady-State Pumping

The population of Johnson County in the North Corridor area is estimated to increase by about 15,400 by the year 2025 (Dan Swartzendruber, Johnson County Planning and Zoning Department, written commun., 2005). Assuming an average domestic water use of 65 gal/d per person in Iowa (Hutson and others, 2004, table 6), an additional 1.0 Mgal/d would be needed to provide water for the increased population. This water will mainly be provided by existing and new wells drilled into the Silurian-Devonian aquifer system. Additionally, Coralville, Solon, and the University of Iowa anticipate additional withdrawals from the Silurian-Devonian aquifer system in the future and provided estimates of the anticipated withdrawals to the USGS (R.C. Buchmiller, U.S.Geological Survey, written commun., 2005). These additional withdrawals will have some effect on the ground-water system, and the

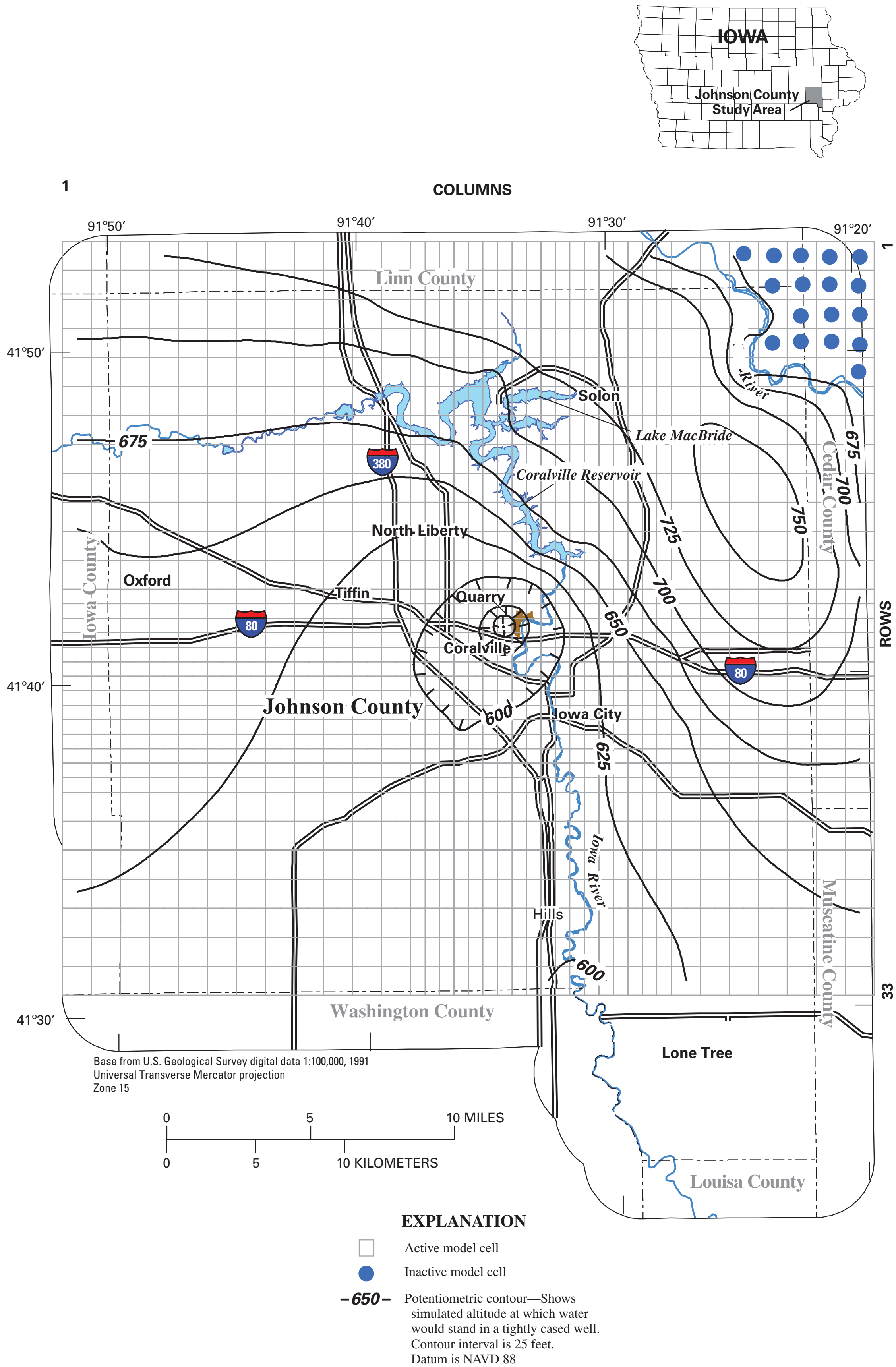


Figure 24. Simulated potentiometric surface for 2004 steady-state conditions.

model was used to estimate the effect of the projected future withdrawals on the Silurian-Devonian aquifer system.

Simulated withdrawals were increased to 7.2 Mgal/d for the simulation of potential 2005 steady-state pumping conditions (table 4). The increased ground-water withdrawals for the anticipated population growth in the North Corridor area was simulated by adding a pumping well in each model cell in the southern two-thirds of that area (fig. 25), which is expected to contain most of the additional growth. This method assumes that the increased population will obtain ground water from either individual homeowner's wells or those of additional small housing developments distributed throughout that part of the North Corridor. The total increase in pumpage of 1.0 Mgal/d was evenly distributed over the 106 North Corridor model cells, at a rate of about 9,400 gal/d per cell. Additionally, anticipated new Silurian-Devonian aquifer system wells for Solon, Coralville, and the University of Iowa, with a total additional withdrawal of 0.5 Mgal/d, were added. Additional simulated ground-water withdrawals for 2025 were about 2.3 Mgal/d greater than those simulated for 1996 conditions and about 1.5 Mgal/d greater than those simulated for 2004 conditions (table 4). All other model-input values and boundary conditions were the same as those for the 2004 simulation, including simulation of discharge from the quarry through the use of a constant-head cell.

The simulated ground-water conditions documented in this section using estimated pumping rates for 2025 and potential reductions in recharge caused by drought conditions (discussed in the next section) would not necessarily occur in the year 2025. Not only are differences between estimated and actual model-input parameters likely to exist, steady-state ground-water conditions would take some unknown length of time to become established in response to the changing stresses. Additionally, changes in pumping rates and recharge are assumed to occur instantaneously in the model when, in reality, these changes would occur over a period of years.

Simulated steady-state ground-water levels using estimated 2025 pumping rates were lower than 2004 simulated levels throughout the county, and simulated water-level declines ranged from less than 1 to about 11 ft (fig. 25). The largest declines occurred east of the lakes, but water-level declines were generally 3-6 ft over much of the North Corridor area. Simulated water-level declines may be somewhat underestimated because constant-head boundary conditions were used as they were in the 1996 (fig. 17) and 2004 simulations. This type of boundary condition does not allow simulated water levels to change for the cells that coincide with that boundary, and it allows simulation of additional ground-water inflow along those boundaries to support the unchanging water levels. This amount of additional inflow generally results in minimal water-level changes near the constant-head boundary cells.

The model-calculated water-budget components for 2025 steady-state conditions are shown in table 4. The overall water budget for the 2025 steady-state pumping simulation increased by about 0.6 Mgal/d over the 2004 water budget. The increase was due to an increase of ground-water inflow from the lakes in response to the increased pumpage of 1.5 Mgal/d over the 2004 pumpage. The remaining 0.9 Mgal/d of increased pumpage was obtained by interception of ground-water outflow to surrounding areas, the lakes, and the quarry. Outflow to areas adjacent to the model area decreased by 0.3 Mgal/d, and outflow to the lakes decreased by 0.2 Mgal/d. Additionally, simulated discharge from the quarry was reduced from the 2004 simulation by 0.4 Mgal/d to about 4.7 Mgal/d in response to the lower water levels in the surrounding areas.

Simulation of Potential Future Drought Conditions

Droughts have occurred periodically in Johnson County, and these extended periods of below-average precipitation can be seen in figure 4. The longest period of below-average precipitation occurred in the 1950s, when precipitation ranged from about 3 to 13 in/yr less than the 1931-2004 average of about 35 in/yr. The average precipitation during this period was 26.8 in/yr, which is about 76 percent of the long-term average.

During prolonged periods of drought, ground-water withdrawals are typically increased to help make up for the lack of rainfall. Several of the municipalities in Johnson County have estimated their increased rates of ground-water withdrawals are about 125 percent of the average annual withdrawals during times of drought (R.C. Buchmiller, U.S. Geological Survey, written commun., 2005).

In order to simulate prolonged future drought conditions, pumping rates for all municipal and private-development wells were increased by a factor of 1.25, so that total simulated pumpage for these conditions was increased to 14.5 Mgal/d (table 4). Recharge also was reduced by a factor of 25 percent, to a rate of 2.2 in/yr in those cells in which areal recharge was simulated for other time periods (fig.18). All other model input values and boundary conditions remained the same, and the model again simulated steady-state ground-water conditions.

Water levels for simulated future drought conditions were compared to simulated 2004 steady-state conditions. Overall, simulated water levels for future drought conditions were greater than 5 ft lower than simulated 2004 steady-state conditions and were a maximum of 31 ft lower in the northeastern part of the county (fig. 26). As with the 2025 steady-state simulation, these water levels indicate minimum declines because of the constant-head boundary conditions.

Model-calculated water-budget components for simulated future drought conditions are listed in table 4. The overall simulated water budget decreased by 1.6 Mgal/d from the 2004 simulation to 18.2 Mgal/d in 2025. Total model-calculated recharge for simulated future drought conditions was 3.8 Mgal/d less than simulated recharge for 2004 conditions. Model-calculated inflow from surrounding areas and from the lakes increased by 0.4 and 1.8 Mgal/d, respectively, over 2004 simulated conditions. Model-calculated outflow to surrounding areas and to the lakes for future drought conditions

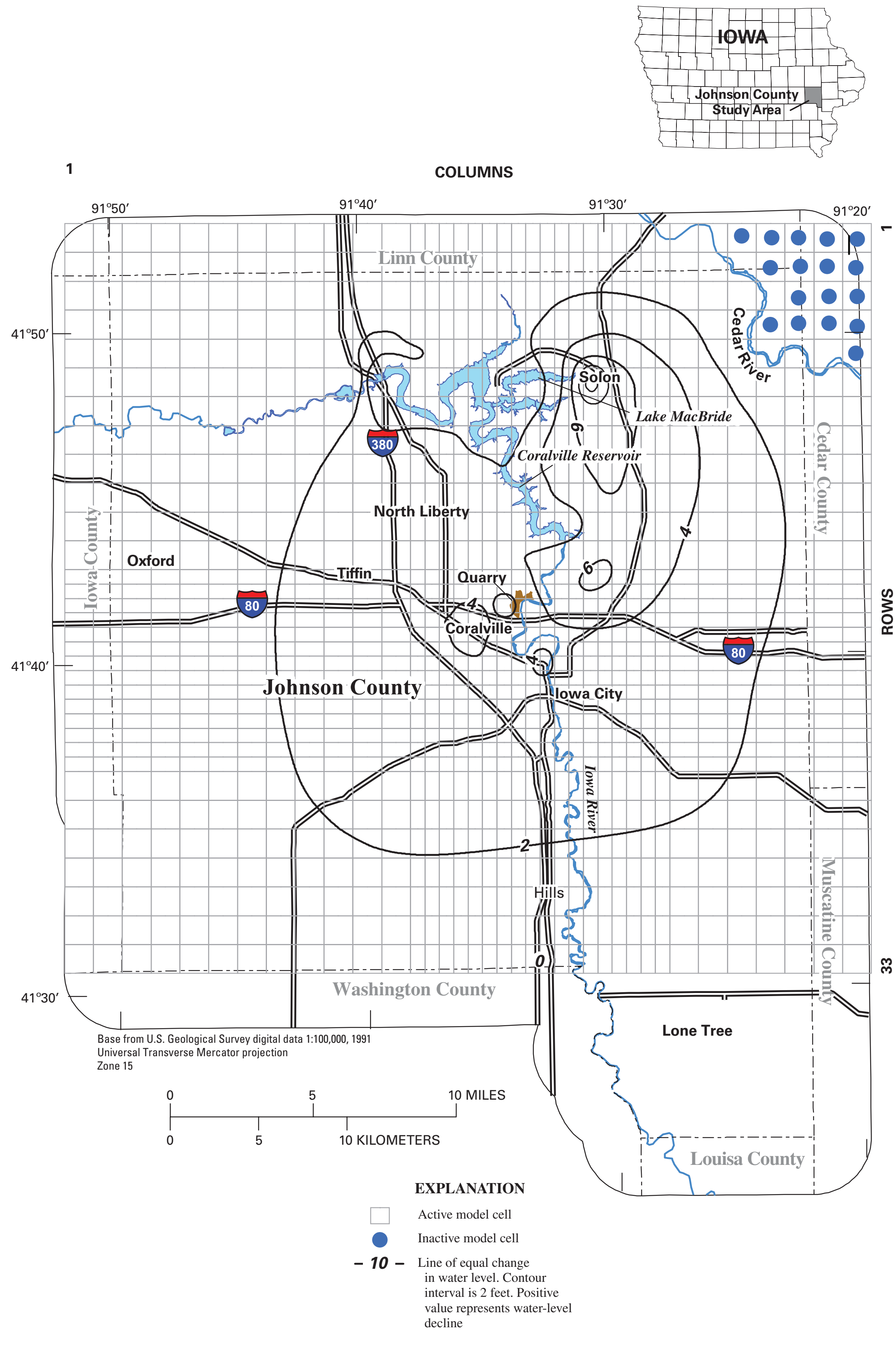
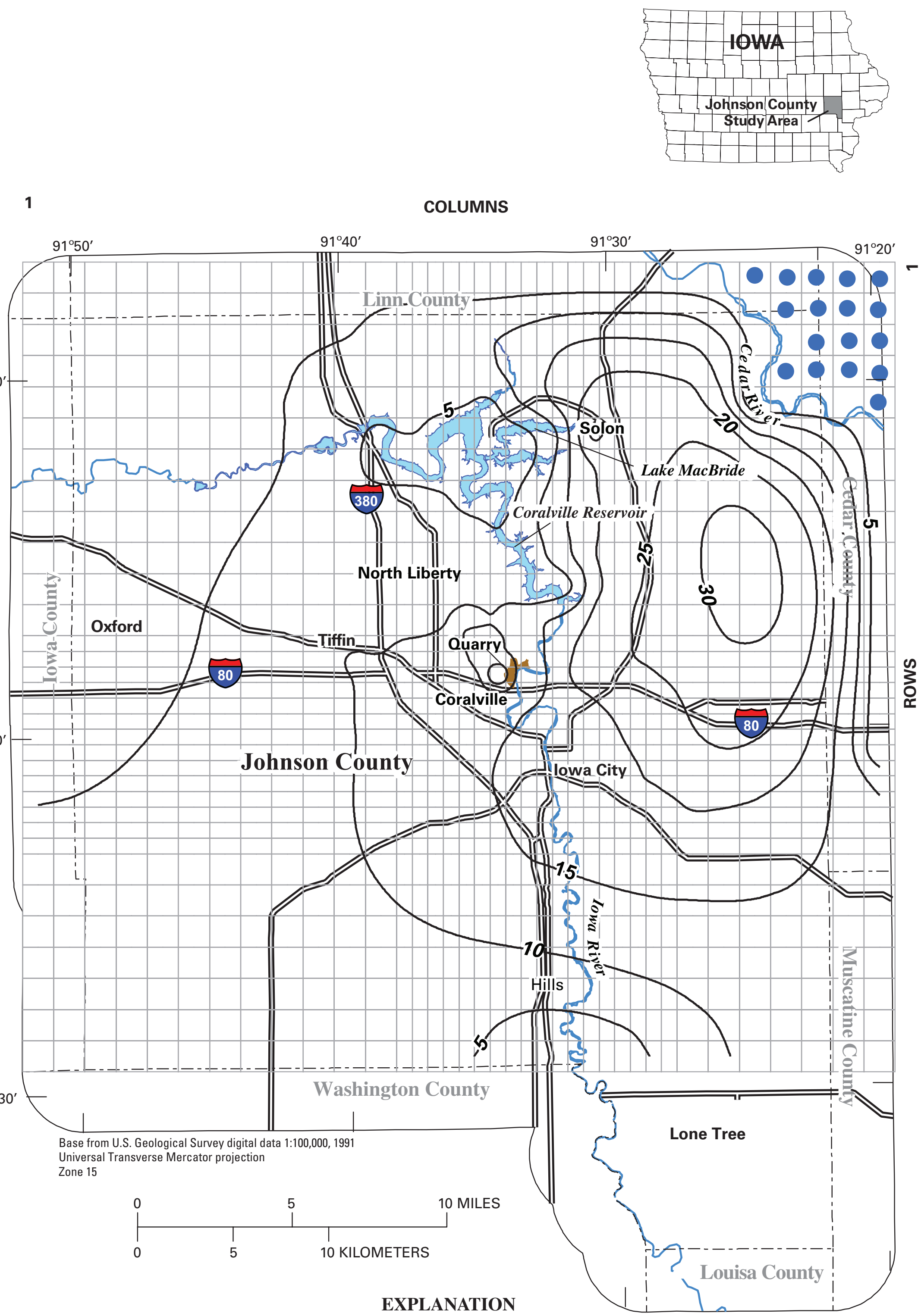


Figure 25. Changes in simulated water levels between 2004 and future steady-state conditions using estimated pumping for 2025.



EXPLANATION

- Active model cell
- Inactive model cell
- —10— Line of equal change in water level. Contour interval is 5 feet. Positive value represents water-level decline

Figure 26. Changes in simulated water levels between 2004 steady-state and potential future drought conditions.

decreased by 3.1 and 0.5 Mgal/d, respectively, from simulated 2004 conditions, and total simulated pumpage from wells was 3.2 Mgal/d greater than 2004 simulated pumpage. Model-calculated discharge from the quarry further decreased to 3.9 Mgal/d in response to the lower water levels in surrounding areas.

Model Limitations and Additional Data Needs

Models, by their nature, are not exact replicas of natural systems. They are limited by factors such as scale, by inaccuracies in estimated hydraulic properties or boundary conditions, and by the underlying assumptions used in their construction. The model constructed for this study is no exception. Improvements to the model and reduction in the uncertainty of the model results can be achieved by acquiring additional hydrogeologic data and, if necessary, revising the conceptual model of the ground-water flow system. In the following discussion of model limitations, additional data needed to improve the model also are described.

The greatest limitation to the model is the lack of measured or estimated water-budget components for comparison to simulated water-budget components. The few estimated water-budget components available for the study have a high degree of uncertainty and were not considered reliable enough to use as calibration targets. Because the model is only calibrated to measured water levels and not to water-budget components, the model results are nonunique. In other words, different combinations of simulated model parameters (for example, recharge rate and hydraulic conductivity) can produce the same residuals between measured and simulated water levels. This conclusion is supported by model correlation coefficients that are close to 1.0 (table 5). The effect of this model limitation is that water-level changes simulated by the model for drought conditions or increases in pumping have a high degree of uncertainty. A water balance for Coralville Reservoir and Lake MacBride, which would estimate the ground-water-flow components to or from these water bodies, and detailed low-flow measurements for the portion of the Iowa River that flows over bedrock would provide water-budget data that could be compared to model results. Additional pumpage data for municipal, industrial, and private-development wells, as well as an inventory of private homeowner's wells, also are needed. The pumping rates used for private-development wells are highly uncertain and are based on average values for a few reported rates. Improvements in the estimates of pumping would also greatly improve the model because the pumping from these wells is a large percentage of the total ground-water outflow in the model. Such additional data should substantially reduce the correlation coefficients for the model parameters and reduce the uncertainty in the model results.

Simulated water levels and water-budget components, as well as water-level changes due to drought conditions and changes in pumping in Johnson County, are heavily dependent on the hydraulic conductivities and recharge rates used in the model. The calibrated values for hydraulic conductivity appear to be reasonable, and they are close to the average values estimated by the IGS from specific-capacity test data. Because hydraulic-conductivity values are highly correlated with both areal recharge and pumpage from the quarry (as discussed previously), the values must be considered nonunique and may introduce some error in the model results. Recharge to the Silurian-Devonian aquifer system appears to be somewhat controlled by the overlying glacial deposits of the Quaternary confining unit. A detailed hydrogeologic characterization of these deposits, including the lithology, thickness, and water levels, could provide information to better quantify recharge to the aquifer system. Additional information on water-budget components, described previously, would help to reduce the uncertainty in the estimates of recharge used in the model.

The model is most sensitive to the value used for pumpage from the quarry. There is a large discrepancy between the reported 2005 pumping rate from the quarry (0.04 Mgal/d) and the simulated pumping rate (5.6 Mgal/d) for the 1996 simulation, but the reason for this discrepancy is unknown. During summer months, evaporation from open water in parts of the quarry may account for some discharge from the ground-water system, but it is unlikely that this process accounts for all of the discrepancy. Some of the discrepancy probably is due to differences between simulated and actual hydraulic-conductivity values and recharge rates. If these parameters are overestimated in the model, then discharge rates for the quarry also will be overestimated. A model simulation using the reported pumping rate for the quarry could not reproduce the low water levels in the central part of the county. Simulated water levels near the quarry were 25 to 30 ft higher than measured levels and were nearly 60 ft above the bottom of the quarry. The discrepancy between simulated and reported pumping rates for the quarry results in a high degree of uncertainty in all of the model simulations reported for this study. Additional model simulations, using updated pumpage data and refined model layering and parameter zonation (supported by additional water-level and other hydrogeologic data), may help to resolve the discrepancy between the reported and simulated quarry pumping rates.

Model results are somewhat affected by the relatively coarse scale of the model. The smallest cell size for the model is 0.5 mi on a side, which is too large to accurately simulate ground-water flow through individual fractures that may range from less than an inch to several inches in width in the limestone (fig. 13). Similarly, the large scale precludes predicting water levels in individual wells with the model. The model is based on the assumption that flow through these types of fractures can be approximated as flow through an isotropic, porous medium. Inaccuracies in the simulation results (large differences between measured and simulated water levels) could be caused by deviations of existing hydrologic conditions from this assumption. Acquisition of additional water-level data, particularly near the lakes and the pumping centers, would justify use of a finer model-grid resolution (smaller cell size).

Another example of potential model limitations caused by scale effects is the potential errors introduced into the model by the very coarse vertical resolution of the model. The model simulates ground-water flow in a complex sequence of Silurian- and Devonian-age rocks of differing hydraulic characteristics as a single aquifer system. Perhaps the largest effect of this simplification is in the model-calculated discharge to the quarry. The large discrepancy between the model-calculated discharge in the 1996 simulation (5.6 Mgal/d) and the reported pumpage (0.04 Mgal/d) is probably caused, in part, by the use of a 1-layer model to simulate a more complex system. The bottom of the quarry is close to the top of the Kenwood Member of the Wapsipinicon Group (table 1), which is about 15 to 20 ft thick at the quarry and acts as a confining unit between the Cedar Valley aquifer and the underlying Silurian aquifer. The resulting hydrologic isolation of the two aquifers may allow the quarry operators to pump less water than the amount indicated by the model, which lacks this detail and cannot simulate this hydrologic isolation.

Because the Silurian-Devonian aquifer system is simulated with only one layer in the model, vertical water-level gradients that occur within the aquifer cannot be replicated by the model. The model will only simulate horizontal flow within the Silurian-Devonian aquifer system, not any vertical ground-water flow that may be occurring in recharge or discharge zones in the aquifer. For example, at the wells completed in Silurian- and Devonian-age rocks near Coralville, the water levels are about 15 ft higher in the Devonian-age rocks than in the Silurian-age rocks (fig. 16), indicating a potential for downward flow of water. The simulated water level for 1996 conditions at this site is about 599 ft, which is closer to the average measured water level in the Devonian-age rocks than to those in the Silurian-age rocks during 1996. Because ground-water conditions in the aquifer are represented only by a single water level at this site, the model is not simulating the downward ground-water flow. Additionally, if the simulated water levels are being compared to levels that are measuring conditions in only the Silurian- or Devonian-age rocks, then the model may be simulating water levels that are too low or too high in comparison to the measured levels.

Another effect of the use of a 1-layer model to simulate a complex aquifer system is that in the Silurian-Devonian aquifer system there is a mix of unconfined and confined ground-water conditions. For example, in the area within the large cone of depression, water levels are below the top of the Devonian-age rocks, resulting in unconfined conditions in these rocks; however, confined conditions may still exist within the underlying Silurian aquifer. In the 1-layer model, the entire Silurian-Devonian aquifer system is simulated as unconfined in this area. The effect of this discrepancy for the steady-state simulations conducted for this study is a minor difference in computed transmissivities in simulated unconfined areas; however, the effect would be much greater for transient simulations in which substantially different storage properties for unconfined and confined conditions would be required.

Although existing geologic data are available to support a multiple-layered model of ground-water flow in the Silurian- and Devonian-age rocks, existing water-level and well-construction data are insufficient to justify construction of a more detailed model. Additional water-level data for wells completed only in the Silurian- and Devonian-age rocks are needed to replace monitoring wells with unknown or multiple completions, particularly along the county boundaries, in order to simulate both horizontal and vertical ground-water flow in those rocks.

The assumption that the average 1996 hydrologic conditions simulated by the model are representative of steady-state conditions also may limit the model. In reality, ground-water conditions are in a constant state of change (Appendix). Water levels in 1996 were both increasing and decreasing in response to local and regional changes in hydrologic conditions, such as changes in pumping or rainfall. Some of the differences between measured and simulated water levels may be due to a deviation of 1996 conditions from steady state. A similar argument could be made for the 2004 steady-state simulation. Model calibration to transient conditions rather than steady-state conditions may provide an improved model; however, values for the storage properties of the aquifer, detailed historical pumpage data, and additional time-series water-level data are required for a transient calibration. Long-term aquifer tests, conducted at several locations throughout the county, would provide values for areally distributed aquifer-storage properties.

The model simulations of potential future steady-state and drought conditions have additional limitations. Anticipated population growth and ground-water use, both in magnitude and geographic distribution, are uncertain, and actual growth could be very different from conditions simulated using the model. Actual future drought conditions could be much less severe than conditions simulated by the model, which was used to simulate anticipated worst-case conditions, and water-conservation efforts during a prolonged drought could result in lower-than-simulated pumpage. Additionally, uncertainties inherent in the 2004 steady-state simulation, which was used as a starting point for the future simulations, are carried through those simulations. For example, simulated 2004 water levels were higher than measured water levels in most of the comparison wells, so the simulated water levels for future conditions also will include this discrepancy and may add to it.

Summary

Bedrock of Silurian and Devonian age (termed the "Silurian-Devonian aquifer system") is the primary source of ground-water for Johnson County in east-central Iowa. Population growth within municipal and suburban areas of the county has resulted in increased amounts of water withdrawn from this aquifer and water-level declines in some areas.

The U.S. Geological Survey, in cooperation with the Iowa Department of Natural Resources Water Supply Bureau, City of Iowa City, Johnson County Board of Supervisors, City of Coralville, the University of Iowa, City of North Liberty, and the City of Solon, began an assessment of the hydrogeology of Johnson County in late 2002. The purpose of the 3-year study was to provide a quantitative assessment of ground-water in the Silurian-Devonian aquifer system and to construct a ground-water flow model that can be used by local governmental agencies as a management tool to meet the needs of the area. Only available data were used; additional information, such as hydraulic conductivity of the aquifer, was developed from available data.

The major drainage feature of Johnson County is the Iowa River, which enters the northwestern part of the county and flows east and south out of the county. Two reservoirs, Coralville Reservoir and Lake MacBride, are in the north-central part of the county. The Cedar River flows across the northeastern part of the county. Several large limestone quarries are present within Johnson County. Of particular note for this study is a quarry adjacent to the Iowa River on the north side of Coralville. The bottom of this quarry generally is kept dry and is well below the level of the adjacent Iowa River.

Johnson County is underlain by unconsolidated deposits of Quaternary age and Paleozoic-age bedrock units. The bulk of the Quaternary deposits consists of weathered and unweathered glacial till; however, shallow alluvium and buried sand and gravel deposits also are present. The Quaternary deposits range in thickness from zero feet to more than 300 ft.

Six bedrock hydrogeologic units are present in Johnson County: Maquoketa confining unit, Silurian aquifer, Wapsipinicon Group (aquifer and confining unit), Cedar Valley aquifer, Upper Devonian shale confining unit, and Cherokee confining unit. Those units defined as confining units are primarily composed of shale, and those units defined as aquifers are primarily composed of limestone and (or) dolomite. Although separate aquifers and confining units are described here, the Silurian- and Devonian-age units are considered as a single aquifer system, the Silurian-Devonian aquifer system. The top of the Silurian-Devonian aquifer system is considered as the top of the Cedar Valley aquifer, where present, and the base of the aquifer system is considered as the top of the Maquoketa confining unit. The bedrock units generally dip slightly (18-30 ft/mi) to the southwest, although in some areas the rocks dip much more steeply (about 200 ft/mi).

The hydraulic properties of the rocks that compose the Silurian-Devonian aquifer system are highly variable. This variability is caused by the variable composition of the rocks and the presence of solution features in the some of the carbonate-rock units. Specific-capacity data were available for 261 wells completed in the Silurian-Devonian aquifer system. These data were used to estimate transmissivity and hydraulic-conductivity values for the aquifer. For the combined Silurian-Devonian aquifer system, specific capacity averaged 2.1 gal/min per foot of drawdown, transmissivity averaged about 580 ft^2/d, and hydraulic conductivity averaged 8.3 ft/d.

Recharge to the Silurian-Devonian aquifer system in Johnson County is from precipitation infiltrating bedrock outcrops, leakage to the aquifer from Coralville Reservoir, Lake MacBride, and the Iowa River where they directly overlie bedrock, downward flow through the overlying glacial deposits, and underflow from outside the county. Discharge from the aquifer is to pumping wells, discharge to Coralville Reservoir, Lake MacBride, and underflow to surrounding counties. Reliable estimates of the amount of recharge to or discharge from the ground-water system in Johnson County are not available.

A potentiometric-surface map for the Silurian-Devonian aquifer system was constructed for average 1996 conditions. Altitude of the potentiometric surface ranges from more than 750 ft in northern Johnson County to less than 575 ft in the central part of the county. A large cone of depression within the potentiometric surface is present in the central part of the county, within Coralville and Iowa City. This area includes municipal pumping centers for those cities but is not centered on either of their well fields. The quarry on the north side of Coralville is close to the center of the cone of depression.

Ground water in the Silurian-Devonian aquifer system occurs under confined conditions over most of Johnson County; however, within the cone of depression in the central part of the county, ground water in the Devonian rocks is unconfined. Ground water generally flows from the northern and western parts of Johnson County either toward the large cone of depression in the center of the county or south out of the county. Ground water also flows toward the Cedar River in the northeastern part of the county. A ground-water divide in the northeastern part of the county roughly approximates the surface-water divide between the Iowa River and Cedar River basins. Some vertical flow probably occurs within the Silurian-Devonian aquifer system; however, data to support this concept are sparse.

A numerical model of the Silurian-Devonian aquifer system in Johnson County was used to test concepts of ground-water flow, to assess the need for additional data, and to evaluate the potential effects of anticipated increased ground-water development and drought. The area of the model extends approximately 2 mi beyond the Johnson County line on the north, west, and east sides and corresponds to the boundary between Johnson and Washington counties between townships 78 N. and 77 N. on the south. The model grid consists of 33 rows and 37 columns, and grid spacing is variable, ranging from 0.5 to 1.0 mi on a side. The model was calibrated to average 1996 ground-water conditions, which were assumed to approximate steady-state flow conditions. The model also was used to simulate steady-state conditions for 2004 and potential future average steady-state and drought conditions by using anticipated pumping rates for 2025.

The Silurian-Devonian aquifer system is simulated as a single model layer. The top of the Cedar Valley Limestone, where present, is the top of the model. Where the Cedar Valley is missing, the top of the Silurian-age rocks is the top of the model. The bottom of the model corresponds to the top of the Maquoketa Formation, and this model boundary is assumed to be a no-flow boundary. The Iowa River, where it is believed to flow over bedrock, Coralville Reservoir, and Lake MacBride were simulated in the model as river cells. Municipal and private-development wells and discharge from the quarry on the north side of Coralville also were simulated in the model.

Parameter-estimation modeling techniques were used during the 1996 calibration to provide values for model parameters that produced the closest match between measured and simulated water levels. Parameters were defined for hydraulic conductivity, recharge, riverbed conductance, lakebed conductance, and pumpage from the quarry.

Two zones (parameters K1 and K2) of uniform hydraulic conductivity were defined for the steady-state model. The estimated hydraulic-conductivity values were 5.6 ft/d for parameter K1 and 18.7 ft/d for parameter K2. Two zones (parameters RECH1 and RECH2) of uniform recharge rate were defined for the steady-state model. Parameter RECH1 represents a zone of no recharge and was based on the concept that in this area recharge to the Silurian-Devonian aquifer system is inhibited by the Upper Devonian shale confining unit and by thick, low-permeability glacial till, and that pumping in the center of the county intercepts any recharge to the system. The final estimated recharge rate for parameter RECH2 was about 2.9 in/yr and is based on the concept that the recharge rate is larger in this area because the aquifer is closer to the surface and much of the Upper Devonian shale confining unit has been removed by erosion.

The riverbed conductance value (parameter RIV1) required for model calibration was 5.4 (ft^3/d)/ft. The lakebed conductance value (parameter LAKE) required for model calibration was 2,045 (ft^3/d)/ft. These conductance values are both quite small and indicate that the river and lakes are not hydraulically well connected to the ground-water system. Despite the presence of limestone at or near the surface beneath these surface-water bodies, accumulated fine-grained, low-permeability deposits along the river and lake bottoms and the low ground-water levels below the Iowa River apparently are restricting ground-water/surface-water interactions.

Initial estimates for a pumping rate from the quarry were obtained by setting the water level in the quarry at a constant altitude of 524 ft, which is approximately equal to the altitude of the bottom of the quarry. The model then calculated the amount of discharge from that model cell required to keep the water level at that altitude. This value was then used as an initial rate for use in the parameter-estimation process. The final value for this parameter (WELL1) was about 5.6 Mgal/d, which is much greater than the reported value (0.04 Mgal/d) of pumping from the quarry. The reason for this discrepancy may be caused, in part, by the lack of vertical resolution in the model.

The simulated potentiometric surface generally replicates the potentiometric surface for 1996 conditions. Forty-one wells completed in the Silurian-Devonian aquifer system had water levels available for this time period or times close to it. The calculated RMSE value for the 1996 steady-state simulation is 13.6 ft. This value is about 30 percent of the average historical fluctuation in potentiometric levels in the 41 wells used for comparison to simulated levels. About 30 percent of the simulated water levels are within ± 5 ft of measured levels, about 60 percent of the simulated water levels are within ± 10 ft of measured levels, and 90 percent of the simulated water levels are within ± 20 ft of measured levels. Overall, simulated water levels were neither substantially higher nor lower than measured levels. Of the 41 measured water levels used for comparison to simulated water levels, 21 were lower than simulated and 20 were higher than simulated.

Total model-calculated inflow to the ground-water system was 19.6 Mgal/d, and the largest model-calculated inflow component was areal recharge (15.1 Mgal/d). Ground-water inflow from surrounding areas (1.7 Mgal/d total) occurred only along parts of the northern and western model boundaries. Ground-water inflow from Coralville Reservoir and Lake MacBride of about 2.8 Mgal/d was simulated along the southern shores of the lakes. Ground-water inflow to the Iowa River was less than 0.1 Mgal/d. Total model-calculated outflow from the ground-water system was 19.7 Mgal/d, and the largest outflow component was discharge to wells (10.5 Mgal/d). About one-half of this discharge (5.6 Mgal/d) was simulated as discharge from the quarry, and the remainder (4.9 Mgal/d) was simulated as discharge from municipal and private-development wells. Ground-water outflow to surrounding areas (8.1 Mgal/d total) occurred along the northeastern, southern, and western model boundaries. Ground-water outflow in the northeastern part of the county includes outflow to the Cedar River. Ground-water outflow to Coralville Reservoir and Lake MacBride was 1.1 Mgal/d.

The model was most sensitive to the simulated pumping from the quarry. The model also was sensitive to parameters K2 and RECH2. The model was much less sensitive to parameter K1 and was relatively insensitive to parameter LAKE. Parameters RECH1 and RIV1 were fixed during the latter stages of model calibration because they had low sensitivity values. Most of the estimated parameters for the model are highly correlated and produce model results that are nonunique.

One of the objectives of the study was to simulate the potential effects of increased ground-water development. In order to provide a more current baseline than that provided by the simulation of 1996 conditions for such an assessement, 2004 ground-water conditions also were simulated. The output from the simulation of 2004 conditions was then used as starting conditions for simulation of anticipated pumpage 20 years into the future (2025).

Estimated pumpage for 2004 was updated in the model, and the simulated water levels were compared to 2004 water levels in 36 available wells. Discharge from the quarry was simulated by setting the water level in the quarry at a constant altitude of 524 ft and the model calculated the resulting discharge from that model cell. All other model-input values were the same as those for simulation of 1996 conditions. Simulated water levels were an average of 14 ft different from measured levels, and the RMSE was about 18.6 ft, which was somewhat higher than the 1996 simulation. Simulated 2004 water-budget components were similar to simulated 1996 water-budget components, although discharge from the quarry was reduced by 0.5 Mgal/d.

Potential steady-state and drought conditions both were simulated using anticipated pumping rates for 2025. Pumpage both for existing wells and assumed new wells, based on anticipated population growth in the North Corridor and for the nearby municipalities, was included in the model. Simulated 2025 pumpage was about 1.5 Mgal/d greater than simulated 2004 pumpage. Simulated steady-state ground-water levels were lower than 2004 simulated levels throughout the county, and simulated water-level declines ranged from less than 1 ft near the county boundaries to about 11 ft. Inflow to the ground-water system from the lakes increased by 0.6 Mgal/d, and outflow from the ground-water system decreased by 0.9 Mgal/d from simulated 2004 rates in response to the simulated 1.5-Mgal/d increase in pumpage.

Potential future drought conditions were simulated by assuming that recharge to the Silurian-Devonian aquifer system is reduced by a factor of 0.75 and that water-supply pumpage is increased by a factor of 1.25 over the anticipated 2025 pumping rates. Overall, simulated water levels for future drought conditions were greater than 5 ft lower than simulated 2004 conditions and were a maximum of about 30 ft lower in the northeastern part of the county. Simulated recharge was reduced by 3.8 Mgal/d from the 2004 simulated recharge. Inflow from adjacent areas and from the lakes increased by 0.4 and 1.8 Mgal/d, respectively, from 2004 simulated values, and outflow to adjacent areas and the lakes decreased by 3.1 and 0.5 Mgal/d, respectively, from 2004 simulated values.

The greatest limitation to the model is the lack of measured or estimated water-budget components for comparison to simulated water-budget components. Because the model is only calibrated to measured water levels and not to water-budget components, the model results are nonunique. Other model limitations include the relatively coarse grid scale, lack of information on pumpage from the quarry and from private developments, and the lack of separate water-level data for the Silurian- and Devonian-age rocks. Uncertainties in anticipated water needs for 2025, as well as uncertainties in the 2004 simulation, may result in simulated water levels that will be different than actual future water levels. Acquisition of data to supply the model-limiting information would greatly improve the model.

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Appendix. Well information and measured water levels in selected observation wells completed in the Silurian-Devonian aquifer system, Johnson County, Iowa

From 1995 through 2004, water levels were measured about once a month in a network of 41 wells completed in the Silurian-Devonian aquifer system located in Johnson County, Iowa. Measured water levels for these wells are shown in graphs for the entire period of record, which in some cases predates 1995, for each well. All wells were measured using either a steel tape or an airline, according to standardized U.S. Geological Survey procedures (Lapham and others, 1995). The wells are identified by their U.S. Geological Survey site identification number, which consists of a 13-digit number that generally corresponds to the latitude and longitude of the well in degrees, minutes, and seconds, followed by a 2-digit sequence number. The wells also are keyed to numbers shown in figure 2 of this report. Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Altitude, as used in this report, refers to distance above or below NAVD 88.

In order to provide as much direct comparison of water-level fluctuations as possible among the wells, the y-axis scale for most graphs was set at 50 ft. For wells in which water-level fluctuations were greater than 50 ft, y-axis scales of 100, 200, or 400 ft were used for the graphs.

A table is included that lists information concerning land surface altitude, total depth, screened or open interval, and water levels used for the 1996 and 2004 model simulations for selected wells. For the 1996 model simulation, average water levels for 41 wells for either 1996 or 1997-98 were used for comparison to simulated water levels. For the 2004 simulation, average water levels for the period October 1, 2003, through September 30, 2004 (“water year 2004”), for 36 wells were used for comparison to simulated water levels.

The water-level data for the wells can be viewed and downloaded from http://ia.water.usgs.gov/projects/icproj/ground_water_levels.html. Instructions for viewing and downloading the data are listed on that Web site.

Well number shown in figure 2	USGS Site ID	Land- surface altitude a (feet above NAVD88)	Total depth (feet below land surface)	Screened or open interval (feet below land surface)	Measured water level for comparison to 1996 simulated levels and measurement method (feet above NAVD88; A, airline; S, steel tape)	Water-level data used for calibration of the 1996 model simulation	Measured water level for comparison to 2004 simulated levels (Water year 2004 average, in feet above NAVD88)
1	413840091322801	653	363	Not available	624 S	1996 average	619
2	413942091440401	794	495	355-495	632 S	1997-98 average	629
3	414023091263701	783	185	Not available	695 S	1996 average	694
4	414036091322701	645	205	182-205	586 S	1996 average	558
5	414107091322901	736	280	96-280	601 S	1996 average	586
6	414118091323801	722	275	Not available	585 S	1996 average	585
7	414124091315801	787	300	Not available	592 S	1996 average	580
8	414132091305701	689	325	Not available	624 A	1996 average	646
9	414132091345502	791	500	300-500	577 S	1996 average	541
10	414213091325601	743	435	200-435	564 A	1996 average	559
11	414219091394901	709	326	132-326	634 A	1997-98 average	597
12	414221091361101	809	532	362-532	587 S	1996 average	572
13	414225091302201	797	280	Not available	668 A	1996 average	667
14	414225091324501	717	315	236-315	585 A	1996 average	578
15	414248091331001	782	480	345-480	591 A	1996 average	591
16	414254091321201	757	293	185-293	630 S	1996 average	628
17	414256091322601	772	405	275-405	611 A	1996 average	609
18	414306091322701	736	435	226-435	608 A	1996 average	604
19	414313091280701	805	497	Not available	711 A	1997-98 average	708
20	414315091252002	756	83	Not available	739 S	1996 average	739
21	414345091333101	774	400	242-400	630 A	1996 average	623
22	414509091414401	785	400	Not available	657 S	1997-98 average	654
23	414532091300301	830	268	Not available	715 S	1997-98 average	715
24	414823091294901	791	430	60-430	723 S	1997-98 average	732
25	414838091340001	758	355	280-355	706 S	1997-98 average	707
26	414850091454601	830	401	361-401	653 S	1997-98 average	652
27	414853091425101	744	535	130-535	685 S	1996 average	684
28	414902091242201	715	127	87-127	675 S	1997-98 average	675
29	415046091413201	802	390	Not available	713 S	1997-98 average	710
30	414049091325201	714	Not available	Not available	579 S	1996 average	Not available
31	414111091481801	799	558	425-558	634 S	1996 average	Not available
32	414128091324101	711	400	Not available	579 A	1996 average	Not available
33	414146091335501	782	350	Not available	566 S	1996 average	Not available
34	413616091274201	688	378	Not available	624 S	1997-98 average	622
35	413915091360503	788	350	Not available	631 S	1996 average	624

Well number shown in figure 2	USGS Site ID	Land-surface altitude a (feet above NAVD88)	Total depth (feet below land surface)	Screened or open interval (feet below land surface)	Measured water level for comparison to 1996 simulated levels and measurement method (feet above NAVD88; A, airline; S, steel tape)	Water-level data used for calibration of the 1996 model simulation	Measured water level for comparison to 2004 simulated levels (Water year 2004 average, in feet above NAVD88)
36	413925091324001	717	431	235-431	587 S	1996 average	567
37	413940091345701	677	400	211-400	600 S	1996 average	575
38	414302091434101	765	420	358-420	672 A	1996 average	Not available
39	414251091334601	810	383	294-383	587 A	1996 average	583
40	414446091353501	772	500	220-500	626 S	1997-98 average	586
41	413955091320303	711	425	160-425	590 S	1996 average	586

a. Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Altitude, as used in this report, refers to distance above or below NAVD 88.

b. Measurement method is either by airline (A) or steel tape (S).

c. Water year 2004 is from October 1, 2003, through September 30, 2004.

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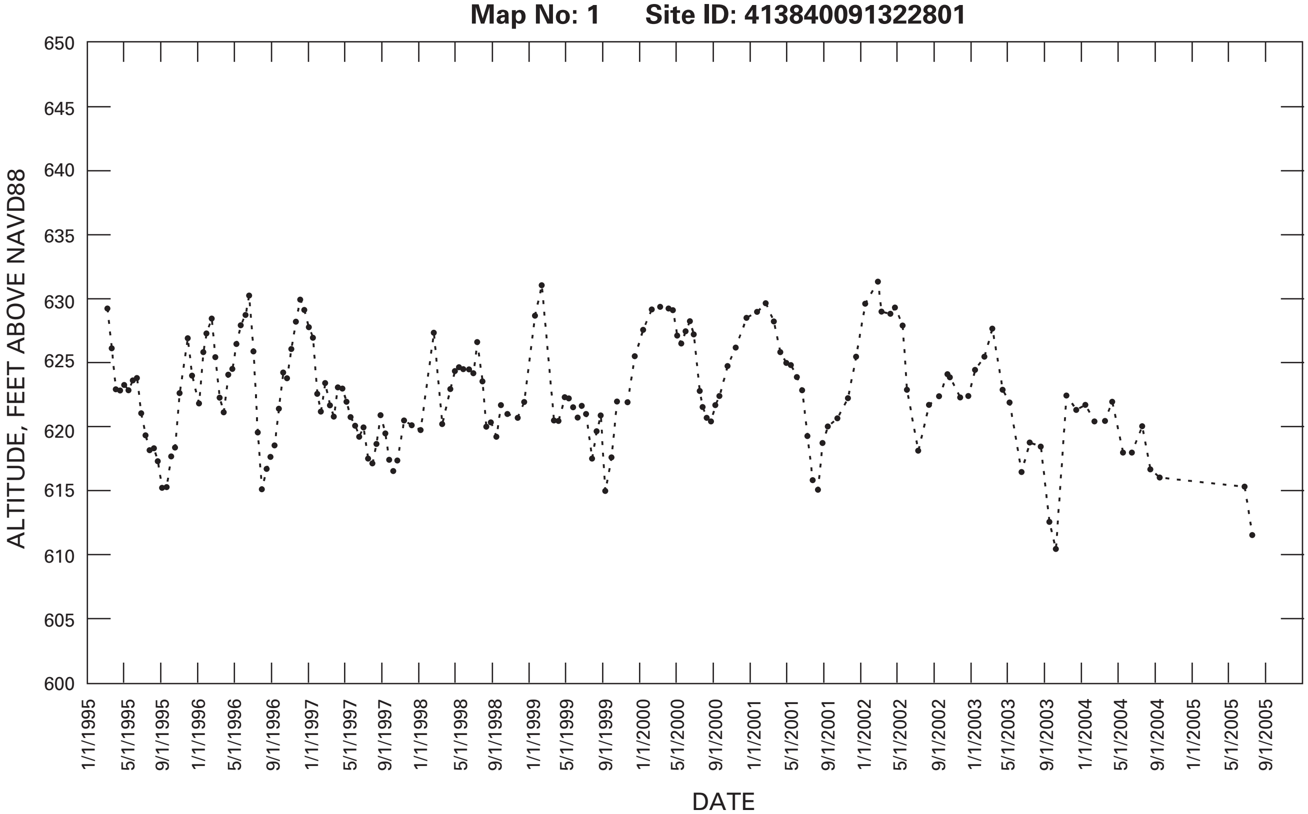

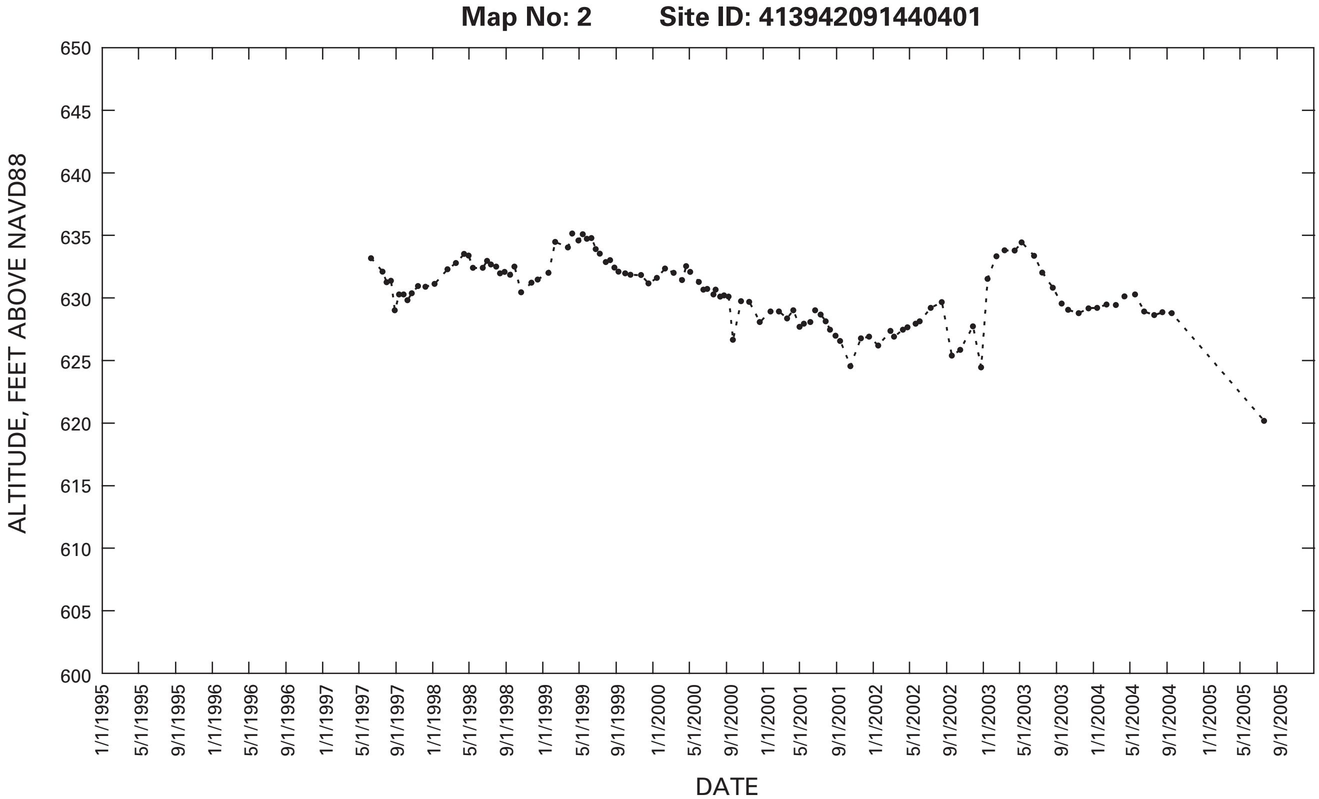
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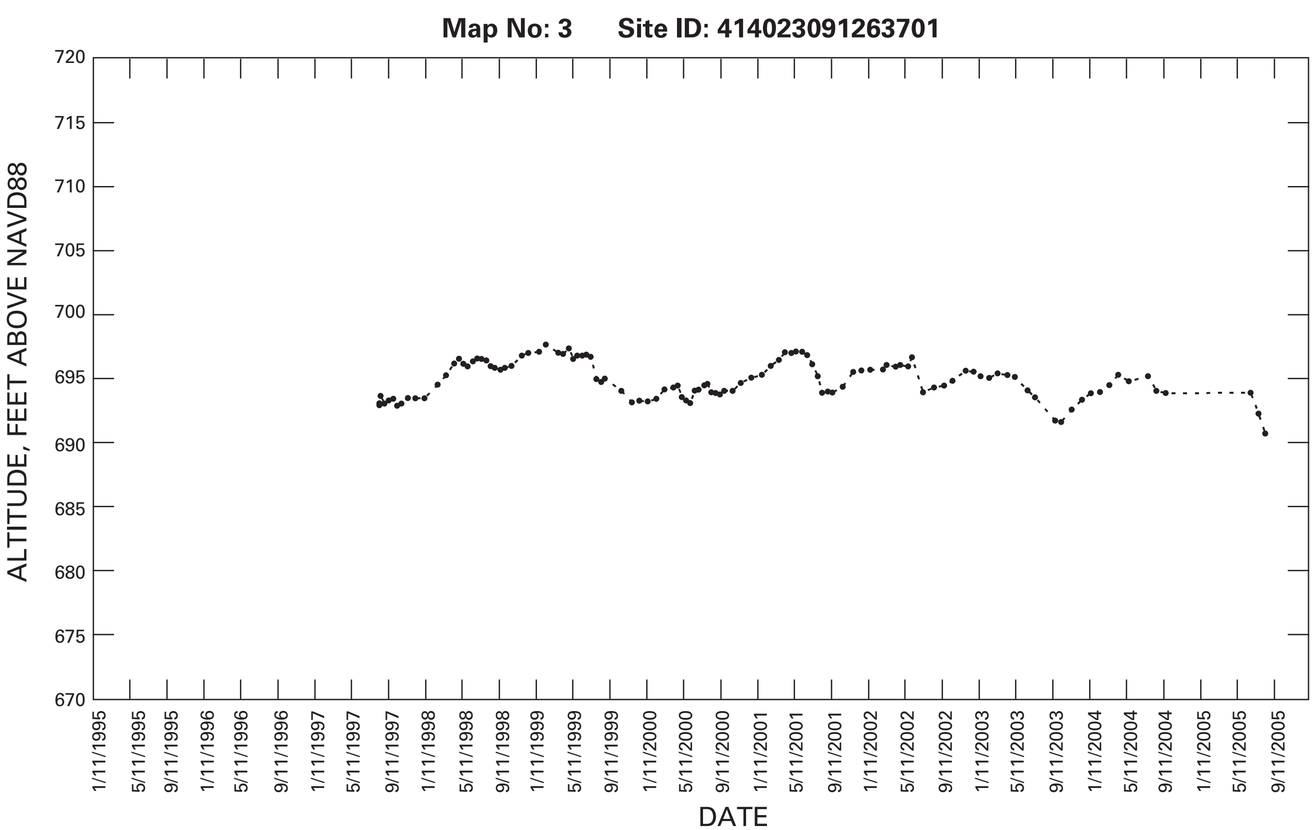
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685
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675
670
1/11/1995
5/11/1995
9/11/1995
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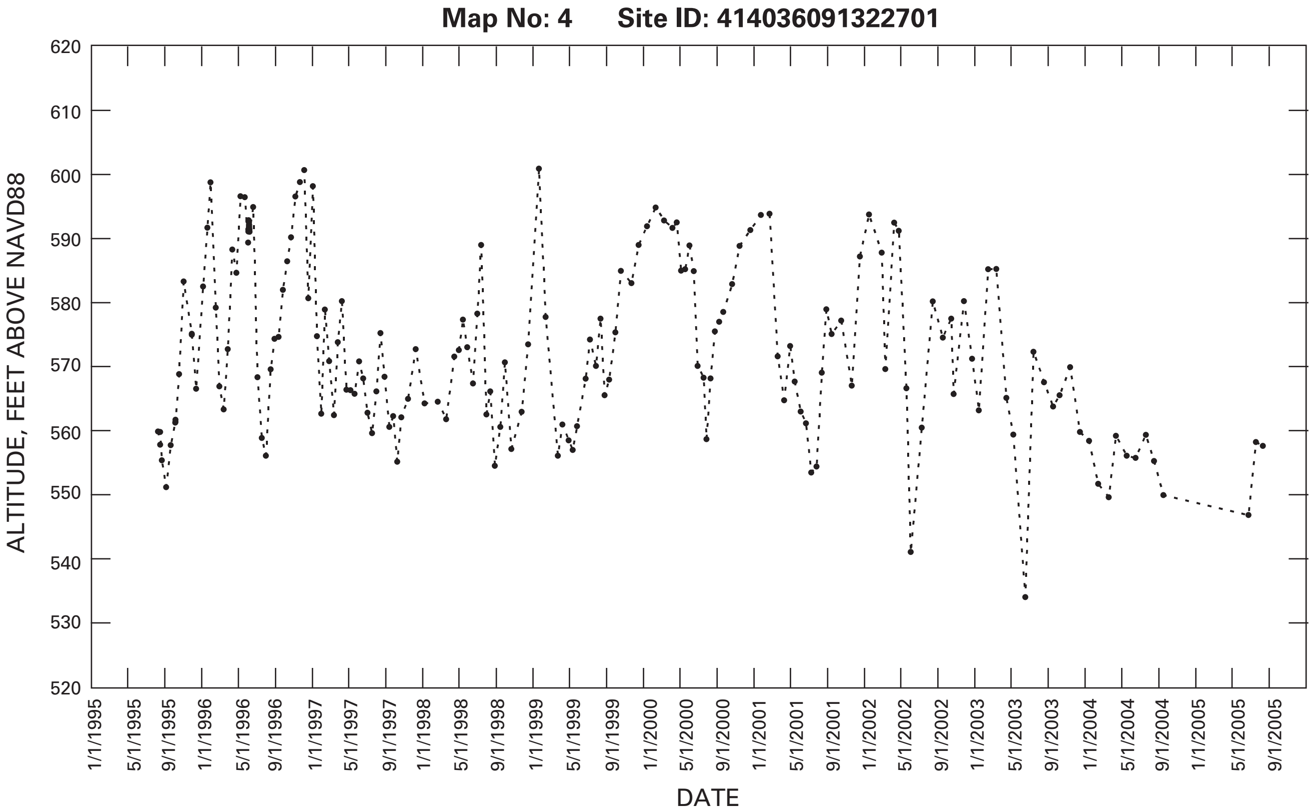
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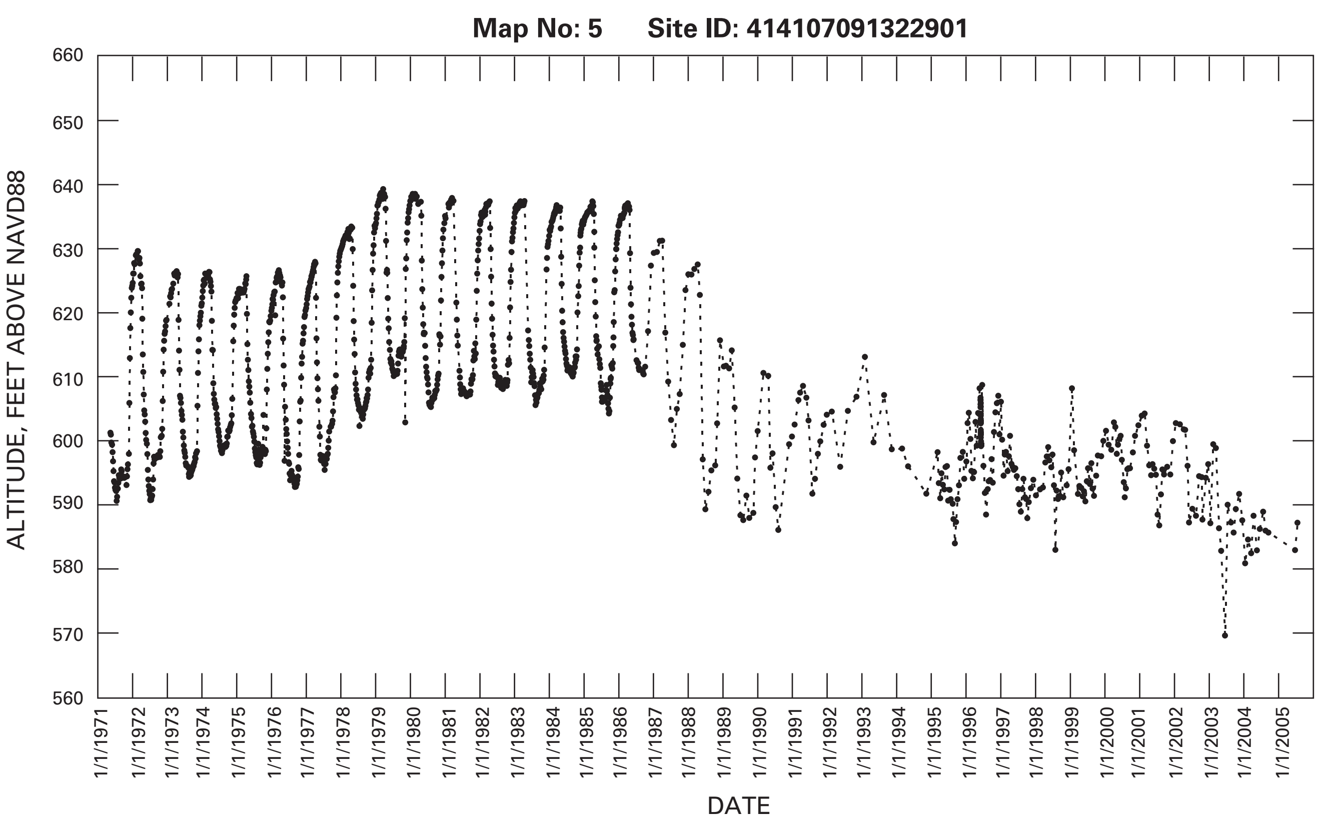
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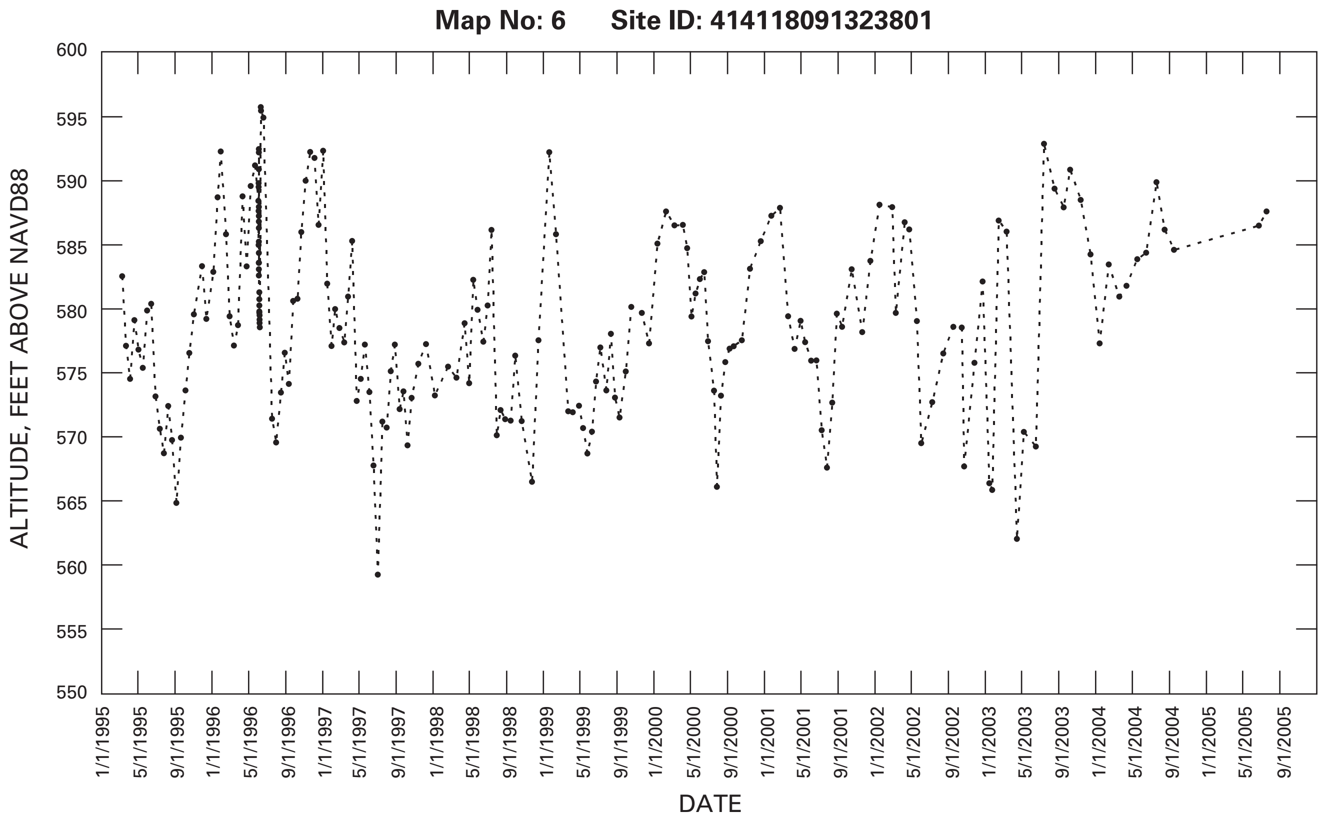
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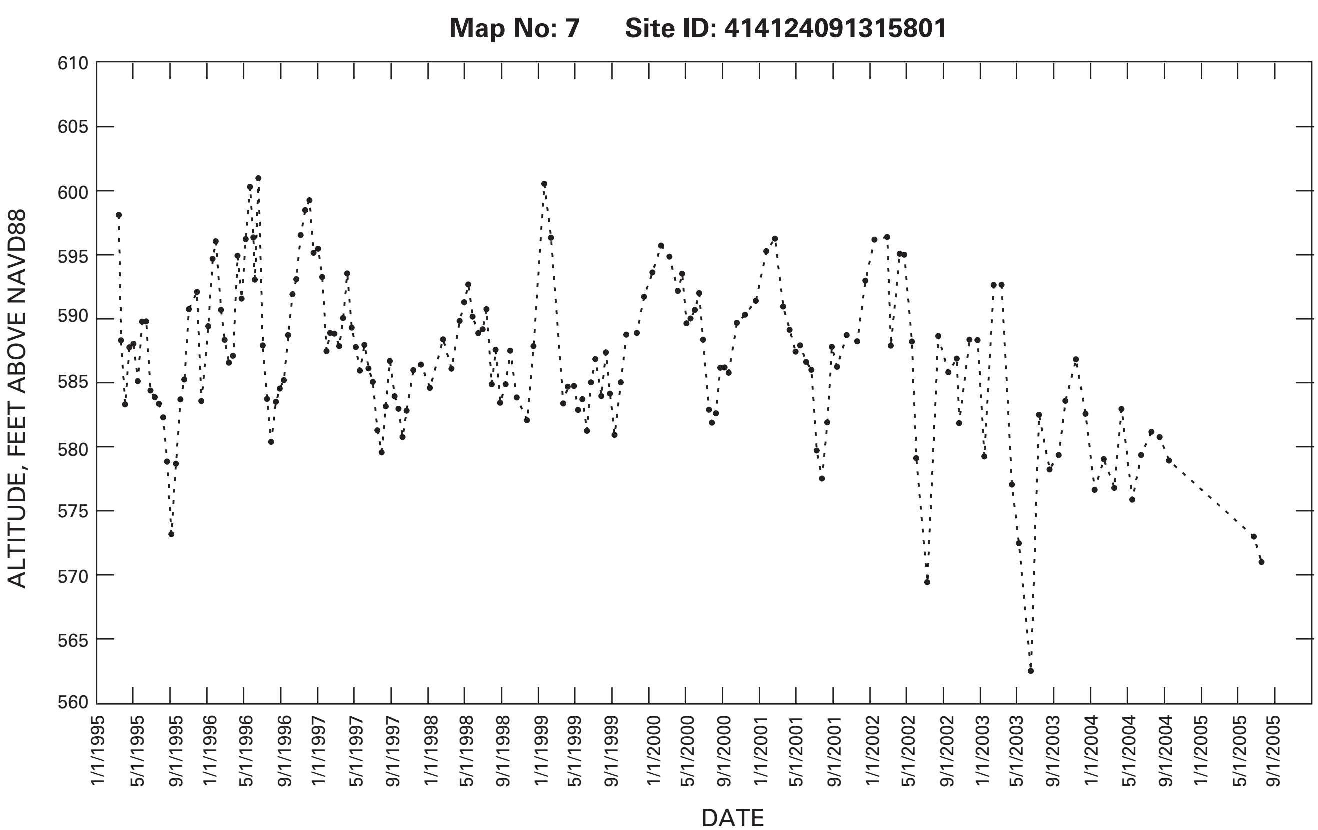
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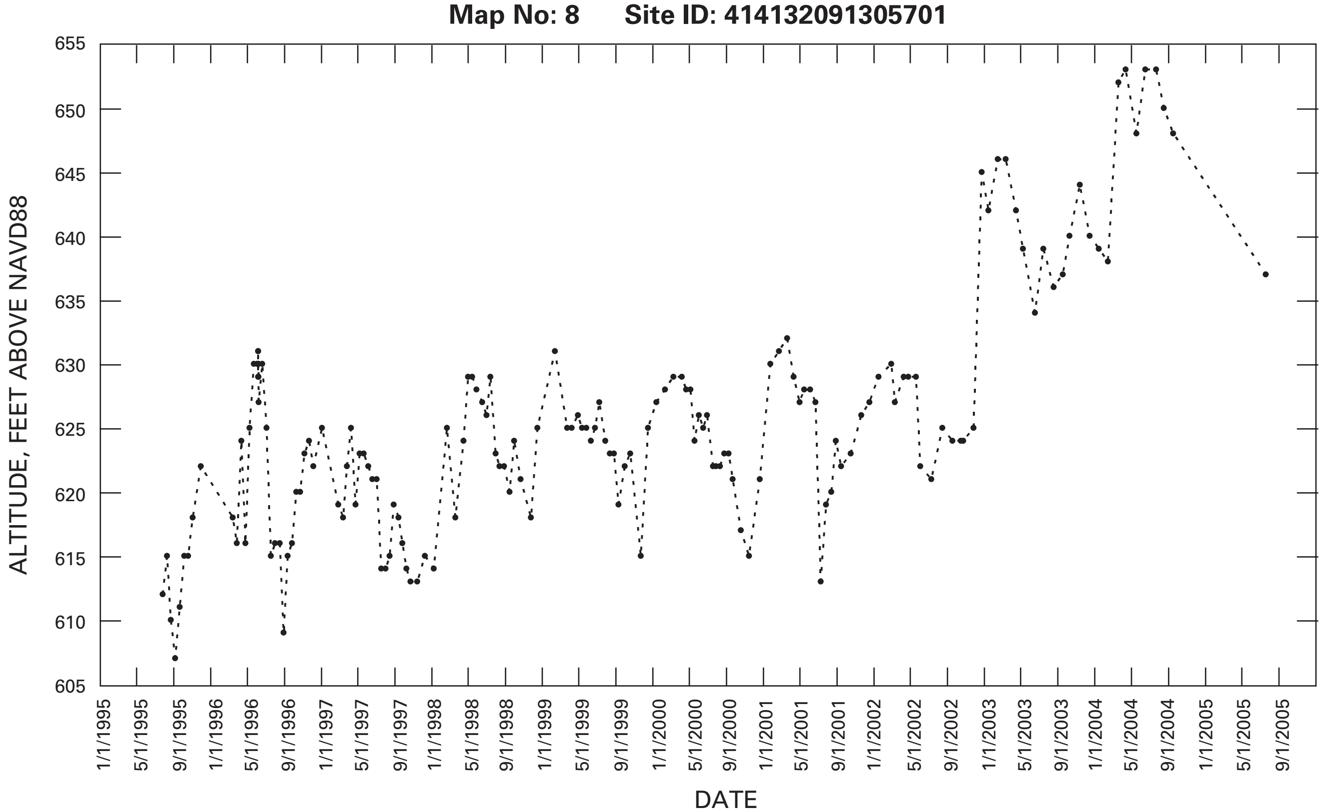
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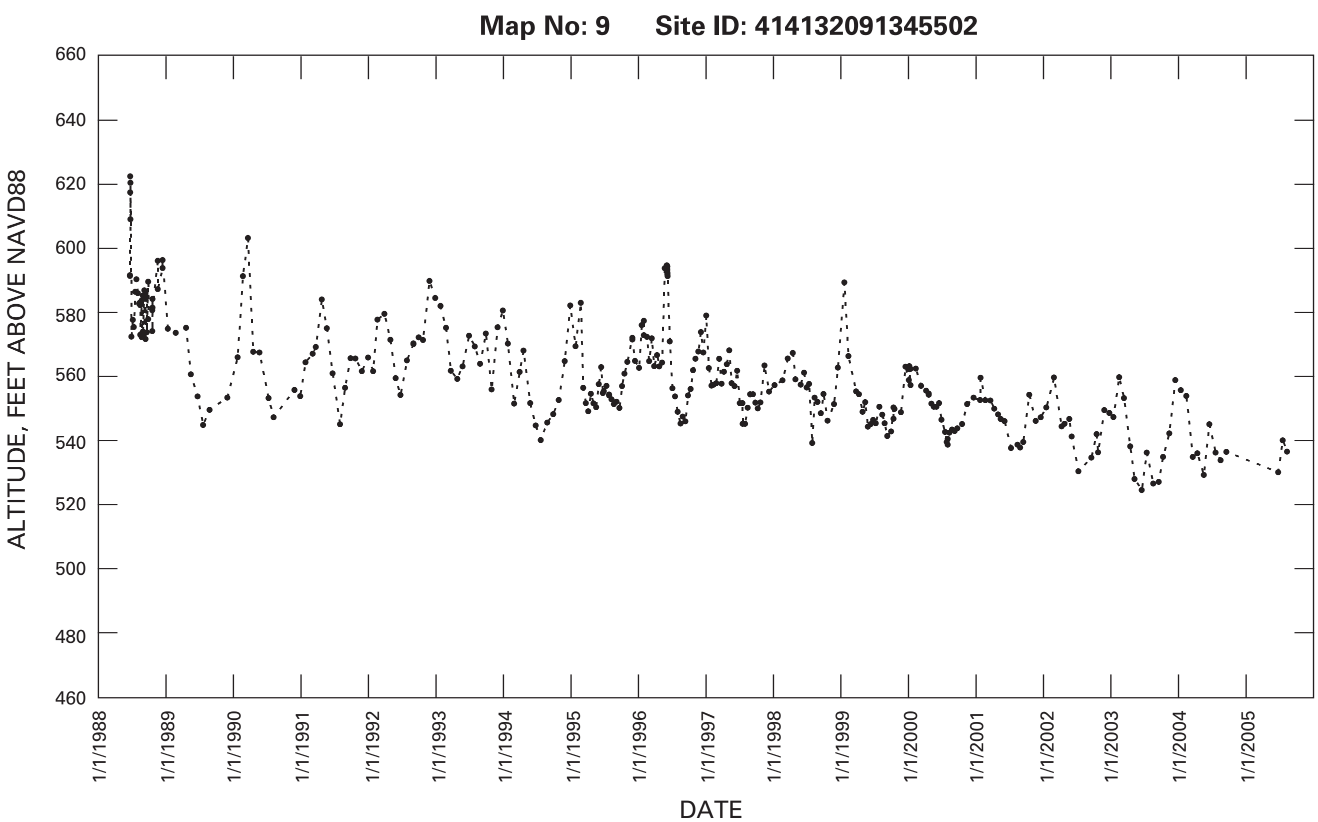
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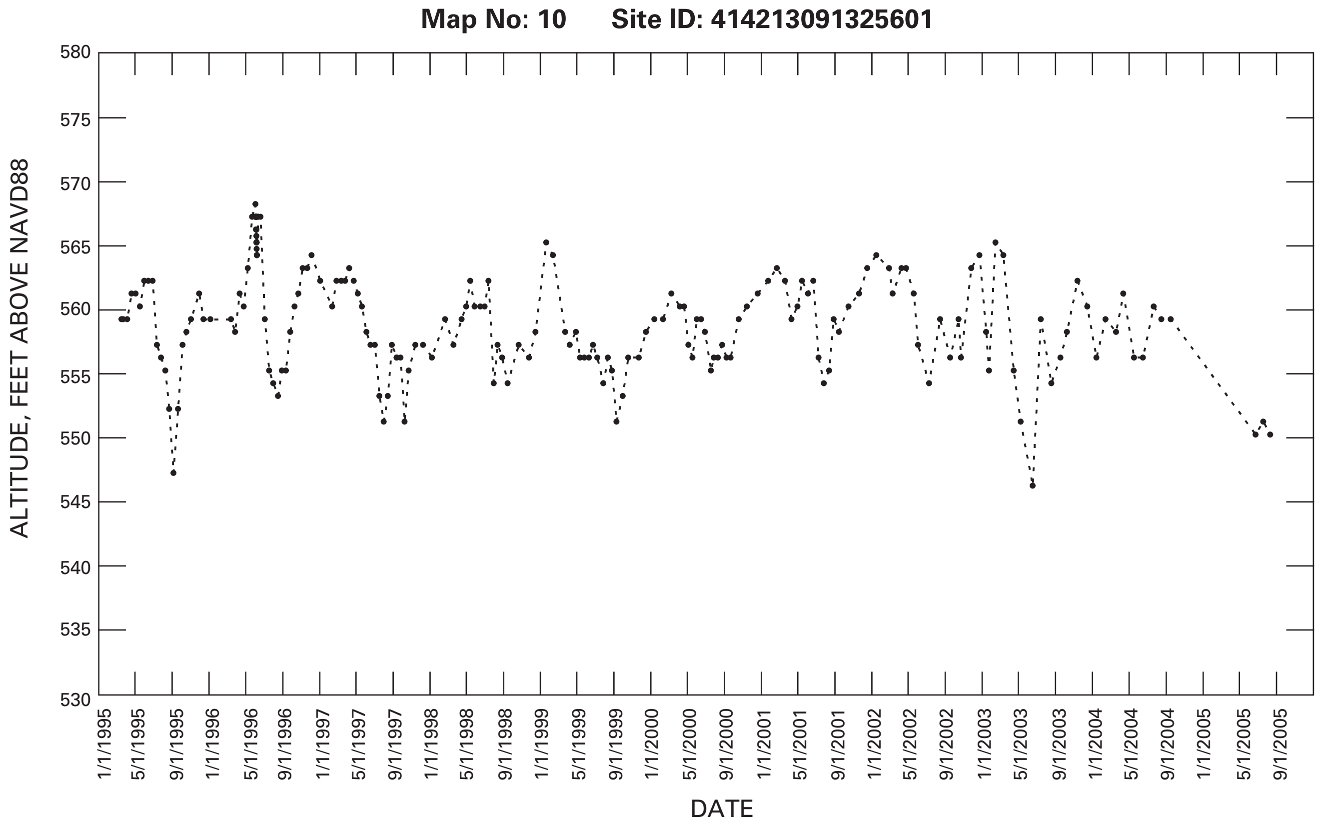
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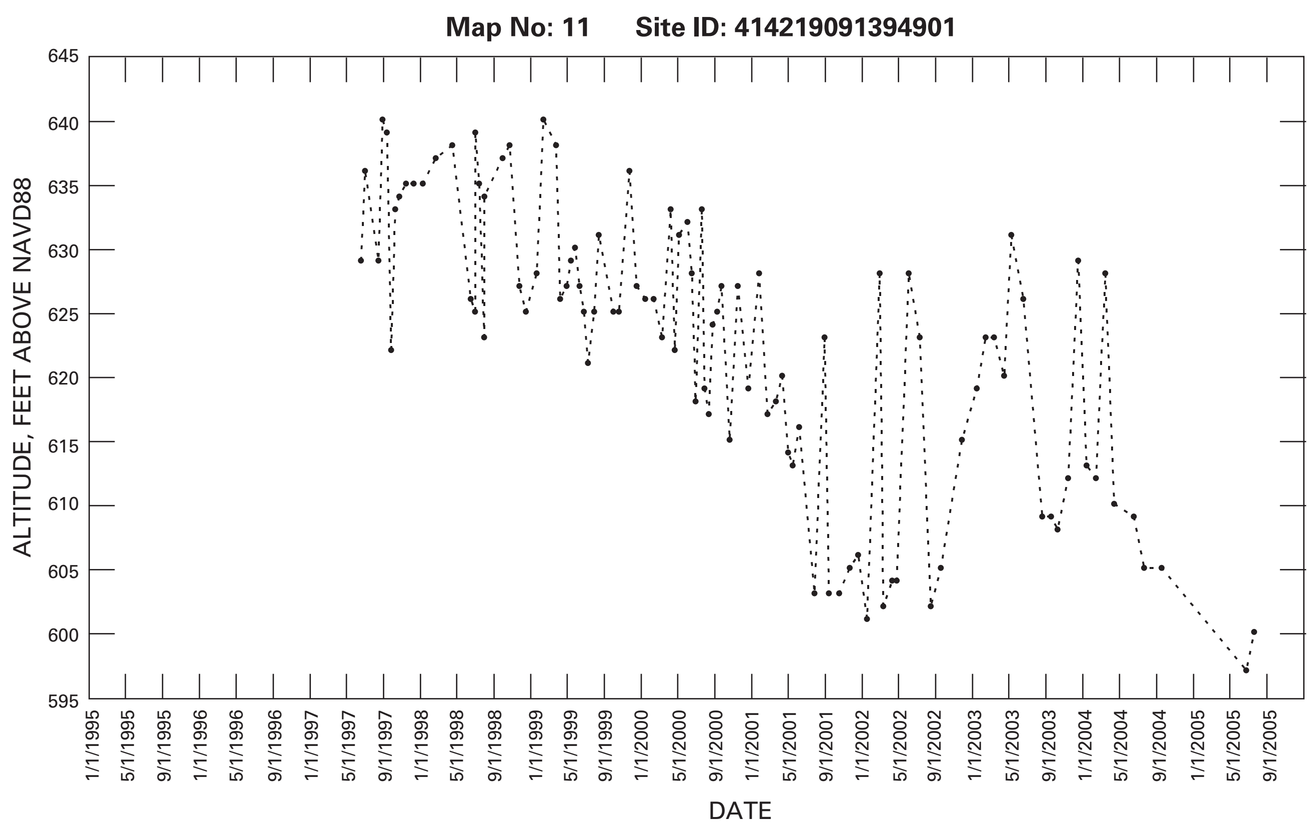
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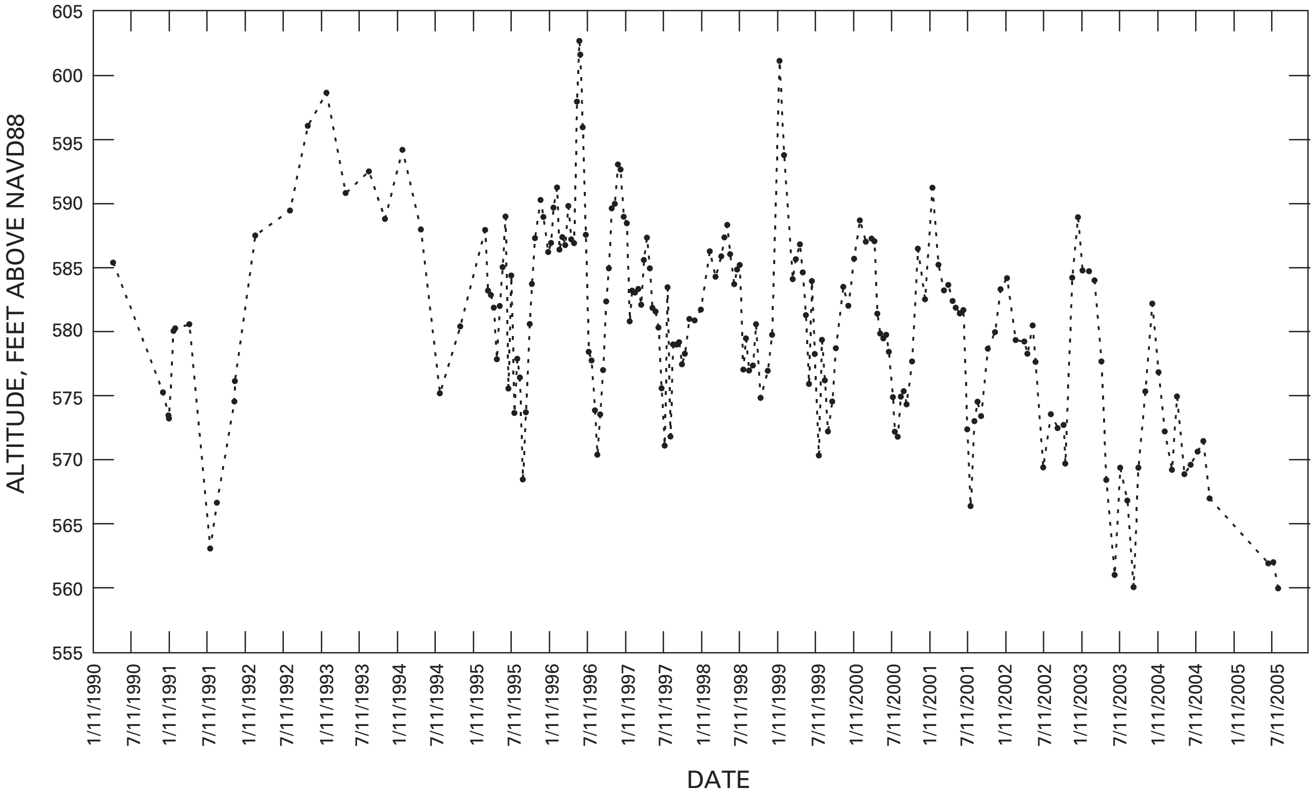

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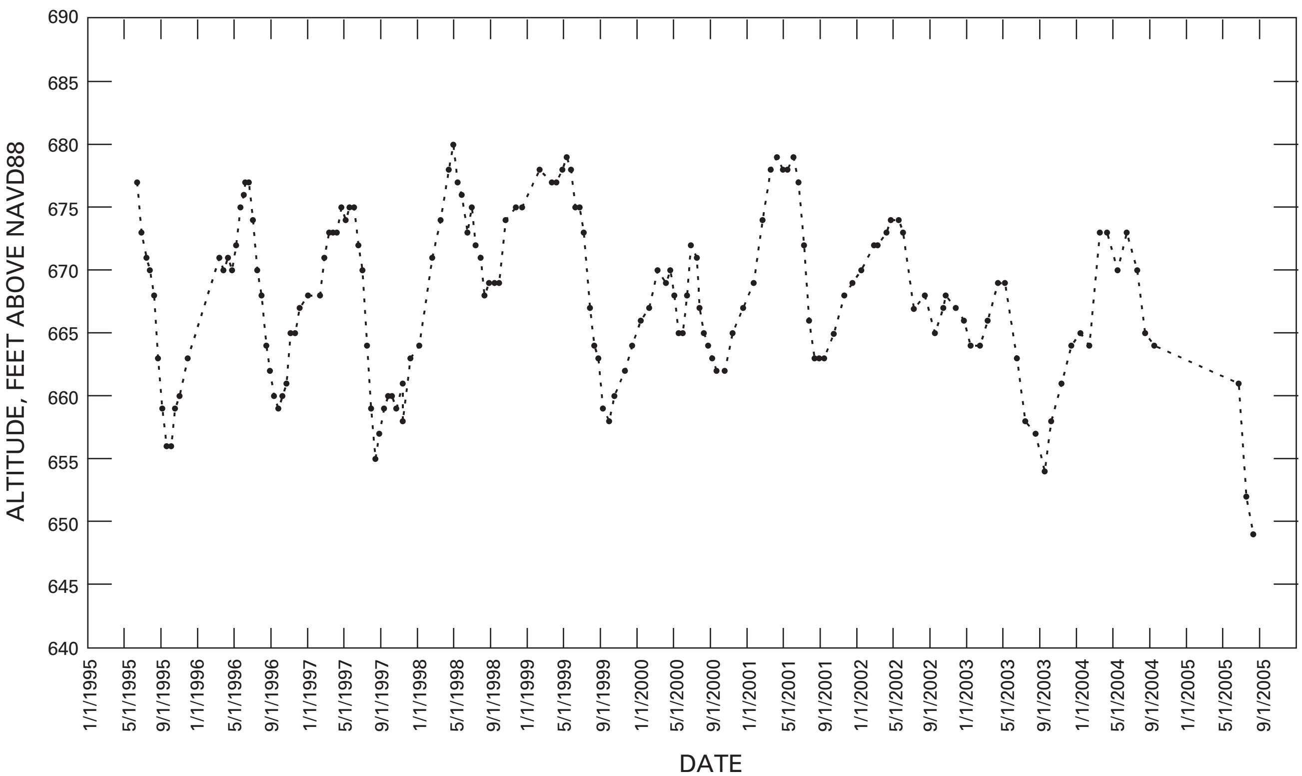

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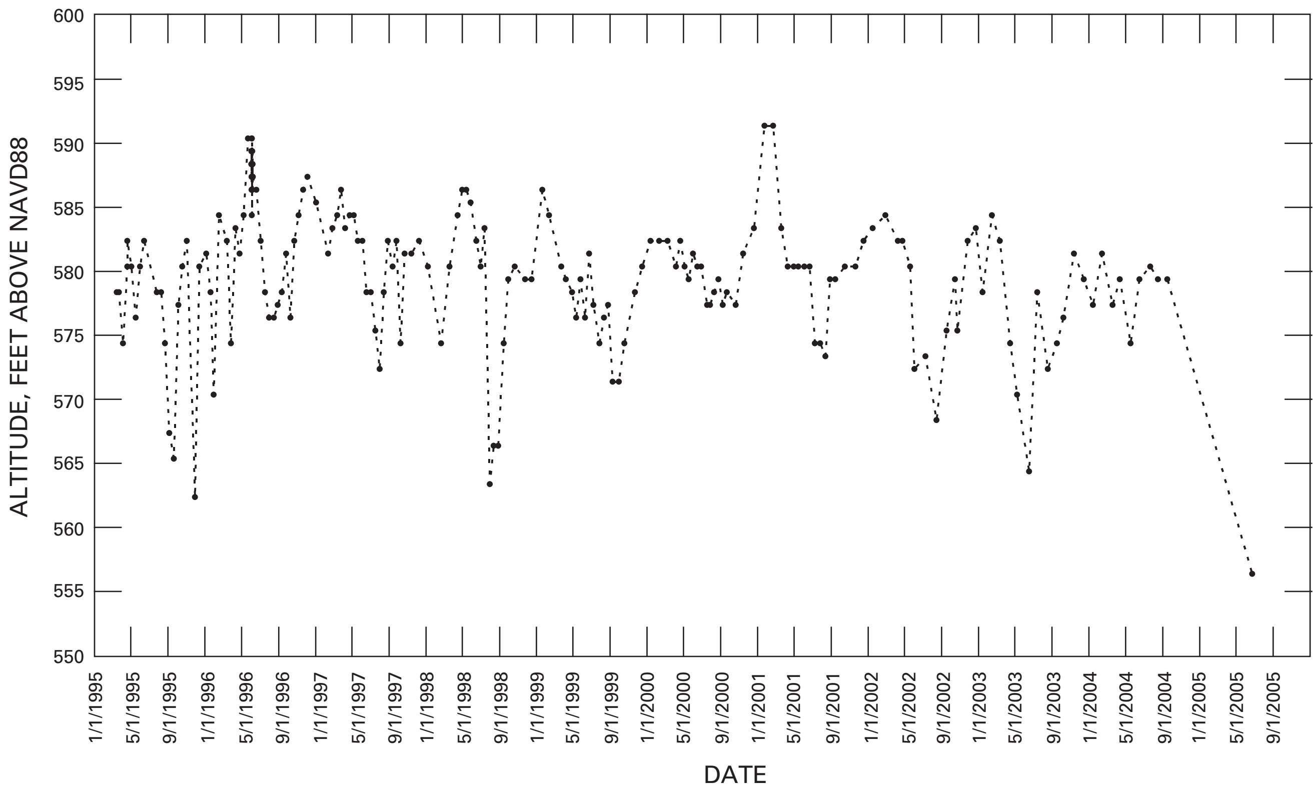

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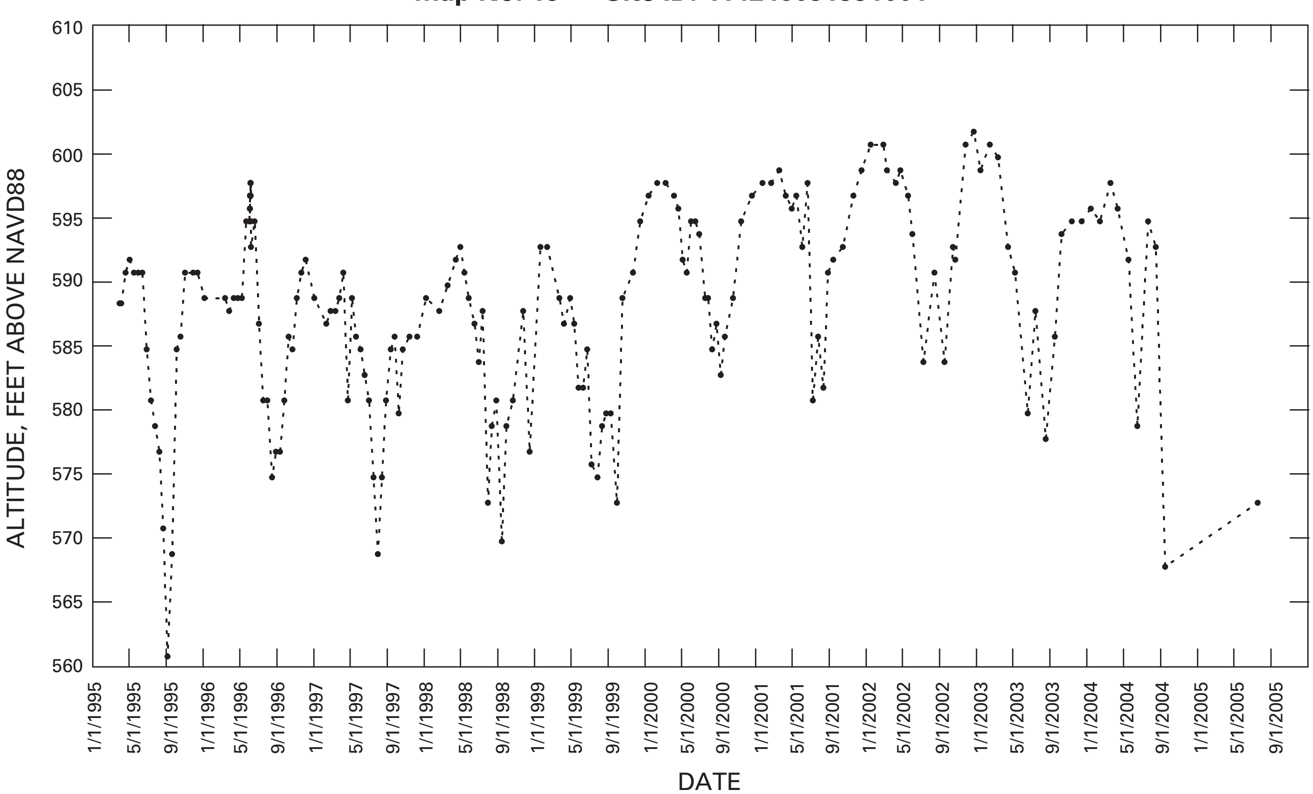

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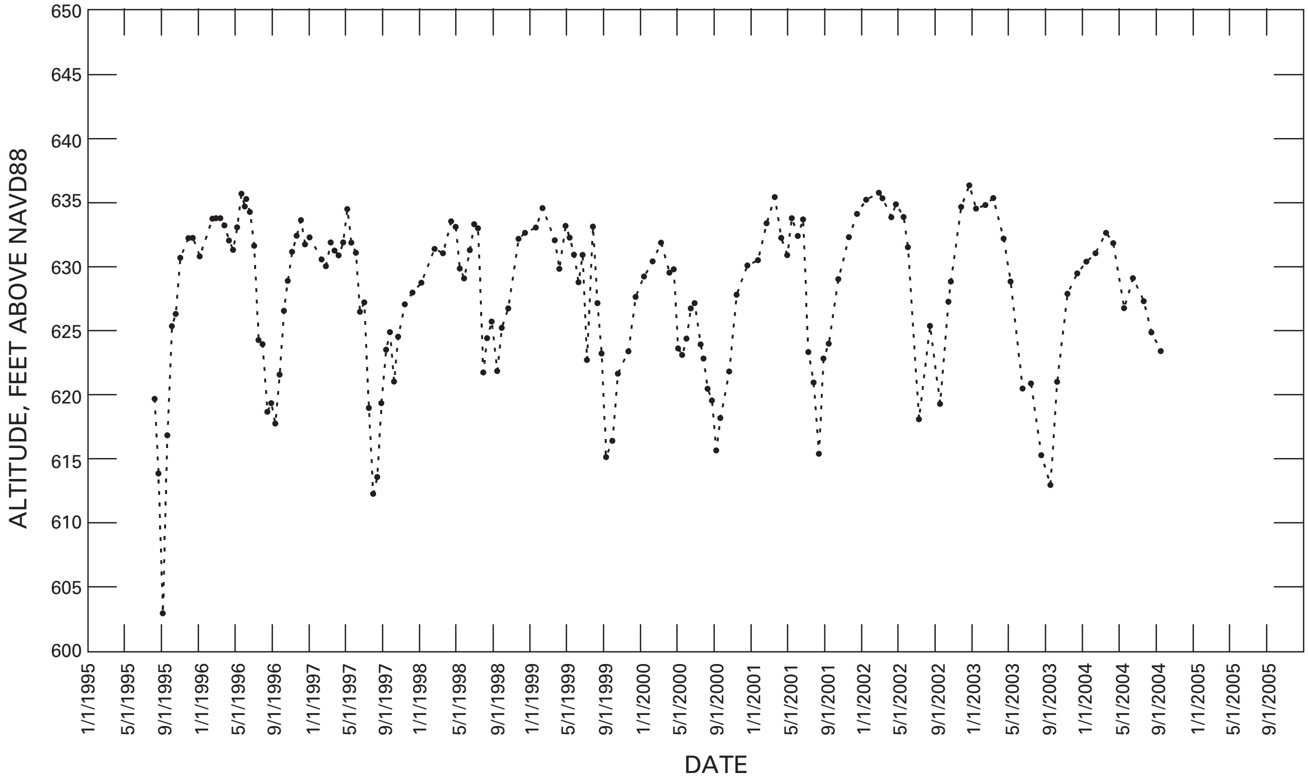

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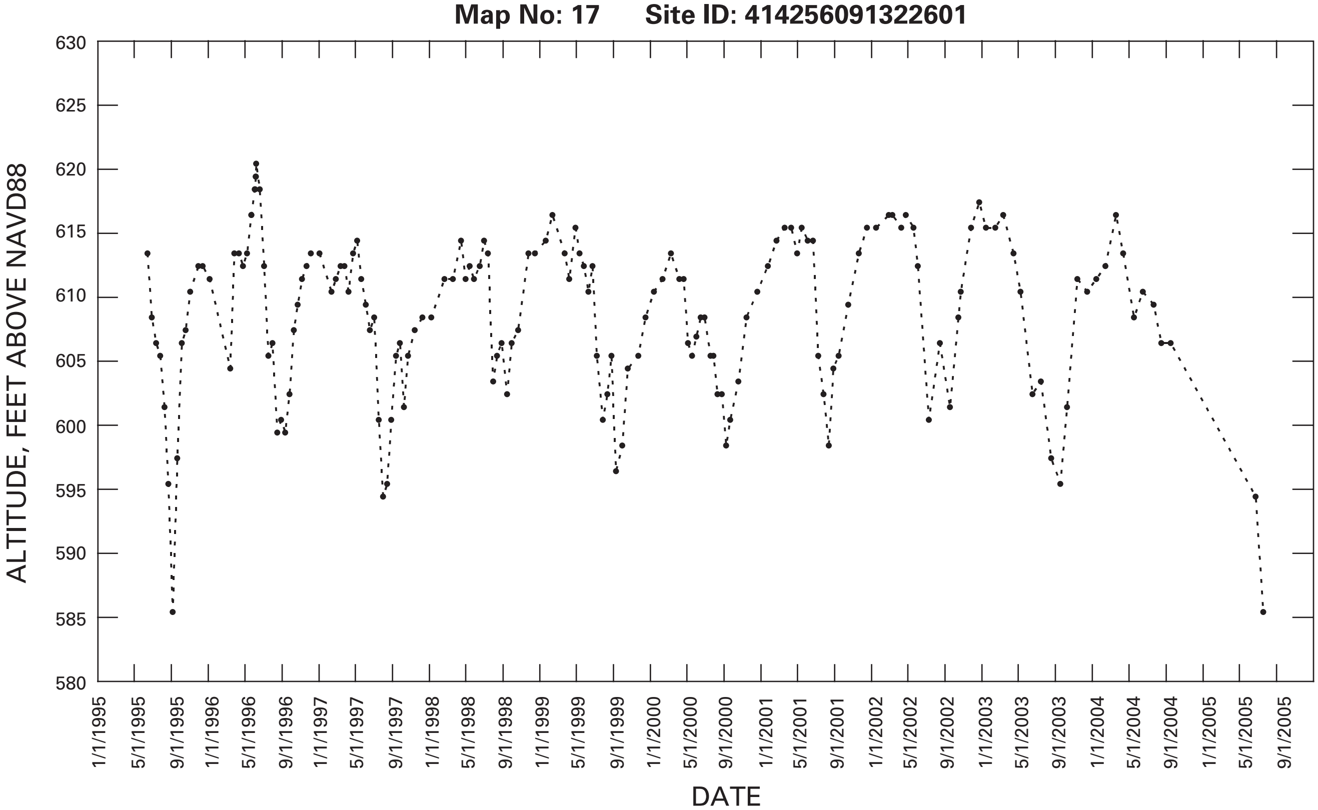

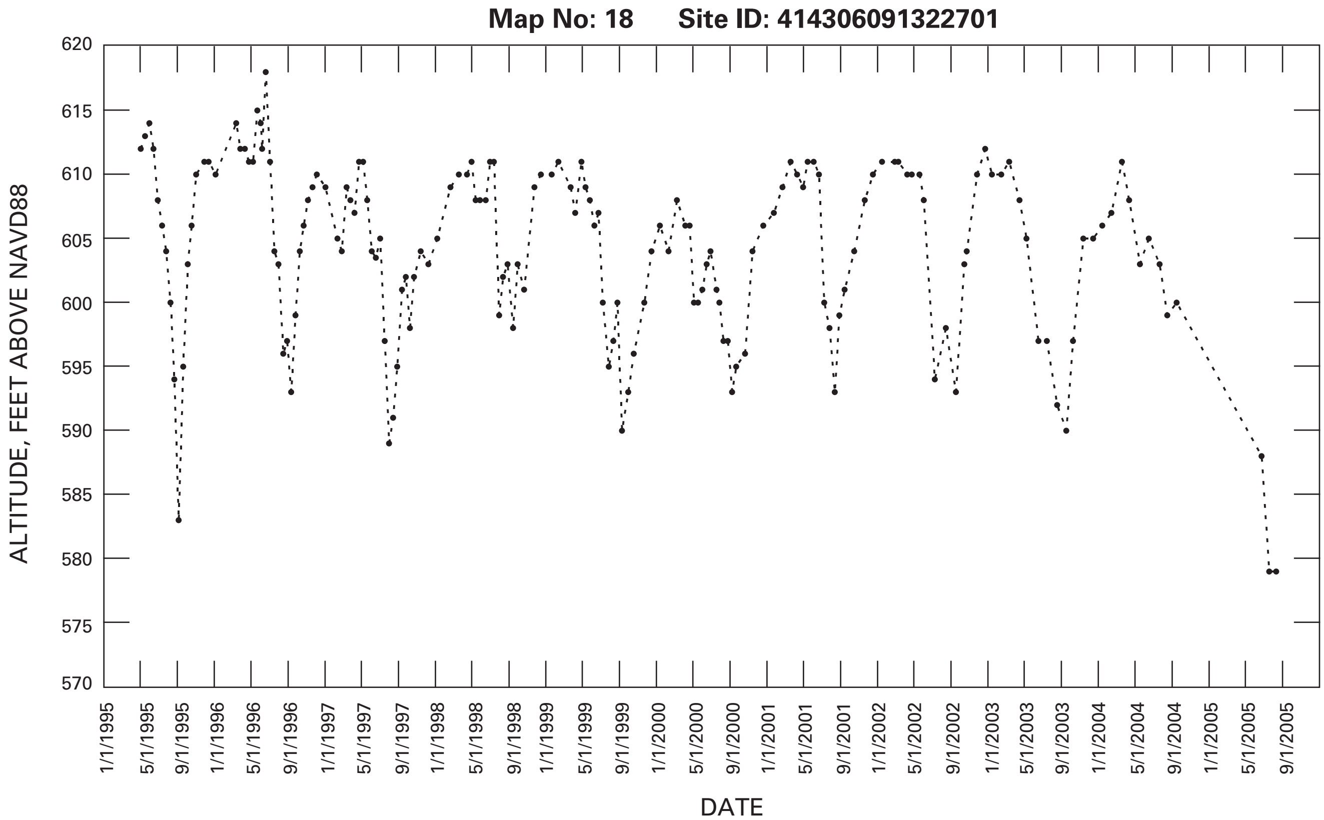
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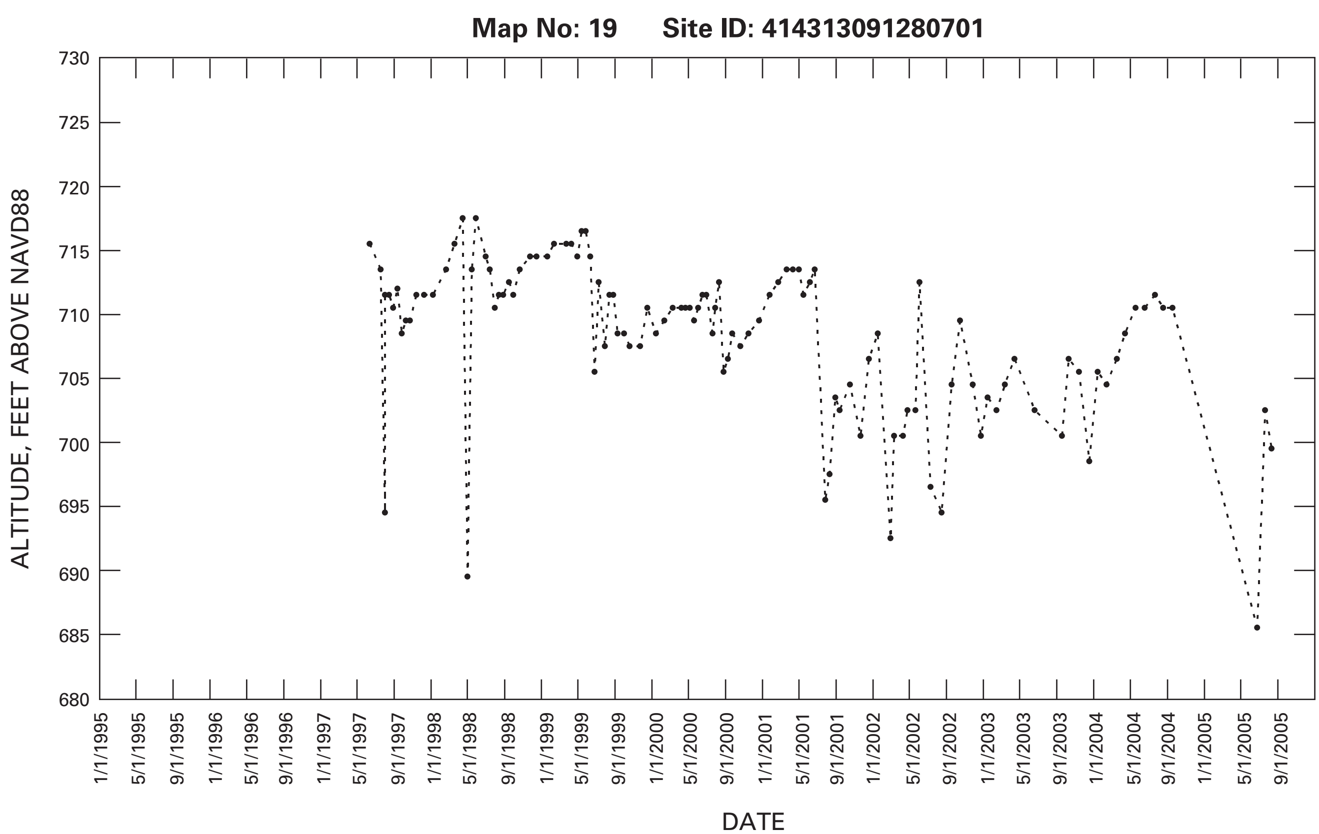
Map No: 19 Site ID: 414313091280701
ALTITUDE, FEET ABOVE NAVD88
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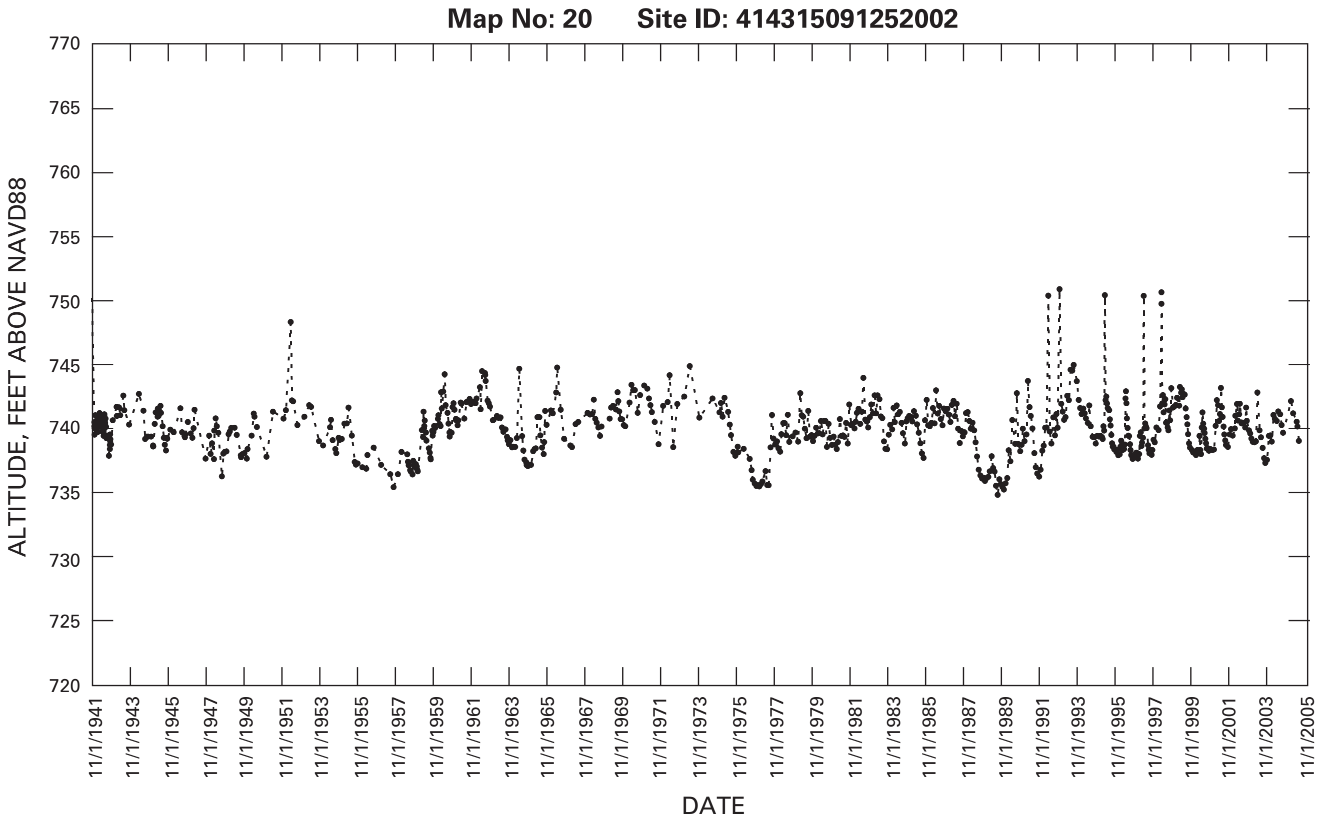
Map No: 20 Site ID: 414315091252002
ALTITUDE, FEET ABOVE NAVD88
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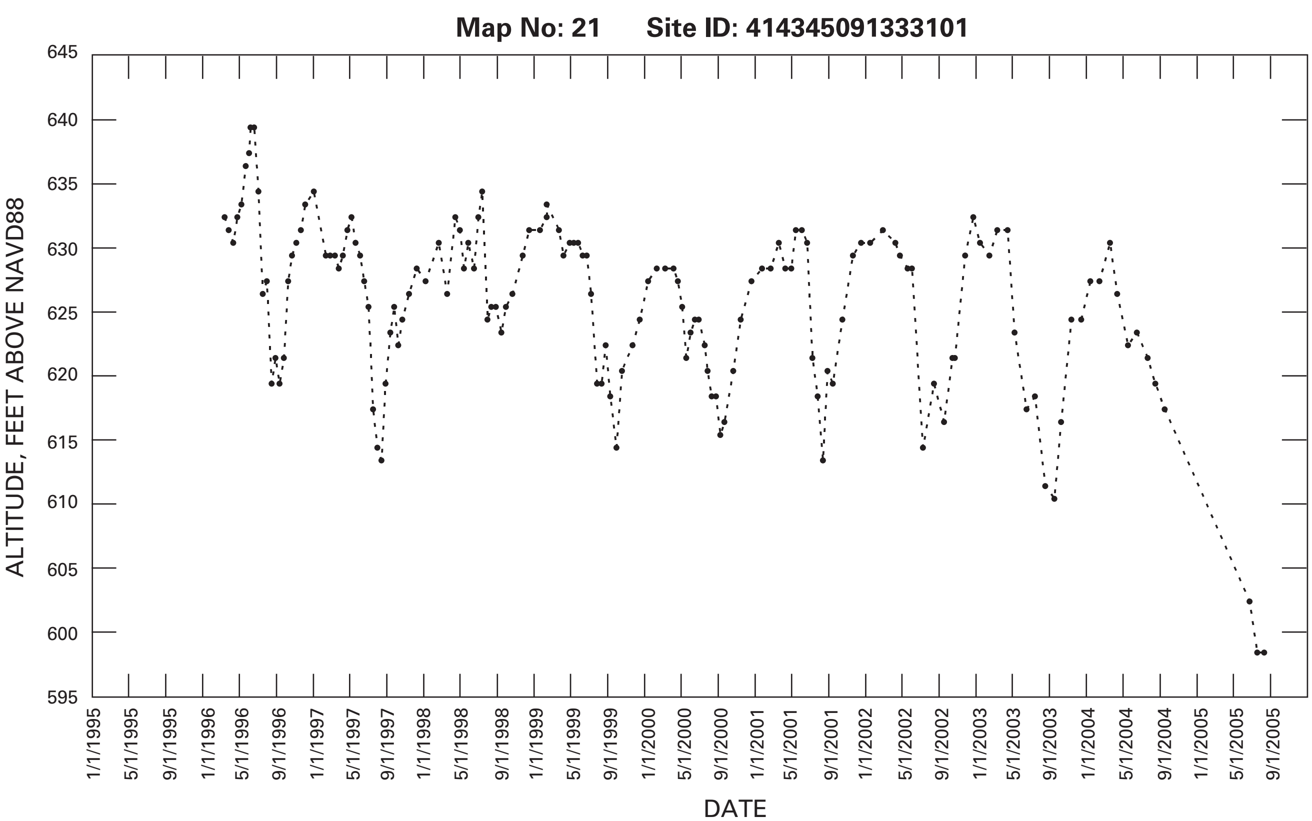
DATE


Map No: 21 Site ID: 414345091333101
ALTITUDE, FEET ABOVE NAVD88
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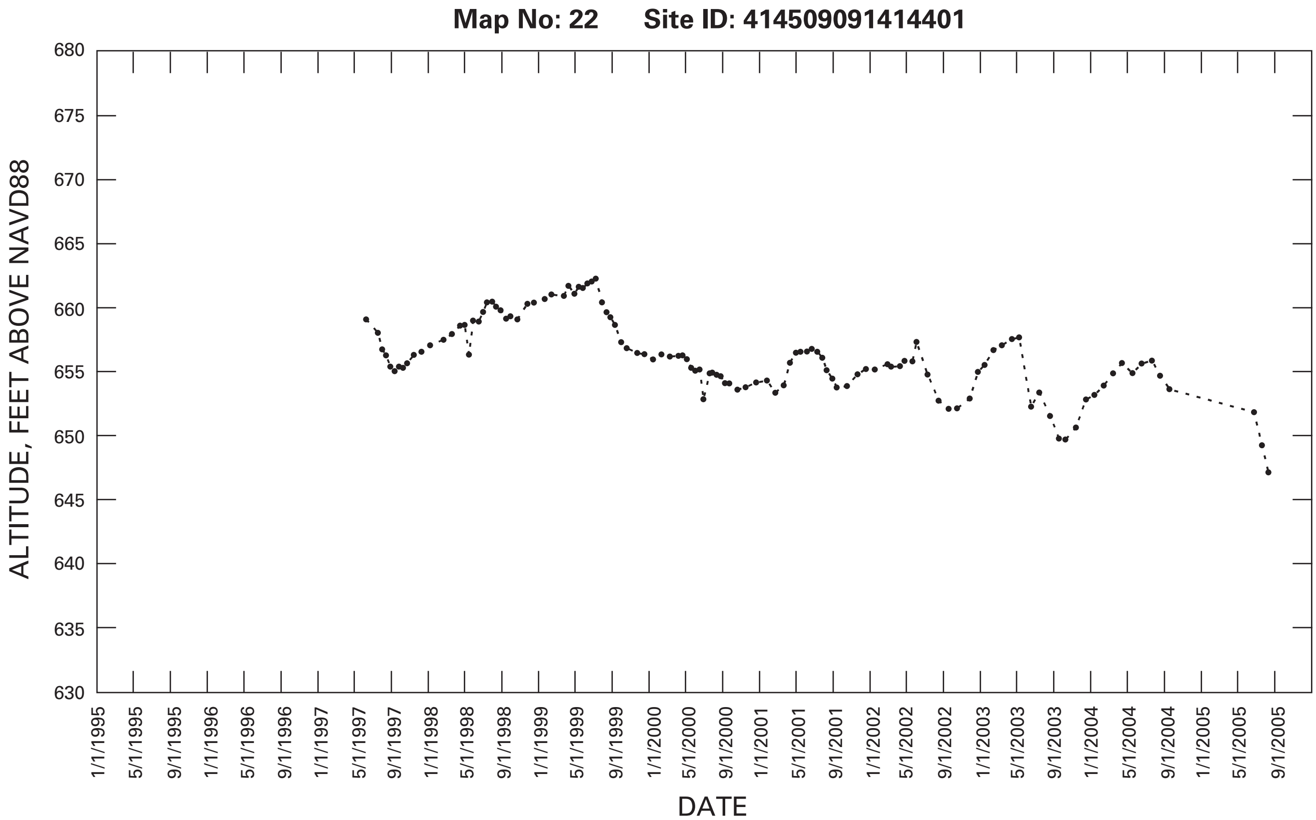
Map No: 22 Site ID: 414509091414401
ALTITUDE, FEET ABOVE NAVD88
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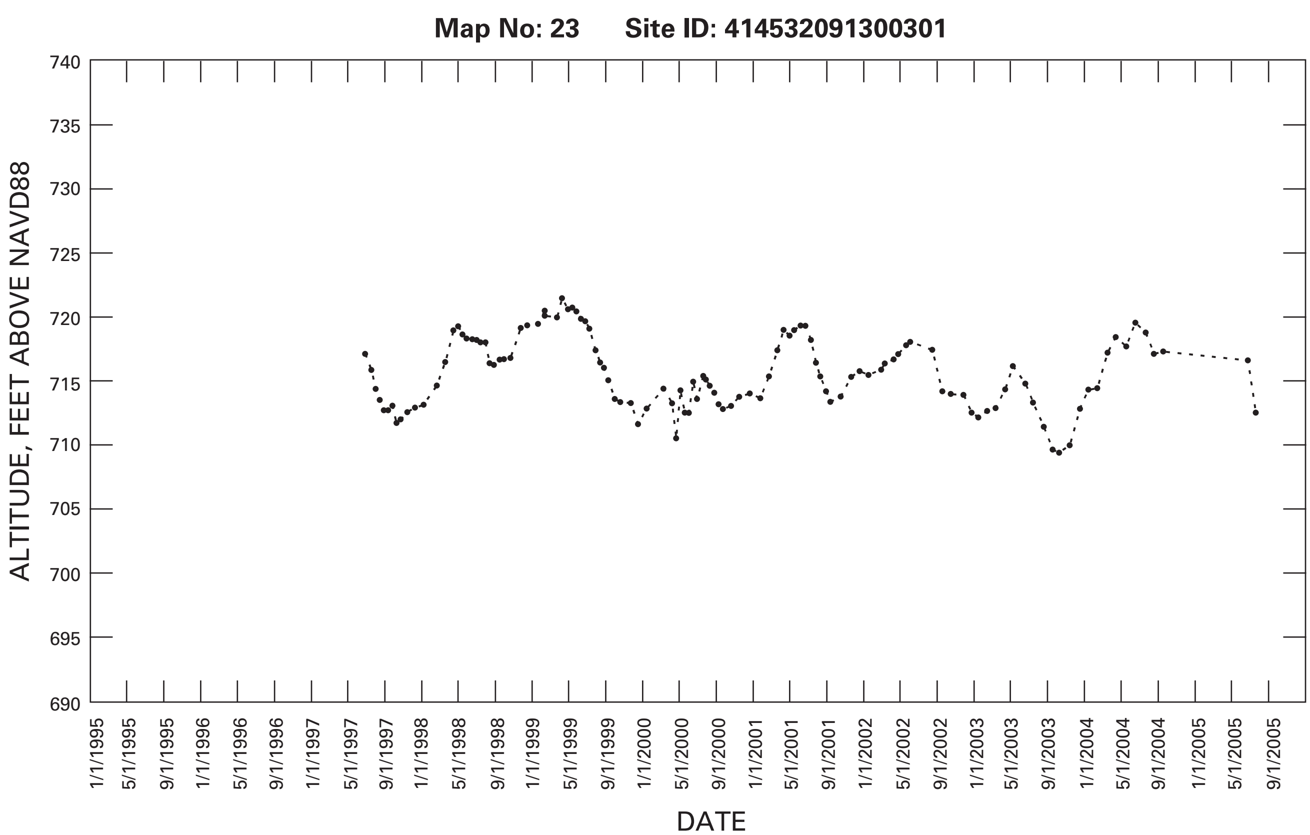
Map No: 23 Site ID: 414532091300301
ALTITUDE, FEET ABOVE NAVD88
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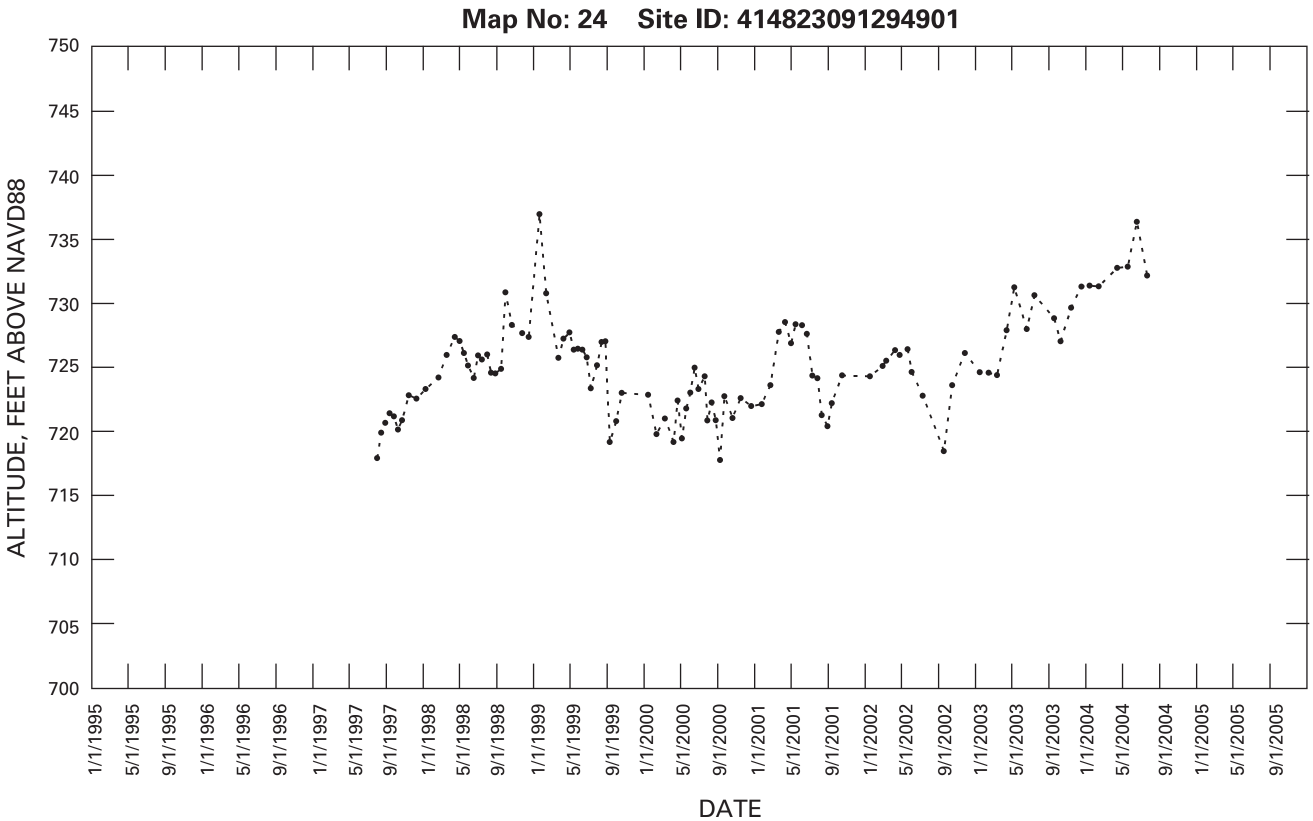
Map No: 24 Site ID: 414823091294901
ALTITUDE, FEET ABOVE NAVD88
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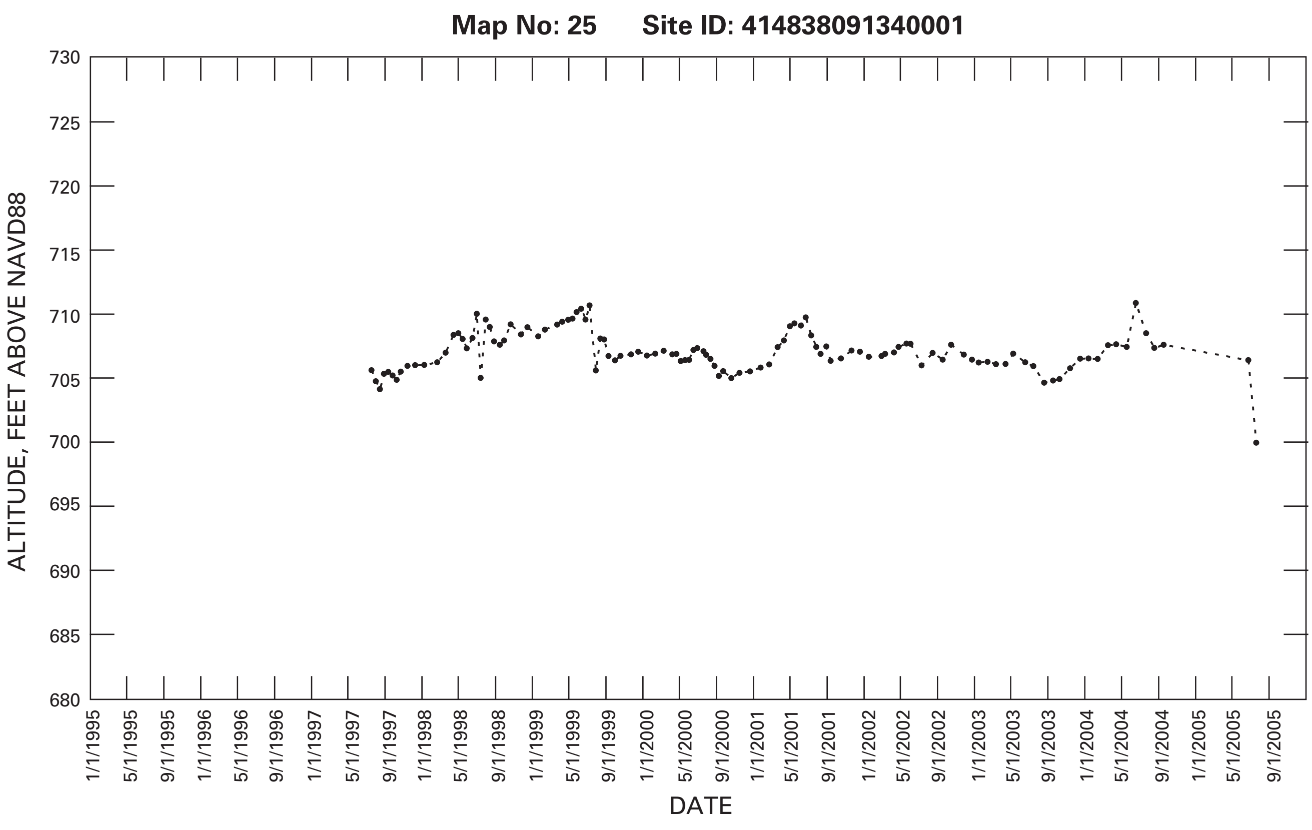
DATE


Map No: 25 Site ID: 414838091340001
ALTITUDE, FEET ABOVE NAVD88
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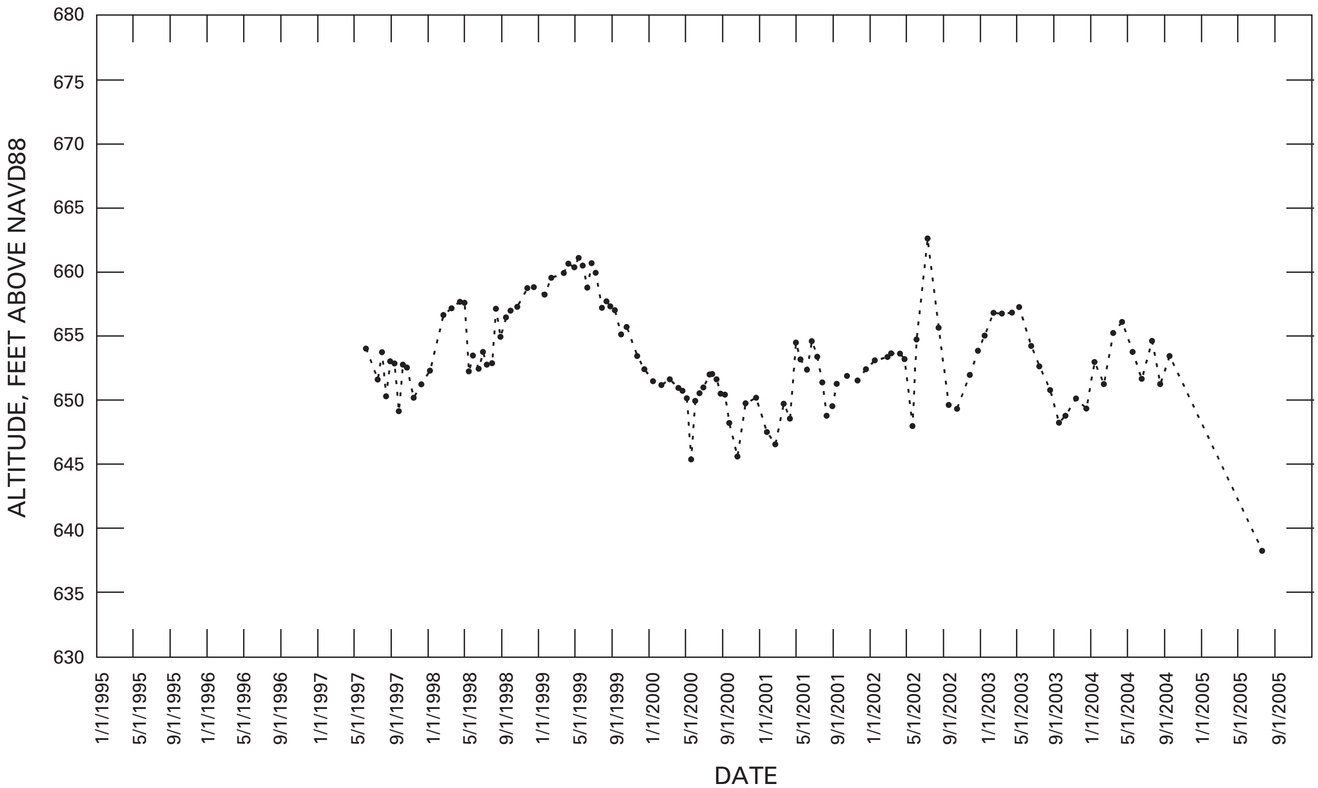
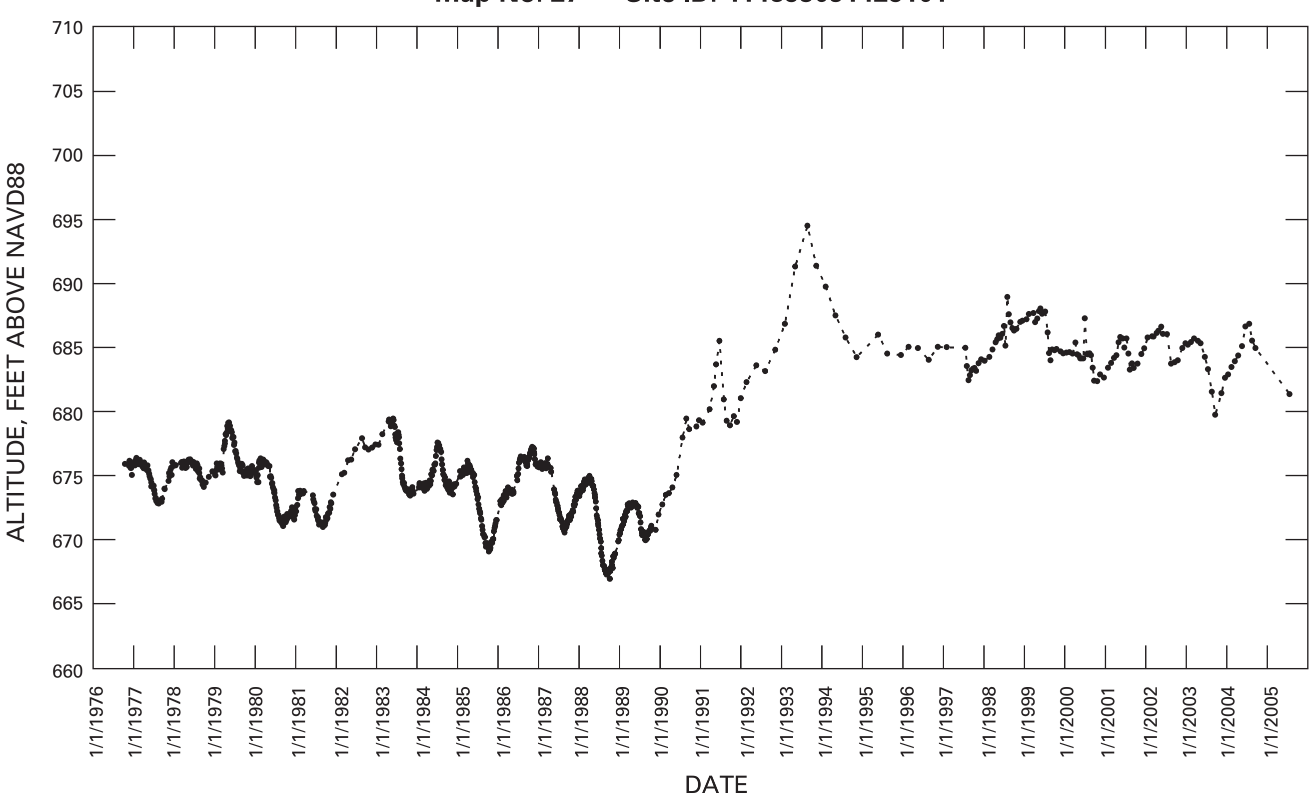
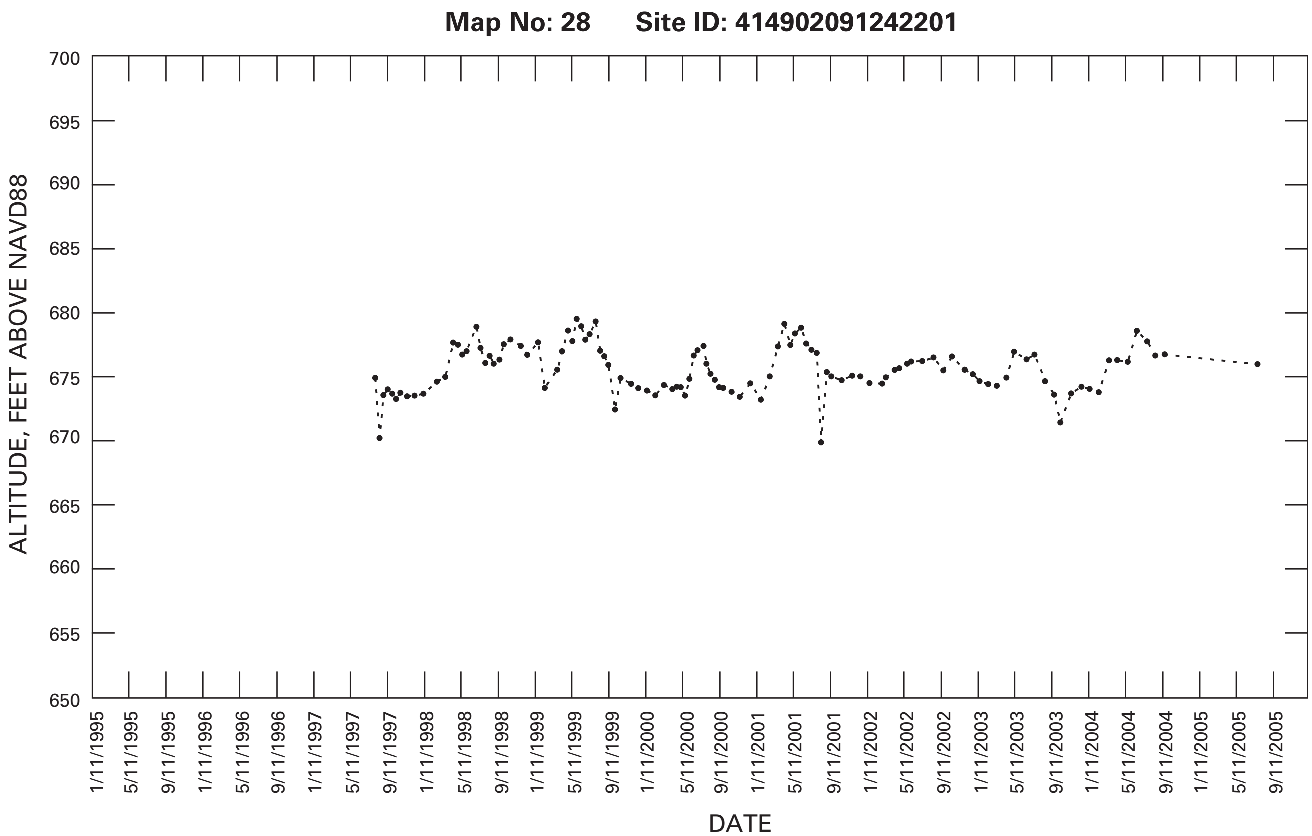
DATE

Map No: 26 Site ID: 414850091454601



Map No: 27 Site ID: 414853091425101




Map No: 28 Site ID: 414902091242201
ALTITUDE, FEET ABOVE NAVD88
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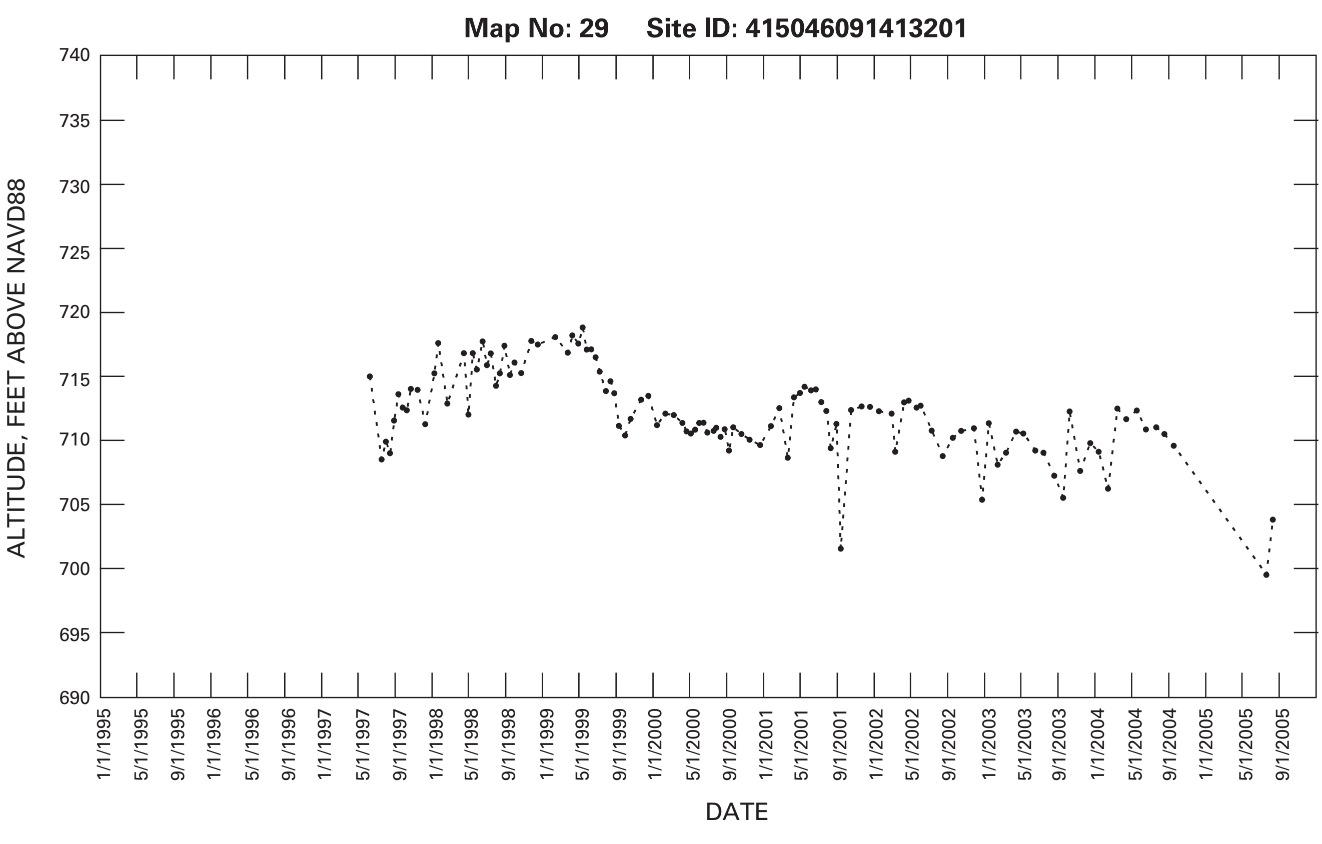
Map No: 29 Site ID: 415046091413201
ALTITUDE, FEET ABOVE NAVD88
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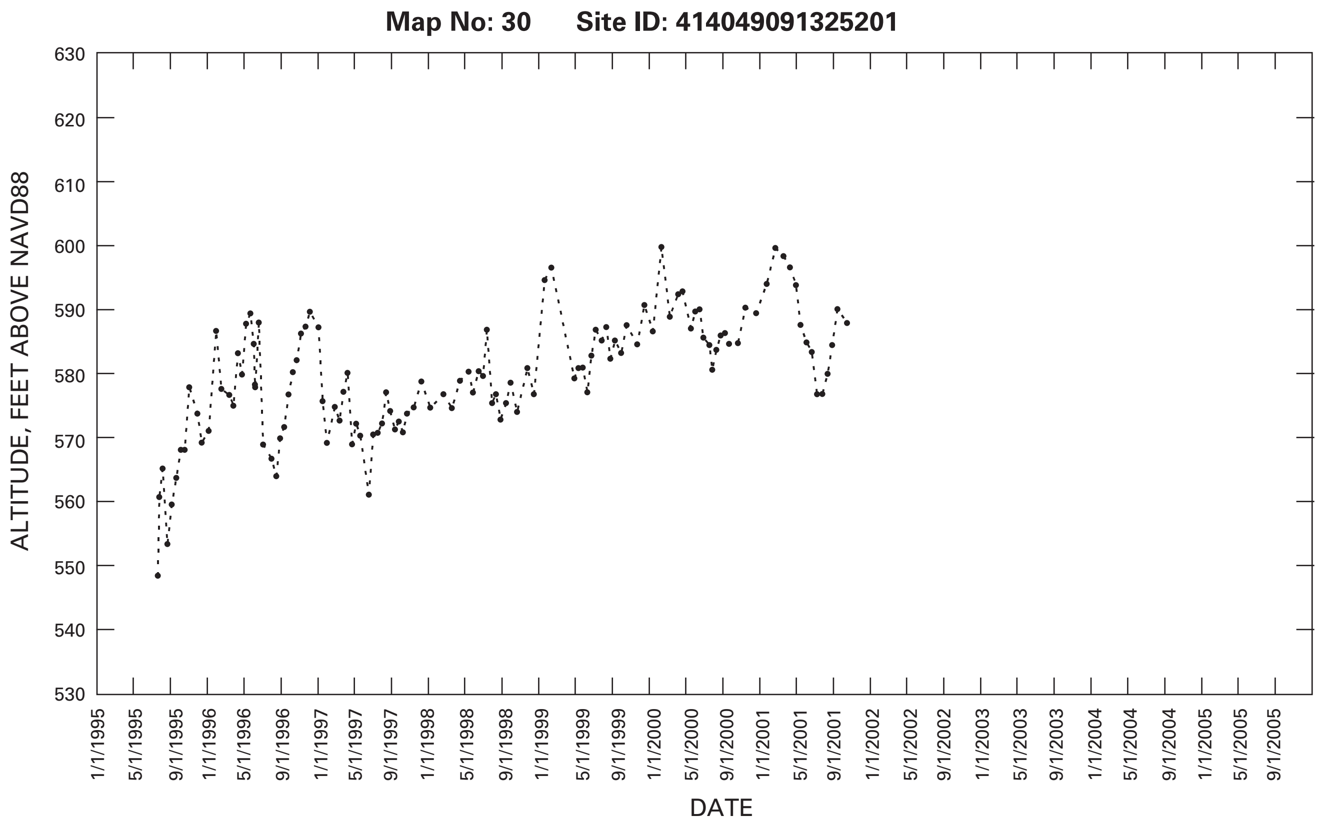
Map No: 30 Site ID: 414049091325201
ALTITUDE, FEET ABOVE NAVD88
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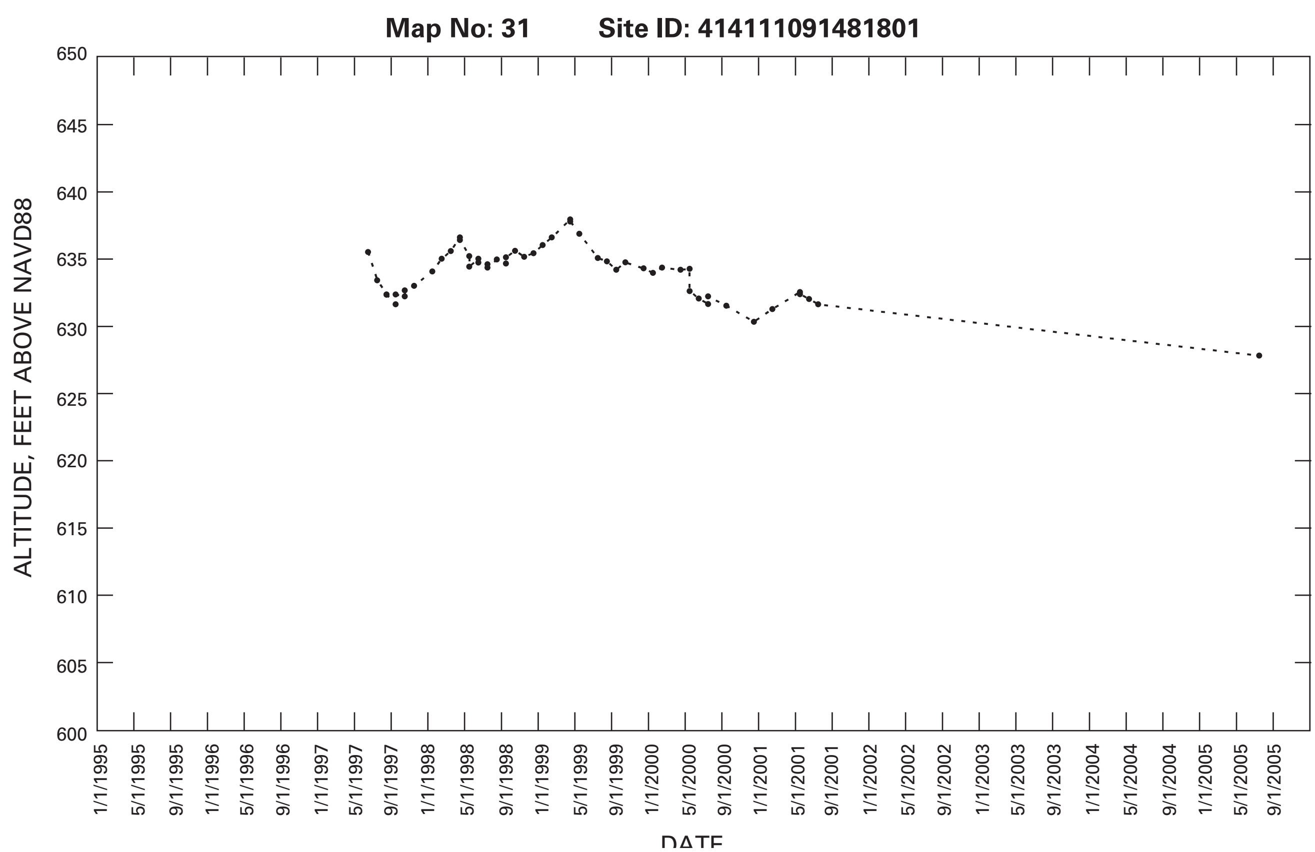
Map No: 31 Site ID: 414111091481801
ALTITUDE, FEET ABOVE NAVD88
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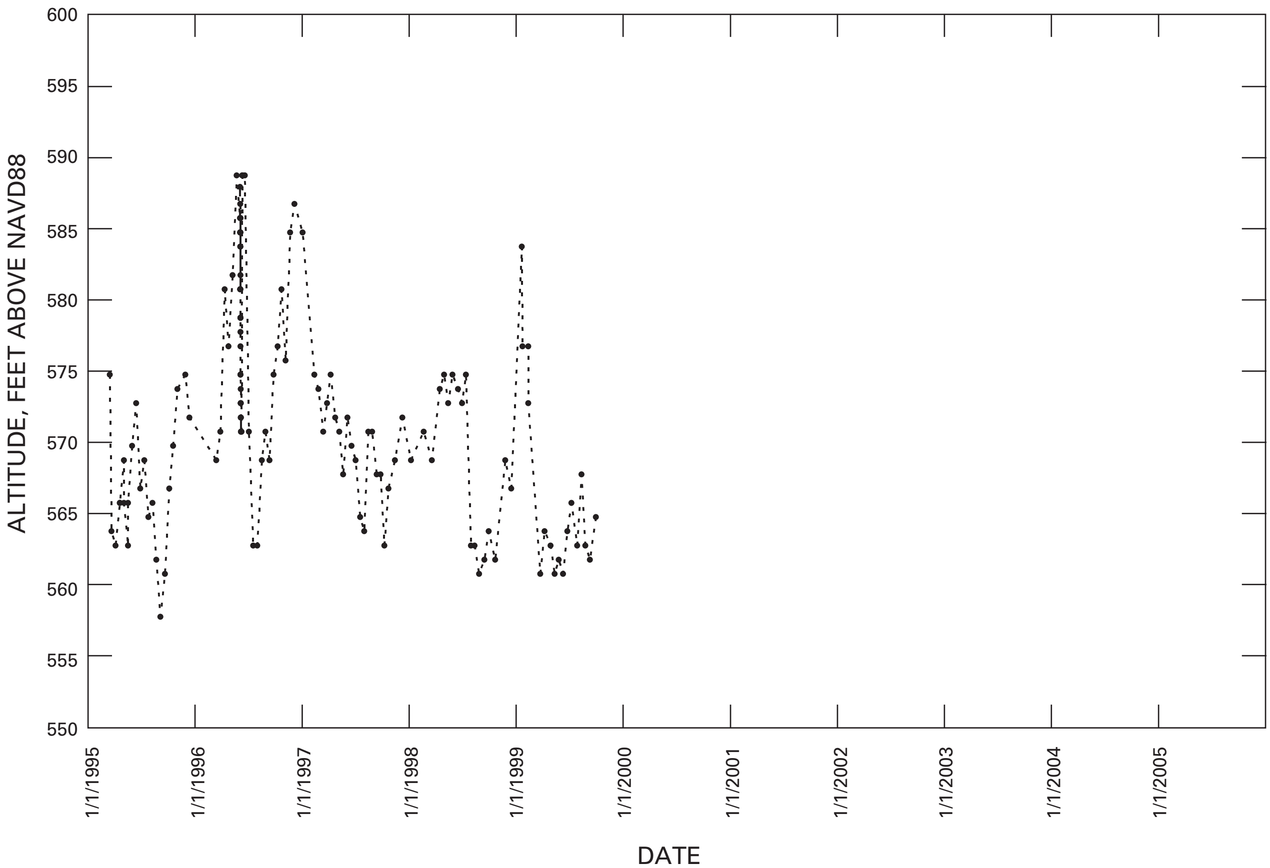
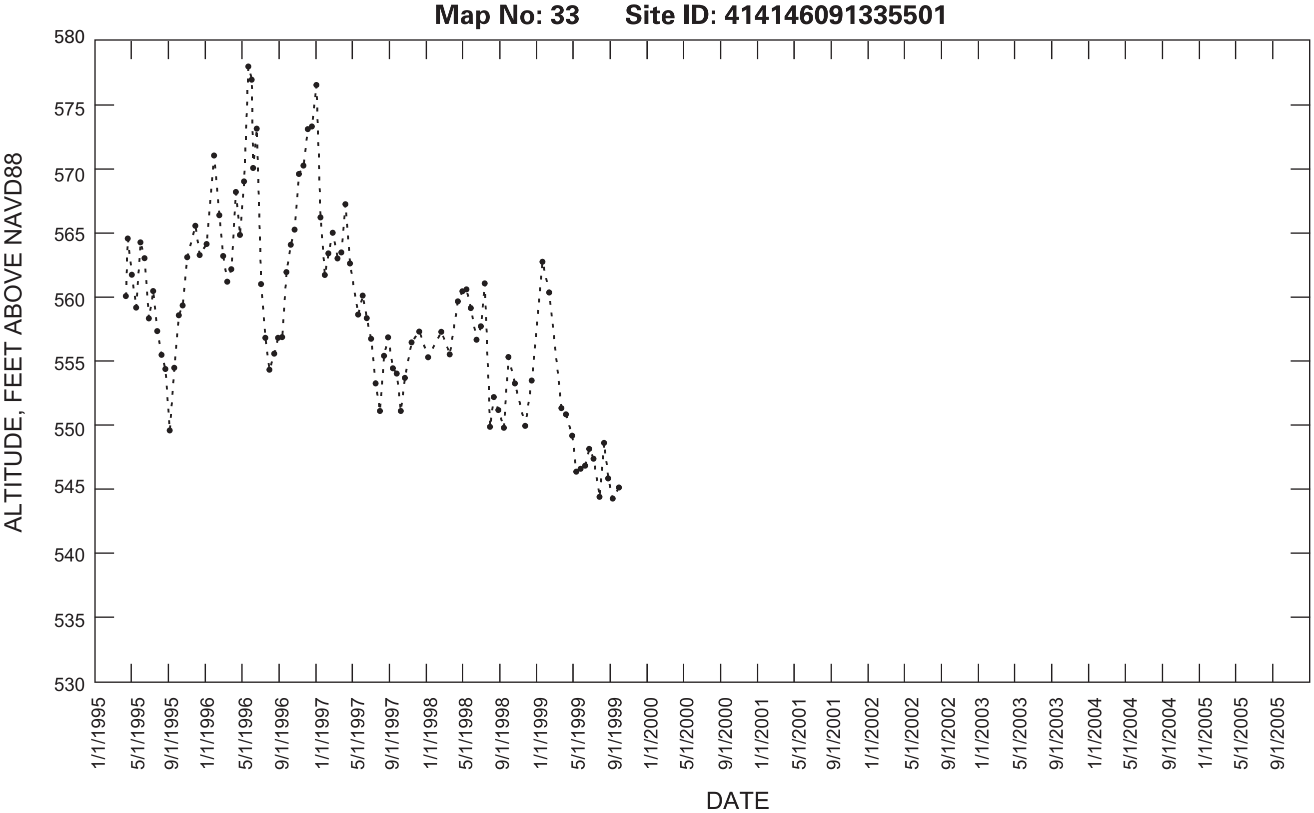
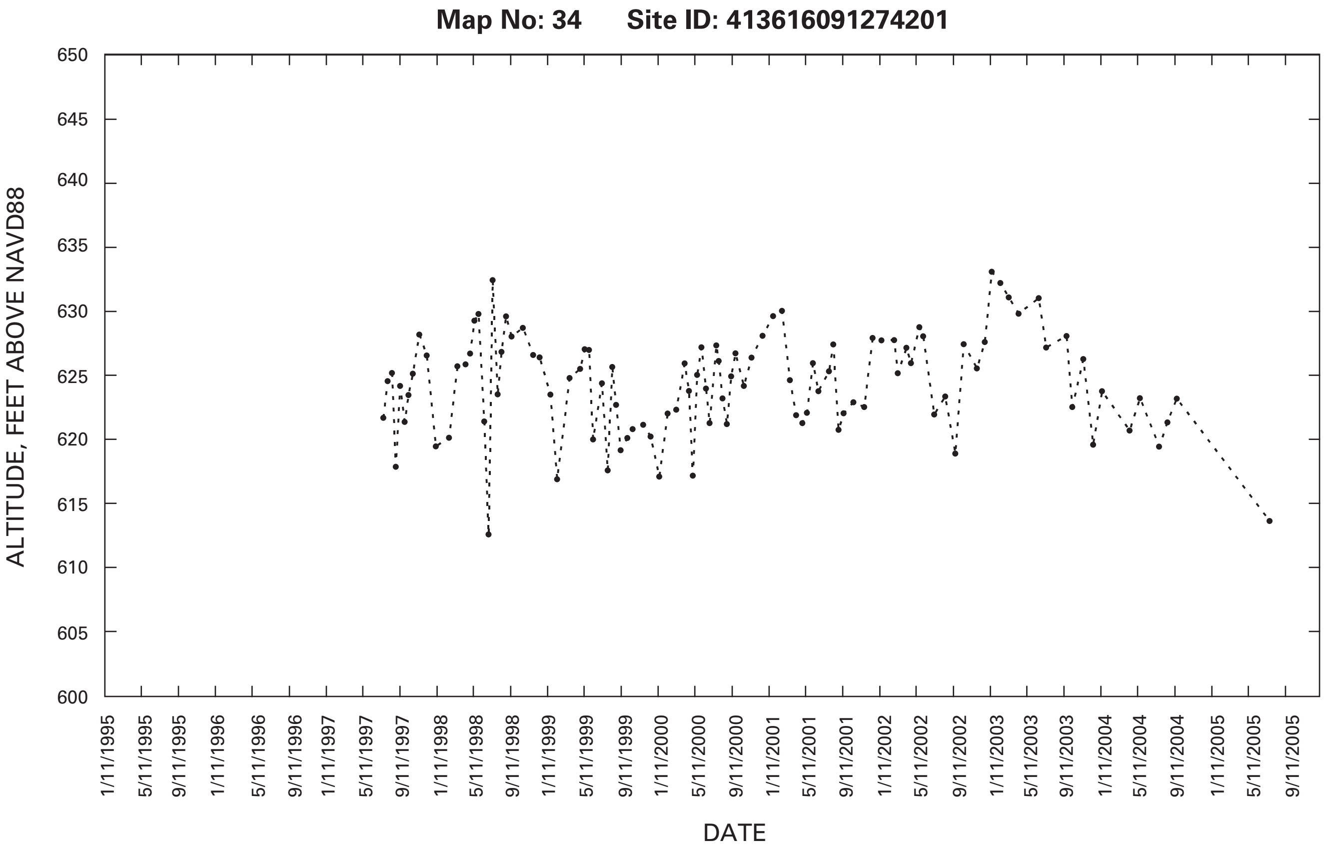
9/1/2005

Map No: 32 Site ID: 414128091324101



Map No: 33 Site ID: 414146091335501




Map No: 34 Site ID: 413616091274201
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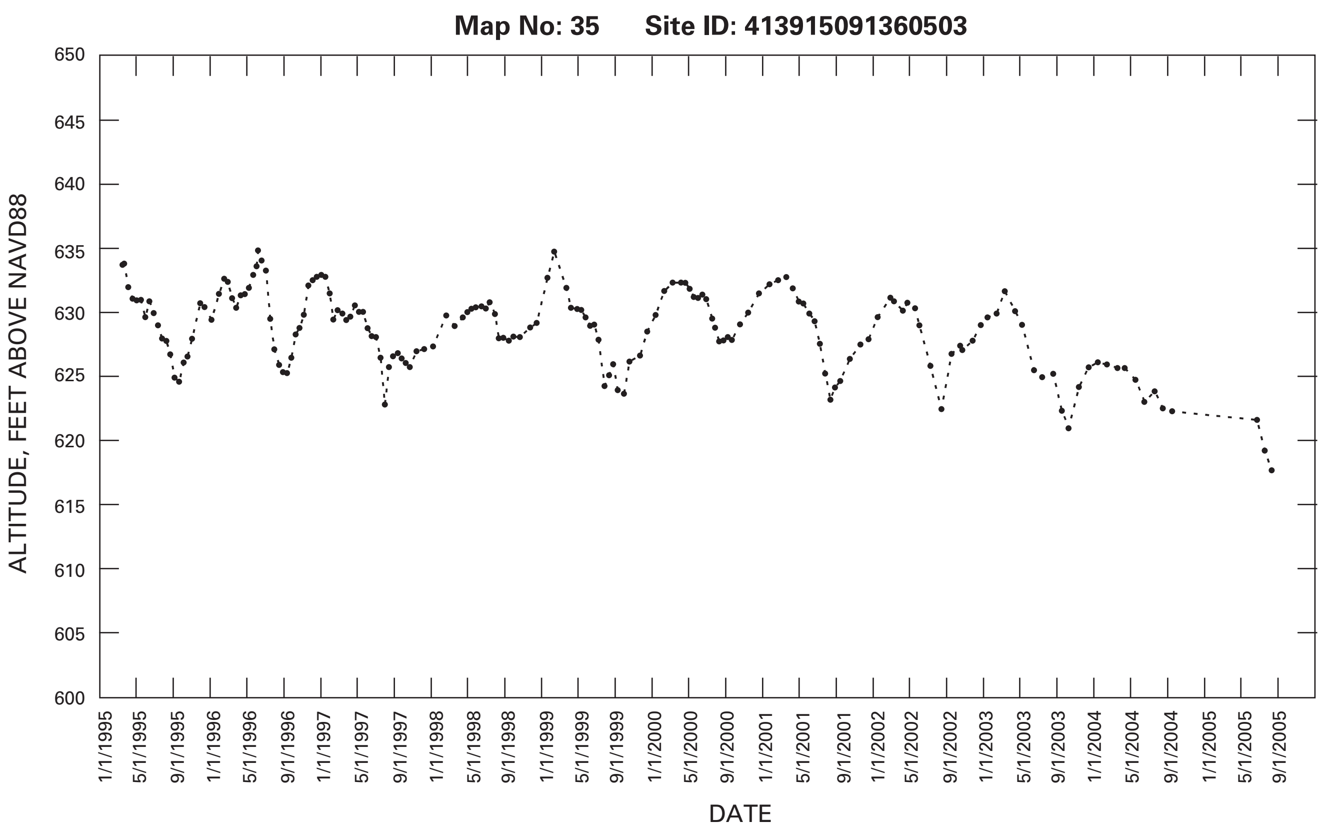
DATE


Map No: 35 Site ID: 413915091360503
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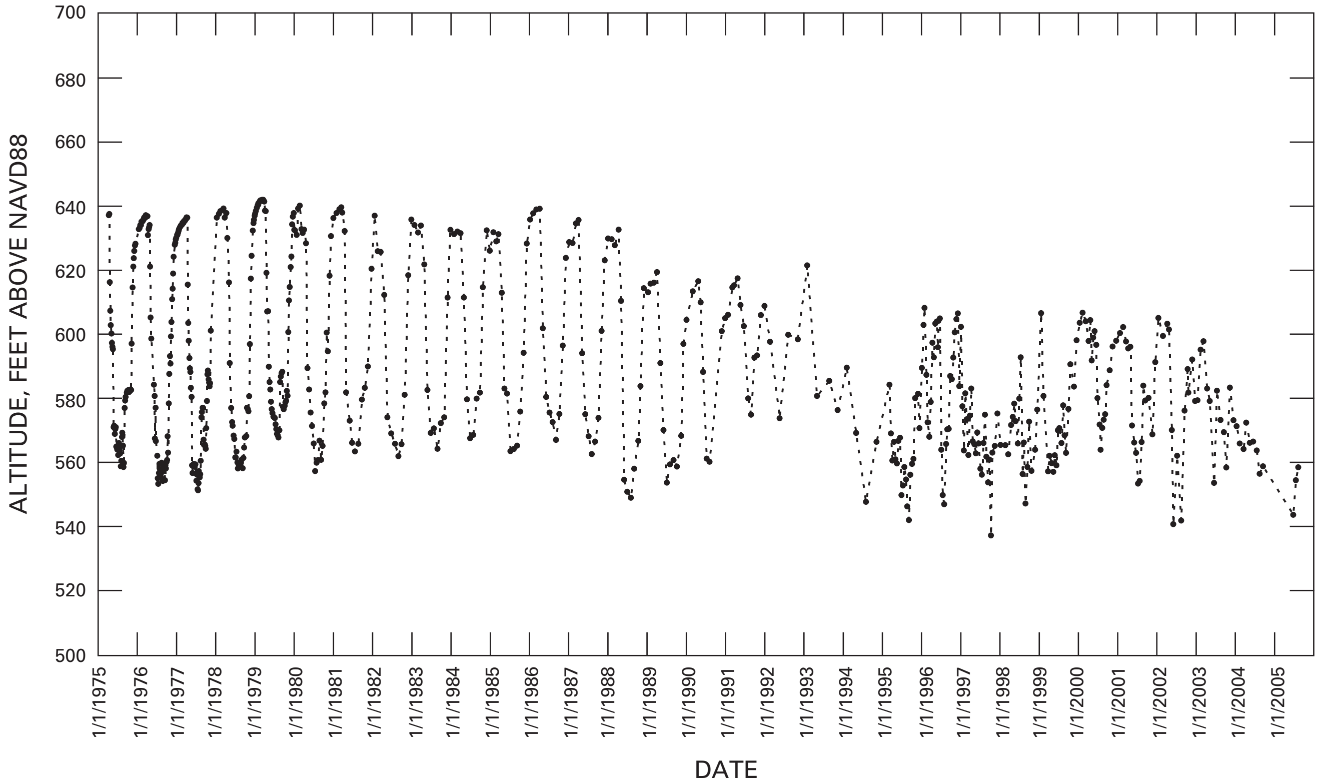
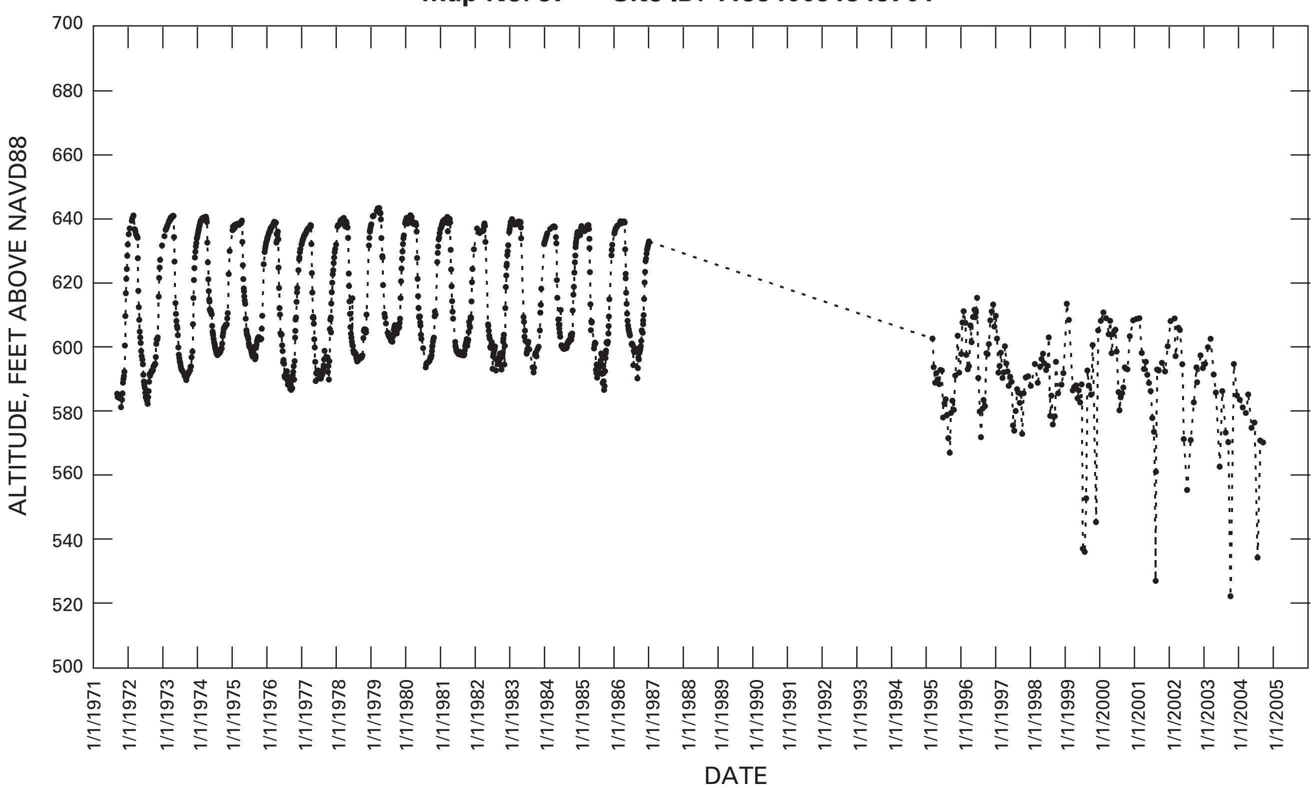
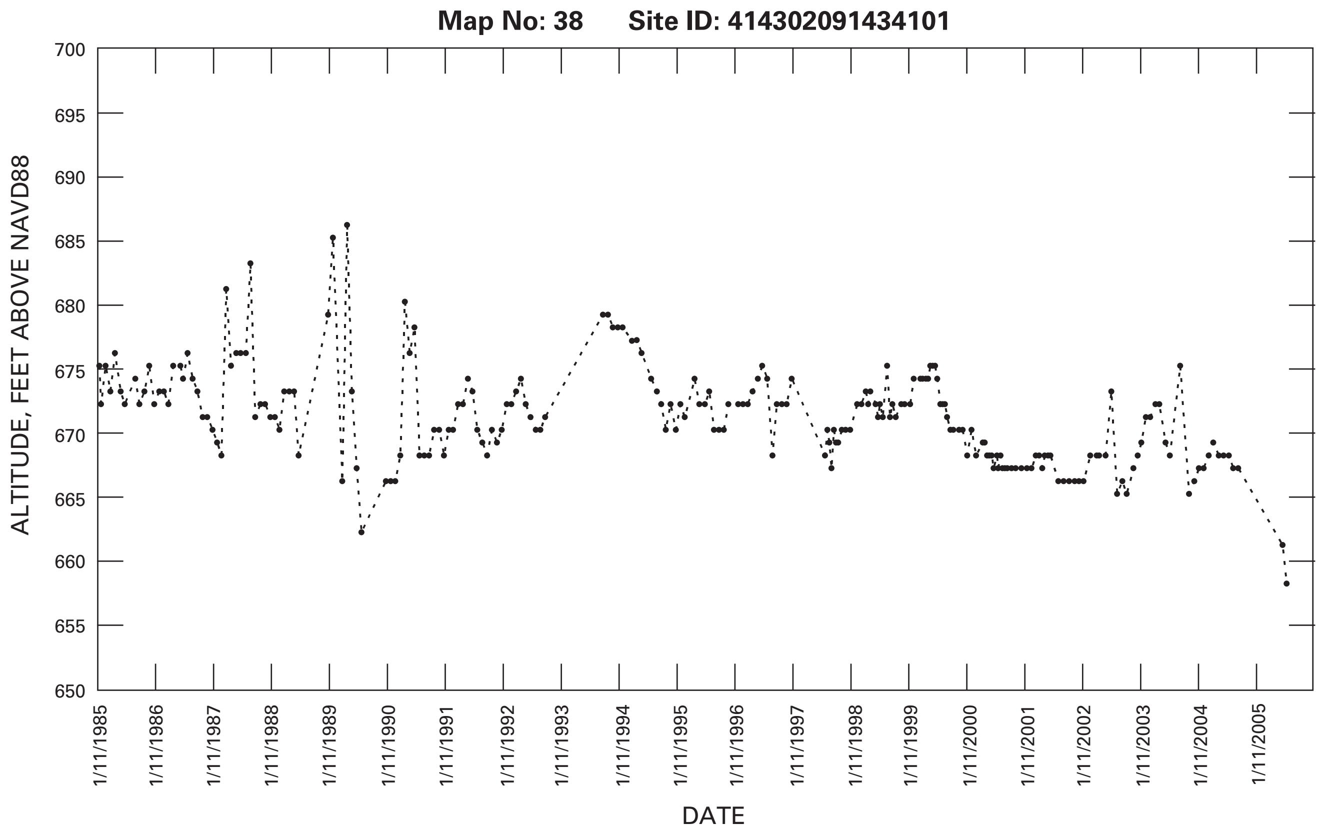
Map No: 36 Site ID: 413925091324001



Map No: 37 Site ID: 413940091345701




Map No: 38 Site ID: 414302091434101
ALTITUDE, FEET ABOVE NAVD88
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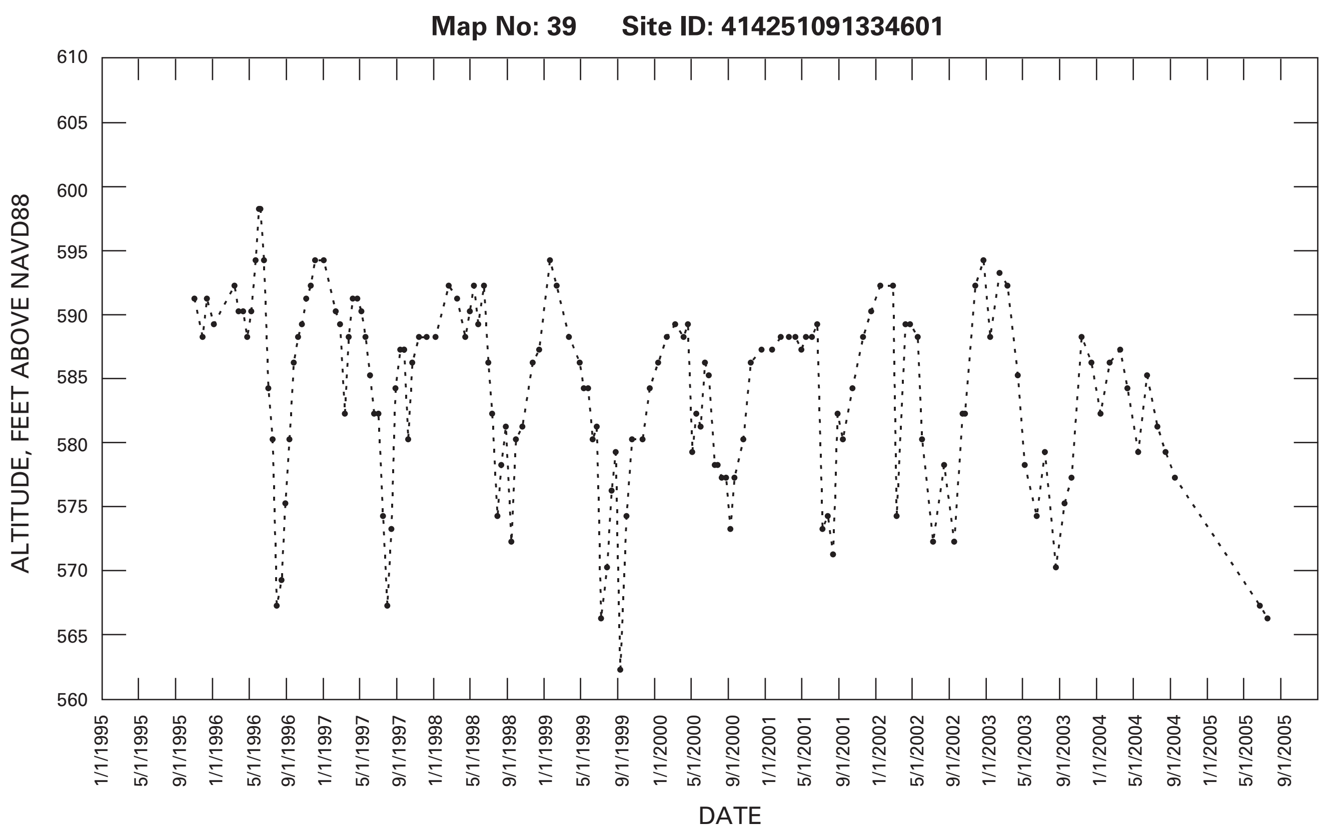
Map No: 39 Site ID: 414251091334601
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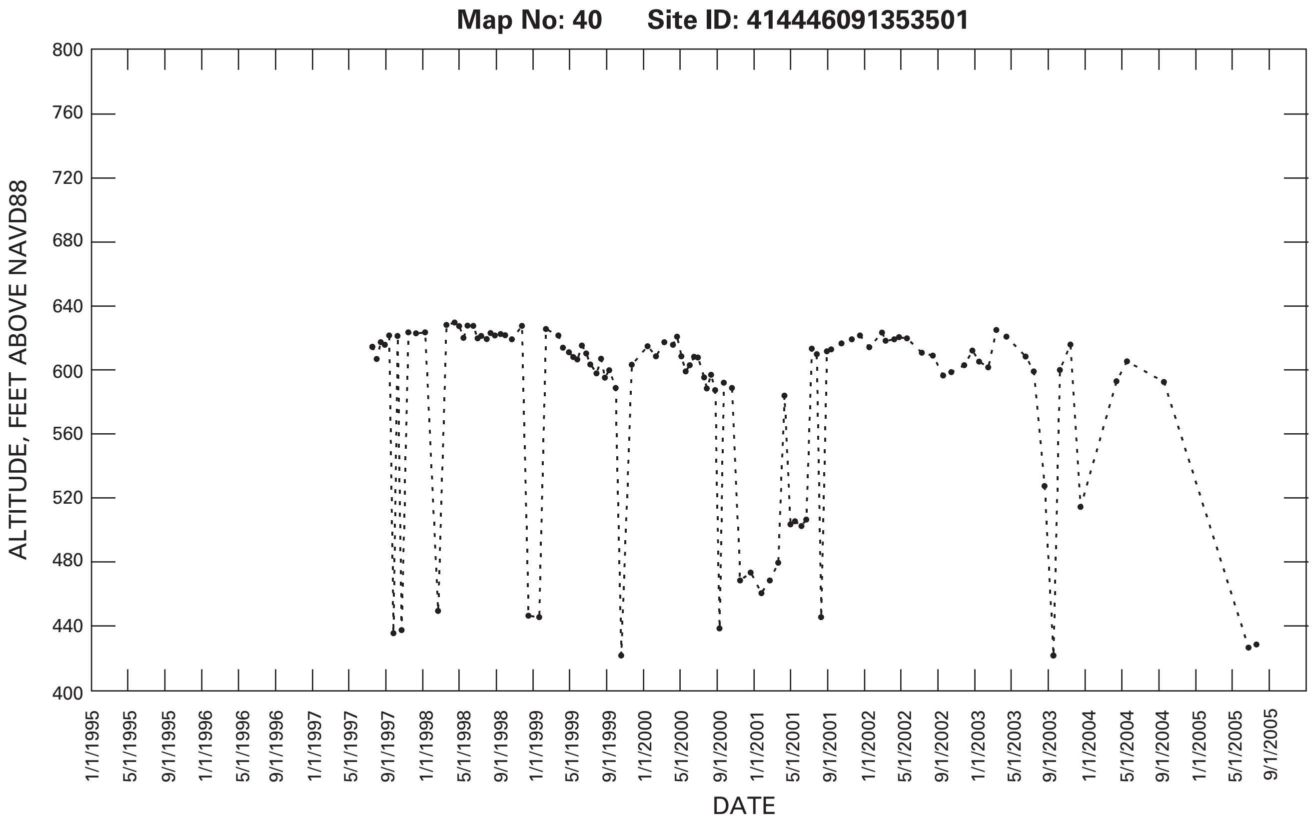
Map No: 40 Site ID: 414446091353501
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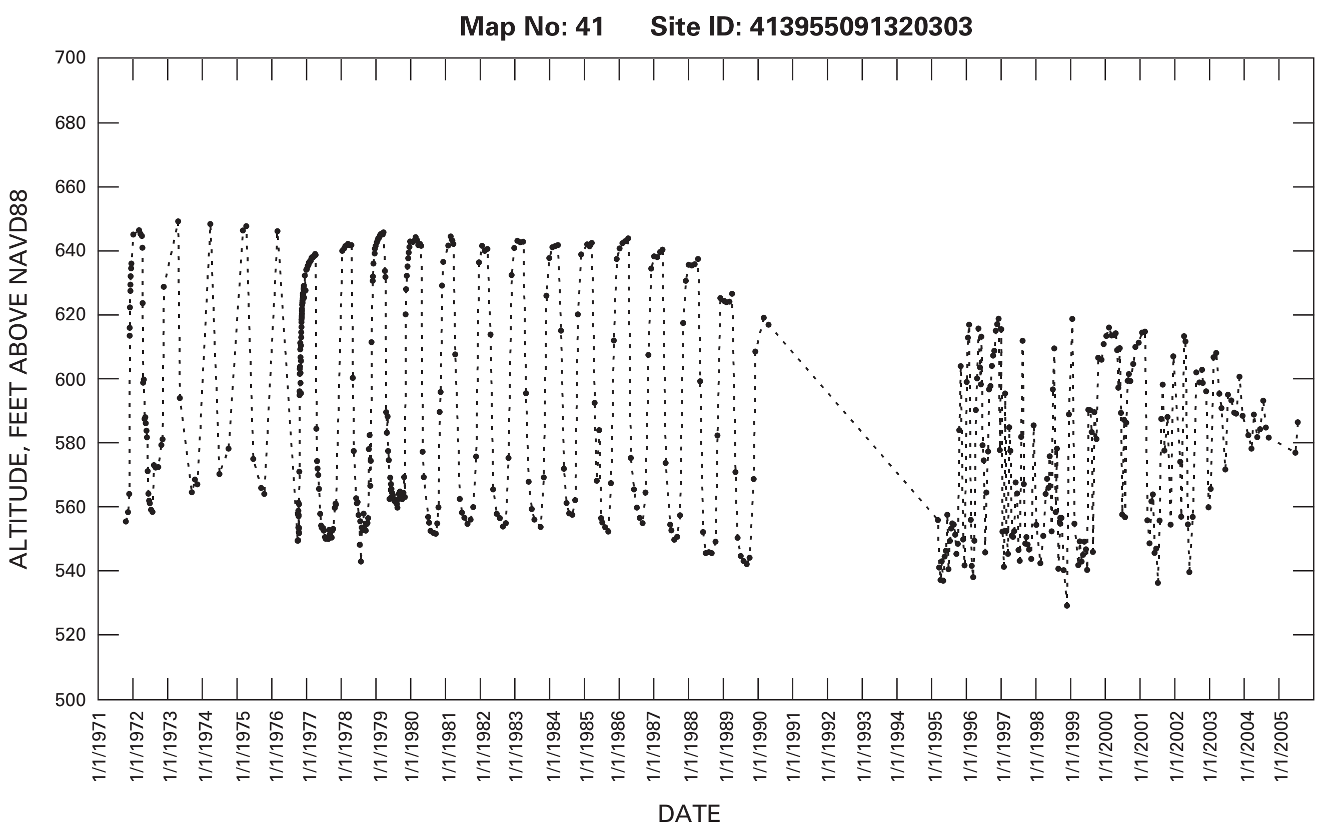
Map No: 41 Site ID: 413955091320303
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