

Recharge Area, Base-Flow and Quick-Flow Discharge Rates and Ages, and General Water Quality of Big Spring in Carter County, Missouri, 2000–04



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Cover photographs: U.S. Geological Survey gaging station on National Park Service wooden handrail bridge over Big Spring branch. A tow-behind acoustic Doppler current profiler used to make discharge measurements in the spring branch is tethered to bridge (left). Big Spring discharging from the base of dolostone bluff (upper right). Big Spring gaging station inundated by flood waters from the Current River, May 8, 2002 (lower right). Photographs by Michael J. Kleeschulte, U.S. Geological Survey.

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By Jeffrey L. Imes, L. Niel Plummer, Michael J. Kleeschulte, and John G. Schumacher

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Conversion Factors and Datum

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi ²)	259.0	hectare (ha)
Volume		
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m ³)
cubic foot (ft ³)	0.02832	cubic meter (m ³)
Flow rate		
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m ³ /d)
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)
mile per day (mi/d)	1.609	kilometer per day (km/d)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)
pound, avoirdupois (lb)	0.4536 x 10 ¹⁴	picogram (pg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
 $^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$

Vertical coordinate information is referenced to the “National Geodetic Vertical Datum of 1929 (NGVD 29).”

Horizontal coordinate information is referenced to the “North American Datum of 1927 (NAD 27).”

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Water year in U.S. Geological Survey reports dealing with surface-water supply is the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 2007, is called the “2007 water year.”

Recharge Area, Base-Flow and Quick-Flow Discharge Rates and Ages, and General Water Quality of Big Spring in Carter County, Missouri, 2000–04

Jeffrey L. Imes, L. Niel Plummer, Michael J. Kleeschulte, and John G. Schumacher

Abstract

Exploration for lead deposits has occurred in a mature karst area of southeast Missouri that is highly valued for its scenic beauty and recreational opportunities. The area contains the two largest springs in Missouri (Big Spring and Greer Spring), both of which flow into federally designated scenic rivers. Concerns about potential mining effects on the area ground water and aquatic biota prompted an investigation of Big Spring.

Water-level measurements made during 2000 helped define the recharge area of Big Spring, Greer Spring, Mammoth Spring, and Boze Mill Spring. The data infer two distinct potentiometric surfaces. The shallow potentiometric surface, where the depth-to-water is less than about 250 feet, tends to mimic topographic features and is strongly controlled by streams. The deep potentiometric surface, where the depth-to-water is greater than about 250 feet represents ground-water hydraulic heads within the more mature karst areas. A highly permeable zone extends about 20 mile west of Big Spring toward the upper Hurricane Creek Basin. Deeper flowing water in the Big Spring recharge area is directed toward this permeable zone. The estimated sizes of the spring recharge areas are 426 square miles for Big Spring, 352 square miles for Greer Spring, 290 square miles for Mammoth Spring, and 54 square miles for Boze Mill Spring.

A discharge accumulation curve using Big Spring daily mean discharge data shows no substantial change in the discharge pattern of Big Spring during the period of record (water years 1922 through 2004). The extended periods when the spring flow deviated from the trend line can be attributed to prolonged departures from normal precipitation. The maximum possible instantaneous flow from Big Spring has not been adequately defined because of backwater effects from the Current River during high-flow conditions. Physical constraints within the spring conduit system may restrict its maximum flow. The largest discharge measured at Big Spring during the period of record (water years 1922 through 2004) was 1,170 cubic feet per second on December 7, 1982.

The daily mean water temperature of Big Spring was monitored during water years 2001 through 2004 and showed little variability, ranging from 13 to 15 °C (degree Celsius). Water temperatures generally vary less than 1 °C throughout the year. The warmest temperatures occur during October and November and decrease until April, indicating Big Spring water temperature does show a slight seasonal variation.

The use of the traditional hydrograph separation program HYSEP to determine the base flow and quick flow or runoff components at Big Spring failed to yield base-flow and quick-flow discharge curves that matched observations of spring characteristics. Big Spring discharge data were used in combination with specific conductance data to develop an improved hydrograph separation method for the spring. The estimated annual mean quick flow ranged from 15 to 48 cubic feet per second for the HYSEP analysis and ranged from 26 to 154 cubic feet per second for the discharge and specific conductance method for water years 2001 to 2004.

Using the discharge and specific conductance method, the estimated base-flow component rises abruptly as the spring hydrograph rises, attains a peak value on the same day as the discharge peak, and then declines abruptly from its peak value. Several days later, base flow begins to increase again at an approximately linear trend, coinciding with the time at which the percentage of quick flow has reached a maximum after each recharge-induced discharge peak. The interval between the discharge peak and the peak in percentage quick flow ranges from 8 to 11 days for seven hydrograph peaks, consistent with quick-flow traveltime estimates by dye-trace tests from the mature karst Hurricane Creek Basin in the central part of the recharge area.

Concentrations of environmental tracers chlorofluorocarbons (CFCs: CFC-11, CFC-12, CFC-113), and sulfur hexafluoride in discharge from Big Spring vary approximately linearly with percent quick flow from about 5 to 45 percent of discharge. Linear extrapolation to 100 percent quick flow implies CFC and SF₆ concentrations nearly identical to those in the 2002 atmosphere and indicates a modern age for the quick-flow component. Tracer concentrations for less than

about 5 percent quick flow are increasingly lower than those expected from linear extrapolation to zero percent quick flow, indicating that the reservoir of older water in the Big Spring watershed may be a series of water mixtures with piston-flow ages greater than those obtained by extrapolation to zero percent quick flow. Each sample point with a low percentage of quick flow (less than 5 percent) may be a unique mixture.

Environmental tracer data from Big Spring plot intermediate to the simple binary mixing of modern and old, pre-tracer water and results from the exponential mixture model. The mean ages of waters in the base-flow component approximately range from 30 to 200 years. The mean age of the base-flow component is youngest (30 to 40 years) in samples containing the highest quick-flow component (45 percent quick flow) and increases to 200 years or more as the fraction of quick flow decreases to less than 5 percent. Tritium data are consistent with a model of dilution of a modern component with an old, pre-tracer component and indicates that the old fraction is mostly pre-1960s in age with mean residence time of more than several hundred years. All of the samples from Big Spring and Greer Spring have water temperatures warmer than their nitrogen-argon recharge temperature, which range from approximately 10.5 to 14 °C, suggesting recharge to the Big Spring watershed occurs primarily in late winter to early spring. The water temperatures at Big Spring are consistent with relatively shallow circulation (less than about 600 feet), and the water does not appear to be warmed by deep circulation along a geothermal gradient.

Specific conductance values and concentrations of most inorganic constituents in water samples from Big Spring generally decrease with increasing discharge because of dilution with quick-flow water of lower ionic strength. Concentrations of some constituents such as chloride and nitrite plus nitrate, and fecal coliform densities, however, did not decrease with increasing discharge, indicating that quick flow probably is a more important source of these constituents compared to base flow. Water samples from Big Spring plot along the line of dolomite dissolution by carbonic acid, are at equilibrium with dolomite and calcite, and have a molar ratio of Ca:Mg of near 1, indicating dissolution of the mineral dolomite as the primary control on concentrations of calcium, magnesium, and bicarbonate. The flux of calcium and magnesium from Big Spring represents the dissolution of about 1,950 cubic feet of dolomite per day. The suspended sediment load of Big Spring was estimated to range from about 1 to about 70 tons per day, and the sediment load during base-flow periods ranged from about 1 to about 7 tons per day.

Introduction

Big Spring (fig. 1) in Carter County, Missouri, emerges from an exposed hydraulic conduit at the base of a dolostone bluff along the western edge of the Current River floodplain (fig. 2). The spring water forms a pool about 200 ft (feet)

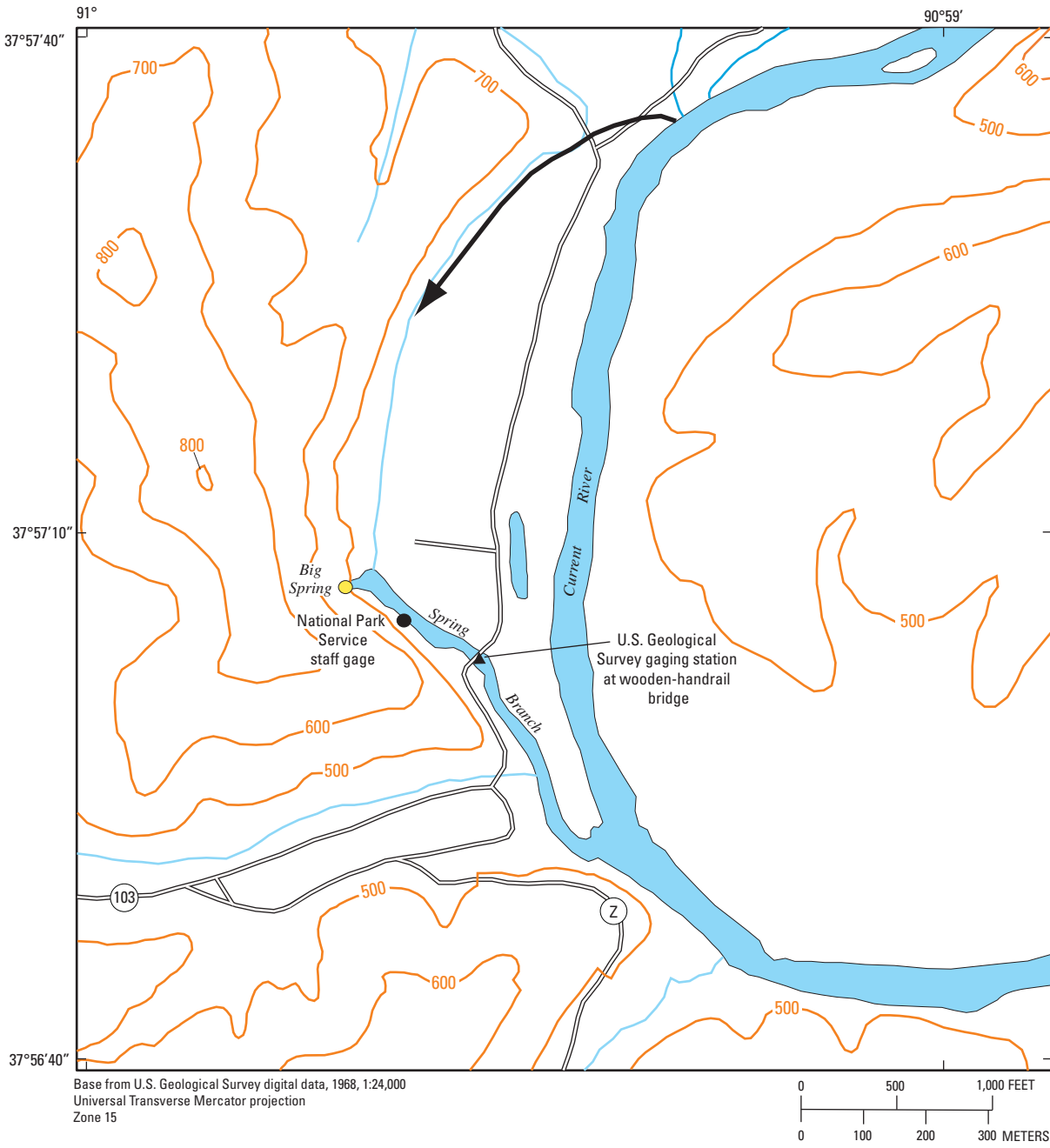


Photograph by Jeffrey L. Imes,
U.S. Geological Survey

Figure 1. Big Spring during a low-flow period in September 2001 at a daily mean discharge of 272 cubic feet per second.

in diameter before flowing southeasterly 2,000 ft along the spring branch to the main channel of the Current River. The alluvial valley and adjacent uplands near the spring are part of the Ozark National Scenic Riverways (ONSR), administered by the National Park Service (NPS). Visitors drive over the NPS small wooden-handrail bridge that spans the spring branch, park across from the spring pool, and walk along a well-maintained path to the spring orifice. The mean annual discharge of Big Spring is 445 ft³/s [(cubic feet per second); 288 million gallons per day; (Hauck and Harris, 2006)], sufficient discharge to create an impressive aural and visual display of power as the ground water is forcefully ejected from the bedrock. Vineyard and Feder (1982) give an overview of Big Spring and its related karst features.

Water is transmitted to Big Spring through rocks that form part of the Ozark aquifer (Imes, 1990a), the most productive aquifer in the Ozark Plateaus aquifer system (Imes and Emmett, 1994) of southern Missouri. The Ozark Plateaus aquifer system rests on granite and rhyolite rocks of Precambrian age that form the Basement confining unit (fig. 3). The Basement confining unit nearly is impermeable except where faults and fractures are present or where it crops out and has been extensively weathered. Well yields in these more permeable areas commonly are less than 10 gallons per minute. Isolated knobs are common on the eroded Precambrian surface and may extend hundreds of feet into the overlying bedrock. The St. Francois aquifer (Imes, 1990b) overlies the Basement confining unit and consists of the Lamotte Sandstone and the Bonneterre Formation. Where the St. Francois aquifer is near land surface, the aquifer yields adequate supplies of water for domestic and small-capacity public-supply wells. The St. Francois confining unit (Imes, 1990c) overlies the St. Francois aquifer and is formed by the Davis Formation and the Derby-Doerun Dolomite. The St. Francois confining unit is composed



EXPLANATION



-  **Topographic contour**—Shows altitude of land surface. Contour interval is 100 feet. Datum is North American Vertical Datum of 1927
-  **Flow path**—Flow path of flood waters from the Current River



Figure 2. Topographic map of Big Spring vicinity showing selected features.

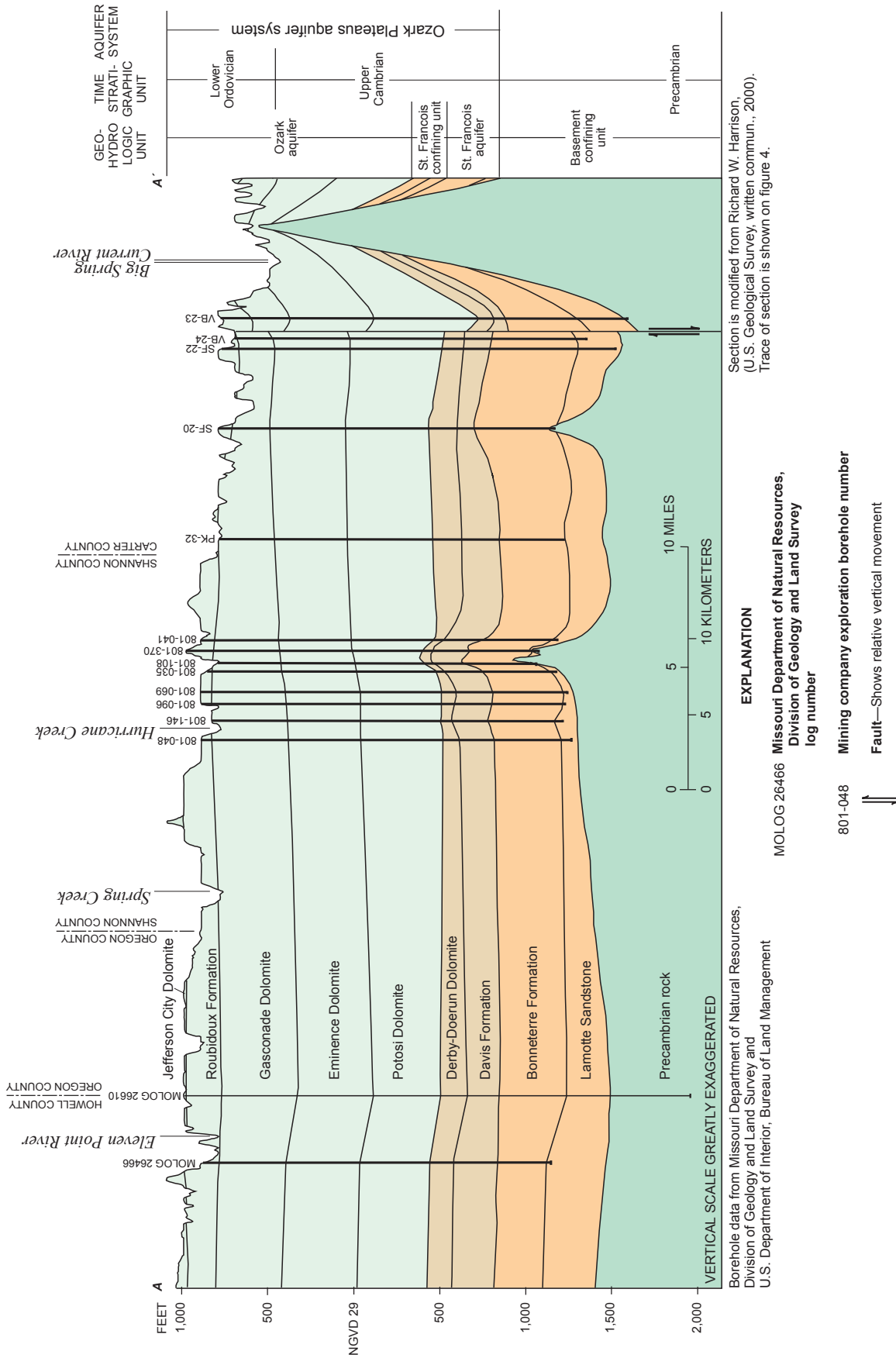


Figure 3. Generalized geohydrologic section from eastern Howell County to eastern Carter County through the Big Spring and Greer Spring recharge areas.

of dense, fine-grained carbonate rock and shale with little primary permeability, and is an effective barrier to ground-water flow between the St. Francois aquifer and Ozark aquifer. Near Big Spring, the overlying and uppermost Ozark aquifer consists of the Potosi Dolomite, Eminence Dolomite, Gasconade Dolomite, Roubidoux Formation, and Jefferson City Dolomite. The predominantly dolostone aquifer contains some thick sandstone units and is the most productive and widely used aquifer in southern Missouri. The Ozark aquifer supplies water to numerous springs in southern Missouri, including several springs that are among the largest in the United States.

Historic dye-trace investigations (fig. 4) in the region show that water flowing to Big Spring originates as precipitation that falls on the Ozark aquifer in drainage basins west of the spring. The general extent of the Big Spring recharge area is known from potentiometric mapping and dye-trace investigations, but the precise boundaries of the recharge area are not well defined in some areas. The difficulty in defining the recharge area is caused by the mature karst terrain that created the spring. Spring recharge areas cannot simply be delineated from the topographic surface-water divides that contain the spring.

In karst areas, subsurface interbasin transfer of water from one surface-water drainage basin to another is common. In the absence of karst, precipitation that falls in a particular watershed becomes recharge to the ground-water flow system and normally would flow through permeable bedrock or alluvium and discharge to streams within the same basin. The presence of a mature karst terrain can increase the quantity of precipitation that recharges the ground-water flow system and also can increase the flow rate of ground water through the bedrock. If the extent of the karst is sufficiently large to cross surface-water divides, an interbasin transfer of ground water can occur. Consequently, precipitation falling in one surface-water basin can be discharged in a neighboring basin.

The karst terrain present throughout the Big Spring recharge area was formed principally by the dissolution of the carbonate bedrock and is characterized by sinkholes, vertical joints, losing streams, caves, and springs linked by a complex underground drainage system of fractures and conduits. Sinkholes are formed when bedrock is dissolved by slightly acidic ground water and bridged rock and soil overburden collapse into the resulting void. Losing streams occur where areas of high streambed hydraulic conductivity exists in combination with ground-water levels below the streambed elevation. This causes a substantial part of the stream to flow through the streambed into the bedrock. For more information, a report by Orndorff and others (2006) gives a detailed description of how the Ozark karst system may have developed.

Most of the land in the recharge area west of Big Spring is part of the Mark Twain National Forest (fig. 4). The surface rights to the forest are administered for the public by the U.S. Department of Agriculture, Forest Service (FS), and the subsurface rights are administered by the U.S. Bureau of Land Management (BLM). Smaller areas of private land holdings are scattered throughout the forest.

Southeastern Missouri has been a prominent lead-mining area since shortly after the first French explorations occurred in the area in about 1700. During the 1700s, lead mining was conducted on a small scale and the first mines were mostly surface diggings performed with pick and shovel by manual labor. Additional mines were opened during the 1800s, especially after the Civil War fueled an increased need for lead. By 1900, a network of surface and shallow subsurface mines (several hundred feet below the ground surface) were in operation throughout the area now known as the Old Lead Belt (fig. 4). By the 1940s, lead reserves in the Old Lead Belt were seriously depleted and the exploration for new lead reserves moved west. Lead ore was discovered near Eminence in the late 1950s, and in the Viburnum Trend in the 1960s. The shallower (500 to 1,500 ft deep) Viburnum Trend discoveries were developed first and eventually 10 mines were opened (Burford, 1978; Warner and others, 1974).

In anticipation of future declining reserves of lead ore in the Viburnum Trend, mining companies continued to explore the area south of Winona and north of the Eleven Point River (fig. 4). More than 300 exploration boreholes have been drilled in this exploration area since the 1980s. Much of the exploration has occurred in the Mark Twain National Forest under prospecting permits issued by the FS and BLM. The exploration area is within a region, highly valued for its scenic beauty and recreational opportunities, which more than 2 million people visit annually. The focus of this exploration has been ancient reef structures associated with buried Precambrian knobs beneath the Spring Creek and Hurricane Creek basins (Kleeschulte and Seeger, 2000). Hurricane Creek is a major losing stream located within the recharge area of Big Spring.

Greer Spring, the second largest spring in Missouri, with an annual mean discharge of 342 ft³/s [(221 million gallons per day; (Hauck and Harris, 2006)] is located at the southern edge of the exploration area within the Eleven Point National Wild and Scenic River (EPNWSR), which is administered by the FS (fig. 4). Based on dye-trace studies and water-level maps [unpublished data on file at the USGS (U.S. Geological Survey) office, Rolla, Missouri], the primary recharge area of Greer Spring may be about 25 mi northwest of the spring at the western edge of the exploration area.

Several smaller springs are present along three streams (Eleven Point River, Spring Creek, and Hurricane Creek; fig. 4) that flow through or near the exploration area. There are concerns that mine dewatering in this area could lower water levels and cause a decrease in ground-water discharge to the springs. The presence of losing streams in the exploration area is of concern because contaminants released during mining activities or from stored mine waste (tailings piles) potentially could migrate into the ground-water flow system, degrade the quality of water at the nearby springs, and threaten aquatic biota. The investigation of Big Spring is part of a larger investigation of the geology, hydrology, and aquatic biology of the exploration area and Viburnum Trend initiated in response to these environmental concerns (Imes, 2002).

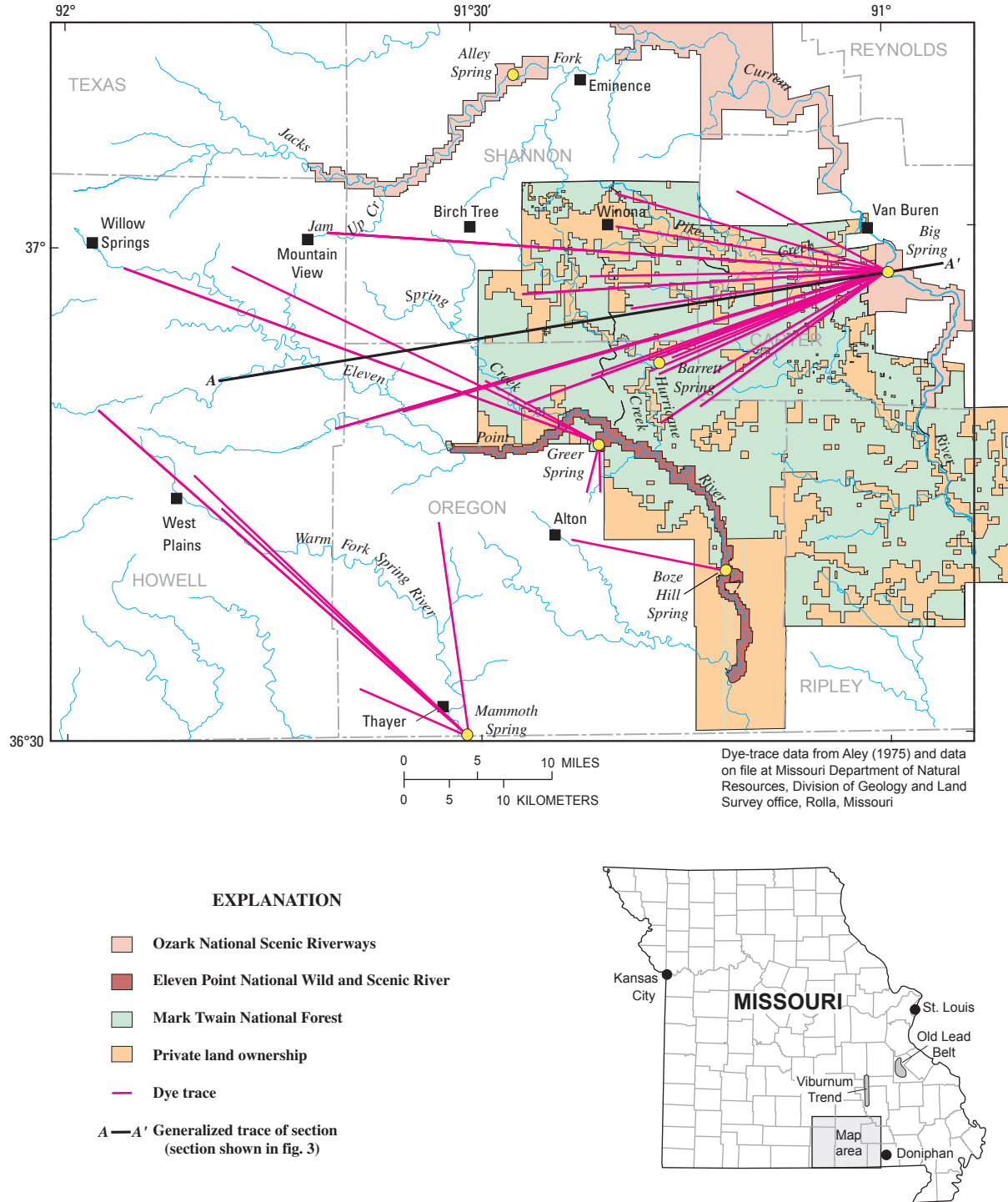


Figure 4. Results of dye-trace investigations that successfully identified a hydrologic connection between a sinkhole or losing stream reach and a major spring.

Purpose and Scope

This report characterizes different aspects pertaining to the general hydrology of Big Spring and includes a delineation of the possible recharge area for Big Spring, a description of

the physical characteristics of the spring and results of hydrograph separation methods used to determine the base-flow and quick-flow components of Big Spring discharge, age dating of the Big Spring base-flow and quick-flow components from isotope data, and the determination of the water-quality,

carbonate-aquifer dissolution rates, and suspended sediment loads. The data collection for this report included the recharge area for Big Spring with the most intense data collection effort occurring at the spring and along the spring branch (fig. 2). The possible recharge areas for adjacent large springs in the region also were defined as a result of data collected during this study. Whereas Big Spring discharge data used in this report span almost the entire period of record (1922 to 2004), most of the analyses were done using hydrologic information collected during water years 2000 to 2004. Water year in U.S. Geological Survey reports is the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months.

Previous Investigations

The unique mature karst geology of the region has initiated many geohydrologic studies over the decades by many land management agencies, academia, and scientists. Some of these studies were general and were intended to give a broad overview of the geohydrology of the area or document existing conditions. Other studies were conducted for more specific purposes. The following discussion provides a basic understanding of the hydrologic information previously collected from the region.

Many dye-tracing investigations have been conducted in the region to determine ground-water flow directions and time of travel. Some of the earliest dye traces were reported by Aley (1975; data on file at the Missouri Department of Natural Resources, Division of Geology and Land Survey) as part of a predictive hydrologic model that was developed for the area. These dye traces generally were conducted using fluorescein dye; however, occasionally stained *Lycopodium* spores were used. All results were determined by visual detection. Thirty-four dye traces were tabulated (Aley, 1975), showing injection and recovery locations, time of travel, straight line distances, and altitude of injection to recovery sites. The results of these dye traces helped to better define the recharge area of both Big Spring and Greer Spring. A dye-trace investigation conducted by the USGS using rhodamine-WT dye and a scanning spectrofluorophotometer as the dye-detection device was performed as a part of another study, and verified a previous trace performed by Aley (Imes and Fredrick, 2002).

The USGS determined ground-water altitudes and seasonal ground-water fluctuations in the study area by measuring the depth-to-water in 57 wells during the spring and fall from 1990 through 1993. The water-level data were used in conjunction with the previously available dye-trace data to determine ground-water flow directions in the area between the exploration area and Big Spring and to further identify areas of mature karst development where water is rapidly transported to Big Spring (Imes and Kleeschulte, 1995). Continuous water-level recorders also were installed on three deep wells during the study to assess the seasonal response of water levels in the wells.

A seepage run (a series of stream discharge measurements made in a short period of time) was conducted in 1995 during a base-flow period (minimum streamflow and minimum daily fluctuations) in the Eleven Point River, Spring Creek, and Hurricane Creek (Kleeschulte, 2000). Losing stream reaches and areas of ground-water discharge to streams were identified. No losing reaches were identified in the mainstem of the Eleven Point River, but the upstream reaches of Spring Creek and Hurricane Creek contain losing stream reaches. Dye-trace information confirms water lost by Hurricane Creek flows eastward through the ground-water flow system, beneath a surface-water basin divide and eventually discharges at Big Spring.

In a series of reports (Kleeschulte and Seeger, 2000; 2001; and 2003), the confining ability of the St. Francois confining unit was assessed in three separate areas (exploration area, region between Big Spring and the exploration area, and Viburnum Trend). Based on the calculated vertical hydraulic conductivity ranges, the St. Francois confining unit is considered "tight" in all three areas as compared to the ranges in the adjacent aquifers. However, in relation to each other, the confining unit in the exploration area has the smallest vertical hydraulic conductivity and the unit in the Viburnum Trend is the most conductive. Other studies (Warner and others, 1974; and Kleeschulte, 2001) have concluded no apparent large cones of depression have developed in the potentiometric surface of the Ozark aquifer as a result of mining activity in the Viburnum Trend. Therefore, using similar mining practices as those along the Viburnum Trend, no large cones of depression in the Ozark aquifer would be expected in the exploration area, unless preferred-path secondary permeability has developed along faults or fractures or resulted from exploration activities (Kleeschulte and Seeger, 2003).

Recharge Area of Big Spring

Two extensive synoptic water-level measurements were made in and around the estimated recharge areas of Big Spring and Greer Spring (as inferred from previous dye-tracing investigations and limited potentiometric mapping) to better define the recharge areas of these springs. The area in which water levels were measured also was large enough to include Boze Mill Spring and part of the Mammoth Spring (fig. 4) recharge area. Water levels were measured or observed in 346 wells and 7 springs during the summer and fall of 2000 (table 1, at the back of this report). The altitudes of water levels in these wells and the altitude of several springs reported in table 1 were used in the construction of potentiometric maps. The 24.5 inches of measured rainfall in 2000 at Alley Spring [fig. 4, about 10 mi (miles) north of the Big Spring recharge area] was 17.5 inches less than the normal annual rainfall of 42 inches per year, and reflected the drought conditions that began in late summer 1999 (University of Missouri—Columbia, 2006) and generally dry conditions experienced to fall 2001.

8 Recharge Area, Discharge Rates and Ages, and Water Quality of Big Spring in Carter County, Missouri, 2000–04

Ground-water levels generally were low because of these dry conditions and even lower in areas drained by karst features in the mature karst terrain.

The locations of measured wells and springs (table 1) are shown by latitude and longitude coordinates and by the local site number, which follows the General Land Office coordinate system (fig. 5). According to this system, the first three sets of numbers representing a site location designate township, range, and section. The letters that follow indicate quarter section, quarter-quarter section, and quarter-quarter-quarter section. The quarter sections are represented by letters A, B, C, and D in counterclockwise order, starting in the northeastern quadrant. Land-surface altitude at the wells and springs were determined by interpolating contour data on 7.5-minute topographic maps and are considered accurate to one-half the contour interval, which is generally plus or minus 10 ft. Well construction information usually is difficult to obtain for the older domestic wells encountered during the well survey. Total well depth is known for 210 of the wells with measured water levels, and casing depth is known for 74 of the wells.

The total well depth and the open interval of the well bore can be used to determine if the water level in the well is a good approximation of the water table or is more representative of the potentiometric surface of a deeper part of the aquifer. During this study, the depth to ground water in the measured wells ranged from 0 to more than 400 ft. In areas with little or no karst development, the depth to water commonly ranges from only a few feet in perennial stream valleys to as much as 150 ft in upland areas. The depth to ground

water in areas underlain by karst can exceed 150 ft, with the greater depths to water occurring in upland areas and areas of more mature karst development. Zero depth-to-water values in table 1 indicate data from springs. The land-surface altitude of springs is assumed to represent the approximate altitude of the water table.

The measured depth-to-water during the summer of 2000 ranged from 2.1 to 448.4 ft, but exceeded 200 ft in most wells in the headwater areas of the Eleven Point River, Spring Creek, Hurricane Creek, and Pike Creek (table 1; fig. 4). These upland areas have land-surface altitudes ranging from about 900 to 1,200 ft and are areas of mature karst that supply water to Big Spring (altitude 413 ft) and Greer Spring (altitude 565 ft). Depth-to-water ranged from 200 to 300 ft in several wells along the Warm Fork Spring River near West Plains and in a small area west of the Eleven Point River near Boze Mill Spring. Land-surface altitudes range from about 750 to about 1,100 ft in the Warm Fork Spring River area, which supplies water to Mammoth Spring (altitude 506 ft). Land-surface altitudes range from about 750 to about 950 ft in the upland recharge area of Boze Mill Spring (altitude 438 ft). Ground-water flow directions and the approximate extent of the recharge area for four large springs (Big Spring, Greer Spring, Mammoth Spring, and Boze Mill Spring) were determined using historic dye-trace data, measured depth to water, and mapped water-level altitudes (fig. 6). The estimated sizes of the spring recharge areas are 426 mi² (square miles) for Big Spring, 352 mi² for Greer Spring, 290 mi² for Mammoth Spring, and 54 mi² for Boze Mill Spring. The designated recharge areas are only meant to be suggestive of the actual spring recharge areas, which can only be more precisely determined by more detailed mapping of vertical and horizontal changes in ground-water levels and additional dye-trace investigations.

Depth-to-water measurements indicate that at least two distinct potentiometric surfaces are represented by the data set. However, several factors make it difficult to determine which potentiometric surface a particular water-level measurement represents. Most wells are open to several hundred feet of the aquifer, and well completion depths and well casing depths are not known for many of the wells. The Ozark aquifer is not homogeneous, and different geologic formations or parts of formations that comprise the aquifer can have considerably different hydraulic conductivity. The vertical and lateral extent of karst in the aquifer and the maturity of the karst are not known in detail, but can have considerable effect on potentiometric head and ground-water flow. Despite these complexities, two distinct potentiometric surfaces can be inferred from the water-level data. A shallow potentiometric surface representing water table or near water-table conditions can be mapped using water levels where the depth-to-water is less than about 250 ft (fig. 6). A deeper potentiometric surface representing ground-water hydraulic heads within the more mature karst areas can be mapped using water levels where the depth-to-water is greater than about 250 ft (fig. 7).

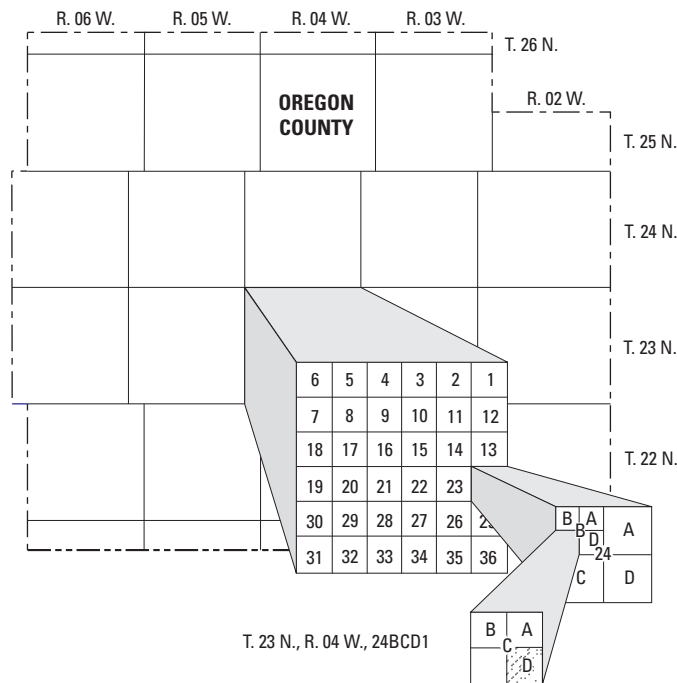
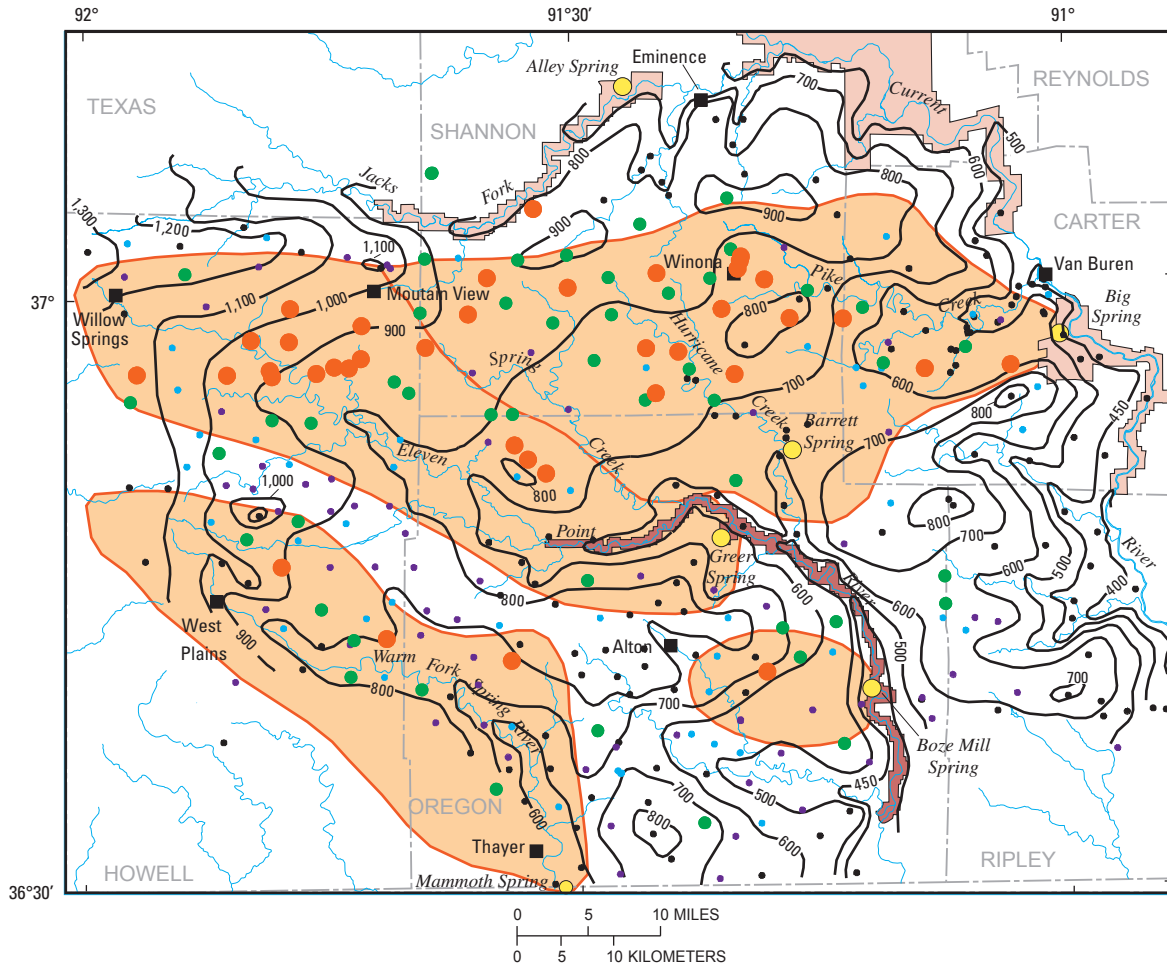


Figure 5. General Land Office coordinate system.



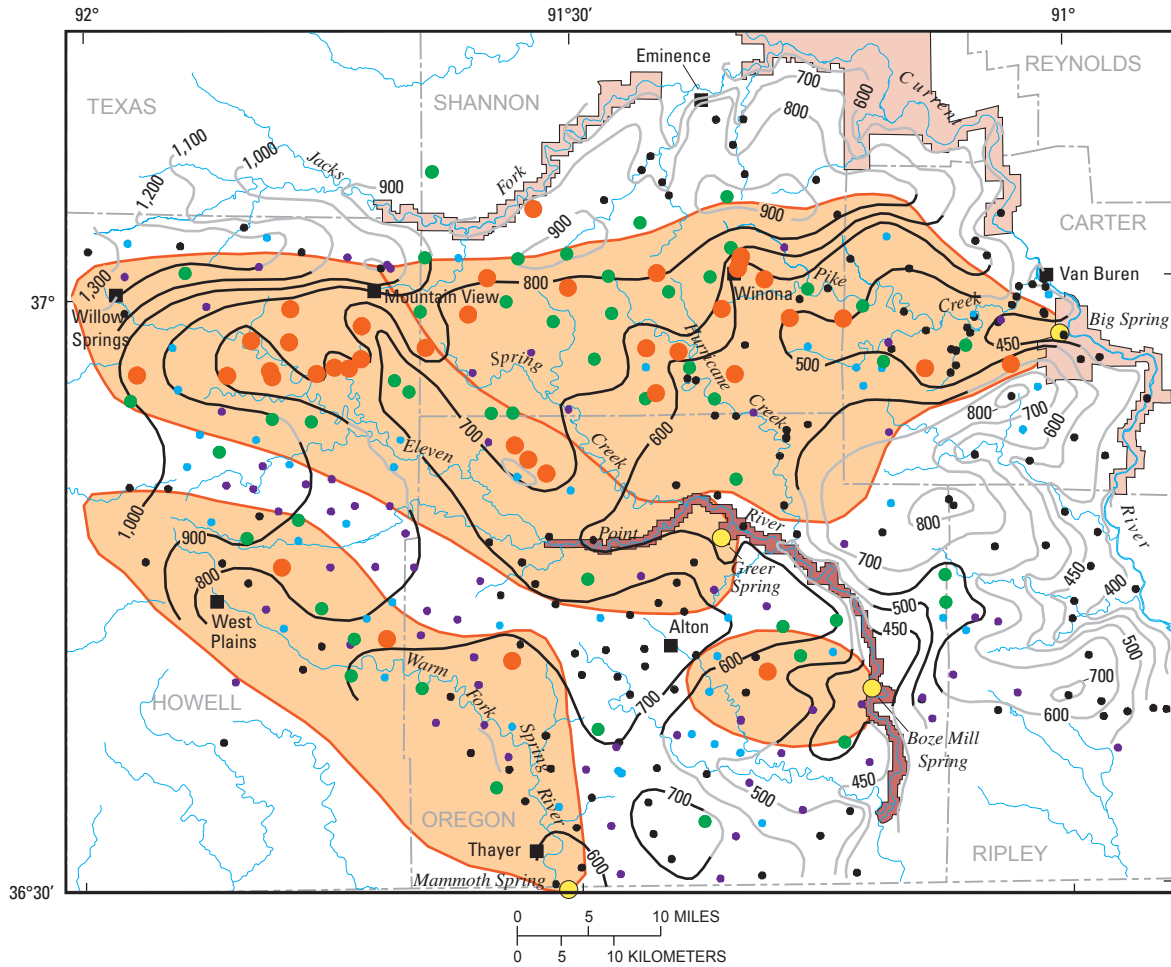
EXPLANATION

- | | | |
|--|---|--|
| | Ozark National Scenic Riverways | Depth to ground water, in feet, summer 2000 |
| | Eleven Point Wild and Scenic River | • 0 to 100 |
| | Approximate spring recharge area | • 100 to 150 |
| | — 500 — Potentiometric contour—Shows altitude of shallowest water levels in the Ozark aquifer. Contour interval is variable. Datum is NGVD 29 | • 150 to 200 |
| | | • 200 to 250 |
| | | • Greater than 250 (not used) |

Figure 6. Shallow measured potentiometric surface of the Ozark aquifer, summer 2000.

The shallow potentiometric surface (fig. 6) is distinctly different in the less well-developed karst areas and along the major rivers as compared to the potentiometric surface in the more mature karst areas within the delineated recharge areas. Water levels tend to mimic topographic features and are strongly controlled by streams along the Jacks Fork and Current River in the northern part of the map area, throughout most of the Current River Basin downstream from Big Spring, in the lower Eleven Point River Basin from about 30 mi upstream from Greer Spring; and in the lower Warm Fork Spring River Basin. In the recharge areas of Big Spring and

Greer Spring where mature karst features are present, water levels in many places do not mimic topographic features and generally are not controlled by the smaller streams. Spring Creek, Hurricane Creek, and Pike Creek are losing streams except near their mouths. Shallow ground-water flow in the central and eastern parts of the mature karst moves beneath these streams and discharges only at the extreme lower reaches of these streams. Shallow ground-water flow in the headwaters of the Eleven Point River (the western part of the mature karst area) appears to occur at depths as great as 300 ft beneath the streambed surface. The potentiometric map indicates that this



EXPLANATION

- Ozark National Scenic Riverways
- Eleven Point Wild and Scenic River
- Approximate spring recharge area
- 500 — Potentiometric contour—Black contour shows altitude of deep water levels in the Ozark aquifer. Gray contours show where mature karst is absent and represent the shallow potentiometric surface. Contour interval is variable. Datum is NGVD 29
- 0 to 100
- 200 to 250
- 100 to 150
- 150 to 200
- Greater than 250 (used to draw black contours)

Figure 7. Deep potentiometric surface of the Ozark aquifer, summer 2000.

ground-water flow is toward lower reaches of the Eleven Point River. Shallow ground-water in the Warm Fork Spring River Basin flows into the middle and lower reaches of Warm Fork Spring River.

A deep potentiometric surface (fig. 7) is identifiable with the maturely developed karst areas. In the eastern part of the Big Spring recharge area, a trough (identified by the 500-ft potentiometric contour) indicates the presence of a deep, highly permeable zone extending about 20 mi west of Big Spring toward the upper Hurricane Creek Basin. The potentiometric head in the western part of this trough area is about 150 to 250 ft lower than the head in

the shallower strata, and ground water in the Big Spring recharge area is directed toward this permeable zone and discharges at Big Spring. In contrast, lateral ground-water flow in the shallower strata is toward the lower reach of Pike Creek. In the absence of the mature karst, ground water from the western parts of the Big Spring recharge area would likely flow toward Spring Creek and Hurricane Creek. Increased permeability associated with the mature karst causes deeper ground water to flow more easterly beneath the upper reaches of Spring Creek and Hurricane Creek toward the deep ground-water trough to discharge at Big Spring.

Indications are of a deep, highly permeable zone (defined by the 600-ft through 800-ft contours) extending about 10 mi west of Greer Spring, then trends to the northwest about 20 mi to an area of intensive karst development between and south of Willow Springs and Mountain View. This area comprises the northwestern end of the long and narrow Greer Spring recharge area. The ground-water trough, associated with this permeable zone appears to approximately parallel the upper dry reaches of the Eleven Point River. Whereas ground water flowing through shallower rocks in northern Howell County converges toward the headwater reaches of the Eleven Point River, deeper flowing ground water converges towards the deep permeable zone in eastern Howell County and eventually discharges at Greer Spring.

Deep flowing water in the Warm Fork Spring River Basin apparently flows beneath the river to discharge at Mammoth Spring. The lack of interbasin transfer of ground water in the Mammoth Spring recharge area (Warm Fork Spring River Basin) may indicate that the karst terrain of this area is not as well developed as in the Big Spring and Greer Spring recharge areas.

The southern one-half of the common boundary of the Big Spring and Greer Spring recharge areas depicted in figures 6 and 7 may not accurately portray the complexities of the ground-water flow pattern. Dye-trace investigations indicate the possibility of overlapping recharge areas in this region. Dye from two traces from the headwater areas of Eleven Point River near Willow Springs in northern Howell County was recovered at Greer Spring, and dye from three traces from the Eleven Point Basin in the northwestern corner of Oregon County was recovered at Big Spring (fig. 4). The straight line paths from the injection to recovery points cross. The traces to Greer Spring were conducted in 1972 and 1975 using fluorescein dye and visual detection methods. The traces to Big Spring were conducted in 1971 and 1972 using fluorescein dye and stained Lycopodium spores (Aley, 1975) using visual detection methods. None of the traces have been verified using state-of-the-art fluorescence detection instruments. The deep potentiometric surface map, measured water levels, and dye-trace data indicate the possibility of a low-gradient ground-water flow path from the lowest reach of Spring Creek and Eleven Point River immediately upstream from Spring Creek (water level at about 600-ft altitude) to the 500-ft contour bounding the deep ground-water trough west of Big Spring. The two lowest measured water levels at Hurricane Creek along this path are 566 and 579 ft, which is consistent with the possibility of flow to the northeast between these areas. However, the available data are not sufficient to map the potentiometric head in this area with the accuracy necessary to show such a flow path clearly, nor are they sufficient to show the underflow or overflow path that must be present for ground water to flow from the Eleven Point River dye injection sites in northwestern Oregon County to the vicinity of the lower reach of Spring Creek without being captured by the Greer Spring recharge area. More potentiometric head data and successful dye traces in this complex region are required to fully understand the ground-water flow pattern.

Water levels generally decreased across the area from summer to fall 2000 (table 1). Of the 303 wells in table 1 that were measured twice, 277 sites showed a water-level decline. Most of these wells (233 wells) had declines of less than 20 ft and were scattered evenly throughout the area. However, 29 wells had declines between 20 and 40 ft; these sites were concentrated on the western side of the study area in the Warm Fork Spring River Basin and the headwaters of the Eleven Point River. Another 15 wells had declines 40 ft or greater (40 to 141 ft). Two of these were in the proposed recharge area for either Big Spring or Greer Spring and the rest were primarily in the Warm Fork Spring River Basin. Despite the extremely dry conditions, of the 26 wells that had a water level increase from summer to fall 2000, most of them were in the eastern one-half of the study area. The largest increase was 58.6 ft; however, most of these wells (20 wells) had water-level increases of less than 20 ft. Because the wells that had a water level increase in the fall 2000 water-level measurements were scattered across the study area and essentially isolated from each other, no changes were made to the possible spring recharge areas based on the fall 2000 data.

Physical Characteristics of Big Spring

The flow from Big Spring has been monitored for several decades using a combination of manual discharge measurements and staff-gage readings. Because of the large size and complexity of the Big Spring flow system and the complexity of the interaction among the spring discharge water, spring branch, and Current River, the accuracy of the discharge estimates made using the spring rating curve and staff measurements vary considerably for different hydrologic conditions. The spring branch was instrumented to continually measure water temperature and specific conductance in October 2000 and water velocity in June 2001. These measurements were analyzed in combination with the standard discharge measurements to provide insights on the nature of the Big Spring flow system and to devise a method to make more accurate discharge estimates.

Measurement of Discharge

The daily mean Big Spring discharge computation is based on a stage-discharge relation. The daily mean gage height (stage at Big Spring) is measured and then converted to discharge based on discharge measurements made at various gage heights according to methods described by Rantz and others (1982). The USGS, in cooperation with the NPS, has been collecting gage-height and discharge data at Big Spring near Van Buren (USGS station number 07067500) since 1921. Prior to October 1923, the data were published as Big Spring near Chicopee (Hauck and Harris, 2006). Before 1925, the computed daily discharge was derived from discharge measurements and staff readings taken two to three times a week.

Discharge was interpolated for the days when the staff was not read. Beginning in 1925, an attempt was made to read the staff daily, although through the rest of the 1920's the discharge data were fragmented with many days of missing data. This was either because no staff reading was made for the day or because the staff was in backwater from the Current River during high-flow conditions. By the 1930's, daily discharges were commonly computed for each day. A water-stage recording gage was installed in the spring branch in February 1971 and was maintained until March 1978. However, because of lack of funding, daily staff readings were again used to compute daily discharge for March 1978 until September 1996. Data collection at the spring was discontinued from September 1996 until February 2000, when data collection was again resumed.

The accumulated daily mean discharge of Big Spring was plotted with time for the historic period of record (water years 1922 through 2004) to identify variations in the spring discharge (table 2, at the back of the report; fig. 8). Variations in discharge rates can be caused by land-use changes, extreme or prolonged wet or dry periods, or physical changes in the spring conduit system. The linear regression trend line represents the expected accumulated flow over time if the daily mean discharge were constant every day (mean annual discharge; fig. 8). Data above the trend line indicate an increase in observed discharge compared to expected discharge, and data below the trend line indicate a decrease in observed discharge.

The accumulated daily mean discharge curve shows no substantial change in the discharge pattern of Big Spring during the period of record. However, the spring discharge deviated from the trend line for extended periods. A plot of the accumulated departure from normal precipitation and Big Spring residual discharge (the observed accumulated discharge minus expected accumulated discharge from the linear regression trend line) for water years 1922 through 2004 clarifies the cause of the deviations (fig. 8). Regional annual precipitation summary data (National Oceanic and Atmospheric Administration, 1922–2004) were used when available. On rare occasions when regional data were not reported for the Ozarks Plateaus, Southeast Region, or East Ozarks, more localized rainfall data from the cities of Birch Tree, Van Buren, or Doniphan were used (table 2 and fig. 4). Observed long-term variations in spring discharge can be attributed to prolonged departures from normal precipitation (fig. 8). During extended periods of above normal precipitation, the observed accumulated spring discharge generally is larger than predicted by the trend line, and during prolonged periods of drought, the observed accumulated spring discharge generally is smaller than predicted by the trend line.

Historically, the quality of the computed discharge from Big Spring has been impaired by two factors. During low-flow conditions, especially in the warm summer months, thick watercress beds growing in the spring branch impede the natural movement of the flowing water. This temporary obstruction causes a higher gage-height reading for a particular flow (backwater) than would normally occur during flow conditions

without obstructions. Another backwater condition occurs during high-flow conditions in the Current River. The storms that cause the spring flow to increase also typically cause flow to increase in the Current River. Because the spring branch is short (2,000 ft) and the fall between the spring and the river is only about 5 to 6 ft, the rising Current River dams water at the mouth of the spring branch during high stages. The spring gaging station on the downstream side of the NPS bridge is affected by backwater after about a 2-ft rise on the Current River. Consequently, during low flow when the watercress beds are extremely thick in the spring branch and when the Current River has increased flow, the stage-discharge relation is inaccurate.

Gage heights measured at the NPS staff gage located in the spring pool about 400 ft upstream from the USGS gaging station on the NPS bridge from October 2, 2001, to December 17, 2002, clearly shows the backwater effect caused by a rising Current River (fig. 9). The water-level difference (fall) between the NPS staff and USGS gage decreases linearly from about 0.5 to 0.1 ft when the gage height at the NPS bridge ranges from 1.0 to 3.0 ft. Above a gage height of 4.0 ft at the bridge, the difference between the water levels at the two locations becomes too small to measure accurately and the spring branch appears to be pooled. The timing of the transition from free-flowing to backwater conditions is dependent on the areal distribution of rainfall in the spring recharge area and river basin and the time when the flow begins to increase in both.

Additional complications caused by backwater from a rising Current River occur when determining Big Spring discharge at gage heights above about 9.5 ft at the bridge. Above this gage height, water from the river flows over its banks about 3,000 ft upstream from Big Spring and enters a shallow slough that lies adjacent to the bluff that bounds the western edge of the Current River alluvial valley (fig. 2). This water flows in the slough toward Big Spring and enters the spring pool immediately downstream from the spring. The slough water (Current River water) mixes with the spring discharge before flowing under the NPS bridge where high-flow discharge measurements are made. Unless the contribution of river flow can be determined and subtracted from the flow measured at the bridge, the spring discharge cannot be accurately determined. When the gage height at the bridge reaches about 11 ft, the entire area is inundated, and spring discharge measurements cannot be made by conventional methods.

Determining the maximum flow from the spring because of the backwater effect has been a concern since the beginning of the period of record. Without a discharge measurement, the assigned daily mean discharges were considered to be estimates at best during periods of high gage height. From 1921 until December 1982, the highest estimated daily discharge for the period of record (water years 1922 through 2004) was 1,300 ft³/s for "sometime in June 1928 during period of backwater from Current River" (Wells, 1955). The largest measured discharge at Big Spring during the period of record was 1,170 ft³/s on December 7, 1982. Because the gage height had decreased substantially from the peak 4 days earlier, the

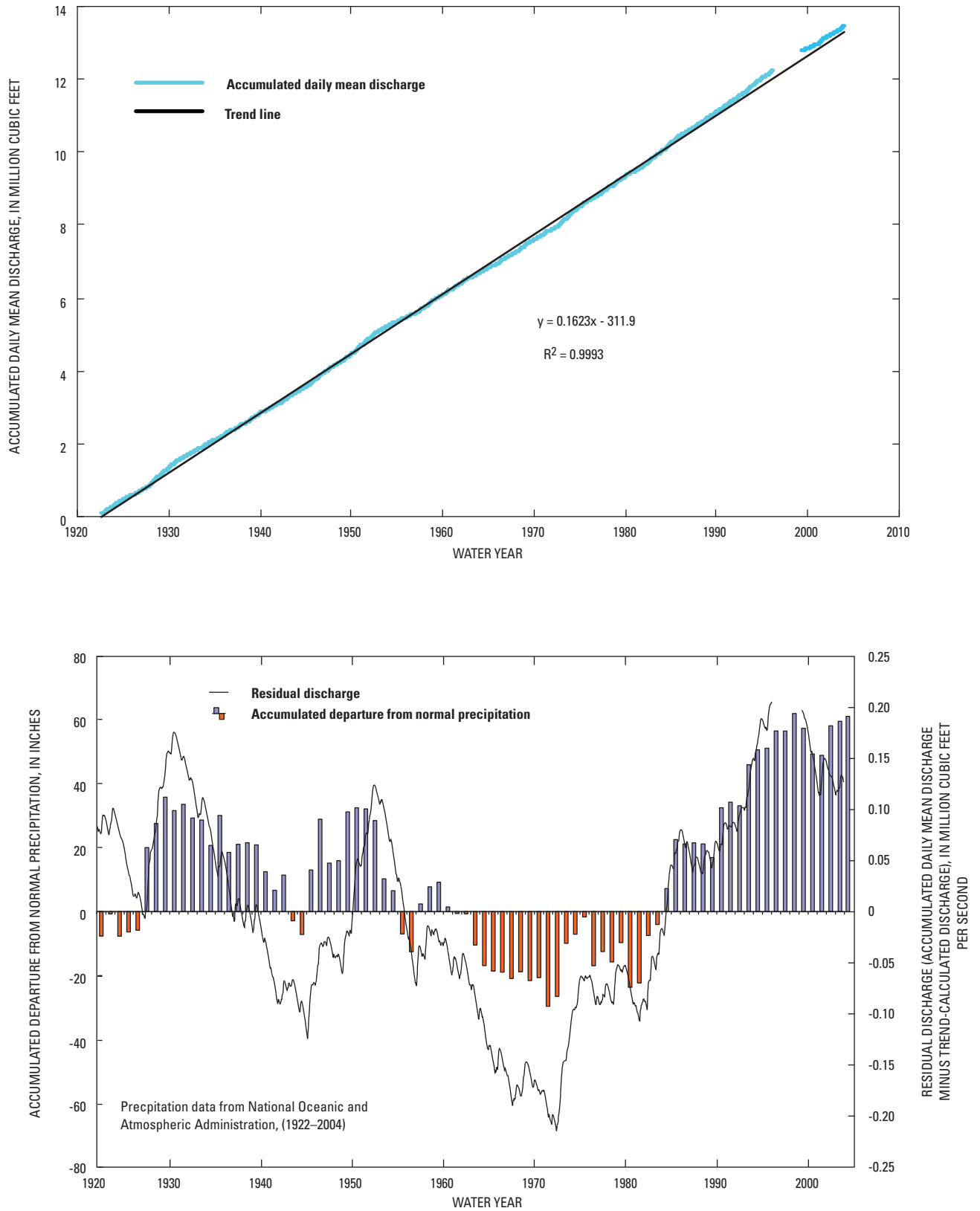


Figure 8. Big Spring accumulated daily mean discharge and residual discharge and accumulated departure from normal precipitation, water years 1922 through 2004.

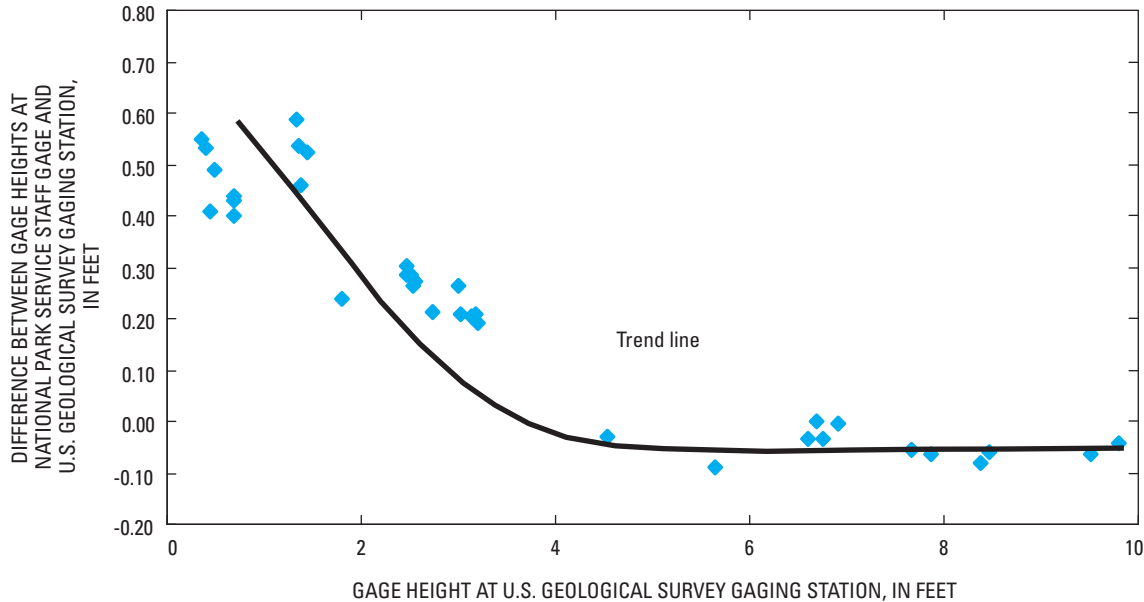


Figure 9. Comparison of gage heights at the National Park Service staff gage and the U.S. Geological Survey gaging station.

discharge also was assumed to have decreased substantially. Therefore, a daily mean discharge of 2,000 ft³/s was estimated for Big Spring at the peak gage height on December 3, 1982 (Waite and others, 1984). The maximum possible instantaneous flow from Big Spring has not been adequately defined, but physical constraints within the spring conduit system possibly restrict its maximum flow to about 1,200 ft³/s. One seep between Big Spring and the NPS staff gage flows almost continuously. Flow from this smaller seep increases during high flow from Big Spring and resembles an overflow spring during these periods. However, this flow is minimal compared to the flow from Big Spring and is measured as part of the total flow at the gaging station. No other Big Spring overflow springs have been observed.

To better characterize the hydraulic properties and help determine the discharge from Big Spring, the USGS installed an acoustic Doppler system to measure and record stream velocities at the gaging station on the downstream side of the NPS bridge. The acoustic Doppler system emits three acoustic beams directed at different distances along a horizontal plane in the water column. Water velocity is measured by detecting the acoustic backscatter from sediment suspended in the water. The three acoustic Doppler-measured water velocities are measured across the thalweg (deepest part of the stream channel), which is about 15 ft wide and near the east bank. These velocities are averaged and used to represent water velocity in the channel. The cross-sectional area of the spring branch also was measured at the downstream side of the bridge and a stage-area relation was developed. The velocity and gage-height data can be measured and recorded at frequent intervals, converted to discharge, and used to improve the estimates for the spring discharge when no manual discharge measurements are available.

At low stage, acoustic Doppler-measured water velocities through the thalweg are about 2.5 ft/s (feet per second; fig. 10). The velocity data show considerable scatter for gage heights less than about 3.0 ft because of the presence of watercress in the channel. Above about 3.0-ft gage height, water velocities drop abruptly to about 1.5 ft/s as the backwater effect caused by the Current River stage propagates up the spring branch and reaches the bridge. Above about 3.5-ft gage height, water velocity in the channel decreases linearly with increasing gage height.

A mean water velocity for the channel was calculated from measured discharge divided by cross sectional area as determined from measured stage using the stage-area relation. Comparison of this mean velocity to the velocity measured by the acoustic Doppler unit shows that the calculated mean velocity for the channel is smaller than measured acoustic Doppler velocity when bridge stage is lower than about 3.0 ft. The difference in velocities ranged from -1.00 to -0.50 ft/s and reflects the higher velocities in the thalweg because it conveys a high proportion of the water during low flow. At higher stage (from about 6.0 ft to nearly 10 ft), the calculated mean velocity is uniformly larger than the acoustic Doppler velocity by about 0.10 to 0.20 ft/s. In this stage range, the higher velocities shift from the thalweg to the middle of the channel, which now conveys a higher proportion of the flow.

The value of the acoustic Doppler velocity data for determining a universal correction to the stage-discharge rating is equivocal. The relation between gage height and the recorded acoustic Doppler water velocity at the USGS gaging station as seen across many hydrologic conditions shows a non-unique behavior (fig. 11). The data were tabulated every 6 hours from February 1, 2002, to January 23, 2004. Different hydrologic events show slightly different relations between gage height

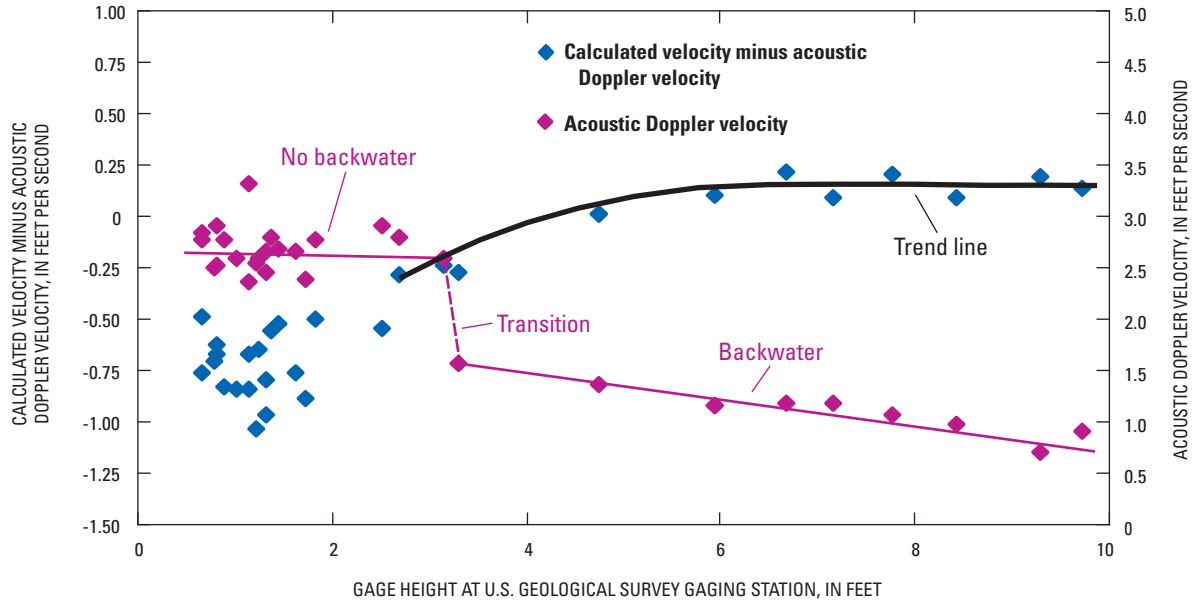


Figure 10. Relation between water velocity and gage height in the Big Spring branch at the U.S. Geological Survey gaging station.

and velocity, although the general trend is that higher spring branch gage heights correspond to smaller measured acoustic Doppler water velocities. During high flow at Big Spring and the Current River, the discharge of Big Spring increases well before flow increases in the Current River adjacent to the spring branch. During this period, no backwater occurs in the spring branch and the stage in the spring branch slowly

rises in response to the increased flow from the spring. Hours later, the flow in the Current River at the mouth of the spring branch begins to rapidly increase, causing the stage of the spring branch to rise quickly and eventually causing backwater conditions in the spring branch. During this period of rapid stage increase in both the river and the spring branch, the spring discharge does not substantially change, even though

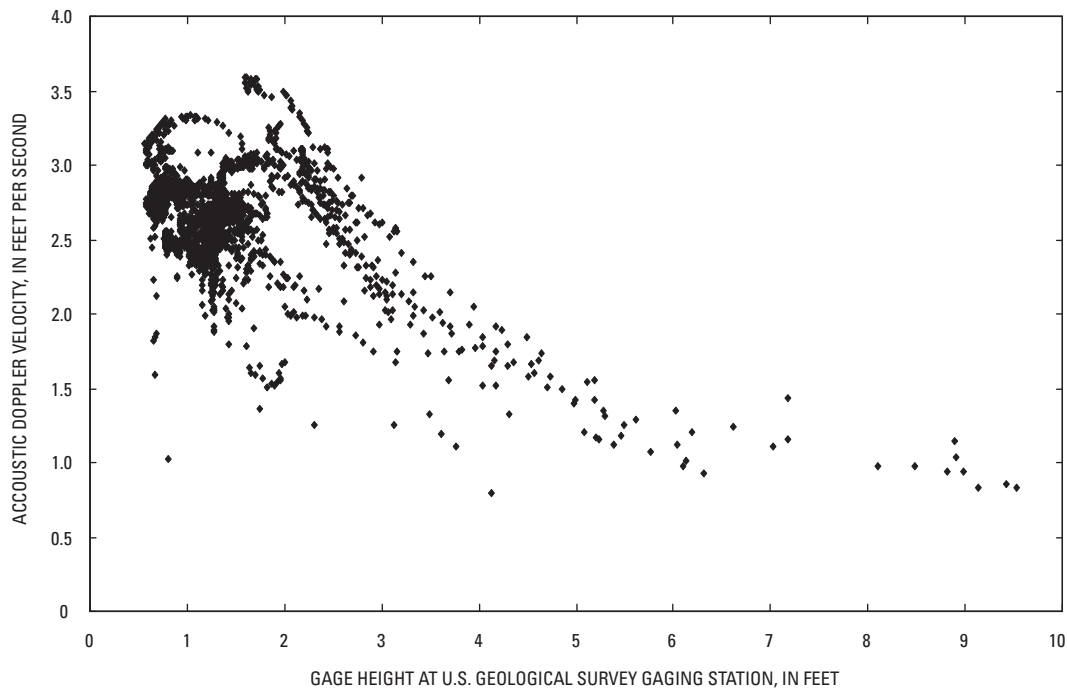


Figure 11. Gage height and average acoustic Doppler velocity recorded in 6-hour time increments from February 1, 2002, to January 23, 2004.

the cross-sectional flow area in the spring branch dramatically increases in response to the backwater. The result is that the recorded spring branch velocities begin to decrease even though the flow from Big Spring is increasing slightly or remaining constant.

The variation between stream velocity and gage height for individual hydrologic events likely occurs because of variable timing between the increase in flow from Big Spring and the rise of the Current River at the mouth of the spring branch. The timing is affected by differences in the initial conditions encountered at the onset of each period of high rainfall and the distribution of rainfall within the Big Spring recharge area and the Current River Basin. Consequently, each event is unique. However, for spring branch stages above 3.5 to 4.0 ft (when the backwater effect is at its greatest), the relation between stage and water velocities is more uniform, and the acoustic Doppler velocity data may be used as an aid to refine discharge data normally derived directly from the stage-discharge curve for Big Spring.

Temperature of Ground Water Discharging from Big Spring

In October 2000, a water temperature and specific conductance monitor was installed at the USGS gaging station at the spring branch. Even though the gage is 800 ft downstream from the spring orifice, water temperature difference at the gage and orifice generally is 0.2 °C (degree Celsius) or less (table 3, at the back of the report). The daily mean water temperature for the water years 2001 through 2004 (October 2000 through September 2004) had little variability ranging from 13 to 15 °C (fig. 12). The lower daily mean water temperatures (13.1 to 13.5 °C) were recorded from March to April 2002. This was a period of above normal precipitation and flooding of the Current River. Floodwater from the Current River flowed into the spring branch upstream from the monitor during March 20 to 21, 2002. On March 21, the daily mean water temperature was less than 13.5 °C and stayed below 13.5 °C until May 1, 2002. Even though spring and river water mixed for less than a day, the water temperature stayed abnormally low for nearly 6 weeks. During this period, there were other storm events that caused increased spring flow and consequently lower spring water temperatures. During several periods from May 8 to 19, 2002, flood waters mixed with spring water upstream from the monitor; however, water temperatures were not less than 13.5 °C at any time during this period, probably because of the higher ambient temperatures.

The daily mean spring water temperature dropped below 14.0 °C several times during the 2001 to 2004 water years, and each incident was during or immediately following intense storms that occurred during the winter or spring. Not all of these incidents had mixing of river flood and spring water; consequently, spring water temperatures less than 14.0 °C appear to be the result of recharge from storms occurring during periods of cold ambient air temperatures.

The mean monthly and daily mean water temperatures for Big Spring during the water years 2001 to 2004 show the temperatures normally vary less than 1 °C throughout the year (fig. 12). The warmest temperatures occur during October and November, traditionally low-flow periods, and the temperature decreases until April at which time water temperatures begin to increase. Because the period of temperature determination is short, the abnormally low temperatures during March and April 2002 have an overriding effect on the general shape of the graph. Without these low temperatures, the mean monthly for March and April would be higher. Nevertheless, Big Spring water temperature does show a slight seasonal variation.

Specific Conductance of Ground Water Discharging from Big Spring

Specific conductance is a measure of the ability of water to conduct electric current (Hem, 1992). Because current is conducted in water by dissolved chemicals, specific conductance is proportional to the TDS (total dissolved solids) concentration present in water. Specific conductance also is temperature dependent, so it is commonly standardized to the conductance at 25 °C to facilitate comparison of measurements made at different temperatures. The specific conductance of water flowing from Big Spring is a result of the mixing of waters of different specific conductance. Water that has moved more slowly through the karst terrain and surrounding bedrock in the Big Spring recharge area accumulates dissolved solids to an equilibrium concentration that yields higher specific conductance values than water that moves more quickly through the larger fractures and conduits of the recharge area in response to intense rainfall.

The specific conductance of water discharging from Big Spring (fig. 13) was continually monitored beginning in October 2000 at 15-minute intervals by a water-quality monitor in the USGS gaging station on the NPS bridge. These values were compared to specific conductance values that were manually measured by field personnel during site visits using a portable conductivity meter with temperature compensation designed to express readings in microsiemens per centimeter at 25 °C ($\mu\text{S}/\text{cm}$). The manual specific conductance measurements were considered the standard and were used to verify the accuracy of the water-quality monitor, which was adjusted as necessary.

During extended periods of little rainfall or moderate rainfall insufficient to cause measurable increase in spring discharge, the specific conductance of the spring water stabilized at about 357 $\mu\text{S}/\text{cm}$. This conductance is representative of ground water that has remained in the smaller fractures of the rock matrix in the Big Spring recharge area for sufficient time to establish chemical equilibrium with the surrounding bedrock. The equilibrium conductance was measured during much of the last 14 months of an extended dry period that ended in the fall of 2001. During intervals of intense rainfall or

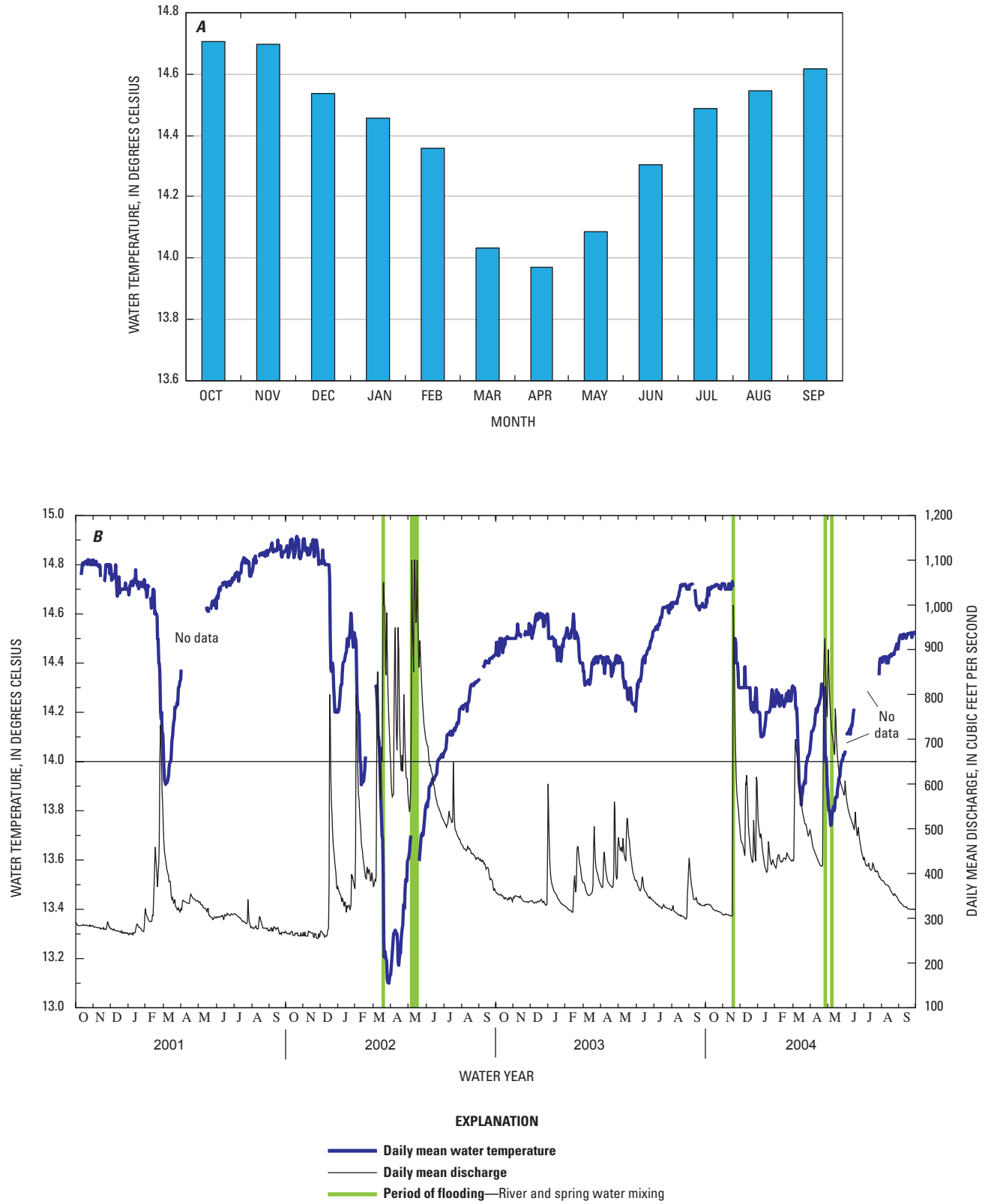


Figure 12. Big Spring mean monthly (A) and daily mean water temperatures and daily mean discharge (B) for water years 2001–04.

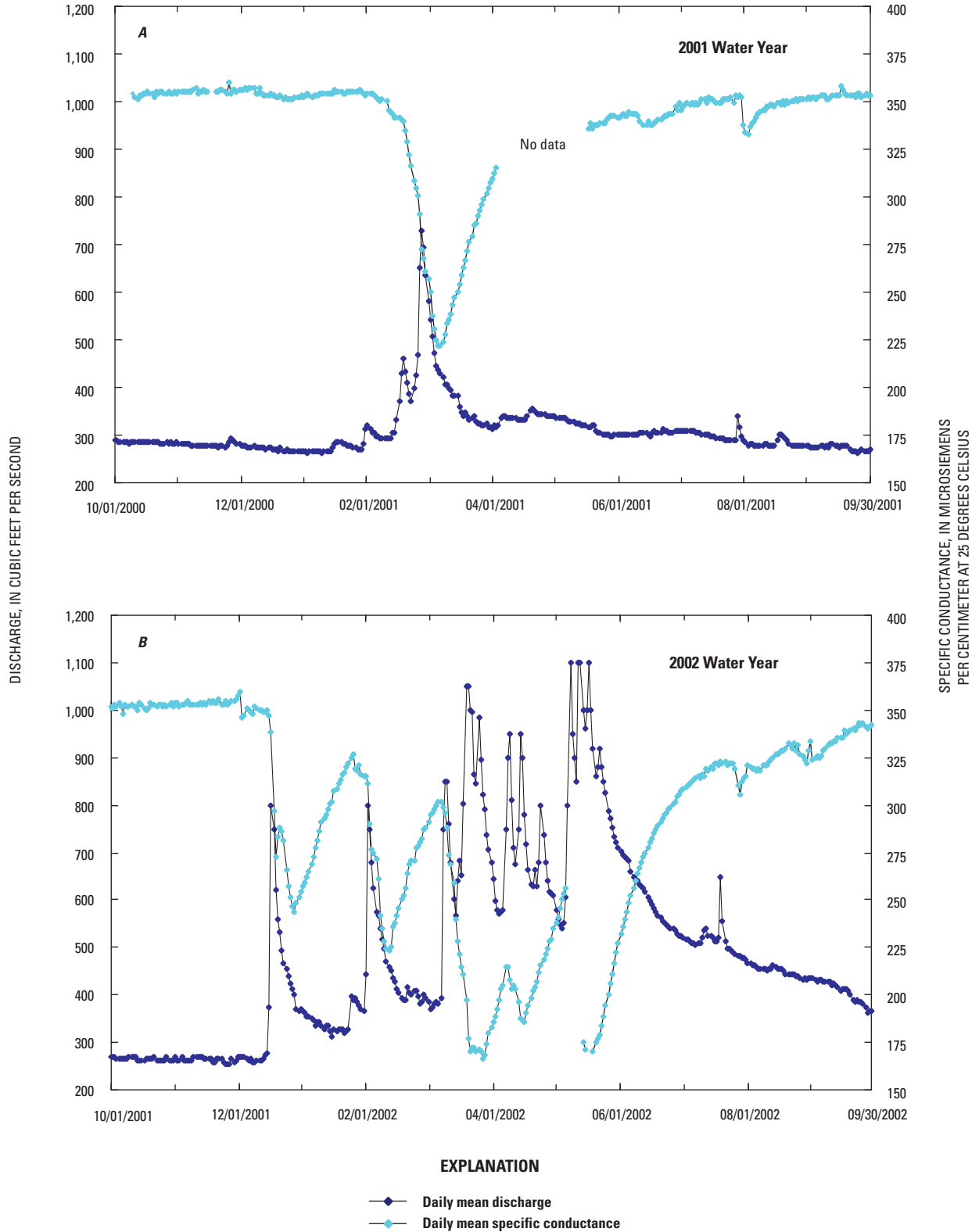


Figure 13. Big Spring daily mean discharge and specific conductance for water years 2001–04.

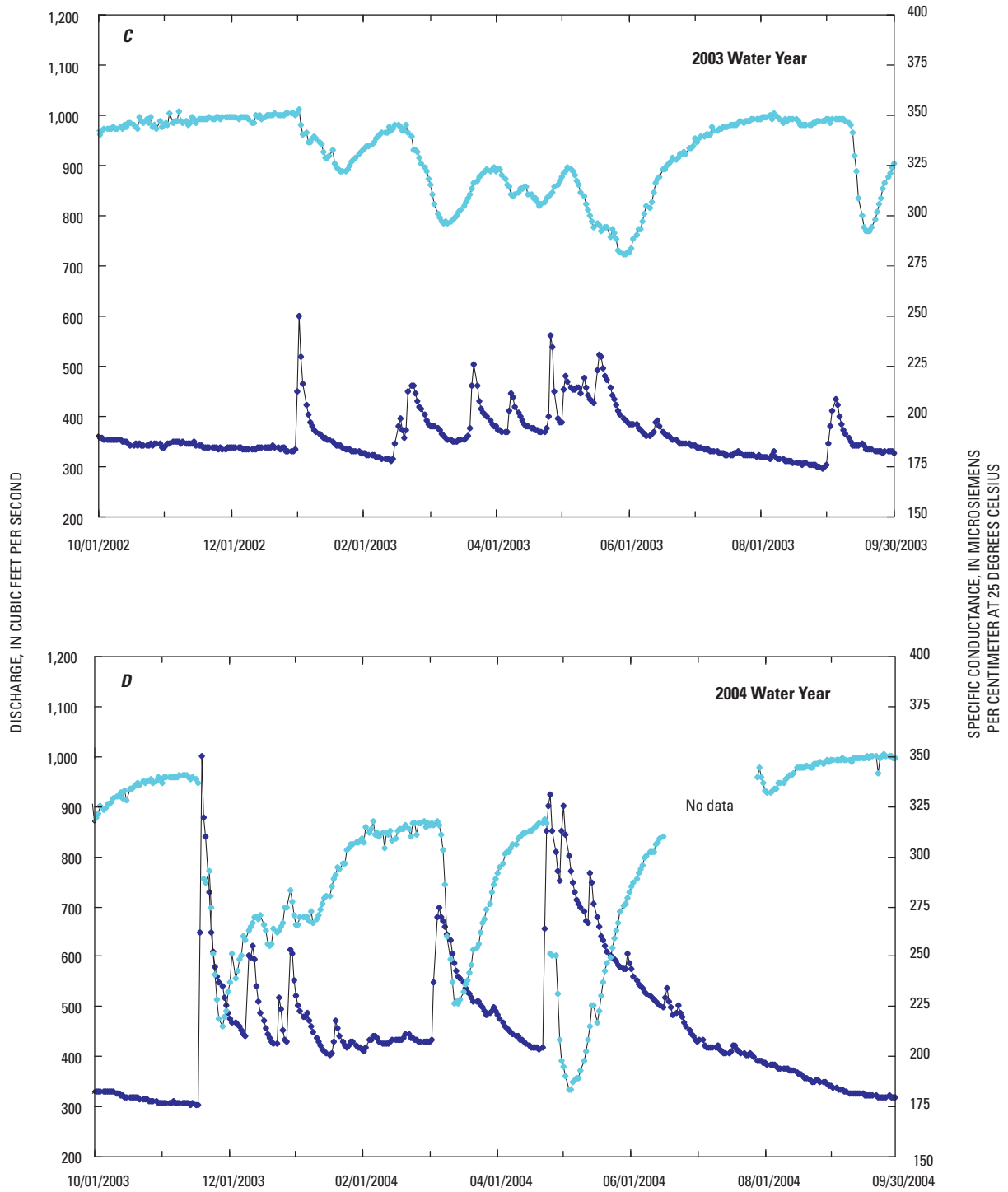


Figure 13. Big Spring daily mean discharge and specific conductance for water years 2001–04.—Continued

prolonged periods of moderate rainfall, water of lower specific conductance that enters the larger fractures and conduits in the Big Spring recharge area quickly moves toward the spring orifice and discharges before reaching chemical equilibrium with the surrounding rock. The specific conductance of the ground water that discharges at the spring decreases as the ratio of quick-flowing water in the large fractures and conduits increases relative to the slower-flowing water in the smaller fractures. Depending on the amount and areal distribution of rainfall, the decrease in specific conductance values can be abrupt and short-lived or a complex series of increasing and decreasing values.

A short period of intense rainfall in late February and early March 2001 caused the specific conductance values of the spring water to decrease abruptly to about 220 $\mu\text{S}/\text{cm}$, and then recover to pre-rainfall levels (fig. 13A). A series of intense storms from mid-December 2001 to May 2002 caused specific conductance values to alternately decrease and recover (fig. 13B). However, the specific conductance values never fully recovered to pre-storm levels in the intervals between storms, and the specific conductance values oscillated several times during the period, attaining the lowest value of 170 $\mu\text{S}/\text{cm}$ in late March 2002. Lighter or less intense rainfall in the recharge area results in a smaller fraction of low specific conductance water in the system causing less abrupt and minor decreases in specific conductance values of the spring water. This is demonstrated by the smaller decreases in specific conductance values during January 2003 through June 2003 (fig. 13C) as compared to February 2002 through June 2002. Even during prolonged periods of lighter rainfall, the specific conductance values do not recover to pre-storm values between storm events. Observation of the rise in specific conductance after a rainfall-induced decline shows that the recovery is slow and that the specific conductance approaches pre-storm values exponentially with time.

Base-Flow and Quick-Flow Components of Big Spring Discharge

Base flow has traditionally been associated with ground-water discharge to streams and is defined herein as the component of spring flow derived from water that has traveled through smaller fractures and pore space in the bedrock. Base flow has a long traveltime from recharge area to the spring and rates typically decrease gradually and slowly under dry conditions. Base flow is characterized by higher specific conductance than quick flow. Quick flow is associated with storm events and is defined herein as the component of spring flow derived from water that has traveled through larger fractures and conduits as a result of rapid recharge of recent rainfall. Quick flow, therefore, has a shorter traveltime from recharge area to the spring, and flow rates vary rapidly under hydrologic conditions caused by storms. Hydrograph separation, or the extraction of base-flow and quick-flow components from a time-discharge relation for a spring, can provide clues about the

mechanism by which the water moves through the spring flow system. However, hydrograph separation techniques involve many assumptions and can be difficult to apply accurately.

Dye-Trace Estimates of Quick-Flow Traveltime

Fluorescent tracer dyes have been used to ascertain the hydraulic connection between Big Spring and losing streams or sink holes in its probable recharge area for at least 35 years (Aley, 1975). When injected tracer dye is detected at a monitored spring, the calculated traveltimes and distances provide information about the quick-flow component of the spring discharge. Dye mixing with the ground water that forms the base-flow component of a spring, chemical degradation occurring during extremely long traveltimes, adherence of dye to rock and clay surfaces, and substantial dilution can all greatly decrease the amount of dye detected at the monitored spring. Results of some of these dye-trace tests have been reported in Aley (1975) and Imes and Fredrick (2002), and many more results are stored in unpublished data files at the USGS and Missouri Department of Natural Resources, Division of Geology and Land Survey offices in Rolla, Missouri. As part of this study, several dye-trace investigations were conducted to better define the common boundary between Big Spring and Greer Spring. Three dye-trace tests that were conducted are described herein because they demonstrate the range of quick-flow traveltimes observed in the large Big Spring recharge area.

Pike Creek is a tributary of the Current River that drains the eastern side of the Big Spring recharge area (fig. 4) and enters the Current River about 7 mi north of Big Spring. The creek normally is dry except for the lowermost reach. Ten pounds of fluorescein dye were injected into the creek bed at an altitude of 910 ft on May 10, 1973, and subsequently detected visually in Big Spring about 18.8 mi from the injection site (Missouri Department of Natural Resources, Division of Geology and Land Survey, written commun., 2004). Dye was visually detected in the solvent used to elute the adsorbed dye from the charcoal packets that were placed at Big Spring from May 16 to May 22, 1973. Because of the weekly replacement schedule for the charcoal packets, the range for the traveltime for the dye to reach Big Spring was 6 to 12 days, and the quick-flow velocity was approximately 1.5 to 3.0 mi/d (miles per day).

Two dye-trace tests were conducted after storms occurred and during runoff at a small spring (Barrett Spring) in the Hurricane Creek Basin (fig. 6), a major dry and losing stream valley in the central part of the Big Spring recharge area (fig. 4). Both injection locations were about 16 mi from Big Spring at an altitude of about 630 ft. The first test was started on January 31, 2002, when 4 pounds of Rhodamine-WT dye was placed in the Barrett Spring Branch. The spring water and dye traveled about 50 ft to the dry bed of Hurricane Creek, before percolating through the gravel into the karstic dolostone. Water samples were collected from Big Spring by an automatic sampler at the USGS gaging station on the NPS

bridge from January 31 to March 7, 2002, at intervals ranging from 12 to 28 hours. The samples were analyzed in a scanning spectrofluorophotometer for the presence of fluorescence emission spectra characteristic of the injection dye. The peak concentration of the dye (fig. 14) was detected in a water sample collected from Big Spring on February 10, a traveltime of about 11 days, and a quick-flow rate of about 1.5 mi/d. The second test was started on March 8, 2002, with the injection of 2 pounds of Rhodamine-WT dye in the flow of Barrett Spring. The dye was again carried about 50 ft to the dry bed of Hurricane Creek, where it percolated through the gravel into the karstic dolostone. Water samples were collected from Big Spring from March 8 to March 27, 2002, and analyzed using similar techniques as the first injection. The peak dye concentration in the water samples (fig. 14) was detected on March 16, after traveling about 8 days at a flow rate of about 2 mi/d. The dye-detection methods and quantification of recovered dye are discussed in more detail in Imes and Fredrick (2002).

A dye-trace test was conducted from the vicinity of Mountain View (fig. 4) on July 10, 2001, after the accidental discharge of approximately 50,000 gallons of partially treated wastewater into nearby Jam Up Creek (fig. 4; Imes and Fredrick, 2002). Four and one-half pounds of Rhodamine-WT dye were placed into Jam Up Creek downstream from

the Mountain View wastewater-treatment plant. The injection site is 38 mi from Big Spring and near the western edge of the Big Spring recharge area at an altitude of about 1,100 ft. Jam Up Creek flowed at about 0.5 ft³/s at the injection site, but lost the entire flow into the subsurface within a mile of the injection site. Water samples were collected at 12- to 24-hour intervals using the automatic water sampler at Big Spring and analyzed for the presence of dye using a scanning spectrofluorophotometer. Dye was detected in the water samples from about August 12 until about September 20, and the peak dye concentrations in the water samples occurred on August 21. Based on the peak dye intensity (fig. 14), the dye traveled a distance of 38 mi in 42 days, corresponding to an average flow rate of 0.9 mi/d.

These and other dye-trace tests indicate that the quick-flow traveltimes from various parts of the recharge area where precipitation can rapidly enter the karst system can range from a week to nearly a month and a half. Average flow rates for the quick-flow component can range from slightly less than 1 to 3 mi/d. The Hurricane Creek Basin occupies much of the central part of the Big Spring recharge area, and runoff during large storms is concentrated in a permeable streambed that permits rapid transport of large quantities of water into the groundwater flow system. Thus, a substantial part of the quick-flow

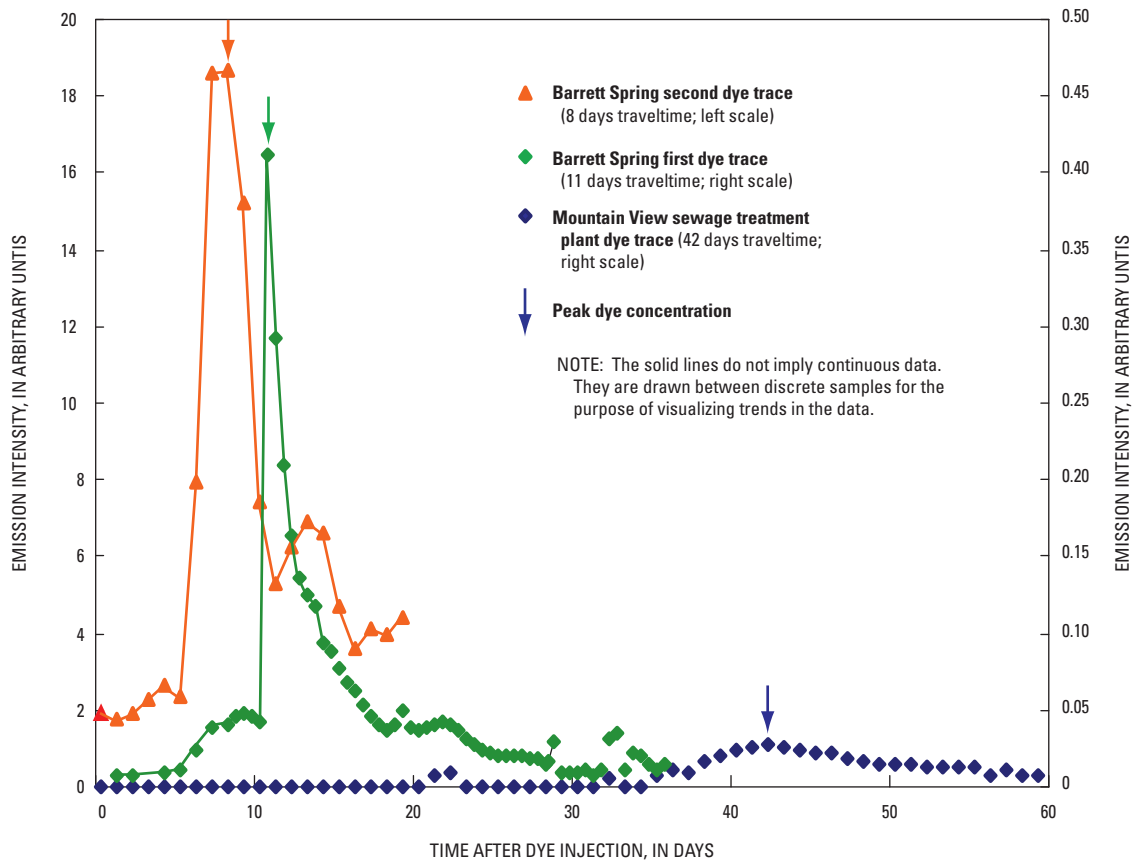


Figure 14. Emission intensity of dye in water samples collected from Big Spring as a function of time after dye injection.

component of Big Spring when rainfall is distributed throughout the recharge area is derived from recharge in the Hurricane Creek Basin. This quick-flow component arrives at Big Spring within about 8 to 11 days after the recharge occurs.

Separation of Base Flow and Quick Flow using HYSEP

The computer program HYSEP was used to separate the Big Spring hydrograph into base-flow and quick-flow components (fig. 15). HYSEP, which was developed to separate base-flow and surface-runoff components of a streamflow hydrograph, uses one of three possible algorithms to smoothly connect the low points along the hydrograph (Sloto and Crouse, 1996; Rutledge, 1998). The local-minimum method was used to execute the HYSEP analysis. The area below the connecting line defines the base flow of the stream. The variables used in the computer programs included the daily mean discharge of Big Spring for water years 2001 to 2004 and an assigned recharge area of 426 mi².

The HYSEP analysis indicates that base-flow discharge at Big Spring is the source of water that sustains spring flow, and the quick-flow discharge is small compared to the base-flow discharge. During water year 2001, Big Spring discharge was mostly base flow (fig. 15A). HYSEP analysis of a rain-induced spike in spring discharge in late February 2001 showed base-flow discharge peaking several days before the total discharge, and quick-flow discharge peaking the same day as spring discharge. Quick-flow discharge is more than 50 percent of total discharge at the discharge hydrograph peak. Base flow declines approximately linearly for about 40 days after peak values, and quick-flow discharge declines abruptly from peak values. The characteristics of the base-flow and quick-flow analysis for other discharge peaks during water years 2001 to 2004 are quite similar, whether the discharge peaks are caused by isolated storms or a rapid sequence of storms, except that the base flow may be linearly increasing or linearly decreasing as the discharge hydrograph rises and falls in response to a storm. The slope of the linear base-flow segments is dependent on the time between two successive rises in the discharge hydrograph.

Separation of Base-Flow and Quick-Flow Components using Discharge and Specific Conductance

Big Spring discharge data were used in combination with specific conductance data to develop an improved hydrograph separation method to estimate the base-flow and quick-flow components of the spring discharge. The TDS concentrations of water discharging from Big Spring is a result of the mixing of a base-flow component containing higher concentrations of dissolved minerals and a quick-flow component containing lower concentrations of dissolved minerals. Nineteen spring-

water samples were collected for chemical analysis from March 2000 through August 2002 at various spring discharge rates. A regression analysis of the specific conductance of the spring water samples and laboratory determinations of their TDS concentrations indicates a linear relation (*r*² value of 0.98). Therefore, specific conductance can be used as a surrogate for TDS concentrations in a mass-balance equation that describes the mixing process of the two components. The following relations describe the discharge rate and specific conductance of the spring water at any point in time:

$$Q_s = Q_b + Q_q \tag{1}$$

$$Q_s * C_s = Q_b * C_b + Q_q * C_q \tag{2}$$

where,

- Q_s* is spring discharge, in cubic feet per second;
- Q_b* is base-flow component of spring discharge, in cubic feet per second;
- Q_q* is quick-flow component of spring discharge, in cubic feet per second;
- C_s* is specific conductance of the spring water, in microsiemens per centimeter at 25 degrees Celsius;
- C_b* is specific conductance of base-flow component of spring discharge in microsiemens per centimeter at 25 degrees Celsius; and
- C_q* is specific conductance of quick-flow component of spring discharge in microsiemens per centimeter at 25 degrees Celsius;

The specific conductance of the base-flow component was estimated at 357 μS/cm using the highest measured specific conductance at Big Spring in November 2000 (table 3) near the end of a prolonged dry period. The specific conductance of the quick-flow component was estimated at 100 μS/cm based on the experience of hydrologic technicians familiar with water-quality sampling of streams in the carbonate bedrock terrain of southern Missouri during storms (R.E. Whitaker, U.S. Geological Survey; oral commun., 2004). Equations 1 and 2 can be combined and the estimated specific conductance values inserted to yield the following equations:

$$Q_b = Q_s * (C_s - 100) / (357 - 100) \tag{3}$$

$$Q_q = Q_s - Q_b \tag{4}$$

Equation 3 was applied to the daily mean discharge and specific conductance data at Big Spring for the water years 2001 to 2004 to calculate the base-flow and quick-flow components of spring discharge (fig. 16). Quick flow commonly is the smaller component of the spring discharge except when unusually large or sustained storms cause the spring discharge to exceed about 800 ft³/s. Big Spring discharge during water year 2001 was generally near base-flow levels except in

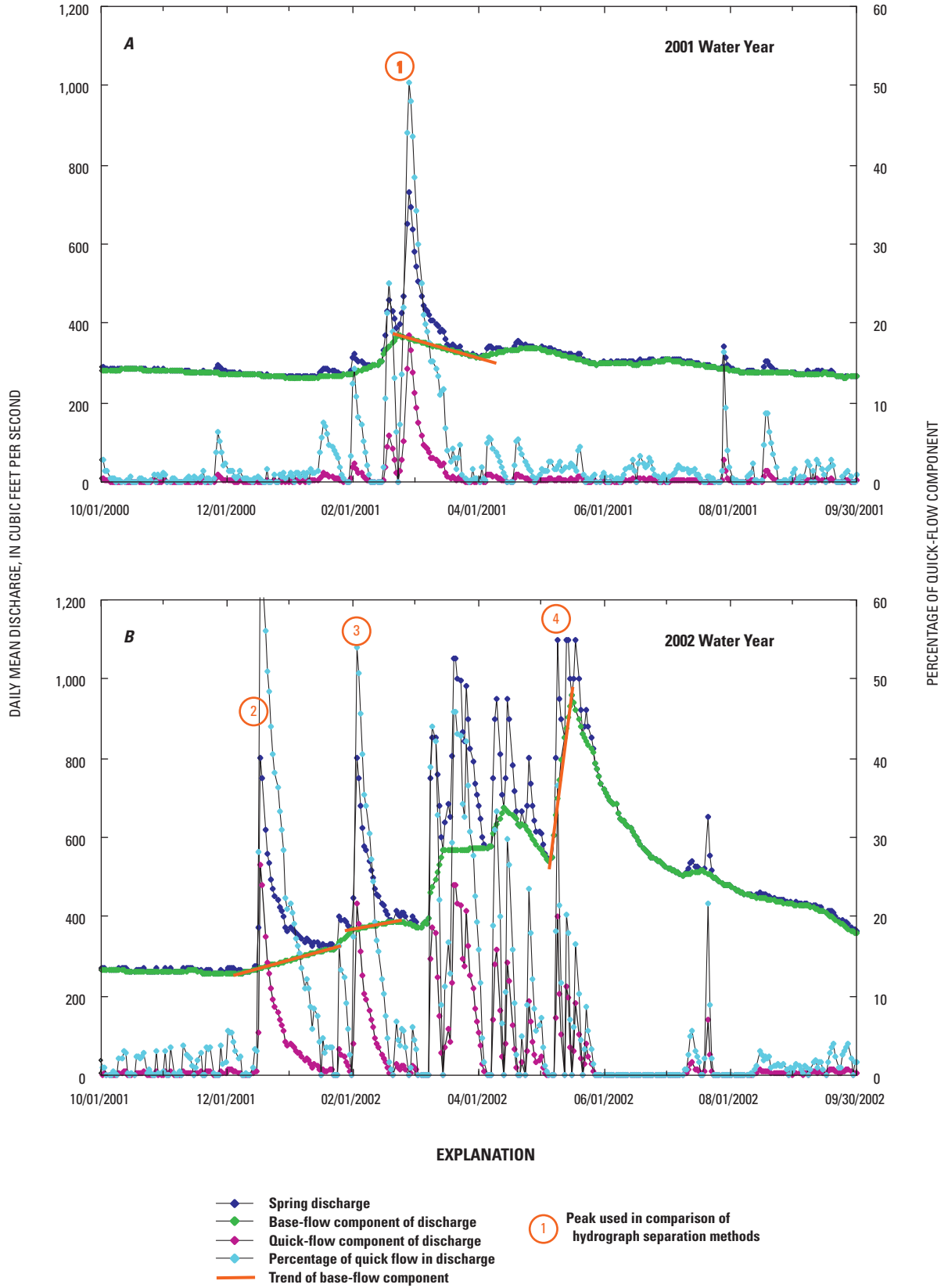


Figure 15. Base-flow and quick-flow components of Big Spring discharge derived using HYSEP hydrograph separation method.

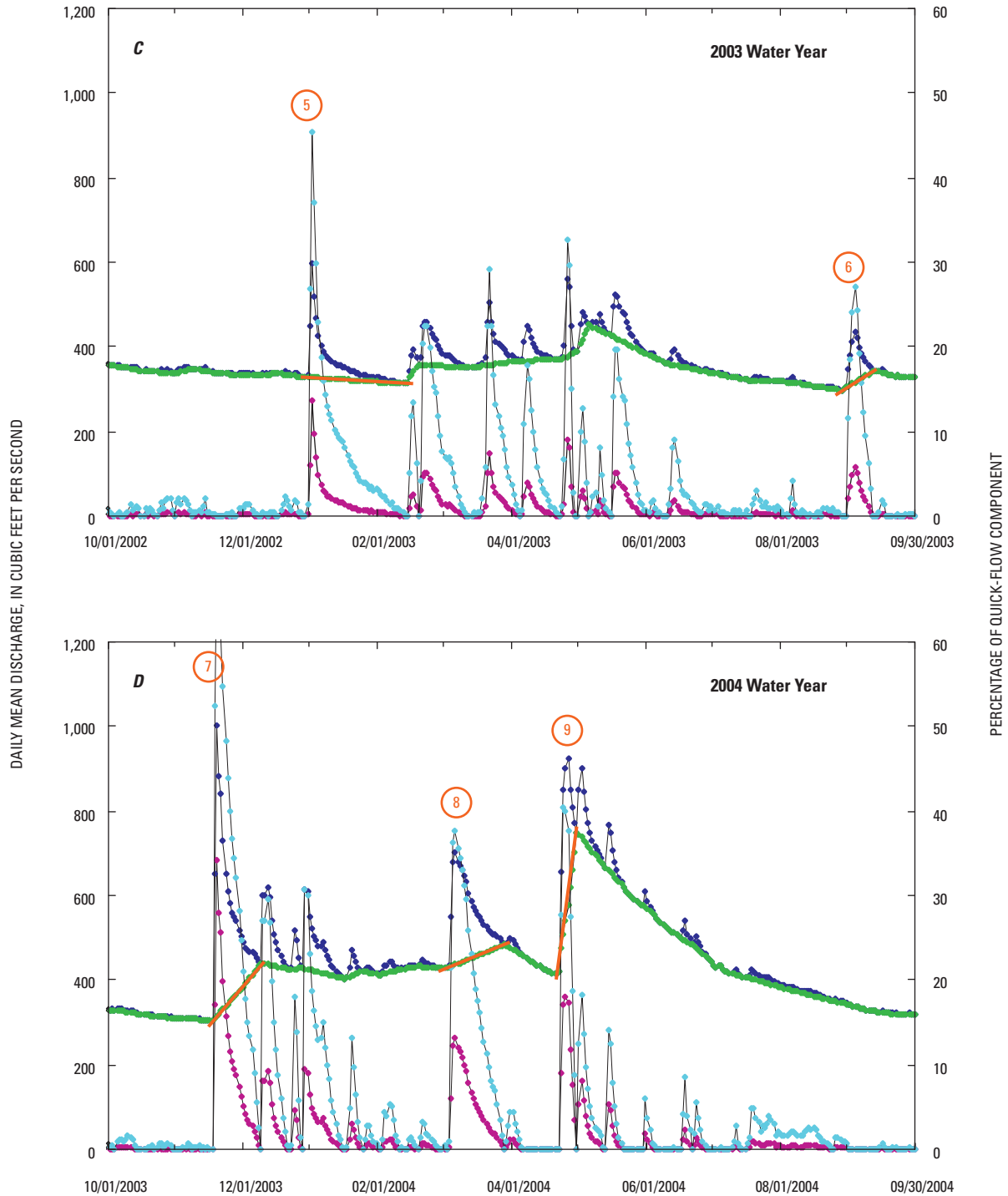


Figure 15. Base-flow and quick-flow components of Big Spring discharge derived using HYSEP hydrograph separation method.—Continued

late February and early March 2001 when rainfall increased spring discharge to more than 700 ft³/s (fig. 16A; Peak 1). The characteristics of base-flow and quick-flow discharge during this isolated rainfall are more clearly visible than during periods when multiple rainfalls occur before the spring can recover to base-flow conditions. Both base-flow and quick-flow discharge components rise abruptly after the rainfall. The

increase in base flow is caused by the increased pressure head on the karstic aquifer as infiltrating rainwater fills fractures and voids above the water table. Base flow peaks with the total spring discharge and then declines rapidly. Quick flow also peaks with the total spring discharge, then declines slightly and remains approximately the same for nearly 10 days before declining. Because of the more rapid decrease in base flow

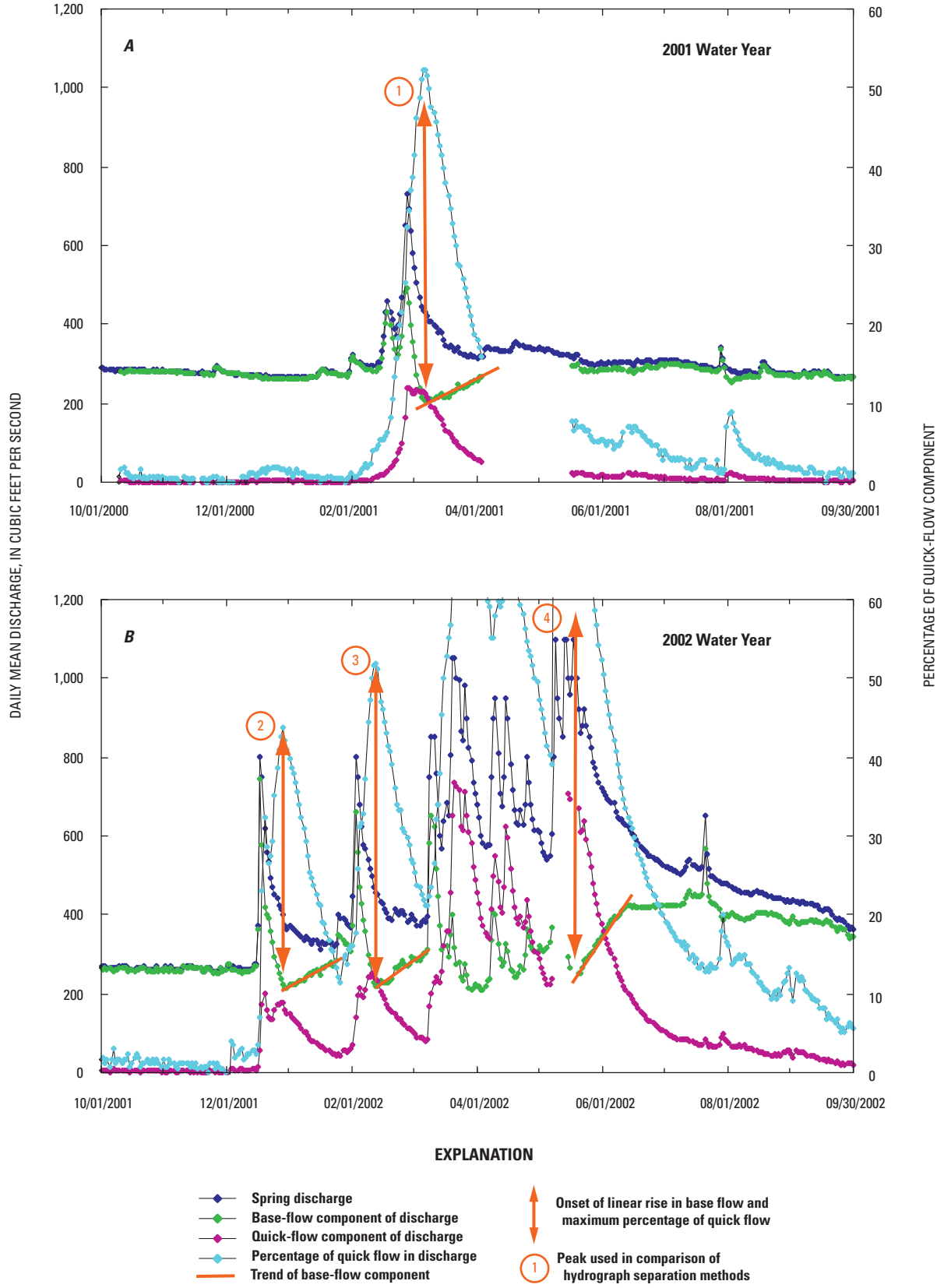


Figure 16. Base-flow and quick-flow components of Big Spring discharge derived using spring discharge and specific conductance data.

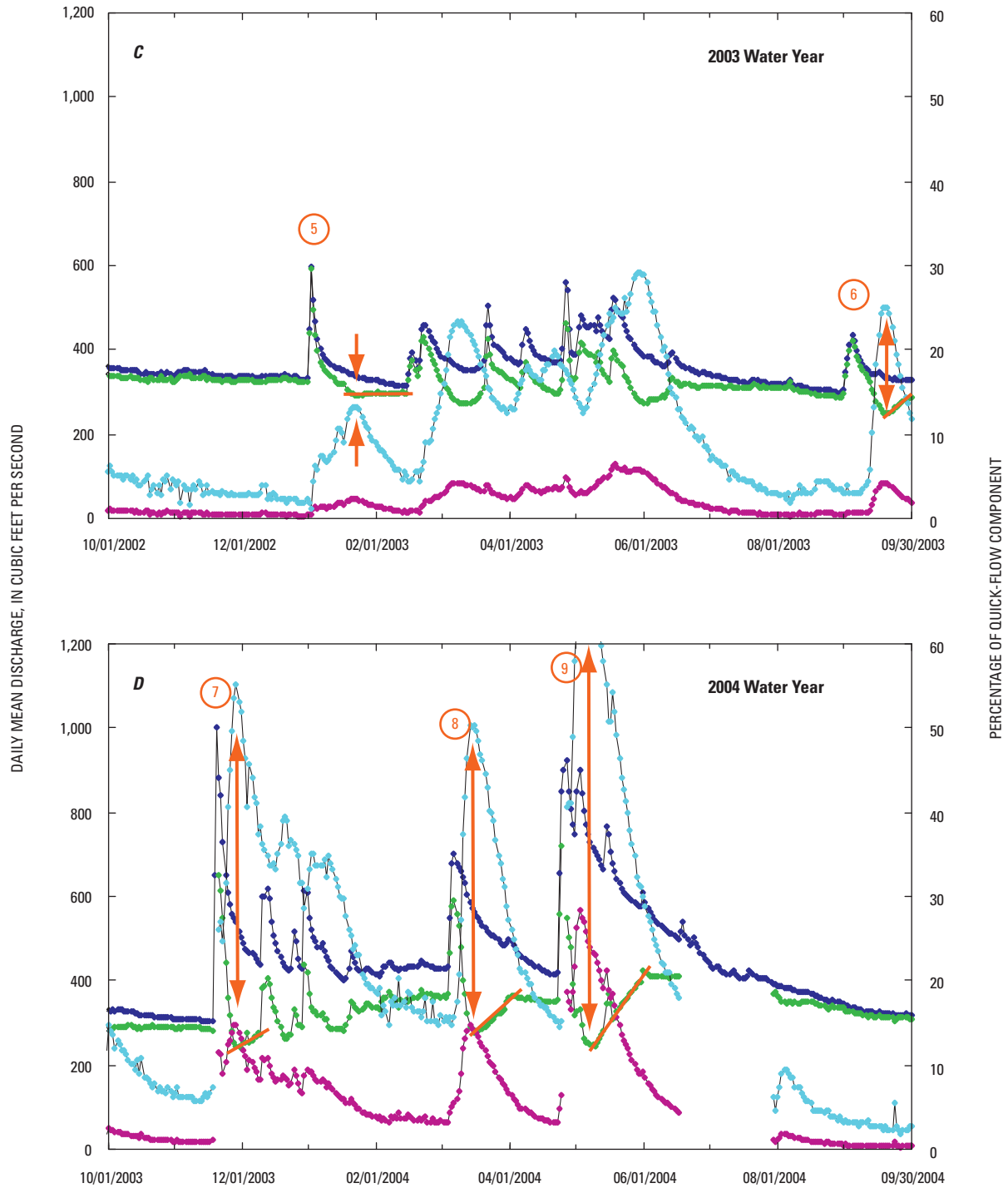


Figure 16. Base-flow and quick-flow components of Big Spring discharge derived using spring discharge and specific conductance data.—Continued

and the lag time before the quick-flow discharge recedes, the percentage of quick-flow discharge peaks at slightly greater than 50 percent of the total spring discharge about 10 days after the hydrograph peak. Spring discharge was much more complex during water year 2002 (fig. 16B) than during water year 2001. Slight hydrograph variation occurred during the fall of 2001 and spring base-flow discharge was nearly constant at

approximately 260 ft³/s. The remainder of the water year was characterized by multiple storms in the spring recharge area from December 2001 through May 2002. Although spring discharge reached 800 ft³/s during December (Peak 2), the percentage of quick-flow discharge did not exceed 50 percent of total discharge. The second major rainfall occurred in early February 2002 (Peak 3) before the spring discharge had recov-

ered to base-flow levels, and the percentage of quick-flow discharge was slightly more than 50 percent of the total discharge. The more frequent rainfalls from early March to mid-May 2002 (Peak 4) caused the quick-flow discharge to peak at more than 600 ft³/s in March, April, and May and caused the percentage of quick-flow discharge to exceed 60 percent of total discharge for 26 days. This larger quick-flow percentage may also explain the lower Big Spring water temperatures that were observed during this period (fig. 12).

Rainfall in water year 2003 was not sufficient to cause the large spring discharges that were observed in water year 2002. Base flow of less than 400 ft³/s occurred during much of the year with peak flows between 400 to 600 ft³/s occurring in the winter and spring of 2003 (fig. 16C). Quick-flow discharge never exceeded 150 ft³/s during the year and never exceeded 30 percent of the total spring discharge.

Water year 2004 was similar to water year 2002 and was characterized by larger, more-frequent storms that caused spring discharge to exceed 600 ft³/s in November and December 2003 and March, April, and May 2004 (fig. 16D). Intense rainfall in late April and early May caused the instantaneous quick-flow discharge to briefly exceed 600 ft³/s, even though the calculated daily mean discharge was slightly less than 600 ft³/s. The percentage of quick-flow discharge exceeded 50 percent in December 2003, March 2004, and May 2004.

The rate of decline of the quick-flow discharge was made for seven rainfall-induced peaks in the spring hydrograph to

assess their degree of similarity (fig. 17). A typical but subtle feature of short duration occurs to the base-flow discharge component during these rainfall-induced peaks that is best shown by peak 5 on figure 16C. The base-flow discharge initially peaks, then is followed by a short, approximately stable post-peak discharge that ends immediately prior to the start of the extended period of recession. The normalized quick-flow discharge value was calculated by dividing the quick-flow discharge during the extended period of quick-flow recession by the maximum quick-flow discharge at the beginning of this period of recession. This represents the fraction of quick-flow discharge remaining relative to the discharge at the beginning of the decline. The reference quick-flow discharge at the beginning of the seven periods of decline occurred on March 8, 2001, December 28, 2001, February 11, 2002, May 23, 2002, June 15, 2003, March 16, 2004, and May 4, 2004. The normalized quick-flow discharge declines at a similar rate for each of the events independently of the nature of the hydrograph before rainfall stopped and spring discharge began to stabilize toward base-flow conditions. The decline trend can be approximated by an exponential decay equation with a decay constant of 0.05 per day. The quick-flow discharge component decays to one-half of its initial value in about 14 days and to one-tenth its initial value in about 46 days. Because it takes so long for the quick-flow discharge to drain from the large area of karstic terrain that supplies ground water to Big Spring, the spring flow rarely declines to base levels during wetter seasons.

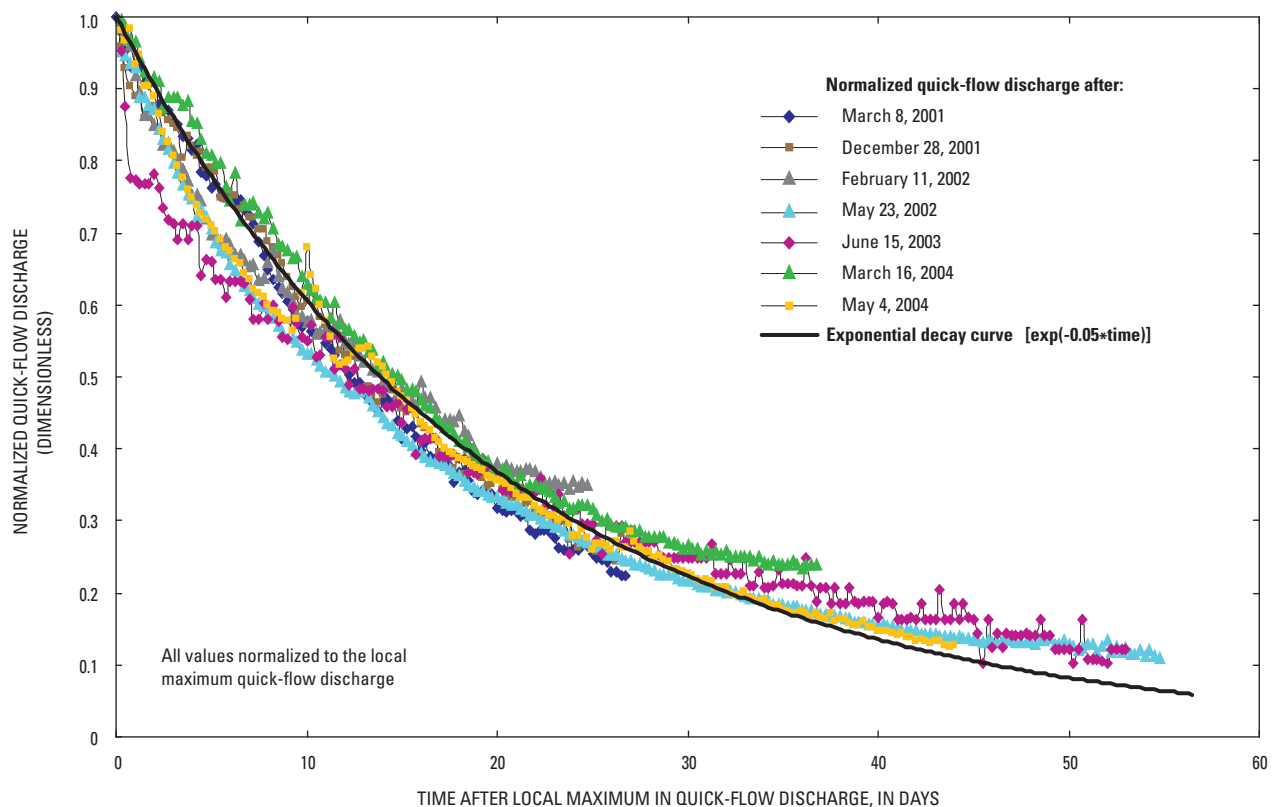


Figure 17. Normalized rate of decline of quick-flow discharge for seven hydrograph events.

Comparison of Hydrograph Separation Methods

Daily mean values determined using HYSEP and the discharge and specific conductance hydrograph separation methods were summarized as annual mean values for water years 2001 to 2004 (table 4). Daily mean Big Spring discharge values computed using a stage-discharge relation, and therefore daily mean computed values using the HYSEP method, are available for every day of the 4-year period. Because there were some intervals when specific conductance data were not collected, there are missing data for the discharge and specific conductance method. To make the comparison among the three data sets more meaningful, the analysis includes only days where all three data sets were available. The estimated annual mean quick flow ranged from 15 to 48 ft³/s for the HYSEP analysis and 26 to 154 ft³/s for the discharge and specific conductance method. The discharge and specific conductance method consistently estimates a larger percentage of quick flow for each of the 4 water years. The discharge and specific conductance method estimated percentage of quick flow to be most similar to the HYSEP estimated percentage of quick flow in water years 2001 and 2003; although, the estimated percentage of quick flow using the discharge and specific conductance method was 1.8 and 2.1 times larger than the HYSEP estimate in water years 2001 and 2003. The difference between the two methods was even larger for water years 2002 and 2004. The estimated percentage of quick flow using the discharge and specific conductance method was 3.2 and 3.3 times larger than the HYSEP estimates in water years 2002 and 2004. This result occurs because recharge from precipitation in water years 2001 and 2003 was limited to isolated events that caused a moderate rise in the spring hydrograph (2001) or a series of smaller events that caused small rises in the spring hydrograph (2003). In contrast, the spring hydrograph for water years 2002 and 2004 shows evidence of large and frequent recharge events that caused spring flow to be substantial during the winter and spring months.

A more-detailed observation of base-flow and quick-flow component separation for individual hydrograph peaks indicates that the HYSEP method is not as accurate determining these components at Big Spring as the discharge and specific conductance method. During periods characterized by large and abrupt rises in the spring hydrograph, HYSEP invariably calculates a linear change in base flow. At each of nine major or more-isolated hydrograph peaks that occurred during water years 2001 to 2004 (fig. 15), calculated base flow increased linearly or near linearly during the spike in discharge [for example, December 2001 (peak 2), February 2002 (peak 3), May 2002 (peak 4), September 2003 (peak 6), November 2003 (peak 7), March 2004 (peak 8), and April 2004 (peak 9)], or decreased linearly or near linearly during the spike in discharge [for example, February 2001 (peak 1) and January 2003 (peak 5)]. The increasing or decreasing pattern appears to be a function of the length of time from the onset of a substantial rise in the hydrograph to the next recharge-induced rise; the shorter the time between recharge, the greater the slope of the base-flow trend. The local-minimum method of HYSEP checks each day to determine if it is the lowest discharge during a specified time both before and after the day that is being considered. The time that is used is based on the drainage (recharge) area for the site. If that day is the lowest discharge, then it is a local minimum and is connected by straight lines to adjacent local minimums (Sloto and Crouse, 1996). The method can be visualized as connecting the lowest points on the hydrograph with straight lines. Thus, the estimated base flow during periods of high discharge is dictated more by events that follow the hydrograph peak than the peak characteristics.

At each of the nine mentioned hydrograph peaks, the HYSEP-estimated quick flow rose abruptly and peaked on the same day as the discharge hydrograph peak, then declined to near zero within a month. Even during long periods of sustained recharge by frequent storms, the estimated quick flow declined rapidly between storms with no apparent accumula-

Table 4. Summary of base-flow and quick-flow hydrograph-separation methods for Big Spring, 2001–04.

[ft³/s, cubic feet per second; %, percent]

Water year	Big Spring calculated annual mean discharge ¹ (ft ³ /s)	Number of days in calculation of mean (days)	HYSEP analysis			Discharge and specific conductance analysis		
			Annual mean		Quick flow (%)	Annual mean		Quick flow (%)
			Base flow (ft ³ /s)	Quick flow (ft ³ /s)		Base flow (ft ³ /s)	Quick flow (ft ³ /s)	
2001	306	308	291	15	4.8	280	26	8.4
2002	482	355	434	48	9.9	328	154	31.9
2003	363	365	345	18	4.9	325	38	10.5
2004	461	321	424	37	8.0	338	123	26.7

¹Annual mean discharge calculated by stage-discharge relation using only days where both discharge and specific conductance data were available.

tion of quick flow from storm to storm (for example, from March 2002 to June 2002, February 2003 to June 2003, and November 2003 to February 2004). The abrupt decline in quick-flow discharge appears to be inconsistent with quick-flow traveltimes (8 to 42 days) estimated from dye-trace investigations in the recharge area of Big Spring.

The discharge and specific conductance method of hydrograph separation yields different characteristic curves for the base-flow and quick-flow components. At all nine of the major or more-isolated hydrograph peaks that occurred during water years 2001 to 2004, the estimated base-flow component rises abruptly as the spring hydrograph rises, and attains a peak value on the same day as the discharge peak (fig. 16). The base-flow component declines more abruptly from its peak value than quick flow, then several days later begins to increase at an approximately linear trend until interrupted by a following recharge event [for example, December 2001 (peak 2), February 2002 (peak 3), January 2003 (peak 5), and November 2003 (peak 7)] or until hydraulic conditions change and base flow enters a period of stable to slowly declining flow rates [for example, February 2001 (peak 1), May 2002 (peak 4), September 2003 (peak 6), March 2004 (peak 8), and April 2004 (peak 9)]. The onset of the period of linear rise in base flow approximately coincides with the time at which the percentage of quick flow has reached a maximum after each recharge-induced spring discharge peak (see linear trend lines and marker arrows in fig. 16).

The interval between the spring discharge peak and the peak in percentage quick flow is quite similar for peaks 1, 2, 3, 4, 7, 8, and 9. The intervals are 8 to 9 days, 11 days, 11 days, probably 9 days, 9 days, 9 days, and 9 to 10 days for these seven hydrograph peaks. The interval for peak 4 is estimated because specific conductance values were not available during part of that peak. The average interval of about 9.5 days is a similar lag time for each peak, and indicates that large amounts of recharge from the Hurricane Creek Basin in the central part of the recharge area, where dye tracing shows an 8 to 11 day quick-flow traveltime, are arriving at the spring. The interval between the spring discharge peak and the peak in percentage quick flow for two of the mentioned peaks (peaks 5 and 6) are somewhat longer than the others. The interval for peak 5 is 12 to 13 days, and the interval for peak 6 is 15 days. These longer intervals may indicate that more of the rainfall that produced the rise in these discharge hydrographs occurred in the western parts of the large Big Spring recharge area.

To summarize, the incorporation of specific conductance values into the hydrograph separation process for springs yields more reasonable hydrograph separation results than HYSEP, which uses only the shape of the discharge hydrograph. The characteristics of the base-flow and quick-flow components of spring discharge peaks calculated using the discharge and specific conductance method indicate, and are consistent with, the following spring-flow mechanism. The initial recharge of precipitation increases the pressure head on the karstic aquifer and pushes the higher specific conductance

values (base flow) stored ground water toward the spring orifice, as seen by the sudden rise in base flow as the discharge hydrograph rises. This occurs because hydraulic pressure can be transmitted through an aquifer much faster than water can flow. Recharging precipitation also drains rapidly into the solution-enlarged fractures and voids of the karst and moves toward the spring orifice. The distribution and intensity of the rainfall, the size and geometry of the karst fracture and conduit system, and the resistance of the flow path (particularly that of its narrowest part) all control the rate at which the quick flow moves through the karst and discharges at the spring. This situation is complicated when the Current River is at a high stage, which inundates the spring with backwater, creates a higher hydraulic head over the spring, and increases the back pressure at the spring. As the quick flow subsides (usually after about 8 to 11 days), the hydraulic head differential between the conduits and the orifice is reduced, and the base flow increases again to a new equilibrium level before beginning the slow decline characteristic of a gravity draining aquifer.

Atmospheric Environmental Tracers in Base Flow and Quick Flow: Estimation of Ground-Water Ages

In the previous section, discharge from Big Spring was modeled as a mixture of two components—quick flow and base flow. A hydrograph separation model was developed using data on discharge and specific conductance from Big Spring to estimate the fractions of quick flow and base flow in Big Spring discharge. Concentration data of selected environmental tracers [chlorofluorocarbons (CFCs: CFC-11, CFC-12, and CFC-113), sulfur hexafluoride (SF_6), and tritium (^3H)] in discharge from Big Spring also were used to test the hydrograph separation model, estimate ages of quick-flow and base-flow components, and estimate mixing fractions.

CFCs are volatile, synthetic compounds of carbon, chlorine, and fluorine that were manufactured for uses in refrigeration, air conditioning, blowing agents in foams and insulation, and in many other industrial and domestic applications. CFC-12 (dichlorodifluoromethane, CF_2Cl_2) was produced commercially from 1930, and CFC-11 (trichlorofluoromethane, CFCl_3) was produced from 1936. Many other CFC compounds have since been produced—most notably CFC-113 (trichlorotrifluoroethane, $\text{C}_2\text{F}_3\text{Cl}_3$), produced commercially from 1944 and used primarily by the electronics industry. Release of CFCs to the atmosphere and subsequent incorporation into the hydrologic cycle has closely followed production (Gamlen and others, 1986; Midgley and Fisher, 1993). By the late 1980s, cumulative production of CFC-11, CFC-12, and CFC-113 totaled approximately 7.7, 10.2, and 2.4 million tons (Alternative Fluorocarbons Environmental Acceptability Study, 2006a), and in the northern hemisphere, atmospheric

concentrations had risen to about 260, 480, and 70 pptv (parts per trillion by volume).

By 2001, atmospheric CFC concentrations were nearly constant or falling because of regulations imposed in 1987 by the Montreal Protocol to Reduce Substances that Deplete the Ozone Layer and subsequent amendments (Alternative Fluorocarbons Environmental Acceptability Study, 2006b; International Atomic Energy Agency, 2006), following recognition that atmospheric CFCs caused depletion of the earth's ozone layer and may contribute to global warming. Most of the samples collected from Big Spring were obtained between 2001 and 2003, when atmospheric concentrations of CFCs were nearly constant (table 5). In 2002, which represents the mid-point of the sample collection period, the average northern hemisphere concentrations of CFC-11, CFC-12, and CFC-113 in air were about 260, 545, and 81 pptv.

Sulfur hexafluoride (SF_6) is another atmospheric gas that is primarily of anthropogenic origin, but also occurs naturally in some rocks (Harnisch and Eisenhauer, 1998; Busenberg and Plummer, 2000). SF_6 is mainly used as an electrical insulator in high voltage switches and transformers. The concentration of SF_6 in the troposphere has increased from a steady-state value of 0.054 plus or minus 0.009 to about 6 pptv during the past 45 years (Busenberg and Plummer, 1997; 2000). The atmospheric history of SF_6 is now well established (Maiss and Levin, 1994; Maiss and Brenninkmeijer, 1998; U.S. Geological Survey, 2006a) and the mixing fraction of SF_6 is currently (2007) increasing at a rate of about 6 percent per year while those of the CFCs are nearly constant or decreasing. North American air contained about 5.1 pptv of SF_6 in 2002 (table 5).

Tritium, the radioactive isotope of hydrogen (half-life of 12.32 years; Lucas and Unterweger, 2000), is the most commonly used environmental tracer to indicate the presence of modern recharge. Environmental tritium is formed naturally in the upper atmosphere from the bombardment of nitrogen by the flux of neutrons in cosmic radiation and in the recent past from atmospheric testing of nuclear weapons. Since 1952, the source from atmospheric tests of nuclear weapons overwhelmed the natural source and, therefore, the ^3H concentration in precipitation is represented by a series of pulses with the largest pulse occurring during 1963 and 1964. The shape of the ^3H pulse differs substantially from the relatively smooth concentration functions for CFCs and SF_6 . Because of various

meteorological processes and atmospheric moisture sources (Rozanski and others, 1991), a local record of tritium in precipitation for a particular region being studied generally needs to be constructed. Several scaling procedures exist for reconstruction of local ^3H records on the basis of records from parts of North America (Michel, 1989, 2005). In 2002, precipitation in the study area averaged about 7.2 TU (tritium units). The concentration functions of CFCs, SF_6 , and ^3H used to interpret the spring data are shown in figure 18.

Ground-water dating and environmental tracer applications with CFCs and SF_6 are possible because (1) the history of the atmospheric concentrations is known or has been reconstructed from production/release data; (2) the Henry's Law solubilities of these tracers in water are known as a function of temperature, pressure, and salinity; and (3) instrumentation and analytical procedures are available to measure the concentrations of CFCs and SF_6 in air and water (Busenberg and Plummer, 1992, 2000). Following recharge and isolation from the atmosphere, ground waters generally are unaffected by gas exchange processes because gas diffusion coefficients in water are approximately five orders of magnitude smaller than in air. Because the shape of the tritium concentration function differs substantially from that of CFCs and SF_6 (fig. 18), the combined use of CFCs or SF_6 with tritium can provide considerable information that is of value in interpreting ground-water mixing and ages of young and old fractions in mixtures.

Collection of Water Samples

Ground water issuing from Big Spring was sampled with a stainless steel, nitrogen-operated, submersible piston pump at a low-flow rate to minimize loss of CFCs and SF_6 and contamination from unsuitable pump-construction materials in the sample. The pump discharge line was made of refrigeration-grade copper tubing to avoid contamination from plastic materials. The CFC samples were fused into borosilicate glass ampoules with a ultra-pure nitrogen headspace. The SF_6 samples were collected in 2-liter glass bottles with polycone seal caps without headspace. The samples were analyzed at the USGS Chlorofluorocarbon Laboratory in Reston, Virginia. Samples for tritium determination were collected in 1-liter plastic bottles and analyzed at the USGS Low-Level Tritium

Table 5. Atmospheric concentrations of CFC-11, CFC-12, CFC-113, SF_6 , and ^3H in precipitation in southern Missouri, 2001–03.

[pptv, parts per trillion by volume; TU, tritium units; --, no data]

Year	CFC-11 (pptv ¹)	CFC-12 (pptv ¹)	CFC-113 (pptv ¹)	SF_6 (pptv ¹)	^3H (TU ²)
2001	262	547	82	4.9	6
2002	260	545	81	5.1	7
2003	258	543	80	5.3	--

¹ <http://water.usgs.gov/lab>.

² R.L. Michel, U.S. Geological Survey, Menlo Park, Calif., written communication, 2006.

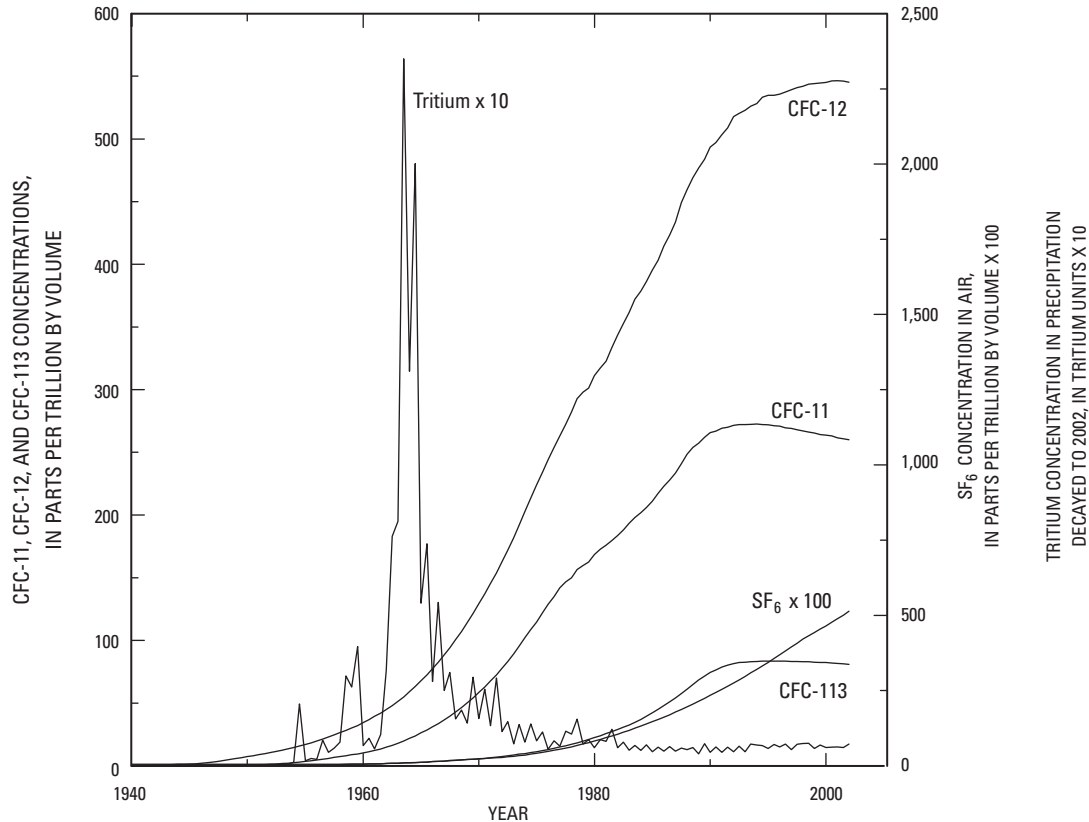


Figure 18. Concentrations of chlorofluorocarbons (CFC-11, CFC-12, and CFC-113) and sulfur hexafluoride (SF_6) in North American air and tritium in precipitation in Missouri decayed to 2002, 1940 to 2002.

Laboratory in Menlo Park, California, by electrolytic enrichment and liquid scintillation counting. Details of the sample collection procedure are described in U.S. Geological Survey (2006b), along with information on methods of laboratory analysis. CFCs are routinely detected at the USGS Chlorofluorocarbon Laboratory in water at concentrations greater than 0.3 to 1.0 pg/kg (picogram per kilogram of water). The detection of CFC-12 indicates post-1945 recharge or older water samples that contain a fraction of post-1945 water. Similarly, detection of CFC-11 and CFC-113 indicates post-1950 and post-1957 water, or their mixtures. The detection of SF_6 generally indicates post-1970 water or mixtures containing a fraction of post-1970 water.

Concentrations of CFCs, SF_6 , and ^3H in recharging meteoric water are assumed to be consistent with air-water equilibrium at the time of infiltration or of the concentration of tritium in local precipitation at the time of recharge. The concentrations of atmospheric gases in recharge depend on temperature of recharge, altitude of recharge (barometric pressure), and entrapment of excess air in pore spaces above the water table that is forced downward during recharge. Measurements of the concentrations of dissolved nitrogen (N_2) and argon (Ar) in the water samples permits determination of recharge temperature and excess air (U.S. Geological Survey, 2006b). The altitude of recharge was assumed to be that of the altitude of the water table in the catchment area of Big

Spring. Because the water in Big Spring remains aerobic, no potential for degradation of CFCs exists in the ground-water environment, or of denitrification. However, some of the water samples may contain an excess of SF_6 from terrigenous sources. Although depth to ground water in the mature karst recharge area of Big Spring can range from a few feet to more than 400 ft, air probably moves freely through the larger fractures and conduits of the mature karst, so that infiltration water remains in contact with modern air during recharge even through deep unsaturated zones. As a result, the CFC “age” remains modern until sufficient recharge occurs isolating the water sample from the unsaturated zone air. In karst environments such as Big Spring, the next storm probably provides sufficient recharge to isolate the sample from gas exchange with the unsaturated zone air.

By measuring concentrations of the CFCs and SF_6 in ground water and by estimating the temperature, altitude of recharge, and excess air, the partial pressures of the gases in the water sample can be calculated in parts per trillion by volume. The estimated parts per trillion by volume concentrations are then compared with historic measured atmospheric data to estimate the apparent age of the ground water (Busenberg and Plummer, 1992; Cook and Solomon, 1995; Plummer and Busenberg, 1999; Busenberg and Plummer, 2000). The apparent age applies only to unmixed water samples. However, different aquifer flow regimes can cause ground-water samples

collected from wells or springs to be a mixture of water of different ages. Consequently, these tracers can be used to assess the mixing of water of different ages in discharge from Big Spring.

Interpretation of Mixing and Water Ages using Environmental Tracer Data

The environmental tracer data collected as a part of this study are summarized in tables 6, 7, and 8 (at the back of this report) along with selected calculated results. Dissolved N_2 and Ar data along with the calculated recharge temperature and quantity of excess air are listed in table 6. The measured concentrations of CFCs in ground water from Big Spring and Greer Spring are summarized in table 7. The concentrations in table 7 are calculated from Henry's Law at the recharge temperature given in table 6 and reported in parts per trillion by volume. The corrections of the measured CFC values for excess air were small. Two sets of CFC ages are given in table 7. The first is the apparent, piston-flow age, calculated assuming an unmixed sample. The second is the age of the young fraction calculated using a binary mixing model that assumes that the young fraction is mixed (diluted) with old, pre-tracer water. The percentage of young water is calculated for the binary mixing model according to guidelines provided by the International Atomic Energy Agency (2006). As shown in table 7, neither of these models yield useful age information for discharge from Big Spring, but are given for reference purposes. The SF_6 data are summarized in table 8, giving the measured concentration, and the parts per trillion by volume concentration calculated at the recharge temperature and corrected for excess air (table 6). Because of the extremely low solubility of SF_6 in water, the excess air correction is substantial for SF_6 . The apparent piston-flow age for SF_6 , for reference purposes, and the available tritium concentrations are listed in table 8.

Assignment of an age to a ground-water sample depends on the model used to interpret the age; that is, all ground-water ages are model dependent. Several models were used to make preliminary age estimates with the CFC and SF_6 data in tables 7 and 8. The first model (piston-flow) assumes the samples are unmixed, as if recharge water flows through a pipe from point of recharge to discharge at Big Spring. Using the piston-flow model, CFC ages range from 13 to 31, 1 to 30, and 10 to 24 years for CFC-11, CFC-12, and CFC-113, (table 7). The binary mixing model results shown in table 7 assume mixing of a young component water with old tracer free water. The implied ages of the young fraction in this case (based on the CFC-113/CFC-11 ratio) range from 5 to 16 years with calculated mixing fractions of 31 to 99 percent young water (table 7). The SF_6 piston flow apparent ages range from 9 to 21 years (table 8). The ages calculated from both models are all inconsistent with some of the physical and hydrogeologic observations at Big Spring because of the complexities of ground-water flow in karst areas, and are, therefore, invalid.

The first contradiction with the hydrogeologic data comes from the dye traces (discussed earlier) indicating traveltimes of first arrival of some fraction of discharge at Big Spring on the order of a few tens of days, followed by an attenuation of the dye pulse lasting over a period of at least several months. Because the dye traces have a relatively short traveltime to Big Spring does not mean that all the water discharging at Big Spring has ages of tens of days, but instead, discharge contains a component of fresh meteoric water that presumably is mixed with somewhat older stored ground water. Those fractions correspond with the quick-flow and base-flow components of the hydrograph. Based on the discharge and specific conductance hydrograph separation analysis, the fraction of quick flow varied from about 2 to 45 percent on the days environmental tracer samples were collected. The binary mixing model results would be consistent with the hydrograph separation results only if the quick-flow component had ages on the order of tens of years (table 7). This seems unlikely based on traveltimes from dye traces, but additional data are needed to resolve the question of the age of the quick-flow and base-flow components.

Age of the Quick-Flow and Base-Flow Components at Big Spring Inferred from Tracer Concentrations as a Function of Percentage Quick Flow

During this study, measured discharge made in conjunction with isotope sampling at Big Spring ranged from about 275 to 525 ft^3/s , with one maximum discharge of 800 ft^3/s . Most of the values of percentage quick flow, calculated using the discharge and specific conductance method, vary linearly with spring discharge (fig. 19). The concentrations of CFC-11, CFC-12, CFC-113, and SF_6 (in parts per trillion by volume) in discharge from Big Spring are plotted as a function of percent quick flow in figure 20. For quick-flow components ranging from about 5 to 45 percent of discharge, the CFC and SF_6 concentrations vary approximately linearly with percent quick flow. The highest calculated percentage of quick flow was 45 percent. Extrapolation of the linear relation between tracer concentration in spring discharge and percentage quick flow to 100 percent quick flow implies CFC and SF_6 concentrations nearly identical to those in the 2002 atmosphere (table 5). This indicates most samples containing more than 5 percent quick flow have tracer concentrations consistent with dilution of modern water that was determined from the discharge and specific conductance analysis. The CFC concentration functions for air have been nearly constant for the past decade (fig. 18); therefore, a modern age based on CFCs applies to an age range of recharge from the early 1990s to the date of sample collection. In comparison, SF_6 has increased steadily and indicates a modern age for the quick-flow component that is resolved approximately within 1 year. At the other extreme, extrapolating the linear relation of CFC and SF_6 concentration from the modern air value (dot on the ordinate of figure 20) to zero

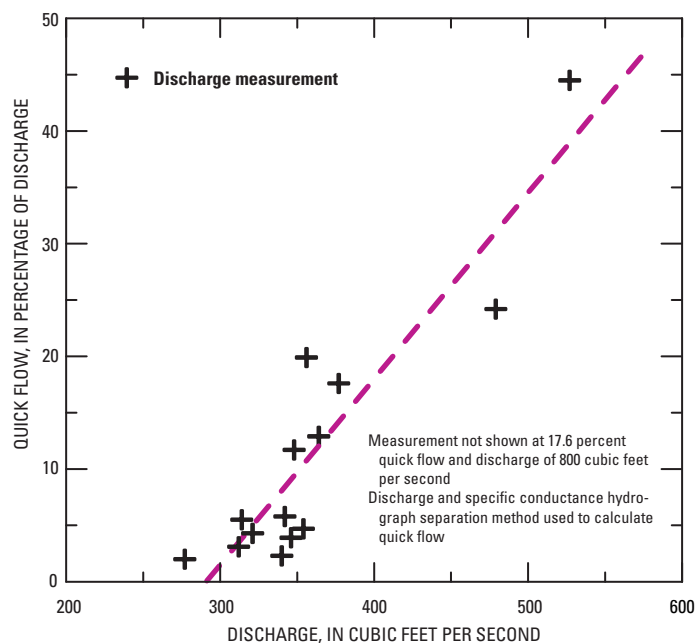


Figure 19. Discharge from Big Spring as a function of percentage quick flow, water years 2001–04.

percent quick flow implies concentrations of approximately 100 (90–105), 238 (220–250), 29 (20–35), and 1.4 (1.2–1.9) pptv for CFC–11, CFC–12, CFC–113, and SF₆ in the base-flow component, if discharge from Big Spring were a mixture of two components—modern water and an older component containing fixed constant tracer concentrations. The extrapolated tracer concentrations to zero percent quick flow imply base-flow (piston flow) recharge dates of about 1976 (1975–1977), 1974 (1973–1974), 1982 (1979–1983), and 1985 (1983–1988) based on CFC–12, CFC–11, CFC–113, and SF₆ values. The difference in implied base-flow ages from the various tracers may indicate some concerns in the tracer systematics, but more likely indicate that the mixing scenario, while correctly identifying the quick-flow component as modern, does not adequately describe the age of the older base-flow water. As percent quick flow decreases to less than about 5 percent (between 5 and 2 percent quick flow), the tracer concentrations, particularly those of CFC–12 and CFC–11, decrease substantially less than the values extrapolated to zero percent quick flow (fig. 20). For example, if a line is drawn between modern CFC–12 and the lowest concentration measured (fig. 20), none of the other CFC–12 observations lie along the dilution line (fig. 20). This indicates that, while the old component was nearly constant in composition in mixtures containing more than about 5 percent quick flow, the reservoir of older water in the Big Spring watershed may be a series of water mixtures with piston-flow ages greater than those obtained by extrapolation to zero percent quick flow. Each sample point with a low percentage of quick flow (less than 5 percent) may be a unique mixture. By assuming a mixing model more complex than the binary model, the age of the old fraction can be estimated.

Tracer Relations among CFC–11, CFC–113, and SF₆—Mean Age of Base Flow

Tracer-tracer plots provide a useful tool for examining more complex mixtures in ground water. Two such tracer-tracer plots are shown in figures 21 (CFC–11 and SF₆ concentrations) and 22 (CFC–113 and SF₆ concentrations). The lines on the figures represent several age/mixing models. The solid black line represents unmixed, piston-flow samples with the plus signs corresponding to water recharge dates along the piston-flow line. The straight dashed purple line, extending from the year 2002 to 0 concentration, represents the simple binary mixing of modern and old, tracer-free water. Results from two more-complex mixing models (exponential mixing and exponential-piston flow mixtures—the latter assuming a piston flow to exponential ratio of 1) are shown as dashed blue and dashed turquoise lines. The exponential model applies to a well-mixed reservoir or, in the case of a spring, an average of the ages of all the flow lines discharging from the spring. Further details of exponential and exponential-piston flow mixing can be found in Cook and Böhlke (1999).

The young component of quick flow is modern (fig. 20), so lines can be drawn from the modern point (upper right hand corner on figs. 21 and 22) through each sample point to the intersection with another model line to estimate the age of the old, base-flow component. The orange dots on figures 21 and 22 represent tracer-concentration measurements from Big Spring and the point labels give the percentage quick flow calculated from the hydrograph separation technique. If the ages of the base-flow water were described by piston flow, the apparent recharge dates of the base-flow component would decrease from about 1974 (45 percent quick flow) to about 1960 (2 percent quick flow) based on CFC–11 and SF₆ data (fig. 21).

Although the actual mixing model for the base-flow component is uncertain, the data of figure 20 indicate that the base-flow component contains low concentrations of the measured environmental tracers, indicating relatively old age. Further, the base-flow component is likely a mixture because the piston-flow apparent ages differ among the various tracers in the base-flow component. If base-flow waters were unmixed, the piston-flow ages would agree between the various tracers; however, they do not. The lowest concentrations of CFC–11, CFC–12, and CFC–113 at low percentage quick flow (fig. 20) correspond to piston flow apparent ages of 1972, 1972, and 1979. Agreement in piston-flow CFC–11 and CFC–12 apparent ages and young CFC–113 apparent age is characteristic of binary mixing of young and old (pre-tracer) water, although other mixing models could also result in this observation.

Although the precise mixing model for the base-flow component is uncertain, the exponential model can be applied to the tracer data from Big Spring to infer ranges of mean ages of water in the base-flow component. As the percentage of quick-flow water decreases to less than about 5 percent, the apparent age of the base-flow component decreases (fig. 20). Each storm would result in a small fraction of mixing of the

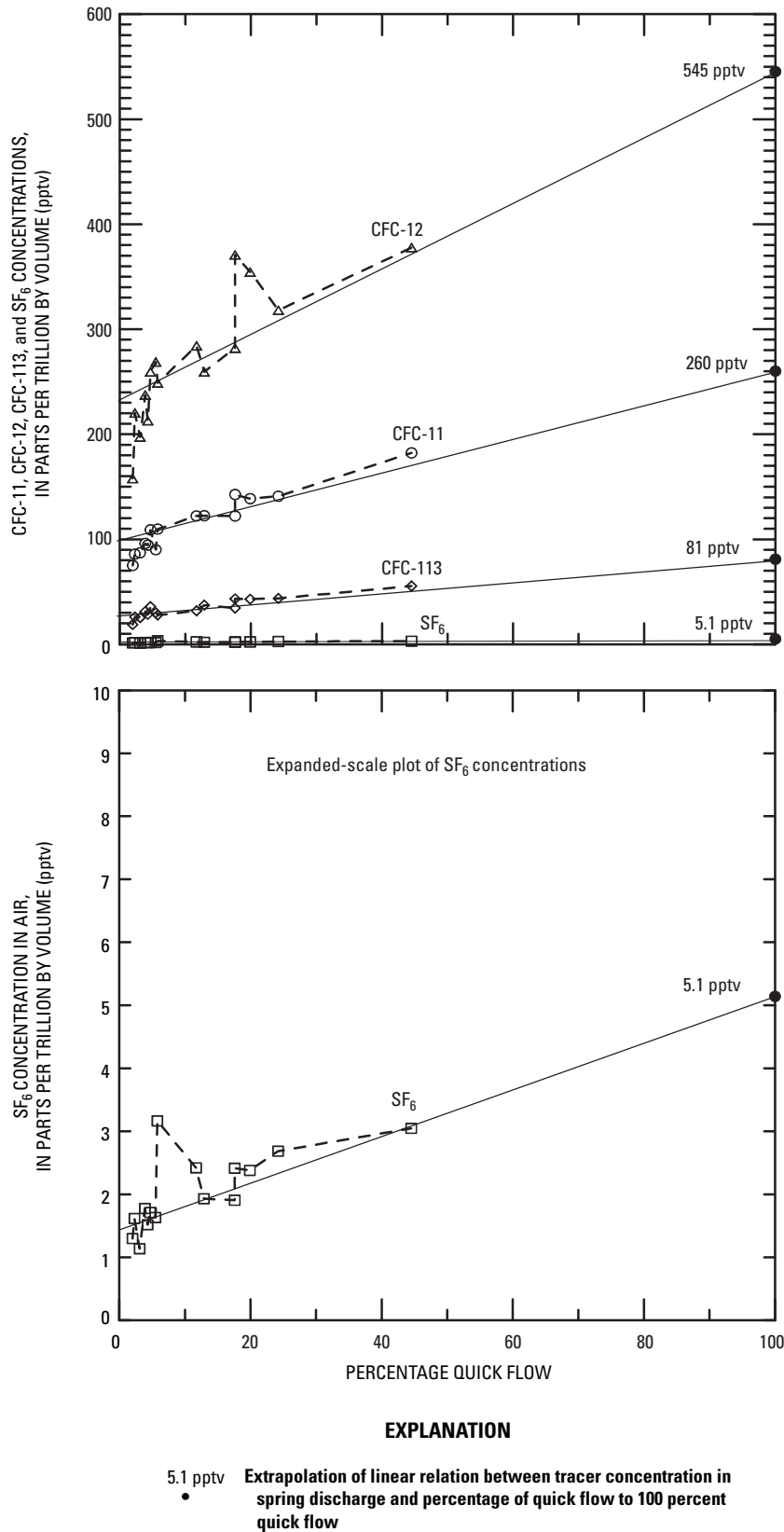


Figure 20. Concentrations of chlorofluorocarbons (CFC-11, CFC-12, and CFC-113) and sulfur hexafluoride (SF_6) in discharge from Big Spring as a function of percentage quick flow.

young component with the base-flow component. The environmental tracer data from Big Spring plot intermediate to the simple binary mixing of modern and old, pre-tracer water and results from the exponential mixture model (figs. 21 and 22). Based on the observation of short travel times of dye traces that discharged at Big Spring, the discharge contains fractions of modern water mixed with older water. Three binary mixing lines (dashed orange lines on figs. 21 and 22) were drawn from the modern water (2002) component, through the measured tracer concentration points, and projected to the exponential model to indicate mean ages of waters in the base-flow component. These binary mixing lines encompass most of the CFC-11, CFC-113, and SF_6 data and indicate mean ages of water in the base-flow component ranging from approximately 30 to 200 years. The mean age of the base-flow component is youngest (approximately 30 to 40 years) in samples containing the highest quick-flow component (45 percent quick flow) and increases to 200 years or more as the fraction of quick flow decreases to less than 5 percent (figs. 21 and 22). This is a further indication that base flow is part of a continuum of older water of varying average ages. One sample from Big Spring plots outside the model boundaries on both figures (figs. 21 and 22) and may contain an excess of SF_6 from terrigenous sources. The samples from Greer Spring appear to be mostly dilutions of modern water with old, pre-tracer water.

Tracer Relations among CFC-11, CFC-12, and SF_6 —Mean Age of Base Flow

The tracer-tracer plots (figs. 21 and 22) indicate generally concordant results among the data for CFC-11, CFC-113, and SF_6 . These data also are concordant with the few tritium measurements that were available (discussed in following tritium section). However, the CFC-12 data do not conform as well when used with the other tracer data. Inspection of the CFC-12 data in relation to the other tracers indicates local enrichment of CFC-12 of as much as 25 percent relative to CFC-11 in North American air (fig. 23). Unfortunately, the concentrations of CFCs in local air were

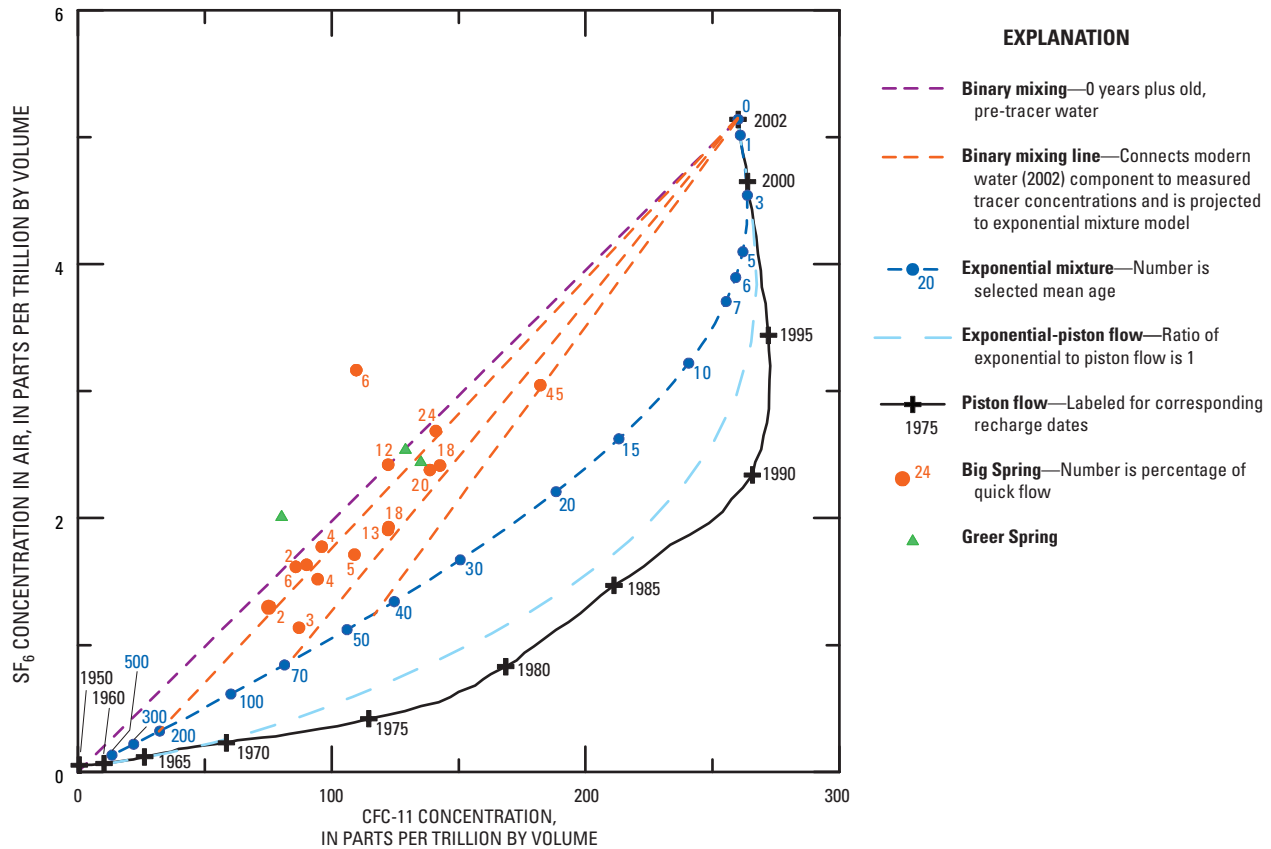


Figure 21. Concentrations of chlorofluorocarbon (CFC-11) and sulfur hexafluoride (SF_6) in discharge from Big Spring and Greer Spring in relation to several possible mixing models.

not measured during this investigation. In previous studies, observations similar to those of figure 23 have been interpreted as degradation of CFC-11 relative to CFC-12 in soils during infiltration (Plummer and others, 2001; International Atomic Energy Agency, 2006). However, because of the general concordance of CFC-11 with all the other environmental tracer data, CFC-11 degradation was not expected. Apparently, recharge from storms passes fairly rapidly to the water table in this karstic environment. Only the CFC-12 data seem elevated. The extrapolation of CFC-12 concentrations as a function of percent quick flow in figure 20 to 100 percent quick flow, though they may be consistent with the composition of modern air, is poorly constrained at quick-flow fractions greater than 45 percent. This conclusion becomes apparent when the CFC-12 data are compared to CFC-11 (fig. 23). Even though the Big Spring waters appear elevated in CFC-12, the CFC-12 results generally are still concordant with the mixing relations indicated by the CFC-11, CFC-113, and SF_6 data. When CFC-12 concentrations are plotted with SF_6 concentration data (fig. 24), none of the samples plot along the binary dilution of modern and old (pre-tracer) water, but instead are shifted to somewhat elevated CFC-12 concentrations and approach the model line for exponential mixing (blue line on fig. 24). Though these results differ somewhat from other tracer-tracer results, they still are consistent with the model of dilution of

modern water (year 2002) with old water, and if the age distribution in the base flow can be modeled by exponential mixing, mean ages of approximately 20 years, increasing to approximately 200 years, with generally decreasing fraction of quick flow are implied (fig. 24).

Inference of Base-Flow Age from Tritium Analysis

Only six samples of tritium were collected. Three samples were from Big Spring, with percent quick-flow values of 2, 18, and 45 percent, and three samples were from Greer Spring. These tritium values are shown in relation to CFC-11, CFC-113, and SF_6 in figure 25. All three plots are consistent with a mixing model of a modern component with an old component that does not contain tritium (pre-tracer). All three plots extrapolate to extremely low tritium values and indicate that the old fraction is mostly pre-1960s in age, and, if an exponential mixture occurs (dashed dark blue line on figure 25), the mean residence time would be more than several hundred years to be consistent with the measured tritium values. The one sample from Big Spring with 45 percent quick flow had a tritium concentration nearly one-half that of modern precipitation, consistent with the binary mixing sce-

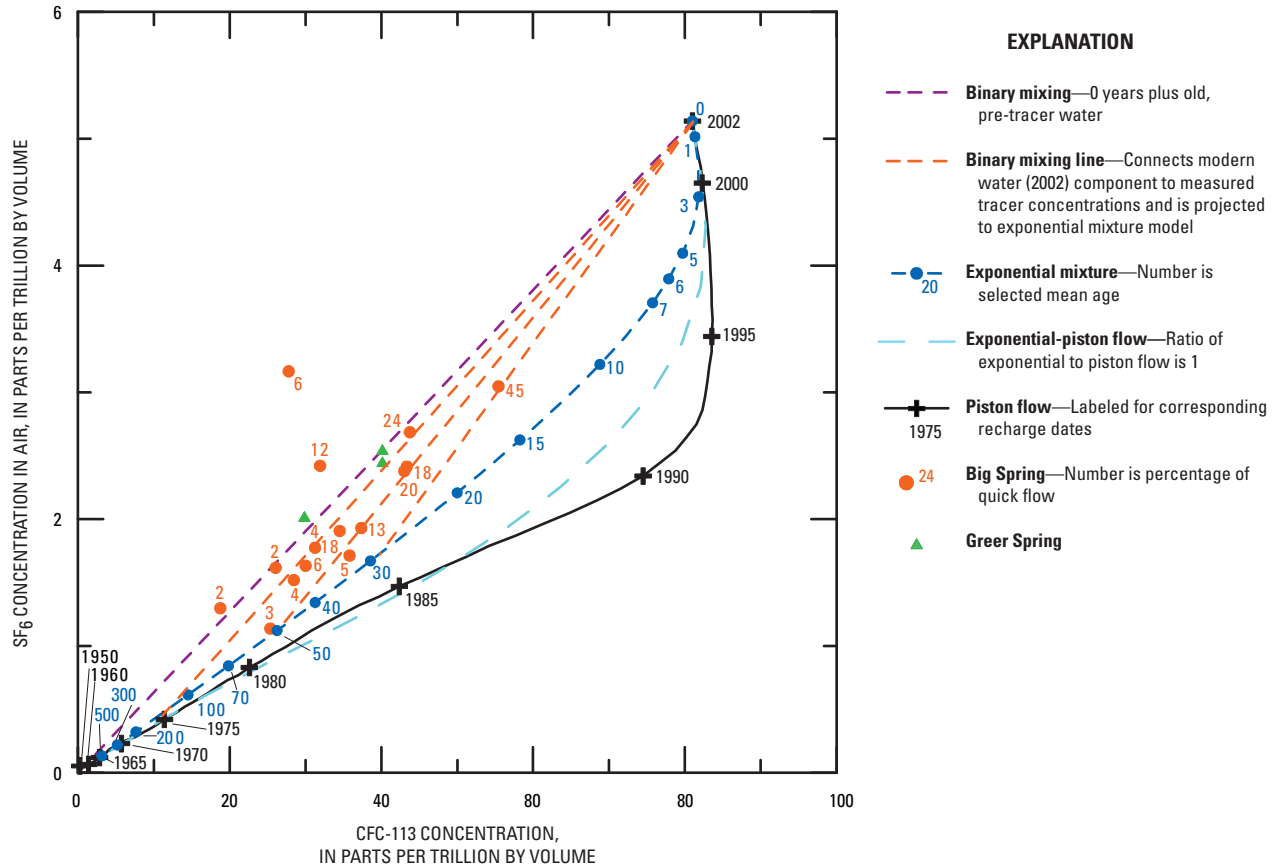


Figure 22. Concentrations of chlorofluorocarbon (CFC–113) and sulfur hexafluoride (SF₆) in discharge from Big Spring and Greer Spring in relation to several possible mixing models.

nario. Although the data point for 45 percent quick flow plots slightly below the binary mixing lines in figure 25, the slope of the binary mixing line is expected to vary somewhat with seasonal variations in the tritium content of precipitation. The available tritium data are consistent with the previous observations obtained from CFC–11, CFC–113, and SF₆. If the old fraction of discharge from Big Spring contained water from the mid-1960s, elevated tritium concentrations (fig. 18) would be detected in samples with a low percent quick flow. Instead, a decrease in tritium concentration occurs as percentage quick flow decreases (and fraction of baseflow increases; fig. 25). Therefore, the tritium data, in combination with the CFC and SF₆ data indicate a mostly pre-nuclear weapons testing age in the base-flow component of the water.

Inference of Base-Flow Age by Hydrograph Separation and Environmental Tracers

Equations 1 to 4 permitted calculation of the percentage of base flow and quick flow in spring discharge. The extreme specific conductance values (quick flow 100 μS/cm and base flow 357 μS/cm) used in the calculations of the quick-flow and base-flow components were determined from field observations or personal communication with technicians and were

assumed constant with time. This was a reasonable assumption from thermodynamic considerations; the composition of the base-flow component should approach a nearly constant composition as water-rock reactions proceed toward equilibrium. That is, as the age of the base-flow component increases, the specific conductance of the base-flow component (Cb value of 357 μS/cm) is assumed to approach a constant value. In general, the application of equations 1 to 4 to discharge would not be as reliable using concentrations of environmental tracers to obtain estimates of percent quick flow, unless it can be demonstrated that the ages of both flow components were constant. Still, there are advantages and limitations to using equations 1 to 4 with specific conductance and/or with environmental tracer data, both in conjunction with discharge data.

By solving equations 1 to 4 using transient environmental tracer data (CFCs, SF₆, and tritium), information can be obtained about the concentration of an environmental tracer in the base-flow component. That information can then be used through an appropriate mixing model to obtain information on the age of the base-flow component. Using the calculated values of percent quick flow (based on the discharge and specific conductance method), the calculated concentrations of CFC–11, CFC–12, and CFC–113 in the base-flow component for Big Spring are given in figure 26 (SF₆ not shown).

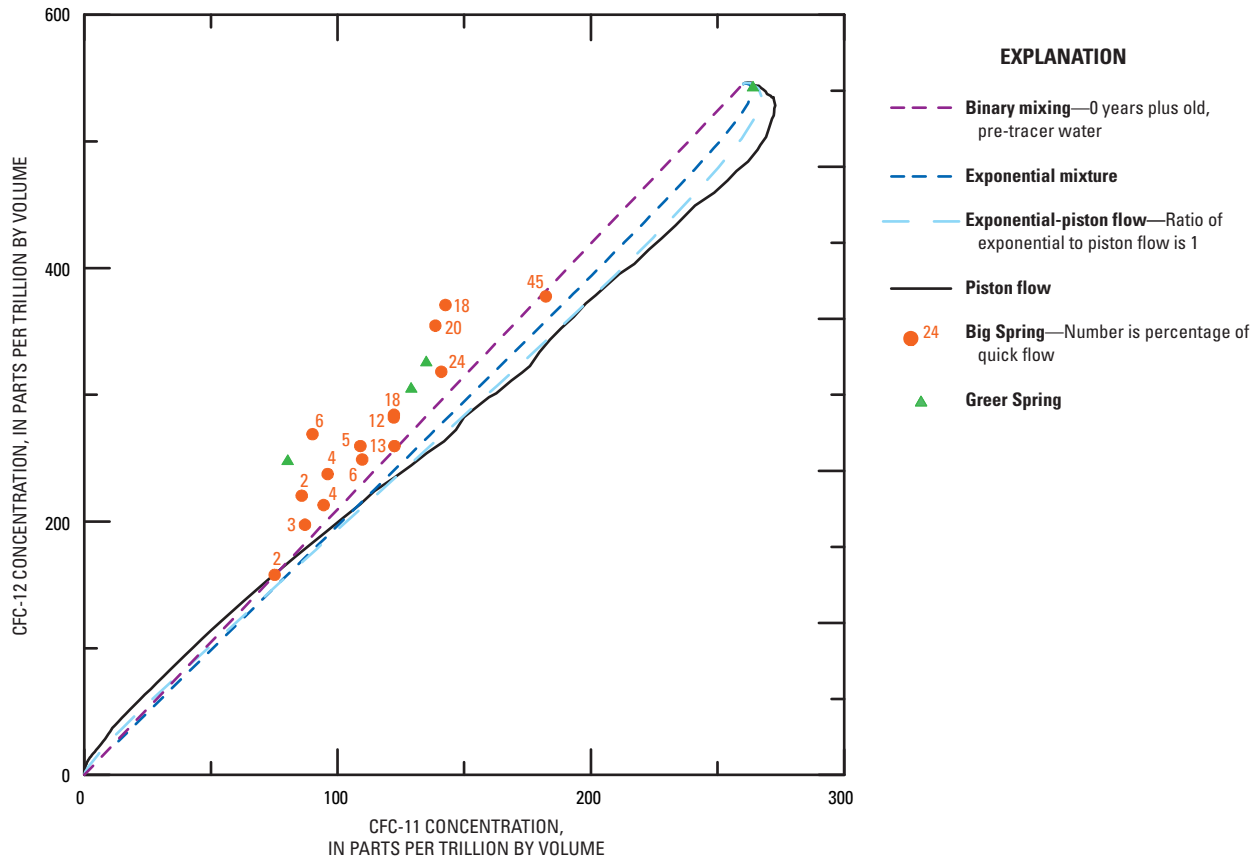


Figure 23. Concentrations of chlorofluorocarbons (CFC-11 and CFC-12) in discharge from Big Spring and Greer Spring in relation to several possible mixing models

The median concentrations of CFC-11, CFC-12, CFC-113, and SF_6 in base flow were 100.9, 237, 28.1, and 1.4 pptv. The age of the base-flow component depends on the model used to interpret age. If piston flow is assumed, the median concentrations in base flow correspond to apparent recharge dates of 1974, 1976, 1982, and 1985, for CFC-11, CFC-12, CFC-113, and SF_6 . As discussed previously, the piston-flow model is unlikely to be applied to base flow from Big Spring. The calculated CFC concentrations of the base-flow component are nearly constant when percent quick flow is greater than about 5 percent of spring discharge, but decreases as percent quick flow decreases to less than 5 percent, implying older ages in the highest fraction of base flow (fig. 26). If the exponential model applies, the calculated base-flow concentrations indicate mean ages of 40 to more than 200 years. Apparently, some age stratification is present in the older resident water in the Ozark aquifer discharging to Big Spring.

Recharge Temperatures and Water Temperatures

The calculated recharge temperature determined from dissolved N_2 and Ar concentrations in relation to the actual

temperature of discharge from Big Spring (fig. 27) provides useful information about depth of ground-water flow through the Ozark aquifer that discharges at Big Spring and Greer Spring and the predominant season of recharge. All of the water samples from Big Spring and Greer Spring have water temperatures warmer than their N_2 -Ar recharge temperature. The N_2 -Ar recharge temperatures range from approximately 10.5 to 14 °C and are in the range of long-term average air temperatures recorded in April (13.0 °C) and October (13.6 °C) in southeast Missouri (National Oceanic and Atmospheric Administration, 2005). More precipitation occurs in April than in October in southeast Missouri (National Oceanic and Atmospheric Administration, 2005) and it is assumed that evapotranspiration may still be occurring in October and intercepting moisture that would otherwise be used to recharge the ground-water system. Based on this reasoning, the N_2 -Ar recharge temperature data indicates recharge to the Big Spring watershed occurs primarily in late winter to early spring. The water temperatures at Big Spring were slightly warmer than the mean annual temperature in southeast Missouri (12.8 °C; National Oceanic and Atmospheric Administration, 2005) and consistent with relatively shallow circulation (less than about 600 ft); that is, the discharge from

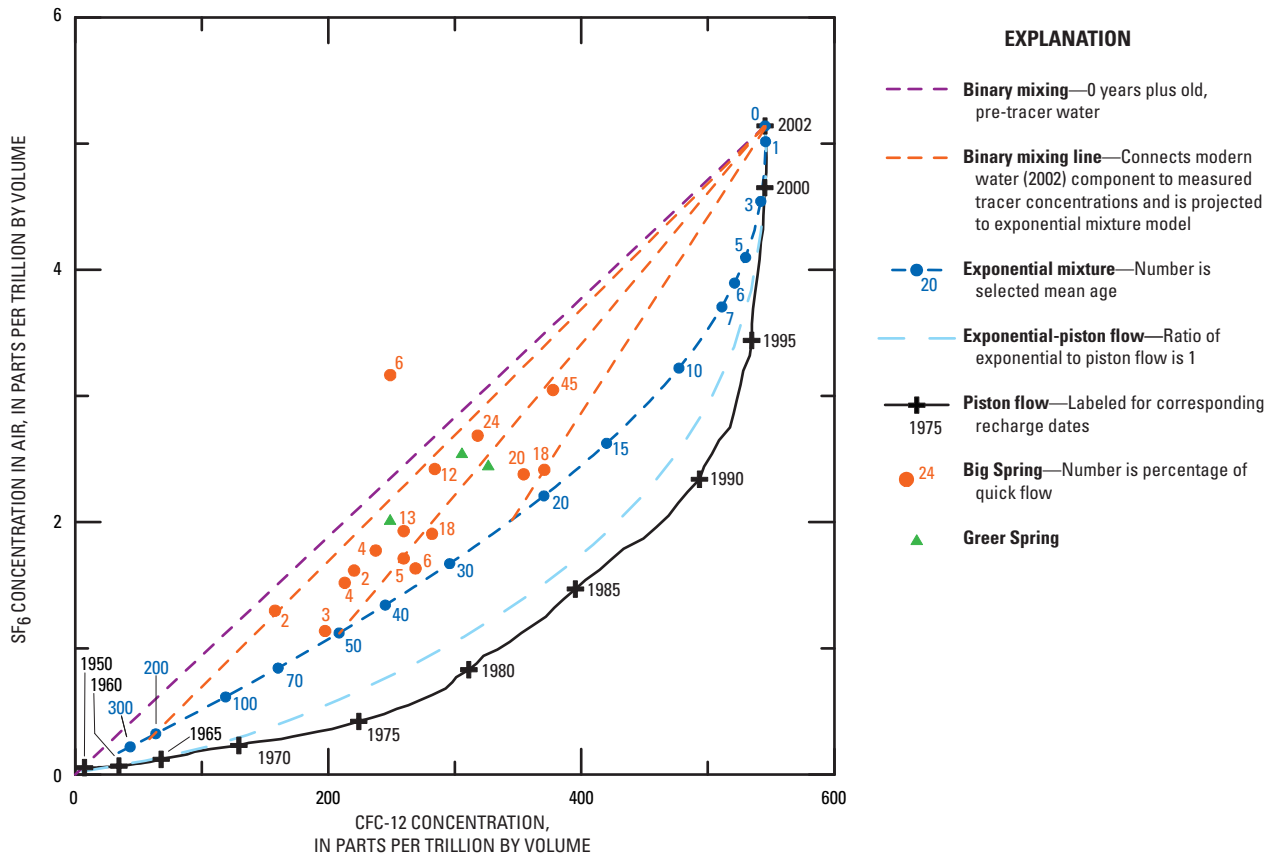


Figure 24. Concentrations of chlorofluorocarbon (CFC-12) and sulfur hexafluoride (SF₆) in discharge from Big Spring and Greer Spring in relation to several possible mixing models.

Big Spring does not appear to be warmed by deep circulation along a geothermal gradient.

General Water Quality

Springs are excellent sites for monitoring water quality in karst areas because springs typically are the point to which ground-water flow converges. Unlike water samples from wells that represent the quality of the ground water in the vicinity of the well, the quality of water discharging from a spring is representative of the aquifer in the spring recharge area. In the case of Big Spring, the recharge area includes several hundred square miles.

Water Quality and Dissolution Rates of Carbonate Rock in the Big Spring Recharge Area

The USGS has collected more than 130 water-quality samples at Big Spring since 1973. These samples were collected for multiple programs with different objectives resulting in a variety of chemical constituent suites being collected

using several different sample-collection methods. Water sample-collection methods used over the years include equal-width increment (EWI) cross sections, grab samples from the spring orifice, and pneumatic pumps placed in the spring orifice. The guidelines and procedures for these collection methods are described by Wilde and others (1999).

Since 1973, water samples from Big Spring have been analyzed for a variety of chemical constituents ranging from physical properties and major ions, nutrients, or indicator bacteria only, to extensive analyte suites including dissolved and total recoverable major and trace inorganic constituents, nutrients, indicator bacteria, pesticides, or stable isotopes. The following discussion of water quality is limited to general observations of selected physical properties, dissolved major cations and anions, nutrients, and indicator bacteria from 1973 through 2005. While the constituents being analyzed in water samples varied over time, these constituents were determined using standard USGS field and laboratory methods. Discharge, specific conductance, pH, water temperature, and alkalinity were determined onsite at the time of sampling. The procedures for performing these field measurements are described by Wilde and Radtke (1998). Water samples for analysis of dissolved chemical constituents were filtered onsite through a 0.45- μ m (micrometer) membrane filter. Water samples for

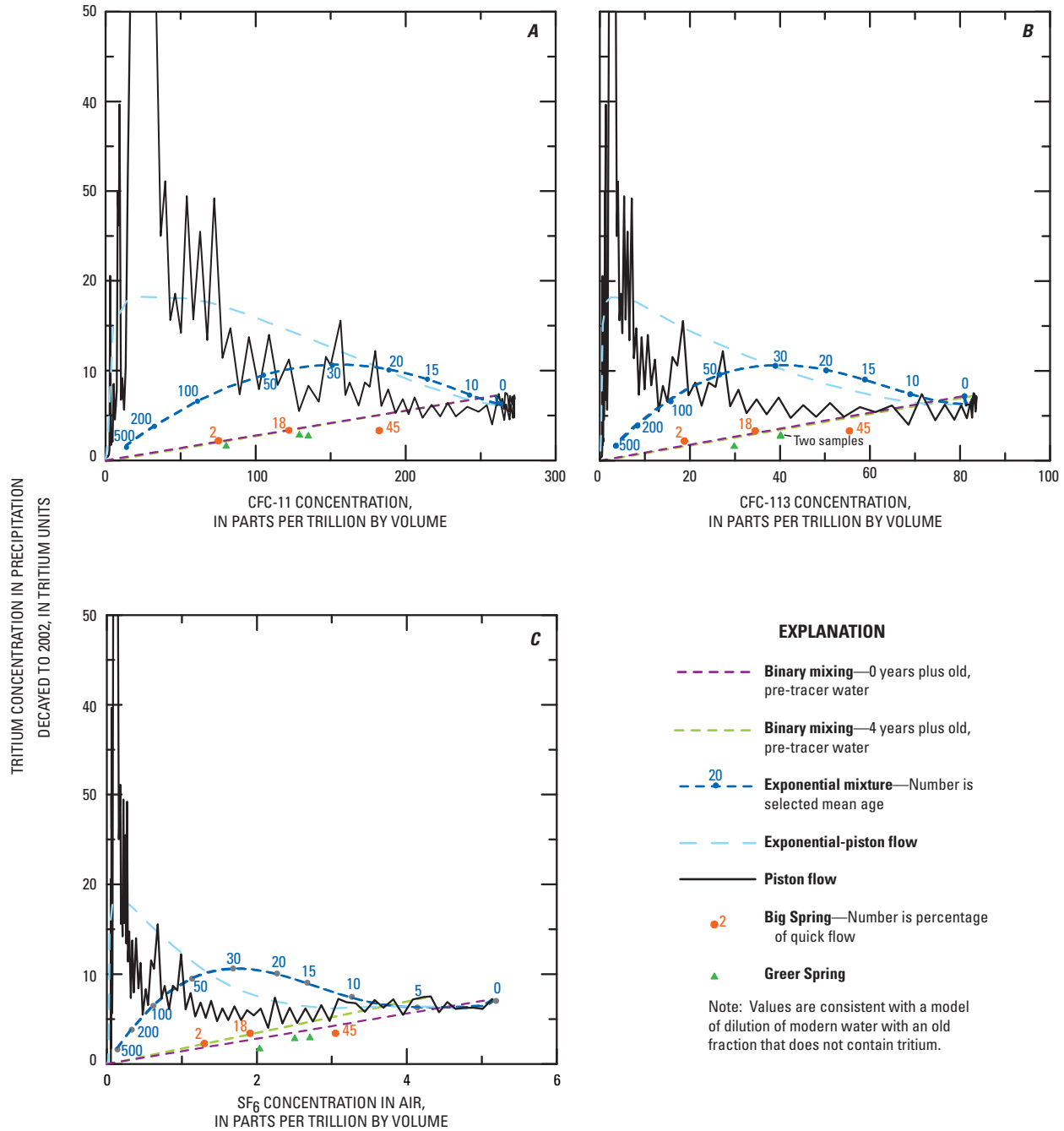


Figure 25. Tritium concentrations in precipitation, decayed to 2002, with concentrations of chlorofluorocarbons (CFC-11 and CFC-113) and sulfur hexafluoride (SF₆) in discharge from Big Spring and Greer Spring.

dissolved anions were placed into polyethylene bottles and samples for dissolved cations were placed in acid-washed polyethylene bottles and preserved with ultrapure nitric acid to a pH less than 2. All water-quality samples were analyzed by laboratories of the USGS. Water samples were analyzed for inorganic substances according to methods described by Fishman and Friedman (1989). Physical properties and inorganic constituent concentrations in water samples collected from

2000 to 2002 at Big Spring, specifically for this study are in table 9 (at the back of this report). Water quality data collected outside of this study are available at <http://nwis.waterdata.usgs.gov/mo/nwis/qwdata> accessed April 23, 2007.

Water samples collected at Big Spring from 1973 to 2002 indicate specific conductance values and concentrations of most inorganic constituents, for example, calcium (Ca), magnesium (Mg), sodium (Na), and bicarbonate (HCO₃) generally

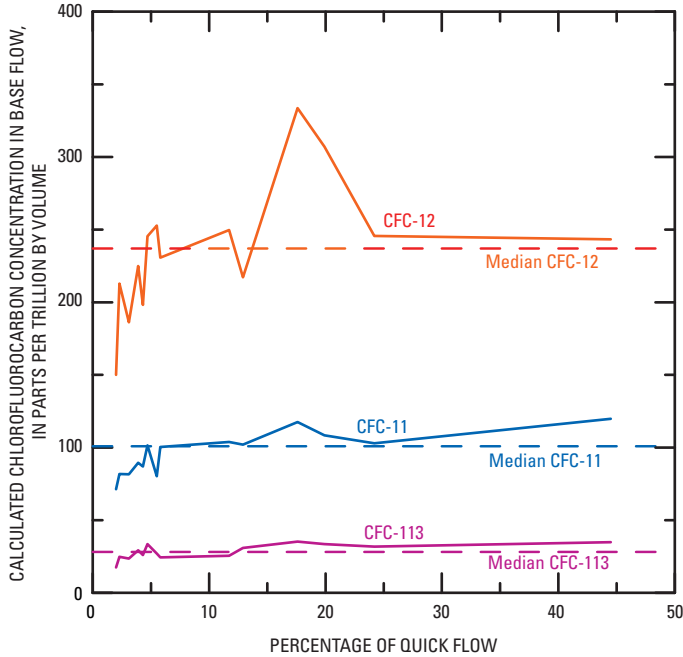


Figure 26. Calculated and median concentrations of chlorofluorocarbons (CFC–11, CFC–12, and CFC–113) in base flow as a function of percentage quick flow for Big Spring discharge.

decreased with increasing discharge (fig. 28). The decrease in constituent concentrations with increasing discharge indicates dilution of these predominantly base flow derived constituents with lower ionic strength quick flow. Concentrations of other constituents such as chloride (Cl) and nitrite plus nitrate

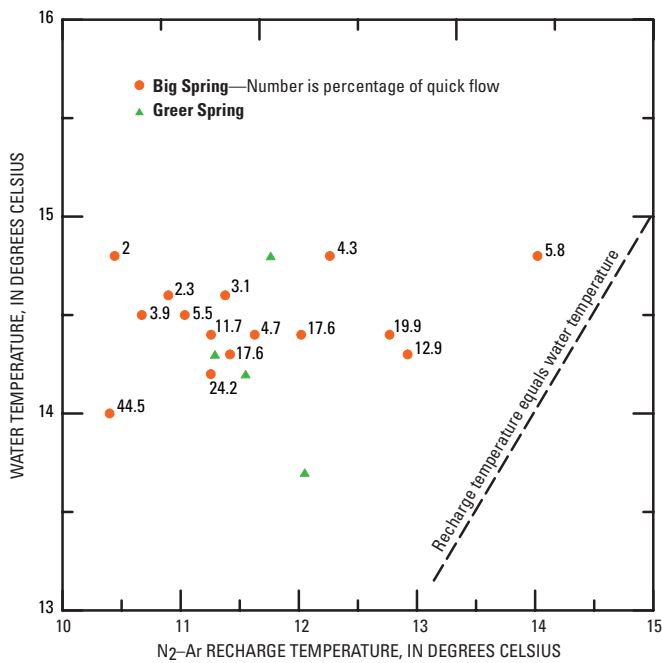


Figure 27. Recharge temperature determined from analyses of dissolved nitrogen (N₂) and argon (Ar) gas with the field-measured water temperature, 2001–03.

(NO₂+NO₃), and fecal coliform densities, however, exhibit little or no decrease with increasing discharge, indicating quick flow probably is a more important source of these constituents compared to base flow.

The predominant ions in water samples from Big Spring are Ca, Mg, and HCO₃, which is consistent with the predominance of carbonate rocks in the spring recharge area. Strong positive linear relations existed between specific conductance and concentrations of Ca, Mg, and HCO₃ (r² values of 0.91, 0.90, and 0.76), whereas constituents such as Cl and NO₂+NO₃ exhibited no relation with specific conductance (r² values less than 0.10). Strong positive linear relations also existed between barium (Ba) and strontium (Sr) and specific conductance (r² values of 0.71 and 0.91). The strong positive linear relations between these major and trace constituents and discharge is related to these constituents being common in carbonate rocks of the Ozark aquifer. Because of the strong positive relation between specific conductance and constituents such as Ca, Mg, and Sr, specific conductance can be used to estimate concentrations of these constituents when analytical data are not available.

Forty-four water samples collected at Big Spring from 1973 to 2005 plot along the line of carbonic acid weathering (dissolution) of dolomite (fig. 29) and have molar ratios of Ca: Mg of near 1 (1.00 to 1.18). The dissolution of the mineral dolomite is likely the primary control on concentrations of Ca, Mg, and HCO₃. Dissolution of dolomite and dissolution or precipitation of calcite also buffer the pH of the solution. Water in contact with dolomite [CaMg(CO₃)₂] should dissolve equal molar quantities of Ca and Mg, whereas water in contact with limestone [composed mostly of the mineral calcite (CaCO₃)] will have much larger ratios of Ca:Mg (Hem, 1992). Equilibrium-speciation calculations using the geochemical code PHREEQC (Parkhurst and Appelo, 1999) indicates that water samples from Big Spring generally are in equilibrium with the minerals calcite and dolomite. The saturation index (SI), which is the log₁₀ of the ratio of the ion activity product (IAP) divided by the equilibrium constant (KT), was calculated for calcite and dolomite for all water samples with electrical charge balances within 5 percent (total of 40 samples). The SI indicates whether a mineral should be dissolving (SI less than zero), be at equilibrium (SI of zero), or precipitating (SI greater than zero). Because of analytical error and small uncertainties in thermodynamic data, differences in SI values of plus or minus 0.25 probably are insignificant. SI values for calcite ranged from -1.18 to 0.00 (median of -0.38). Dolomite SI values were smaller, ranging from -2.44 to -0.03 (median of -0.81), indicating general slight undersaturation with respect to dolomite in most samples. The smaller SI values were associated with larger spring discharges, indicating that quick flow water entering the spring conduit system does not reach equilibrium with calcite or dolomite by the time it emerges from the spring orifice. While rocks in the recharge area are predominantly dolomite, secondary calcite is common. Because calcite is more soluble, calcite SI values near zero are not uncommon with dolomite slightly undersaturated.

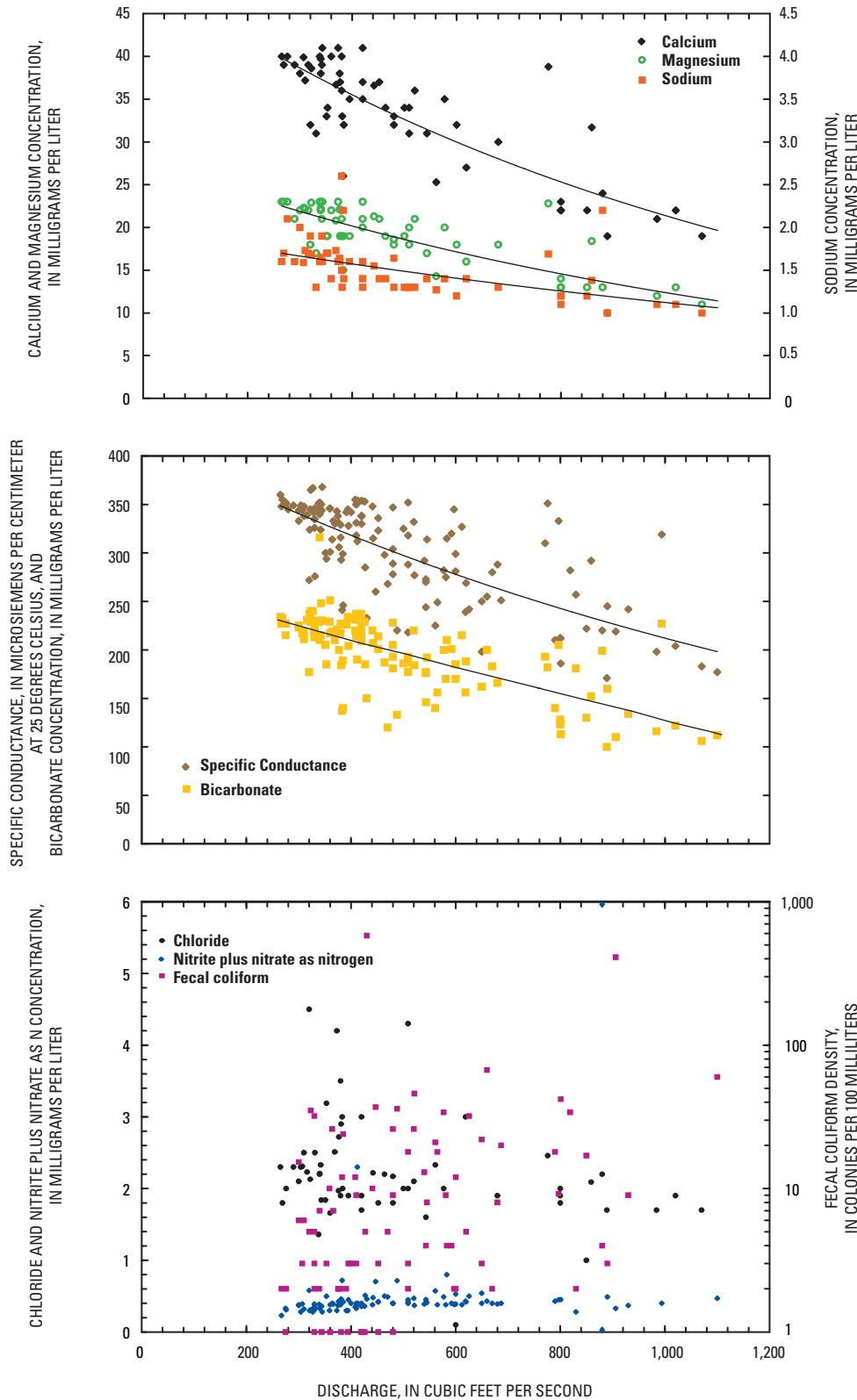


Figure 28. Relations between specific conductance, concentrations of selected inorganic constituents, fecal coliform densities, and discharge at Big Spring, 1973–2002.

Although calcite and dolomite SI values decreased with increasing discharge, molar ratios of Ca:Mg exhibited no trends with discharge, indicating that infiltrating runoff water is buffered by a similar process as base-flow water. The near constant molar Ca:Mg ratios indicated that dissolution of dolomitic rock in the unsaturated and phreatic conduits of the spring conduit system by infiltrating quick flow contributes to the increase in Ca and Mg loads during runoff.

The flux of Ca and Mg from Big Spring represents a considerable quantity of bedrock dissolved each day. Assuming all Mg is derived from dissolution of the mineral dolomite, and using an average Mg concentration of about 19 mg/L (milligrams per liter) at the mean annual discharge of 445 ft³/s (fig. 28), about 157,000 kg (173 tons) of dolomitic bedrock, is dissolved in the Big Spring recharge area each day. This mass of dolomite represents a volume of about 1,950 ft³ or a cube of rock 12.5 ft on each side is dissolved each day.

Estimated Annual Suspended Sediment Load of Big Spring

Suspended sediment concentrations (table 10, at the back of this report) in water samples from Big Spring were determined to estimate the suspended sediment load from the spring. Suspended sediment samples were collected about 1,500 ft downstream from the spring when the spring branch was wadable and at the NPS bridge during high stages. Samples were collected with a depth-integrating sampler using the EWI method and at a single point in

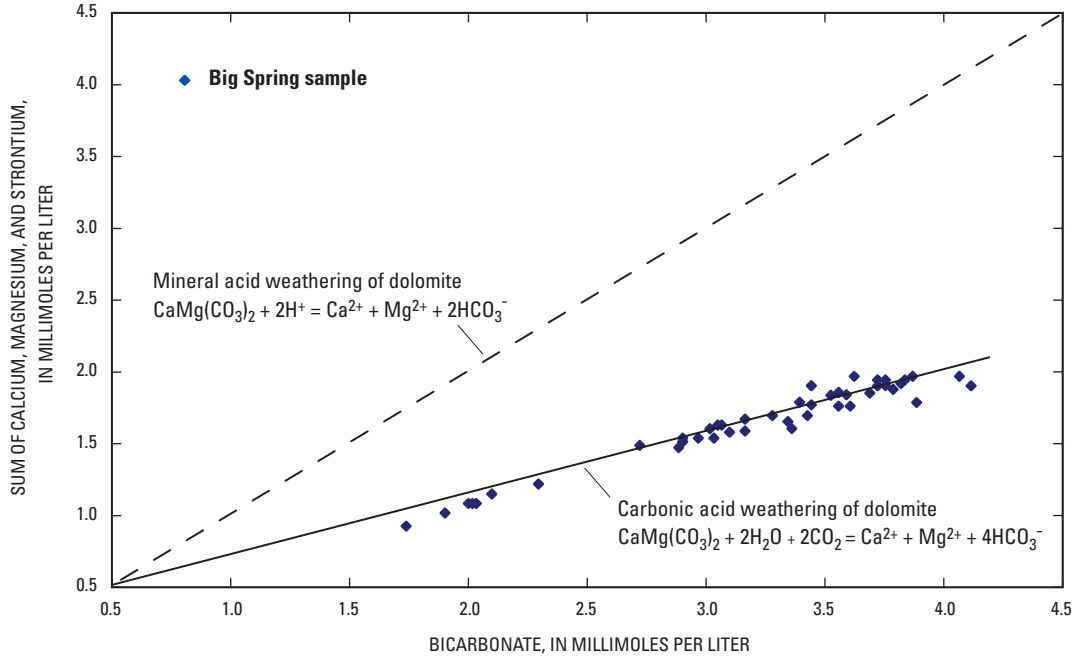


Figure 29. Relation between bicarbonate and the sum of calcium, magnesium, and strontium, 1973–2005.

the spring branch channel using an automatic sampler. All suspended sediment concentrations were determined in the USGS sediment laboratory in Rolla, Missouri. Before June 20, 2002, and from November 2003 to February 2004, suspended sediment concentrations were determined using the evaporation method (Guy, 1969). Samples collected at all other dates were analyzed using the filtration method (Guy, 1969). During evaporation method analyses of Big Spring water samples, dissolved solids concentration in the small quantity of supernatant water left in the sample bottle after decanting typically was greater than the suspended sediment concentration of the sample. Consequently, the filtration method was adopted for the suspended sediment analyses because it is more accurate identifying the smaller suspended sediment concentrations in

extremely clear water than the evaporation method. Most of the high-discharge suspended sediment samples were already collected and analyzed using the evaporation method before this issue was identified.

In an attempt to combine the two data sets from the different analysis methods, a cursory experiment was performed on a Big Spring water sample to determine the suspended sediment and dissolved solids concentrations that would typically be measured and reported using the evaporation method. The water sample was pumped through a filtration crucible to gather the suspended sediment, and the filtered water containing the dissolved solids was collected. The water containing the dissolved solids was processed using the evaporation method and the suspended sediment portion was processed using the filtration method. The results showed the suspended sediment concentration was 1.5 mg/L and the dissolved solids concentration was 17.1 mg/L.

A correction was applied to the reported suspended sediment concentrations based on TDS concentrations estimated from Big Spring specific conductance measurements and the estimated volume of water left in the evaporation dish during decanting. Because of the good correlation (r^2 value of 0.98) between TDS concentrations and specific conductance values from Big Spring, the TDS concentrations could be accurately estimated from the specific conductance (SC) data ($\text{TDS} = 0.5239 * \text{SC}$). The largest unknown variable in the applied correction to the evaporation-method concentrations is the amount of water left in the evaporation dish after decanting. During simulated trials, the supernatant liquid left in the evaporation dish was typically about 90 mL (milliliters) plus or minus 5 mL.

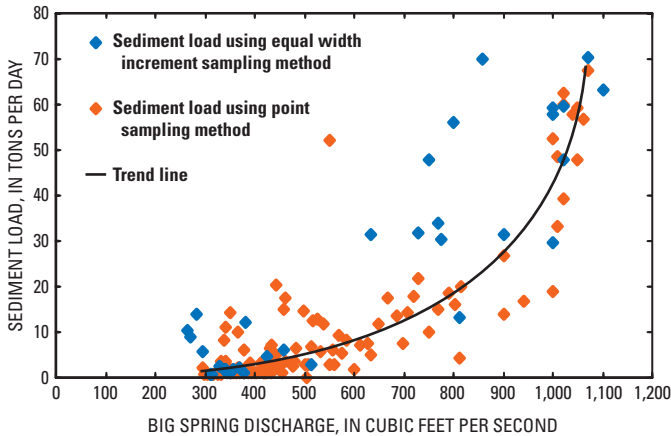


Figure 30. Suspended sediment load in water discharging from Big Spring, 2001–04.

Because the suspended sediment concentration of each sample is small and concerns associated with the analytical methods caused additional uncertainty in the measured sediment concentrations, an accurate comparison was not possible between sediment concentrations obtained from samples using the EWI method and the point sampler method. However, because of the severe turbulence at the orifice of Big Spring, the distance from the spring to the sediment sampling sites is small, and the sediment particles primarily are clay size, the sediment likely is well mixed across the spring branch channel and the point sampling method approximates the EWI sampling method.

Suspended sediment concentrations from both sampling methods (adjusted evaporation and filtration methods) were used with estimated spring discharge to calculate sediment loads carried by Big Spring (table 10; fig. 30). The suspended sediment load conveyed by Big Spring ranged from about 1 to about 70 ton/d (tons per day). Visual observations during high flow indicate the spring water does not become brown because of the sediment load, but normally becomes a light green. Sediment load increases as discharge increases, and the rate of increase is larger when discharge exceeds about 800 ft³/s. The sediment load during base-flow periods ranged from about 1 to about 7 ton/d.

Summary and Conclusions

Southeastern Missouri has been a prominent lead-mining area since shortly after the first French explorations occurred in the area in about 1700. In anticipation of future declining reserves of lead ore, mining companies have explored in a mature karst area of the Mark Twain National Forest, of southeastern Missouri. This is a highly valued and environmentally sensitive area because of its scenic beauty and recreational opportunities. The area contains the two largest springs in Missouri (Big Spring and Greer Spring) both of which flow into federally designated scenic rivers, along with other smaller springs. Concerns exist that mine dewatering in this area could lower water levels and cause a decrease in ground-water discharge to the springs. Also, the presence of losing streams in the exploration area is of concern because contaminants released during mining activities or from stored mine waste (tailings piles) potentially can migrate into the ground-water flow system. This could degrade the quality of water at nearby springs and threaten aquatic biota. The investigation of Big Spring is part of a larger investigation of the geology, hydrology, and aquatic biology of the exploration area initiated by these environmental concerns.

Water levels were measured or observed in 346 wells and 7 springs during the summer and fall 2000 to better define the recharge areas of Big Spring, Greer Spring, Mammoth Spring, and Boze Mill Spring. Ground-water levels generally were low because of the dry conditions and even lower in the mature karst terrain. Measured depth-to-water in summer 2000 ranged from 2.1 to 448.4 feet, but exceeded 200 feet in most wells located in the mature karst headwater areas of the

Eleven Point River, Spring Creek, Hurricane Creek, and Pike Creek. Two distinct potentiometric surfaces can be inferred from the water-level data. The shallow potentiometric surface, representing the water table where the depth-to-water was less than about 250 feet, tends to mimic topographic features and is strongly controlled by streams. The deep potentiometric surface represents ground-water hydraulic heads within the more mature karst areas where the depth-to-water was greater than about 250 feet. The deeper potentiometric surface indicates the presence of a highly permeable zone extending about 20 mile west of Big Spring toward the upper Hurricane Creek Basin. Deeper flowing water in the Big Spring recharge area is directed toward this permeable zone. A similar highly permeable zone extends about 10 miles west of Greer Spring, then trends to the northwest about 20 miles. The estimated sizes of the spring recharge areas are 426 square miles for Big Spring, 352 square miles for Greer Spring, 290 square miles for Mammoth Spring, and 54 square miles for Boze Mill Spring.

A discharge accumulation curve using Big Spring daily mean discharge data shows no substantial change in the discharge pattern of Big Spring occurred during the period of record, (water years 1922 through 2004) and observed long-term variations in spring discharge can be attributed to prolonged departures from normal precipitation. The quality of the computed spring discharge (using Big Spring stage-discharge rating curve and staff measurements) has been impaired by two factors. During low-flow conditions, thick watercress beds in the spring branch impede the natural movement of the flowing water and cause a higher-than-normal gage-height reading. During high-flow conditions increased flow in the Current River blocks the mouth of the spring branch and backwater causes a higher-than-normal gage-height reading. Also, at gage heights above about 9.5 feet water from the Current River flows over its banks upstream from Big Spring and enters the spring pool immediately downstream from the spring, but upstream from the gage on the NPS bridge. This additional river water is gaged along with the spring discharge causing additional complications in the stage-discharge relation. The entire area is inundated when the gage height reaches about 11 feet.

The maximum possible instantaneous flow from Big Spring has not been adequately defined because of backwater effects from the Current River during high-flow conditions. Physical constraints within the spring conduit system may restrict its maximum flow. The largest discharge measured at Big Spring during the period of record was 1,170 cubic feet per second on December 7, 1982.

To better determine the discharge from Big Spring, an acoustic Doppler system was installed to measure and record stream velocities in the spring branch. At low stage, acoustic Doppler-measured water velocities are about 2.5 feet per second, and the velocity data indicate considerable scatter for gage heights less than about 3 feet because of the presence of water cress in the channel. Above about a 3.0 feet stage, water velocities drop abruptly to about 1.5 feet per second as the backwater effect of the Current River stage propagates up the spring branch. Comparison of the calculated mean velocity

(measured discharge divided by channel cross sectional area) to the acoustic Doppler velocity shows that the calculated mean velocity is smaller than the measured acoustic Doppler velocity when stage at the bridge is lower than about 3.0 feet. At higher stage (about 6 to nearly 10 feet), the calculated velocity is uniformly larger than the acoustic Doppler velocity by about 0.10 to 0.20 feet per second. For spring branch stages above 3.5 to 4.0 feet, the relation between stage and water velocities is more uniform, and the acoustic Doppler velocity data may be used to refine discharge data normally derived directly from the stage-discharge curve for Big Spring.

The daily mean water temperature of Big Spring for the water years 2001 through 2004 (October 2000 through September 2004) had little variability, ranging from 13 to 15 °C (degree Celsius). Water temperatures generally vary less than 1 °C throughout the year. Lower daily mean water temperatures were recorded (13.1 to 13.5 °C) from March to April 2002. During the 2001 through 2004 water years, there were many times when the daily mean spring water temperature dropped below 14.0 °C, and each time was during or immediately following intense storms that occurred during the winter or spring. The warmest temperatures occur during October and November, traditionally low-flow periods, and the temperature decreases until April at which time water temperatures begin to increase. This indicates the water temperature in Big Spring shows a slight seasonal variation. The specific conductance values of water flowing from Big Spring is a result of the mixing of waters of different specific conductance. Water that has moved more slowly through the karst terrain and surrounding bedrock in the Big Spring recharge area accumulates dissolved solids to an equilibrium concentration that yields higher specific conductance values than water that moves more quickly through the larger fractures and conduits of the recharge area in response to intense rainfall.

Specific conductance of water from Big Spring (measured from October 2000 to September 2004) stabilized at about 357 microsiemens per centimeter at 25 degrees Celsius during extended periods of little rainfall, or moderate rainfall insufficient to cause measurable increase in spring discharge. During intervals of intense rainfall, or prolonged periods of moderate rainfall, water of lower specific conductance values that enters the larger fractures and conduits in the Big Spring recharge area quickly moves towards the spring orifice and discharges before reaching chemical equilibrium with the surrounding rock. The specific conductance of the ground water that discharges at the spring decreases as the ratio of quick-flowing water in the large fractures increases relative to the slower-flowing water in the smaller fractures. Observation of the rise in specific conductance values after a rainfall-induced decline shows that the recovery is slow and that the specific conductance approaches pre-storm values exponentially with time.

Base flow is defined herein as the component of spring flow derived from water that has traveled a long time through smaller fractures and pore space in the bedrock, and quick flow is associated with rapid transport of water to a spring through larger fractures following storm events. Dye-trace

investigations in the Big Spring recharge area show that (1) quick flow from the eastern part of the recharge area can take 6 to 12 days to reach the spring at a rate of 1.5 to 3 miles per day, (2) quick flow from the central part of the recharge area can take 8 to 11 days to reach the spring, and flow at a rate of 1.5 to 2 miles per day, and (3) quick flow from the western part of the recharge area can take 42 days to reach the spring at a rate of 0.9 mile per day.

The computer program HYSEP was used to separate the Big Spring hydrograph into base-flow and quick-flow components for water years 2001 to 2004. The HYSEP analysis predicted that base-flow discharge was the dominant source of water that sustained spring flow, quick-flow discharge was small as compared to the base-flow discharge, but failed to yield base-flow and quick-flow discharge curves that matched observations of spring characteristics. Big Spring discharge data were used in combination with specific conductance data to develop an improved hydrograph separation method (discharge and specific conductance method) for the spring. The estimated annual mean quick flow ranged from 15 to 48 cubic feet per second for the HYSEP analysis, and ranged from 26 to 154 cubic feet per second for the discharge and specific conductance method. The discharge and specific conductance method consistently estimated a larger percentage of quick flow for each of the 4 water years.

During periods characterized by large and abrupt rises in the spring hydrograph, HYSEP calculated a linear increase or decrease in base flow, which apparently is a function of the length of time from the onset of a substantial rise in the hydrograph to the next recharge-induced rise. At nine major or more-isolated hydrograph peaks, HYSEP estimated quick flow rose abruptly and peaked on the same day as the discharge hydrograph peak, then declined to near zero within a month. The abrupt decline in quick-flow discharge appears to be inconsistent with quick-flow traveltimes estimated from dye-trace investigations.

Using the discharge and specific conductance method of hydrograph separation, the estimated base-flow component rises abruptly as the spring hydrograph rises, and attains a peak value on the same day as the discharge peak. The base-flow component declines abruptly from its peak value, and then several days later base flow begins to increase at an approximately linear trend. The onset of the period of linear rise in base flow appears to coincide with the time at which the percentage of quick flow has reached a maximum after each recharge-induced discharge peak. The time interval between the discharge peak and the peak in percentage quick flow ranges from 8 to 11 days for seven hydrograph peaks, consistent with large amounts of recharge and quick-flow traveltime estimates by dye-trace tests from the mature karst Hurricane Creek Basin in the central part of the recharge area. The incorporation of specific conductance values into the hydrograph separation process for springs can yield more reasonable hydrograph separation results than HYSEP.

The environmental tracers, chlorofluorocarbons (CFCs: CFC-11, CFC-12, CFC-113), sulfur hexafluoride (SF₆),

and tritium (^3H) were used to test the discharge and specific conductance hydrograph separation model, estimate ages of quick-flow and base-flow components, and estimate mixing fractions. The concentrations of CFC-11, CFC-12, CFC-113, and SF_6 in discharge from Big Spring vary approximately linearly with percent quick flow from about 5 to 45 percent of discharge. Extrapolation of the linear relation to 100 percent quick flow implies CFC and SF_6 concentrations nearly identical to those in the 2002 atmosphere, and indicates a modern age for the quick-flow component. As percent quick flow falls below about 5 percent, the tracer concentrations fall below the values extrapolated to zero percent quick flow, which indicates that the reservoir of older water in the Big Spring watershed may be a series of water mixtures with piston-flow ages greater than those obtained by extrapolation to zero percent quick flow. Each sample point with a low percentage of quick flow (less than 5 percent) may be a unique mixture.

Tracer-tracer plots were used to examine several more-complex mixing models such as exponential mixing (an average of the ages of all the flow lines discharging from the spring) and exponential-piston flow mixtures. The environmental tracer data from Big Spring plot intermediate to the simple binary mixing of modern and old, pre-tracer water and results from the exponential mixture model. The mean ages of waters in the base-flow component, derived from extrapolation of binary mixing lines between the modern (2002) component and intersection with the exponential model, and passing through the measured tracer concentration points, approximately range from 30 to 200 years. The mean age of the base-flow component is youngest (30 to 40 years) in samples containing the highest quick-flow component (45 percent quick flow) and increases to 200 years or more as the fraction of quick flow decreases to less than 5 percent.

Tritium data from Big Spring and Greer Spring in relation to CFC-11, CFC-113, and SF_6 are consistent with a model of dilution of a modern component with an old, pre-tracer component and indicates that the old fraction is mostly pre-1960s in age, and if an exponential mixture, the mean residence time would be more than several hundred years to be consistent with the measured tritium values. The equations derived for hydrograph separation using discharge and specific conductance also are applicable to CFC and SF_6 tracer concentrations. Using the calculated values of percent quick flow (from the discharge and specific conductance hydrograph separation method), calculated median concentrations of CFC-11, CFC-12, CFC-113 and SF_6 in base flow were 100.9, 237, 28.1, and 1.4 parts per trillion by volume. The calculated CFC concentrations of the base-flow component is nearly constant when percent quick flow is greater than about 5 percent of spring discharge, but decreases as percent quick flow decreases to less than 5 percent, implying older ages in the highest fraction of base flow. If the exponential model applies, the calculated base-flow concentrations indicate mean ages of 40 to more than 200 years, suggesting some age stratification is present in the older resident water in the Ozark aquifer.

All of the water samples from Big Spring and Greer Spring have water temperatures warmer than their N_2 -Ar recharge temperature, which range from approximately 10.5 to 14 °C. This suggests recharge to the Big Spring watershed occurs primarily in late winter to early spring. The water temperatures at Big Spring are consistent with relatively shallow circulation (less than about 600 feet), and does not appear to be warmed by deep circulation along a geothermal gradient.

Specific conductance values and concentrations of most inorganic constituents in water samples from Big Spring generally decrease with increasing discharge indicating dilution of these predominately base flow derived constituents with lower ionic strength runoff water, or quick flow. Concentrations of some constituents such as chloride (Cl) and nitrite plus nitrate ($\text{NO}_2 + \text{NO}_3$), and fecal coliform densities, however, exhibit little or no decrease with increasing discharge indicating that quick flow is probably a more important source of these constituents compared to base flow. The predominant ions in water from Big Spring are calcium (Ca), magnesium (Mg), and bicarbonate (HCO_3), which is consistent with the predominance of carbonate rocks in the spring recharge area. Water samples from Big Spring plot along the line of dolomite dissolution by carbonic acid, and have a molar ratio of Ca: Mg of near 1, indicating dissolution of the mineral dolomite as the primary control on concentrations of Ca, Mg, and HCO_3 . Equilibrium-speciation calculations indicate that water samples from Big Spring generally are in equilibrium with the minerals calcite and dolomite. The flux of Ca and Mg from Big Spring represents the dissolution of about 1,950 cubic feet of dolomite per day.

The suspended sediment load of Big Spring was estimated to range from about 1 to 70 tons per day. The sediment load during base-flow periods ranged from about 1 to about 7 tons per day.

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Tables

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.

[ddmmss, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Site number	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Depth to water (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
1	363031	911847	T21N R03W 05AAB	725	105	--	06/14/00	37.9	687	10/27/00	41.8	683	-3.9	
2	363024	912122	T21N R04W 01BDB	805	--	--	06/15/00	140.9	664	10/27/00	192.9	612	-52.0	
3	363015	913123	T21N R05W 04CBA	545	130	--	07/05/00	54.2	491	10/26/00	56.5	489	-2.3	
4	363601	911208	T22N R02W 05AAB	650	300	82	06/14/00	141.5	509	11/14/00	153.4	497	-11.8	
5	363337	911321	T22N R02W 18ACD	600	--	--	06/14/00	49.8	550	11/14/00	55.3	545	-5.5	
6	363034	911300	T22N R02W 32CCC	460	--	--	06/14/00	44.0	416	11/14/00	47.4	413	-3.4	
7	363506	911930	T22N R03W 08BBB	610	--	--	06/15/00	135.1	475	10/25/00	146.8	463	-11.7	
8	363343	911616	T22N R03W 15ADD	600	354	--	06/14/00	106.0	494	10/25/00	120.5	480	-14.5	
9	363228	912022	T22N R03W 19CDC	785	--	--	06/20/00	140.9	644	10/25/00	158.3	627	-17.4	
10	363306	911843	T22N R03W 20AAC	690	--	--	06/14/00	162.8	527	10/25/00	187.0	503	-24.2	
11	363225	911511	T22N R03W 23DDA	605	--	--	06/14/00	56.1	549	10/25/00	72.0	533	-15.9	
12	363534	912204	T22N R04W 02ACC	600	250	105	06/15/00	97.6	502	10/25/00	106.5	493	-8.9	
13	363554	912506	T22N R04W 05AAD	670	84	84	06/21/00	46.4	624	10/25/00	76.0	594	-29.6	
14	363413	912539	T22N R04W 08CDD	865	--	--	06/15/00	91.1	774	--	--	--	--	
15	363239	912522	T22N R04W 20DBD	965	--	--	06/15/00	78.1	887	10/25/00	78.1	887	-0	
16	363305	912214	T22N R04W 23BAD	930	450	--	06/15/00	228.4	702	10/25/00	233.3	697	-5.0	
17	363124	912417	T22N R04W 33ABD	865	360	91	06/15/00	70.2	795	10/25/00	98.8	766	-28.6	
18	363540	912717	T22N R05W 01ACD	870	300	--	06/22/00	167.3	703	10/23/00	178.8	691	-11.5	
19	363548	912727	T22N R05W 01BDA	845	240	--	06/15/00	168.9	676	10/23/00	168.1	677	.8	
20	363541	912714	T22N R05W 01DBA	860	220	--	--	--	--	10/23/00	167.7	692	--	
21	363553	912928	T22N R05W 03ACB	865	160	--	06/20/00	124.9	740	10/26/00	131.6	733	-6.7	
22	363557	913136	T22N R05W 05ACB	680	100	--	07/03/00	47.7	632	10/26/00	57.7	622	-10.0	
23	363422	913311	T22N R05W 07CDD	700	210	--	06/30/00	73.5	627	10/23/00	74.6	625	-1.1	
24	363430	912907	T22N R05W 10DAD	670	100	--	06/20/00	39.3	631	10/26/00	73.9	596	-34.6	
25	363404	913107	T22N R05W 16BBC	725	210	--	06/20/00	157.2	568	10/26/00	161.9	563	-3.7	
26	363301	913004	T22N R05W 22BCC	690	170	--	06/20/00	81.3	609	10/26/00	88.8	601	-7.5	
27	363305	912758	T22N R05W 23ADA	895	200	104	06/20/00	127.5	768	10/26/00	131.6	763	-4.1	
28	363103	912948	T22N R05W 34CAD	650	90	--	06/20/00	51.7	598	10/26/00	60.0	590	-8.3	
29	363042	912727	T22N R05W 36DCB	815	400	--	06/20/00	122.7	692	10/26/00	130.9	684	-8.2	

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

[ddmms, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Site number	Latitude (ddmms)	Longitude (ddmms)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
30	363556	913407	T22N R06W 01ABC	710	210	--	06/30/00	74.7	635	10/23/00	79.1	631	-4.4	
31	363454	913459	T22N R06W 11AAD	885	--	--	06/30/00	227.9	657	10/23/00	242.7	642	-14.8	
32	364105	905835	T23N R01E 05AAB	630	--	--	06/07/00	2.1	628	11/15/00	1.6	628	0.5	
33	363824	905442	T23N R01E 13DCC	485	--	--	06/06/00	73.1	412	11/15/00	45.6	439	27.6	
34	363847	905752	T23N R01E 16DBB	690	--	--	06/07/00	36.8	653	11/15/00	53.0	637	-16.2	
35	363907	905952	T23N R01E 18ADB	745	--	--	06/07/00	43.6	701	--	--	--	--	
36	363803	905744	T23N R01E 21ACD	640	260	--	06/06/00	48.8	591	11/15/00	58.1	582	-9.3	
37	363817	905617	T23N R01E 23BBB	630	--	--	06/06/00	68.8	561	11/15/00	73.0	557	-4.2	
38	363629	905657	T23N R01E 34ABC	605	--	--	06/07/00	108.7	496	11/15/00	116.9	488	-8.2	
39	364016	910655	T23N R01W 07BAA	810	295	--	06/08/00	146.3	664	10/27/00	157.0	653	-10.7	
40	363918	910300	T23N R01W 14BBB	750	--	--	06/07/00	123.5	627	11/14/00	132.2	618	-8.7	
41	363827	910411	T23N R01W 21AAA	650	--	--	06/08/00	55.4	595	11/14/00	60.7	589	-5.3	
42	363820	905354	T23N R02E 19BBA	580	--	--	06/06/00	84.1	496	--	--	--	--	
43	363903	910850	T23N R02W 14ACD	655	250	--	06/12/00	85.2	570	10/25/00	97.3	558	-12.1	
44	363852	911233	T23N R02W 17CAC	530	--	--	06/13/00	108.9	421	10/27/00	110.3	420	-1.4	
45	363806	910815	T23N R02W 24CAB	630	280	138	06/12/00	120.5	510	10/25/00	126.4	504	-5.9	
46	363653	911335	T23N R02W 31BAA	650	310	--	06/14/00	222.3	428	11/14/00	226.7	423	-4.4	
47	364111	911612	T23N R03W 02BBB	785	--	--	06/13/00	206.4	579	11/14/00	211.4	574	-5.0	
48	364030	911814	T23N R03W 04CCD	800	450	90	06/13/00	290.1	510	11/14/00	295.6	504	-5.5	
49	364117	911857	T23N R03W 05ABB	845	--	--	06/20/00	68.4	777	10/27/00	118.3	727	-49.9	
50	363933	911935	T23N R03W 18AAA	690	200	60	06/13/00	64.0	626	10/27/00	64.8	625	-8	
51	363813	911957	T23N R03W 19DBA	645	--	--	06/14/00	114.5	531	10/27/00	126.9	518	-12.4	
52	363810	911958	T23N R03W 19DBD	630	--	--	06/14/00	106.0	524	11/14/00	120.6	509	-14.6	
53	363838	911532	T23N R03W 23ABA	630	--	--	06/13/00	130.4	500	11/14/00	139.6	490	-9.2	
54	363635	911958	T23N R03W 31ACD	705	250	--	06/15/00	188.2	517	10/27/00	195.6	509	-7.4	
55	363632	911731	T23N R03W 33DAA	590	150	--	06/13/00	119.1	471	11/14/00	116.8	473	2.3	
56	364055	912543	T23N R04W 05CAA	865	--	160	07/05/00	20.2	845	10/23/00	28.8	836	-8.6	
57	363944	912357	T23N R04W 10CCC	870	--	--	06/13/00	74.1	796	10/23/00	79.3	791	-5.2	
58	363937	912148	T23N R04W 11DDD	745	320	--	06/21/00	198.5	547	10/20/00	238.6	506	-40.1	

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

Site number	Latitude (ddmms)	Longitude (ddmms)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
59	363934	912640	T23N R04W 18ABA	862	160	--	07/06/00	47.6	814	10/23/00	49.2	813	-1.6	
60	363702	912132	T23N R04W 25CCD	750	385	--	06/21/00	192.9	557	10/20/00	195.3	555	-2.5	
61	363732	912255	T23N R04W 26BCC	725	330	--	06/22/00	175.4	550	10/20/00	209.9	515	-34.5	
62	363732	912352	T23N R04W 27BCD	715	--	--	06/22/00	135.6	579	10/20/00	251.4	464	-116	
63	363703	912438	T23N R04W 28CDD	710	350	--	--	--	--	10/20/00	184.6	525	--	
64	363712	912723	T23N R04W 30CBB	785	140	100	06/22/00	84.1	701	10/23/00	102.9	682	-18.8	
65	364114	913355	T23N R05W 06BCB	950	--	--	07/06/00	276.7	673	--	--	--	--	
66	364033	912936	T23N R05W 10AAA	965	--	--	07/06/00	87.7	877	11/13/00	109.9	855	-22.2	
67	364026	912724	T23N R05W 12AAD	870	260	260	07/06/00	33.6	836	10/23/00	45.2	825	-11.6	
68	363803	913354	T23N R05W 19CCD	770	300	--	07/06/00	173.1	597	10/26/00	181.1	589	-8.0	
69	363743	912842	T23N R05W 26ADB	940	300	150	07/06/00	224.5	716	10/23/00	251.7	688	-27.2	
70	363735	913152	T23N R05W 29ADD	670	230	--	07/05/00	19.4	651	10/26/00	34.5	636	-15.1	
71	363658	912735	T23N R05W 36AAB	805	--	--	06/22/00	141.1	664	10/23/00	150.6	654	-9.5	
72	364130	913613	T23N R06W 02BBB	885	--	--	06/22/00	139.9	745	11/17/00	141.8	743	-1.9	
73	364129	913642	T23N R06W 03ABB	935	460	--	--	--	--	11/17/00	330.4	605	--	
74	363952	913927	T23N R06W 08CCC	880	410	--	06/28/00	235.5	645	10/24/00	239.4	641	-3.9	
75	364008	913558	T23N R06W 11CBA	865	--	--	06/22/00	113.8	751	--	--	--	--	
76	363934	913739	T23N R06W 16ACA	820	100	--	06/28/00	77.1	743	10/23/00	72.8	747	4.3	
77	363818	913836	T23N R06W 20DDA	940	--	--	06/29/00	113.4	827	10/23/00	120.7	819	-7.3	
78	363809	913539	T23N R06W 23DCB	770	258	28	07/06/00	133.4	637	11/17/00	154.9	615	-21.5	
79	363647	913628	T23N R06W 34ADC	881	--	--	06/29/00	81.2	800	--	--	--	--	
80	363632	913412	T23N R06W 36DAD	800	290	120	07/05/00	126.1	674	10/26/00	140.7	659	-14.6	
81	364100	914639	T23N R07W 06DCC	920	120	--	06/29/00	71.6	848	10/24/00	74.7	845	-3.1	
82	364032	914348	T23N R07W 10BCC	925	330	--	06/29/00	229.5	696	10/24/00	282.8	642	-53.3	
83	364034	914139	T23N R07W 12BCB	890	294	--	06/28/00	162.8	727	10/24/00	178.8	711	-16.0	
84	364025	915048	T23N R08W 09DAC	1,093	290	--	07/05/00	105.6	987	10/26/00	135.5	958	-29.9	
85	363727	915132	T23N R08W 33BBA	1,040	310	--	07/05/00	82.0	958	10/26/00	98.2	942	-16.2	
86	364527	905820	T24N R01E 08AAA	450	--	--	06/01/00	9.4	441	11/15/00	17.2	433	-7.8	
87	364416	905537	T24N R01E 14BAD	410	--	--	06/07/00	45.5	365	11/14/00	47.1	363	-1.6	

[ddmms, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

[ddmmss, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Site number	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
88	364345	905924	T24N R01E 18DDD	440	--	--	06/06/00	10.8	429	11/14/00	12.5	427	-1.7	
89	364254	905931	T24N R01E 19DDC	470	--	--	06/07/00	30.9	439	11/15/00	47.4	423	-16.5	
90	364631	910104	T24N R01W 01ABC	600	55	--	06/07/00	25.2	575	10/19/00	35.9	564	-10.7	
91	364631	910411	T24N R01W 04ABD	700	56	--	06/12/00	37.2	663	10/19/00	37.8	662	-6	
92	364342	910713	T24N R01W 19BBC	800	420	120	06/12/00	239.7	560	11/14/00	231.4	569	8.3	
93	364302	910531	T24N R01W 20CDD	715	195	180	06/13/00	149.7	565	11/14/00	156.8	558	-7.1	
94	364249	910406	T24N R01W 28AAC	730	--	--	06/08/00	101.9	628	11/14/00	108.1	622	-6.2	
95	364224	910602	T24N R01W 29DBC	785	--	--	06/08/00	182.6	602	11/14/00	191.4	594	-8.8	
96	364647	911326	T24N R02W 06BAA	850	200	--	06/07/00	108.7	741	11/15/00	122.0	728	-13.3	
97	364504	910714	T24N R02W 12DAA	740	--	--	06/08/00	202.3	538	11/15/00	212.1	528	-9.8	
98	363908	910850	T24N R02W 14ACD	680	900	--	06/12/00	144.8	535	10/25/00	156.7	523	-11.9	
99	364342	910716	T24N R02W 24AAD	805	240	160	06/12/00	134.2	671	11/14/00	144.7	660	-10.5	
100	364303	910725	T24N R02W 24DDD	770	510	245	06/13/00	151.2	619	11/14/00	159.0	611	-7.8	
101	364315	912034	T24N R03W 19CCB	960	220	--	06/21/00	156.1	804	11/13/00	174.0	786	-17.9	
102	364347	911815	T24N R03W 21BBC	870	--	--	06/13/00	138.7	731	11/13/00	136.7	733	2.0	
103	364254	911358	T24N R03W 25AAD	810	--	--	06/13/00	206.2	604	10/26/00	191.9	618	14.3	
104	364239	911715	T24N R03W 28ADD	850	--	--	06/13/00	217.5	633	11/14/00	232.2	618	-14.7	
105	364128	911412	T24N R03W 36DDDB	725	--	--	06/13/00	173.4	552	10/26/00	178.7	546	-5.3	
106	364600	912237	T24N R04W 02CCC	885	--	--	06/20/00	96.4	789	10/25/00	102.5	783	-6.1	
107	364523	912555	T24N R04W 08BCC	901	--	--	06/21/00	132.4	769	10/25/00	139.8	761	-7.4	
108	364501	912342	T24N R04W 10CCB	905	--	--	06/15/00	99.7	805	10/25/00	116.5	789	-16.8	
109	364436	912127	T24N R04W 13BCA	790	--	--	06/15/00	111.4	679	11/13/00	117.5	673	-6.1	
110	364402	912450	T24N R04W 16CCC	890	--	--	06/20/00	42.1	848	--	--	--	--	
111	364328	912635	T24N R04W 19DBC	945	--	--	06/20/00	75.4	870	11/13/00	81.8	863	-6.4	
112	364335	912316	T24N R04W 22ACC	885	220	220	06/21/00	31.6	853	11/13/00	39.1	846	-7.5	
113	364147	912545	T24N R04W 32CBA	905	--	--	07/03/00	56.3	849	11/13/00	75.0	830	-18.7	
114	364126	912236	T24N R04W 35CCD	760	115	35	06/21/00	38.0	722	11/13/00	47.5	713	-9.5	
115	364122	912116	T24N R04W 36CDD	800	--	--	06/13/00	172.9	627	10/27/00	186.2	614	-13.3	
116	364608	913310	T24N R05W 06DCB	805	--	--	06/19/00	96.9	708	11/13/00	100.1	705	-3.2	

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

Site number	Latitude (ddmms)	Longitude (ddmms)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
117	364504	913222	T24N R05W 08CDB	705	--	--	06/19/00	15.3	690	11/13/00	18.2	687	-2.9	
118	364509	912911	T24N R05W 11CBD	885	--	--	06/19/00	236.3	649	11/13/00	244.8	640	-8.5	
119	364403	913109	T24N R05W 16CDD	925	113	--	06/22/00	70.1	855	--	--	--	--	
120	364320	912823	T24N R05W 23DDA	925	--	--	06/20/00	154.7	770	11/13/00	156.0	769	-1.3	
121	364206	913321	T24N R05W 31ABC	965	--	--	06/22/00	34.1	931	10/26/00	43.6	921	-9.5	
122	364137	913000	T24N R05W 34CDA	975	--	--	07/05/00	14.9	960	11/13/00	21.2	954	-6.3	
123	364145	912806	T24N R05W 36CAB	985	180	--	07/05/00	55.7	929	11/13/00	96.0	889	-40.3	
124	364709	913510	T24N R06W 02AAA	710	90	--	06/19/00	22.0	688	11/13/00	29.8	680	-7.8	
125	364558	913948	T24N R06W 06DCC	1,000	350	--	06/26/00	125.6	874	10/25/00	141.1	859	-15.5	
126	364515	913546	T24N R06W 11CAC	890	--	--	06/21/00	102.7	787	10/27/00	123.7	766	-21.0	
127	364432	913430	T24N R06W 13ACC	865	--	--	06/22/00	65.7	799	10/26/00	73.2	792	-7.5	
128	364349	913903	T24N R06W 20BDC	985	340	164	06/27/00	138.9	846	10/24/00	154.3	831	-15.4	
129	364322	913712	T24N R06W 22CCC	970	--	--	06/22/00	121.6	848	10/26/00	127.2	843	-5.6	
130	364303	913434	T24N R06W 25BDA	980	300	163	07/05/00	170.9	809	10/26/00	184.3	796	-13.4	
131	364237	913926	T24N R06W 30DDA	915	300	--	06/27/00	149.4	766	10/24/00	150.4	765	-1.0	
132	364601	914456	T24N R07W 08AAD	1,000	280	205	06/26/00	136.4	864	10/25/00	156.6	843	-20.2	
133	364601	914211	T24N R07W 11BAA	1,020	300	--	06/26/00	128.4	892	--	--	--	--	
134	364416	914107	T24N R07W 13CDD	950	--	--	06/27/00	186.0	764	10/24/00	225.6	724	-39.6	
135	364353	914533	T24N R07W 20CAA	1,075	--	--	06/27/00	226.6	848	10/25/00	237.3	838	-10.7	
136	364328	914242	T24N R07W 23CCC	980	280	--	06/28/00	150.2	830	10/24/00	158.7	821	-8.5	
137	364208	914529	T24N R07W 32DBB	950	170	--	06/29/00	20.6	929	10/24/00	66.0	884	-45.4	
138	364221	914335	T24N R07W 34BCA	940	420	183	06/27/00	222.9	717	10/24/00	199.9	740	23.0	
139	364212	914346	T24N R07W 34BCC	925	350	--	06/27/00	139.0	786	10/24/00	163.7	761	-24.7	
140	364228	914135	T24N R07W 36BBB	985	220	147	06/28/00	166.5	819	--	--	--	--	
141	364224	914134	T24N R07W 36BBC	970	510	--	06/28/00	260.1	710	10/24/00	324.5	646	-64.4	
142	364617	915131	T24N R08W 05DDD	1,090	--	--	07/06/00	92.0	998	11/17/00	70.1	1,020	21.9	
143	364600	914758	T24N R08W 12BAC	1,095	--	--	06/27/00	282.4	813	10/24/00	310.7	784	-28.3	
144	364517	914956	T24N R08W 15BAA	1,090	--	--	06/27/00	68.2	1,022	--	--	--	--	
145	364359	914854	T24N R08W 23CAA	965	373	158	06/27/00	124.5	841	10/25/00	157.2	808	-32.6	

[ddmms, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

[ddmms, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Site number	Latitude (ddmms)	Longitude (ddmms)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
146	364302	914747	T24N R08W 25CAD	970	516	434	06/29/00	183.8	786	10/25/00	191.7	778	-7.9	
147	364623	915612	T24N R09W 10AAB	1,200	--	--	06/29/00	28.0	1,172	10/23/00	52.0	1,148	-24.0	
148	365053	905719	T25N R01E 04DDC	470	80	--	06/08/00	30.1	440	11/15/00	27.8	442	2.3	
149	365148	905912	T25N R01E 05BBC	575	250	--	06/08/00	82.2	493	10/19/00	96.1	479	-13.9	
150	364809	905951	T25N R01E 30ABC	450	160	--	06/08/00	19.2	431	10/19/00	34.7	415	-15.5	
151	364707	905752	T25N R01E 33BDB	420	--	--	06/01/00	10.1	410	--	--	--	--	
152	365104	910518	T25N R01W 08BAA	595	130	--	06/09/00	11.2	584	10/19/00	18.6	576	-7.4	
153	365042	910157	T25N R01W 11ACC	535	140	--	06/08/00	32.6	502	10/19/00	33.1	502	-5	
154	364853	910656	T25N R01W 19CBB	900	--	--	06/07/00	79.4	821	10/19/00	84.1	816	-4.7	
155	364834	910640	T25N R01W 19CDC	820	185	--	06/07/00	12.5	808	10/19/00	17.3	803	-4.8	
156	364845	911029	T25N R02W 21DDB	923	300	--	06/07/00	163.4	760	10/26/00	169.9	753	-6.5	
157	364719	911103	T25N R02W 33BDC	780	--	--	06/12/00	49.0	731	10/26/00	49.4	731	-4	
158	365203	911650	T25N R03W 04AAD	660	196	--	06/08/00	32.7	627	10/19/00	35.0	625	-2.3	
159	365203	911650	T25N R03W 04AAD2	660	--	--	06/08/00	30.6	629	--	--	--	--	
160	365109	911715	T25N R03W 09ABC	635	--	--	06/08/00	40.5	595	10/19/00	45.0	590	-4.5	
161	364958	911958	T25N R03W 18CBB	905	350	--	06/08/00	225.6	679	10/20/00	230.2	675	-4.6	
162	364844	911702	T25N R03W 21DDB	555	--	--	06/08/00	24.2	531	10/19/00	28.8	526	-4.6	
163	364744	911933	T25N R03W 31BAD	620	330	--	06/08/00	74.3	546	11/14/00	79.0	541	-4.7	
164	364718	911617	T25N R03W 34CAD	525	--	--	--	0	525	--	0	525	0	
165	364954	912356	T25N R04W 16CDB	620	--	--	--	--	--	10/25/00	84.4	536	--	
166	364949	912338	T25N R04W 16DCA	640	280	--	06/09/00	53.6	586	10/25/00	72.8	567	-19.2	
167	364917	912107	T25N R04W 23ADD	595	--	--	06/08/00	5.3	590	10/19/00	6.3	589	-1.0	
168	365110	913244	T25N R05W 07BDC	1,008	--	--	06/16/00	256.0	752	10/24/00	261.9	746	-5.9	
169	365028	913138	T25N R05W 17BDB	1,025	--	--	06/21/00	262.1	763	10/27/00	263.1	762	-1.0	
170	364940	913006	T25N R05W 21AAB2	915	--	--	06/20/00	184.0	731	10/27/00	186.5	729	-2.4	
171	364723	913129	T25N R05W 32CDA	645	--	--	06/19/00	15.7	629	10/26/00	20.1	625	-4.4	
172	364711	912846	T25N R05W 34DDD	690	--	--	06/19/00	71.1	619	10/26/00	86.6	603	-15.5	
173	365153	913333	T25N R06W 01CAA	990	--	--	06/21/00	273.3	717	11/13/00	279.1	711	-5.8	
174	365156	913434	T25N R06W 02DBB	985	--	--	--	--	--	11/13/00	166.4	819	--	

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

Site number	Latitude (ddmms)	Longitude (ddmms)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	
175	365205	913509	T25N R06W 03ADA	870	--	--	06/21/00	109.3	761	11/13/00	116.5	754	-7.2	
176	365021	913321	T25N R06W 13ACC	995	245	--	06/21/00	188.5	807	11/13/00	192.0	803	-3.5	
177	365215	914029	T25N R07W 01BCB	1,000	360	245	06/21/00	198.8	801	10/25/00	200.7	799	-1.9	
178	365055	914054	T25N R07W 11DDB	970	--	--	06/21/00	175.7	794	10/25/00	184.0	786	-8.3	
179	365023	914447	T25N R07W 17CBA	1,090	--	--	06/22/00	136.4	954	10/25/00	142.5	947	-6.1	
180	364900	914115	T25N R07W 23CDC	965	394	--	06/22/00	116.9	848	10/25/00	123.1	842	-6.2	
181	364902	914324	T25N R07W 28BAA	990	190	--	06/28/00	138.0	852	10/25/00	158.4	832	-20.4	
182	364847	914451	T25N R07W 29BCA	1,050	--	--	07/06/00	122.9	927	11/13/00	158.2	892	-35.3	
183	364810	914352	T25N R07W 33BBB	965	--	--	06/22/00	158.5	807	--	--	--	--	
184	364739	914018	T25N R07W 36CAA	965	260	--	06/22/00	118.6	846	10/25/00	143.2	822	-24.6	
185	365221	914920	T25N R08W 04ADA	1,145	400	--	06/27/00	185.9	959	10/24/00	200.0	945	-14.1	
186	365141	915144	T25N R08W 07AAB	1,150	500	--	06/27/00	232.8	917	10/24/00	242.8	907	-10.0	
187	365103	914900	T25N R08W 10CDB	1,085	400	--	07/06/00	138.6	946	10/26/00	249.6	835	-111.0	
188	365107	914718	T25N R08W 11DAD	1,070	--	--	06/28/00	155.2	915	10/25/00	255.6	814	-100.4	
189	365008	914622	T25N R08W 13DDB	1,060	240	123	07/06/00	116.3	944	10/26/00	116.2	944	.1	
190	365007	915114	T25N R08W 17CDB	1,130	--	--	06/28/00	144.7	985	10/24/00	157.2	973	-12.5	
191	364956	914936	T25N R08W 21AAB	1,085	--	--	07/06/00	132.2	953	10/26/00	134.8	950	-2.6	
192	364816	914655	T25N R08W 25CDC	1,090	--	--	07/06/00	246.5	844	10/26/00	260.6	829	-14.2	
193	364849	914804	T25N R08W 26BCA	1,158	430	--	06/28/00	111.0	1,047	10/24/00	252.4	906	-141.4	
194	364835	914912	T25N R08W 27CAB	1,120	--	--	07/06/00	3.1	1,117	--	--	--	--	
195	364819	915209	T25N R08W 30CDD	1,165	--	--	06/28/00	183.7	981	10/24/00	232.8	932	-49.1	
196	364724	915005	T25N R08W 33CDD	1,125	580	580	07/06/00	209.9	915	10/26/00	251.4	874	-41.5	
197	364721	914649	T25N R08W 36CDD	1,010	--	--	06/30/00	155.6	854	10/24/00	191.8	818	-36.2	
198	365103	915335	T25N R09W 12CCB	1,200	535	--	06/28/00	162.9	1,037	10/23/00	173.6	1,026	-10.7	
199	365004	915708	T25N R09W 20AAB	1,120	270	20	06/29/00	48.0	1,072	10/23/00	59.8	1,060	-11.8	
200	365000	915446	T25N R09W 23BBB	1,218	--	--	07/07/00	75.4	1,143	11/21/00	91.7	1,126	-16.3	
201	365654	910013	T26N R01W 01DDA	470	--	--	05/31/00	19.1	451	10/17/00	22.6	447	-3.5	
202	365539	905841	T26N R01E 08CAD	500	--	--	06/02/00	17.1	483	10/18/00	31.4	469	-14.3	
203	365544	905732	T26N R01E 09CAA	460	--	--	06/02/00	23.2	437	10/18/00	27.1	433	-3.9	

[ddmms, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

[ddmmss, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Site number	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
204	365339	905440	T26N R01E 24BCD	438	--	--	06/02/00	16.5	422	10/18/00	20.5	418	-4.0	
205	365719	910537	T26N R01W 05BBB	550	300	--	06/01/00	44.7	505	10/18/00	48.0	502	-3.3	
206	365704	910526	T26N R01W 05BDB	545	125	--	06/05/00	65.0	480	10/17/00	68.6	476	-3.6	
207	365612	910619	T26N R01W 07ACB	600	144	84	06/01/00	26.1	574	10/18/00	28.7	571	-2.6	
208	365616	910637	T26N R01W 07BBD	610	142	80	06/01/00	20.7	589	10/18/00	25.1	585	-4.4	
209	365623	910541	T26N R01W 08BBB	680	350	--	06/01/00	203.2	477	10/18/00	186.1	494	17.2	
210	365528	910256	T26N R01W 15ABC	900	2,457	300	06/06/00	390.5	510	10/19/00	392.4	508	-1.9	
211	365528	910621	T26N R01W 18BAD	615	70	--	06/01/00	66.7	548	10/18/00	Dry	--	--	
212	365509	910641	T26N R01W 18BCD	650	75	--	06/01/00	40.2	610	10/18/00	42.6	607	-2.4	
213	365354	910259	T26N R01W 22DCC	900	220	--	06/06/00	68.3	832	10/19/00	74.1	826	-5.8	
214	365420	910120	T26N R01W 24CBB	925	245	--	06/08/00	152.9	772	10/19/00	155.7	769	-2.8	
215	365214	910218	T26N R01W 35CDC	845	310	--	06/06/00	175.8	669	10/19/00	178.6	666	-2.8	
216	365713	910809	T26N R02W 02ABA	575	--	--	06/06/00	21.7	553	10/18/00	24.7	550	-3.0	
217	365640	911030	T26N R02W 04DCB	680	280	--	04/18/00	119.9	560	10/18/00	126.5	554	-6.6	
218	365620	911017	T26N R02W 09AAC	675	--	--	04/18/00	93.3	582	10/18/00	93.9	581	-6	
219	365539	911046	T26N R02W 09CDC	730	310	84	04/18/00	207.8	522	10/18/00	214.6	515	-6.8	
220	365521	910813	T26N R02W 14ABD	722	--	--	06/05/00	258.1	464	11/15/00	270.9	451	-12.8	
221	365524	911053	T26N R02W 16BBD1	760	255	130	04/18/00	182.5	577	10/18/00	179.1	581	3.4	
222	365514	911209	T26N R02W 17BCC	790	300	--	--	--	--	11/15/00	188.3	602	--	
223	365527	911227	T26N R02W 18AAC1	760	300	80	04/18/00	159.6	600	10/18/00	162.8	597	-3.2	
224	365433	911202	T26N R02W 20BBD	810	340	40	04/18/00	159.1	651	10/18/00	176.7	633	-17.6	
225	365214	911034	T26N R02W 33DCA	825	--	--	06/07/00	135.8	689	11/15/00	151.1	674	-15.3	
226	365640	911916	T26N R03W 06DCC	905	300	300	06/05/00	54.8	850	10/19/00	97.0	808	-42.2	
227	365632	911524	T26N R03W 11BBB	925	210	--	06/05/00	174.9	750	10/19/00	178.8	746	-3.9	
228	365514	911956	T26N R03W 18CBB	945	1,200	150	06/05/00	359.3	586	10/19/00	300.7	644	58.6	
229	365310	911953	T26N R03W 30CCC	722	400	--	06/06/00	54.7	667	10/19/00	67.8	654	-13.1	
230	365320	911851	T26N R03W 30DDA	705	210	90	06/06/00	126.5	579	11/15/00	132.1	573	-5.6	
231	365226	911648	T26N R03W 33DDA	670	120	20	06/08/00	52.7	617	10/19/00	60.1	610	-7.4	
232	365242	911530	T26N R03W 35BCC	715	--	--	06/08/00	82.4	633	10/19/00	91.4	624	-9.0	

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

Site number	Latitude (ddmms)	Longitude (ddmms)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
233	365635	912521	T26N R04W 08BBB	985	2,400	--	06/12/00	366.4	619	10/20/00	368.3	617	-1.9	
234	365635	912523	T26N R04W 08BBB2	990	350	--	06/12/00	247.3	743	10/20/00	259.9	730	-12.6	
235	365623	912322	T26N R04W 09ADA	980	450	155	06/05/00	285.5	695	10/20/00	283.0	697	2.5	
236	365531	912243	T26N R04W 15BDA2	830	2,700	--	06/15/00	243.4	587	10/20/00	252.0	578	-8.6	
237	365504	912250	T26N R04W 15CDA	840	200	--	06/15/00	90.6	749	10/20/00	99.9	740	-9.3	
238	365458	912219	T26N R04W 15DDC	795	--	--	--	0	795	--	0	795	0	
239	365536	912523	T26N R04W 17BBC	950	350	--	06/05/00	154.9	795	10/20/00	160.7	789	-5.8	
240	365421	912448	T26N R04W 20DBC	1,020	450	--	06/13/00	311.4	709	--	--	--	--	
241	365313	912111	T26N R04W 25DDC	735	100	--	06/06/00	38.6	696	10/19/00	43.9	691	-5.3	
242	365357	912112	T26N R04W 26AAA	810	1,200	--	06/06/00	244.5	566	10/19/00	281.5	529	-37.0	
243	365401	912527	T26N R04W 30AAA	990	--	--	06/07/00	216.2	774	10/19/00	217.0	773	-8	
244	365628	913226	T26N R05W 07BAD	940	340	244	06/20/00	112.5	828	10/24/00	117.4	823	-4.9	
245	365601	912834	T26N R05W 10DAD	1,030	325	--	06/07/00	242.1	788	10/20/00	243.3	787	-1.2	
246	365338	913012	T26N R05W 28DBB	795	500	--	06/14/00	109.6	685	10/20/00	149.8	645	-40.2	
247	365646	913857	T26N R06W 07BAA	1,120	420	245	06/20/00	257.1	863	10/24/00	260.7	859	-3.6	
248	365530	913603	T26N R06W 15BCC	1,018	210	--	06/15/00	130.1	888	10/24/00	134.7	883	-4.6	
249	365325	913339	T26N R06W 25CDB	945	400	--	06/16/00	222.1	723	10/24/00	227.6	717	-5.5	
250	365325	913458	T26N R06W 26CCA	1,040	435	379	06/16/00	235.5	805	--	--	--	--	
251	365615	914256	T26N R07W 09DAC	1,085	--	--	06/20/00	269.0	816	10/24/00	274.5	811	-5.5	
252	365506	914054	T26N R07W 14PCD	1,085	507	--	06/20/00	239.1	846	10/24/00	277.9	807	-38.8	
253	365548	914341	T26N R07W 16BBC	1,105	--	--	06/19/00	381.7	723	--	--	--	--	
254	365551	914435	T26N R07W 17BBD	1,140	600	--	06/19/00	401.8	738	10/24/00	424.1	716	-22.3	
255	365533	914541	T26N R07W 18CAB	1,145	420	--	07/06/00	297.6	847	10/26/00	298.8	846	-1.2	
256	365432	914001	T26N R07W 24CAA	1,090	504	504	06/21/00	245.4	845	10/24/00	278.2	812	-32.8	
257	365708	914721	T26N R08W 02DDB	1,180	550	--	06/26/00	317.9	862	11/21/00	348.2	832	-30.3	
258	365713	914941	T26N R08W 04DBC	1,180	--	--	06/26/00	414.6	765	10/24/00	423.1	757	-8.5	
259	365543	914833	T26N R08W 15ACC	1,145	550	--	06/30/00	402.7	742	10/24/00	419.2	726	-16.5	
260	365525	914825	T26N R08W 15DBD	1,140	525	--	07/06/00	381.4	759	--	--	--	--	
261	365523	914824	T26N R08W 15DBD2	1,140	--	--	07/06/00	238.5	902	10/24/00	239.2	901	-7	

[ddmms, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

[ddmms, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Site number	Latitude (ddmms)	Longitude (ddmms)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water-level change (ft)	
262	365531	915111	T26N R08W 17CCA	1,140	595	284	06/26/00	364.3	776	10/26/00	377.4	763	-13.1	
263	365346	915128	T26N R08W 30DAD	1,120	250	--	07/06/00	141.4	979	11/21/00	145.7	974	-4.3	
264	365316	914827	T26N R08W 34ABD	1,125	400	--	07/06/00	213.6	911	11/21/00	227.8	897	-14.2	
265	365307	914603	T26N R08W 36ADA	1,085	750	--	06/27/00	225.5	860	--	--	--	--	
266	365656	915424	T26N R09W 11BBA	1,265	358	--	06/26/00	195.6	1,069	10/24/00	204.3	1,061	-8.7	
267	365535	915644	T26N R09W 16CCB	1,280	500	440	07/07/00	353.4	927	10/24/00	360.4	920	-7.0	
268	365451	915405	T26N R09W 23ACC	1,205	400	--	06/26/00	170.5	1,035	--	--	--	--	
269	365414	915709	T26N R09W 29ADB	1,220	--	--	06/29/00	218.4	1,002	10/24/00	234.9	985	-16.5	
270	365238	915246	T26N R09W 36DDC	1,220	220	--	06/27/00	196.0	1,024	10/24/00	203.2	1,017	-7.2	
271	370135	910500	T27N R01W 08ABC	538	120	81	06/01/00	30.2	508	10/17/00	29.5	509	.7	
272	370051	910419	T27N R01W 16BBA	630	85	--	05/31/00	21.2	609	10/17/00	21.0	609	.2	
273	365918	910223	T27N R01W 23CCC	470	--	--	--	0.0	470	--	0	470	0	
274	365923	910133	T27N R01W 23DCC	480	--	--	05/31/00	35.8	444	10/17/00	35.0	445	.9	
275	365938	910051	T27N R01W 24CDD	465	650	290	06/01/00	49.4	416	10/17/00	25.2	440	24.2	
276	365914	910045	T27N R01W 25ABC	502	--	--	05/31/00	55.6	446	10/17/00	57.0	445	-1.4	
277	365852	910033	T27N R01W 25DBD	660	375	--	05/31/00	187.0	473	10/17/00	188.5	472	-1.5	
278	365847	910233	T27N R01W 27DAB	530	--	--	06/01/00	59.4	471	10/17/00	60.6	469	-1.2	
279	365759	910513	T27N R01W 32AAC	635	--	--	06/01/00	152.1	483	10/18/00	142.6	492	9.5	
280	365751	910510	T27N R01W 32BDD	520	140	84	06/01/00	33.4	487	10/17/00	35.2	485	-1.8	
281	365740	910334	T27N R01W 33DDA	565	453	--	05/31/00	117.8	447	10/17/00	121.4	444	-3.6	
282	365732	910343	T27N R01W 33DDC	530	165	--	05/31/00	66.0	464	10/17/00	70.2	460	-4.2	
283	365823	910250	T27N R01W 34ABB	495	120	--	06/01/00	25.8	469	10/17/00	29.6	465	-3.8	
284	365802	910055	T27N R01W 36CAB	670	250	--	05/31/00	97.2	573	10/17/00	104.1	566	-6.9	
285	365755	910051	T27N R01W 36CAD	590	160	84	05/31/00	59.6	530	10/17/00	61.3	529	-1.7	
286	370153	911026	T27N R02W 04CDA	735	220	--	06/01/00	181.1	554	10/17/00	151.2	584	29.9	
287	370017	910906	T27N R02W 15DAB	750	--	--	06/01/00	8.8	741	--	--	--	--	
288	370049	911242	T27N R02W 18BAB	830	--	--	06/01/00	20.7	809	--	--	--	--	
289	365825	911159	T27N R02W 29CCA	745	396	150	06/06/00	242.9	502	10/18/00	256.7	488	-13.8	
290	365753	911312	T27N R02W 31BCC	970	610	202	06/06/00	441.8	528	11/14/00	456.0	514	-14.2	

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

Site number	Latitude (ddmms)	Longitude (ddmms)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
291	365810	910928	T27N R02W 34BAA	610	--	--	06/06/00	86.7	523	10/18/00	99.4	511	-12.7	
292	370126	911647	T27N R03W 09ACC	890	300	142	06/07/00	100.1	790	10/18/00	122.4	768	-22.3	
293	370102	911925	T27N R03W 18BAB	1,000	1,190	500	06/13/00	331.0	669	--	--	--	--	
294	370050	911929	T27N R03W 18BDB1	986	1,110	452	06/13/00	348.0	638	--	--	--	--	
295	370026	911938	T27N R03W 18CBD	915	1,150	400	06/13/00	393.0	522	--	--	--	--	
296	365953	911800	T27N R03W 20ACB	880	440	205	06/12/00	281.9	598	--	--	--	--	
297	365918	911521	T27N R03W 23CCC	840	360	--	06/06/00	245.9	594	10/17/00	238.8	601	7.1	
298	365923	911407	T27N R03W 24CBD	785	120	--	06/06/00	56.8	728	10/17/00	57.7	727	-9	
299	365853	911552	T27N R03W 27ACB	850	36	--	06/06/00	15.1	835	10/17/00	14.7	835	.4	
300	365757	911629	T27N R03W 34BCC	900	1,180	350	06/16/00	408.9	491	11/15/00	416.6	483	-7.7	
301	370243	912537	T27N R04W 06ABB	1,065	405	--	06/12/00	245.1	820	10/18/00	245.8	819	-7	
302	370123	912001	T27N R04W 12DAB	990	360	225	06/07/00	217.3	773	--	--	--	--	
303	370125	912003	T27N R04W 12DAB2	975	--	--	06/07/00	203.3	772	10/18/00	213.5	762	-10.2	
304	370017	912438	T27N R04W 17DCB	1,070	--	--	06/16/00	265.9	804	10/18/00	269.4	801	-3.5	
305	365917	912355	T27N R04W 21CDC	1,085	290	--	06/07/00	235.4	850	10/20/00	251.6	833	-16.1	
306	365959	912121	T27N R04W 23ABD	1,060	--	--	06/06/00	238.3	822	10/17/00	240.7	819	-2.4	
307	365828	912040	T27N R04W 25CDC2	1,060	570	340	06/06/00	277.0	783	10/19/00	281.6	778	-4.6	
308	370114	913010	T27N R05W 09CDA	1,130	460	--	06/07/00	218.4	912	10/25/00	224.6	905	-6.2	
309	365938	913008	T27N R05W 21DBB	1,030	1,050	500	06/13/00	277.0	753	--	--	--	--	
310	370006	912737	T27N R05W 23AAB	1,070	400	360	06/13/00	226.5	844	10/18/00	229.0	841	-2.5	
311	365754	913105	T27N R05W 32DBB	1,045	390	227	06/15/00	229.0	816	10/24/00	233.6	811	-4.6	
312	365816	912727	T27N R05W 35AAA	1,025	435	--	06/05/00	238.2	787	10/20/00	254.5	771	-16.3	
313	370110	913646	T27N R06W 09CDD	1,060	--	--	06/19/00	193.5	867	10/25/00	199.2	861	-5.7	
314	370102	913311	T27N R06W 13ABA	1,105	400	--	06/19/00	206.0	899	10/25/00	209.6	895	-3.6	
315	370109	913855	T27N R06W 18BAA	1,140	--	--	06/20/00	238.1	902	10/23/00	239.7	900	-1.6	
316	370010	913506	T27N R06W 22AAA	1,105	--	--	06/19/00	286.0	819	10/25/00	293.1	812	-7.1	
317	365855	913357	T27N R06W 25BCC	1,090	495	267	06/15/00	237.4	853	10/24/00	239.8	850	-2.4	
318	365830	913916	T27N R06W 31BBB	1,150	435	--	06/15/00	196.4	954	10/23/00	219.9	930	-23.5	
319	365829	913915	T27N R06W 31BBB2	1,153	410	--	06/15/00	200.9	952	--	--	--	--	

[ddmms, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

[ddmmss, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Site number	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)	Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Water level change (ft)
320	365823	913618	T27N R06W 33AAB	1,065	435	--	06/15/00	300.0	765	10/23/00	305.0	760	-5.0	
321	370117	914338	T27N R07W 09CCC	1,205	450	260	06/21/00	146.0	1,059	10/23/00	166.5	1,039	-20.5	
322	370053	914111	T27N R07W 14BDB	1,185	--	--	06/21/00	117.9	1,067	10/23/00	121.8	1,063	-3.9	
323	370042	914100	T27N R07W 14BDD	1,180	220	--	06/21/00	105.9	1,074	10/23/00	109.5	1,071	-3.6	
324	370043	914133	T27N R07W 15ADD	1,190	--	--	06/21/00	88.2	1,102	10/23/00	93.1	1,097	-4.9	
325	365753	914252	T27N R07W 33DDDB	1,150	635	--	06/19/00	448.4	702	10/23/00	465.6	684	-17.2	
326	370218	914831	T27N R08W 03DCB	1,380	--	--	07/07/00	166.9	1,213	10/25/00	170.1	1,210	-3.2	
327	370249	914956	T27N R08W 04BCA	1,115	--	--	--	0	1,115	--	0	1,115	0	
328	370134	914625	T27N R08W 12CAD	1,245	400	--	07/07/00	83.1	1,162	--	--	--	--	
329	370052	914904	T27N R08W 15BCC	1,320	--	--	07/07/00	116.8	1,203	10/25/00	118.6	1,201	-1.8	
330	365846	914715	T27N R08W 26DDDB	1,180	495	--	06/26/00	302.0	878	10/24/00	334.9	845	-32.9	
331	365856	915220	T27N R08W 30CBC	1,280	312	260	06/29/00	143.4	1,137	10/24/00	160.2	1,120	-16.8	
332	370205	915705	T27N R09W 08ACA	1,420	470	270	07/06/00	165.8	1,254	10/24/00	170.7	1,249	-4.9	
333	370156	915352	T27N R09W 11ACB	1,365	147	--	07/07/00	99.0	1,266	--	--	--	--	
334	370032	915342	T27N R09W 14DDC	1,345	380	265	07/07/00	203.5	1,142	10/24/00	211.4	1,134	-7.9	
335	370027	915720	T27N R09W 20BAD	1,385	287	--	07/07/00	102.7	1,282	10/24/00	106.4	1,279	-3.7	
336	365839	915720	T27N R09W 32ACB	1,240	--	295	07/07/00	97.0	1,143	11/21/00	94.9	1,145	2.1	
337	370141	915932	T27N R10W 12CDB	1,390	200	--	07/07/00	49.1	1,341	10/24/00	58.7	1,331	-9.6	
338	370256	910324	T28N R01W 32DDA	518	95	--	05/31/00	25.7	492	10/17/00	18.0	500	7.7	
339	370747	911907	T28N R03W 06BAD	735	--	--	06/16/00	15.9	719	--	--	--	--	
340	370505	911906	T28N R03W 19ACB	850	--	--	06/09/00	33.2	817	10/18/00	35.0	815	-1.8	
341	370444	911443	T28N R03W 23CAA	890	120	--	06/01/00	7.3	883	10/18/00	8.1	882	-8	
342	370300	911327	T28N R03W 36DBA	880	18	--	06/01/00	5.5	875	10/18/00	8.0	872	-2.5	
343	370749	912048	T28N R04W 02AAD	860	--	--	06/09/00	23.7	836	10/18/00	34.3	826	-10.6	
344	370632	911947	T28N R04W 12DAC	755	--	--	06/09/00	3.4	752	10/18/00	3.7	751	-3	
345	370603	912452	T28N R04W 17BBD	735	--	--	06/12/00	3.2	732	10/18/00	9.0	726	-5.8	
346	370522	912526	T28N R04W 18DCD	780	120	--	06/12/00	34.5	746	10/18/00	42.7	737	-8.2	
347	370445	912411	T28N R04W 20DAC	770	--	--	--	0	770	--	0	770	0	
348	370356	912013	T28N R04W 25DBB	1,125	--	--	06/09/00	218.0	907	--	--	--	--	

Table 1. Ground-water levels measured in domestic and public-supply wells during the summer (April–July) 2000 and fall (October–November) 2000 and altitudes of selected perennial springs.—Continued

[ddmmss, degree, minute, second; ft, feet; mm/dd/yy, month, day, year; --, no data]

Site number	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land surface altitude (ft)	Total well depth (ft)	Casing depth (ft)	Summer 2000 water levels				Fall 2000 water levels			
							Date (mm/dd/yy)	Depth to water (ft)	Water level altitude (ft)	Depth to water (ft)	Date (mm/dd/yy)	Water level altitude (ft)	Depth to water (ft)	Water level change (ft)
349	370406	912347	T28N R04W 28BDC	810	--	--	--	--	0	810	0	810	0	0
350	370355	912746	T28N R05W 26DBC	870	--	--	--	--	0	870	0	870	0	0
351	370335	913212	T28N R05W 31ABC	1,070	513	264	06/13/00	262.9	807	10/25/00	264.3	806	-1.4	-1.4
352	370524	913823	T28N R06W 19AAC	1,180	318	--	06/09/00	228.9	951	--	--	--	--	--
353	370523	913826	T28N R06W 19AAC2	1,180	400	287	06/09/00	231.3	949	--	--	--	--	--

Table 2. Annual departure from normal precipitation and annual mean discharge data for Big Spring, water years 1922 through 2004.

[ft³/s, cubic feet per second]

Water year	Annual departure from precipitation ¹ (inches)	Accumulated annual departure from precipitation (inches)	Reported source area for precipitation ¹ data	Big Spring	
				Annual mean discharge (ft ³ /s)	Accumulated annual mean discharge (ft ³ /s)
1922	-7.7	-7.7	Birch Tree	456	456
1923	6.9	-.8	Birch Tree	460	916
1924	-6.9	-7.7	Birch Tree	354	1,270
1925	1.3	-6.4	Birch Tree	315	1,585
1926	.6	-5.8	Birch Tree	403	1,988
1927	25.8	19.9	Birch Tree	602	2,590
1928	7.5	27.5	Birch Tree	613	3,203
1929	8.2	35.7	Birch Tree	537	3,740
1930	-4.2	31.5	Birch Tree	462	4,202
1931	2.0	33.5	Birch Tree	375	4,577
1932	-4.3	29.2	Ozark Plateaus	349	4,926
1933	-.6	28.6	Ozark Plateaus	441	5,367
1934	-7.9	20.6	Ozark Plateaus	315	5,682
1935	9.4	30.0	Ozark Plateaus	437	6,119
1936	-11.6	18.4	Southeast region	289	6,408
1937	2.6	21.0	Southeast region	448	6,856
1938	.5	21.5	Southeast region	433	7,289
1939	-.7	20.8	Southeast region	435	7,724
1940	-8.4	12.4	Southeast region	340	8,064
1941	-5.8	6.7	Southeast region	320	8,384
1942	4.7	11.4	Southeast region	479	8,863
1943	-14.3	-2.9	Birch Tree	443	9,306
1944	-4.3	-7.2	Birch Tree	371	9,677
1945	20.1	13.0	Birch Tree	521	10,198
1946	15.9	28.8	Birch Tree	549	10,747
1947	-13.8	15.1	Birch Tree	439	11,186
1948	.8	15.9	Van Buren	403	11,589
1949	15.3	31.1	Birch Tree	509	12,098
1950	1.3	32.4	Birch Tree	648	12,746
1951	-.4	32.0	Doniphan	512	13,258
1952	-3.6	28.4	Birch Tree	561	13,819
1953	-18.2	10.2	Birch Tree	377	14,196
1954	-3.7	6.5	Birch Tree	321	14,517
1955	-13.5	-7.0	Birch Tree	329	14,846
1956	-5.6	-12.6	Birch Tree	293	15,139
1957	14.9	2.3	Birch Tree	459	15,598
1958	5.4	7.7	Birch Tree	494	16,092
1959	1.4	9.1	Birch Tree	416	16,508
1960	-7.7	1.4	Birch Tree	416	16,924
1961	-2.0	-.6	Birch Tree	406	17,330

Table 2. Annual departure from normal precipitation and annual mean discharge data for Big Spring, water years 1922 through 2004.—Continued[ft³/s, cubic feet per second]

Water year	Annual departure from precipitation ¹ (inches)	Accumulated annual departure from precipitation (inches)	Reported source area for precipitation ¹ data	Big Spring	
				Annual mean discharge (ft ³ /s)	Accumulated annual mean discharge (ft ³ /s)
1962	-0.1	-0.7	Birch Tree	448	17,778
1963	-9.8	-10.4	East Ozarks	359	18,137
1964	-6.4	-16.9	East Ozarks	365	18,502
1965	-1.7	-18.6	East Ozarks	346	18,848
1966	-.4	-18.9	East Ozarks	451	19,299
1967	-2.0	-20.9	East Ozarks	340	19,639
1968	2.1	-18.8	East Ozarks	448	20,087
1969	-2.8	-21.6	East Ozarks	511	20,598
1970	.9	-20.6	East Ozarks	383	20,981
1971	-8.9	-29.6	East Ozarks	398	21,379
1972	3.1	-26.5	East Ozarks	387	21,766
1973	16.5	-10.0	East Ozarks	618	22,384
1974	2.9	-7.1	East Ozarks	581	22,965
1975	5.4	-1.7	East Ozarks	527	23,492
1976	-15.3	-16.9	East Ozarks	433	23,925
1977	4.4	-12.5	East Ozarks	386	24,311
1978	-3.2	-15.7	East Ozarks	465	24,776
1979	6.0	-9.7	East Ozarks	520	25,296
1980	-14.0	-23.6	East Ozarks	419	25,715
1981	1.3	-22.3	East Ozarks	348	26,063
1982	14.8	-7.5	East Ozarks	462	26,525
1983	3.4	-4.1	East Ozarks	545	27,070
1984	11.2	7.2	East Ozarks	524	27,594
1985	15.3	22.5	East Ozarks	620	28,214
1986	-1.4	21.1	East Ozarks	542	28,756
1987	.4	21.4	East Ozarks	361	29,117
1988	-.4	21.1	East Ozarks	425	29,542
1989	-4.2	16.9	East Ozarks	481	30,023
1990	15.5	32.4	East Ozarks	462	30,485
1991	1.8	34.1	East Ozarks	495	30,980
1992	-1.1	33.0	East Ozarks	440	31,420
1993	12.8	45.9	East Ozarks	491	31,911
1994	4.6	50.5	East Ozarks	576	32,487
1995	.5	51.0	East Ozarks	545	33,032
1996	5.4	56.4	East Ozarks	493	33,525
1997	-0	56.3	East Ozarks	--	--
1998	5.5	61.8	East Ozarks	--	--
1999	-4.6	57.3	East Ozarks	--	--
2000	-8.0	49.2	East Ozarks	362	33,887
2001	-.5	48.8	East Ozarks	308	34,195

Table 2. Annual departure from normal precipitation and annual mean discharge data for Big Spring, water years 1922 through 2004.—Continued

[ft³/s, cubic feet per second]

Water year	Annual departure from precipitation ¹ (inches)	Accumulated annual departure from precipitation (inches)	Reported source area for precipitation ¹ data	Big Spring	
				Annual mean discharge (ft ³ /s)	Accumulated annual mean discharge (ft ³ /s)
2002	9.2	58.0	East Ozarks	496	34,691
2003	1.9	59.9	East Ozarks	363	35,054
2004	1.0	60.9	East Ozarks	462	35,516

¹ National Oceanic and Atmospheric Administration (1922–2004). Normal precipitation calculated by National Oceanic and Atmospheric Administration for calendar year.

Table 3. Water temperature and specific conductance measurements at the U.S. Geological Survey gaging station and Big Spring orifice, January 2001 to May 2005.

[°C, degrees Celsius; μS/cm, microsiemens per centimeter at 25 degrees Celsius; --, no data]

Date	Water temperature manually measured at gaging station (°C)	Water temperature recorded by monitor at gaging station (°C)	Difference between manually measured and monitor recorded water temperature at gaging station (°C)		Water temperature manually measured at Big Spring orifice (°C)	Difference between water temperature recorded by monitor at gaging station and manually measured at Big Spring orifice (°C)		Specific conductance manually measured at gaging station (μS/cm)	Specific conductance recorded by monitor at gaging station (μS/cm)
			gaging station (°C)	gaging station (°C)		manually measured at Big Spring orifice (°C)	manually measured at gaging station (μS/cm)		
01/05/2001	14.7	14.7	0	--	--	--	356	333	
10/02/2001	14.8	14.8	0	--	--	--	355	355	
11/01/2001	15.3	15.0	.3	--	--	--	360	352	
11/19/2001	14.8	14.9	-.1	--	--	--	357	354	
12/17/2001	14.4	14.3	.1	--	--	--	304	306	
01/07/2002	14.3	14.4	-.1	--	--	--	278	276	
02/07/2002	14.0	14.1	-.1	--	--	--	245	245	
03/07/2002	--	14.3	--	--	--	--	299	302	
03/19/2002	13.7	--	--	--	--	--	212	--	
03/20/2002	13.6	--	--	--	--	--	204	--	
03/27/2002	13.0	13.2	-2	--	--	--	170	171	
07/10/2002	14.5	--	--	--	--	--	318	--	
08/08/2002	14.3	14.3	0	--	--	--	325	320	
09/05/2002	14.4	14.4	0	14.4	0	0	331	329	
10/03/2002	14.5	14.5	0	--	--	--	344	342	
10/11/2002	14.4	14.5	-.1	14.4	.1	0	346	342	
11/15/2002	--	14.5	--	14.5	0	0	350	348	
11/25/2002	14.5	14.5	0	--	--	--	350	348	
12/17/2002	--	14.6	--	14.6	0	0	351	348	
01/17/2003	--	14.4	--	14.4	0	0	321	331	
02/12/2003	14.3	14.5	--	14.5	0	0	339	342	
03/14/2003	14.3	14.3	0	--	--	--	299	298	
03/17/2003	14.4	14.4	0	14.4	0	0	300	303	
03/28/2003	14.4	14.4	0	--	--	--	324	323	

Table 3. Water temperature and specific conductance measurements at the U.S. Geological Survey gaging station and Big Spring orifice, January 2001 to May 2005.—Continued

[°C, degrees Celsius; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; --, no data]

Date	Water temperature manually measured at gaging station (°C)	Water temperature recorded by monitor at gaging station (°C)	Difference between manually measured and monitor		Water temperature manually measured at Big Spring orifice (°C)	Difference between water temperature recorded by monitor at gaging station and manually measured at Big Spring orifice (°C)		Specific conductance manually measured at gaging station ($\mu\text{S}/\text{cm}$)	Specific conductance recorded by monitor at gaging station ($\mu\text{S}/\text{cm}$)
			recorded water temperature at gaging station (°C)	temperature at gaging station (°C)		manually measured at Big Spring orifice (°C)	manually measured at Big Spring orifice (°C)		
04/02/2003	14.7	14.5	0.2	--	--	--	330	323	
04/17/2003	14.4	14.4	--	14.4	0	0	302	311	
04/18/2003	14.3	14.4	-1	--	--	--	305	310	
04/23/2003	14.4	14.4	0	--	--	--	302	311	
05/02/2003	14.4	14.4	0	--	--	--	316	321	
05/21/2003	14.3	14.3	0	14.2	.1	.1	289	290	
06/06/2003	14.3	14.3	0	--	--	--	300	296	
06/16/2003	14.4	14.4	0	--	--	--	327	322	
06/17/2003	--	14.4	--	14.3	.1	.1	330	322	
07/01/2003	14.8	14.5	--	--	--	--	336	338	
07/18/2003	--	14.6	--	14.8	-2	-2	345	345	
07/30/2003	14.6	14.6	0	--	--	--	349	347	
08/12/2003	14.7	14.7	0	--	--	--	330	347	
08/13/2003	--	14.6	--	14.6	0	0	348	348	
09/11/2003	14.8	14.7	.1	14.8	-1	-1	340	342	
10/14/2003	14.8	14.7	.1	--	--	--	335	343	
11/18/2003	14.8	14.7	.1	--	--	--	351	355	
11/20/2003	14.4	14.5	--	--	--	--	292	--	
01/23/2004	13.9	14.3	-4	--	--	--	293	300	
03/03/2004	14.0	14.3	-3	--	--	--	317	318	
03/04/2004	14.4	14.3	.1	--	--	--	320	318	
03/31/2004	14.0	14.1	-1	--	--	--	286	286	
04/14/2004	14.7	14.3	.4	--	--	--	366	315	
04/21/2004	14.6	14.3	.3	--	--	--	318	322	

Table 3. Water temperature and specific conductance measurements at the U.S. Geological Survey gaging station and Big Spring orifice, January 2001 to May 2005.—Continued

[°C, degrees Celsius; μS/cm, microsiemens per centimeter at 25 degrees Celsius; --, no data]

Date	Water temperature manually measured at gaging station (°C)	Water temperature recorded by monitor at gaging station (°C)	Difference between manually measured and monitor recorded water temperature at gaging station (°C)		Water temperature manually measured at Big Spring orifice (°C)	Difference between water temperature recorded by monitor at gaging station and manually measured at Big Spring orifice (°C)		Specific conductance manually measured at gaging station (μS/cm)	Specific conductance recorded by monitor at gaging station (μS/cm)
			gaging station (°C)	gaging station (°C)		manually measured at Big Spring orifice (°C)	manually measured at gaging station (μS/cm)		
04/26/2004	14.3	14.1	0.2	--	--	--	257	270	
05/03/2004	13.8	13.8	0	--	--	--	197	199	
05/04/2004	13.7	13.8	-1	--	--	--	193	194	
05/10/2004	13.9	13.8	.1	--	--	--	196	199	
05/17/2004	13.9	13.9	0	--	--	--	221	225	
05/24/2004	14.0	14.0	0	--	--	--	253	256	
06/01/2004	14.2	14.1	.1	--	--	--	284	281	
06/07/2004	14.3	14.1	.2	--	--	--	296	297	
07/28/2004	14.7	14.4	.3	--	--	--	328	342	
10/05/2004	14.5	14.5	0	--	--	--	355	352	
11/01/2004	14.6	14.6	0	--	--	--	357	349	
11/02/2004	14.6	14.6	0	--	--	--	349	353	
11/08/2004	14.6	14.6	0	--	--	--	352	351	
11/15/2004	14.7	14.6	.1	--	--	--	355	353	
11/22/2004	14.5	14.5	.0	--	--	--	350	346	
11/29/2004	14.4	14.5	-1	--	--	--	340	339	
12/13/2004	14.0	14.1	-1	--	--	--	262	267	
01/06/2005	14.3	14.3	0	--	--	--	320	320	
02/04/2005	12.9	13.9	-1.0	--	--	--	262	263	
03/29/2005	14.4	14.2	.2	--	--	--	327	325	
05/12/2005	14.7	14.4	.3	14.3	.1	.1	334	331	

Table 6. Concentrations of dissolved gases in water samples from Big Spring and Greer Spring, 2001–03.

[°C, degrees Celsius; mg/L, milligrams per liter; CH₄, methane; CO₂, carbon dioxide; N₂, nitrogen; O₂, oxygen; Ar, argon; cc/kg, cubic centimeters per kilogram of water; for each date there was only one sample collected but there were multiple analyses]

Spring name	Date collected	Time collected	Field temperature (°C)	Dissolved gas in mg/L				Ar	Recharge temperature (°C)	Average calculated recharge temperature (°C)	Excess air (cc/kg)	Average calculated excess air (cc/kg)
				CH ₄	CO ₂	N ₂	O ₂					
Big Spring (recharge elevation 750 feet above National Geodetic Vertical Datum of 1929)												
Big Spring	08/27/2001	1715	14.8	0	14.110	24.180	6.740	0.775	10.6	10.4	6.852	6.7
			14.8	0	13.880	24.010	7.030	0.774	10.3		6.576	
	02/01/2002	1730	14.3	0	17.020	22.710	6.150	0.747	11.4	11.4	5.645	5.7
			14.3	0	17.290	22.870	6.200	0.749	11.5		5.838	
	02/07/2002	1530	14.0	0	17.680	21.570	6.760	0.737	10.3	10.4	4.081	4.1
			14.0	0	18.170	21.620	6.530	0.736	10.5		4.184	
	10/11/2002	1430	14.4	0	16.800	23.060	6.620	0.746	11.7	11.6	6.106	6.1
			14.4	0	17.020	22.890	6.380	0.742	11.8		5.980	
			14.4	0	17.420	23.010	5.950	0.746	11.6		6.017	
			14.4	0	16.840	23.310	6.780	0.752	11.5		6.296	
	11/15/2002	1100	14.5	0	15.380	23.230	7.500	0.756	10.8	10.7	5.960	6.0
			14.5	0	15.330	23.120	7.380	0.755	10.7		5.820	
			14.5	0	15.600	23.440	7.330	0.764	10.4		6.019	
			14.5	0	15.460	23.480	7.600	0.761	10.8		6.199	
	12/17/2002	1300	14.6	0	14.710	23.600	7.680	0.763	10.8	10.9	6.320	6.5
			14.6	0	14.910	23.920	7.400	0.769	10.7		6.625	
			14.6	0	14.820	23.450	7.250	0.758	11.1		6.284	
			14.6	0	14.580	23.790	7.570	0.764	11.1		6.635	
	01/17/2003	1300	14.4	0	17.610	22.280	5.910	0.739	11.0	11.3	5.055	5.1
			14.4	0	17.610	22.430	5.990	0.740	11.1		5.269	
			14.4	0	17.090	22.110	6.390	0.731	11.5		5.071	
			14.4	0	17.310	22.240	6.240	0.734	11.4		5.177	

Table 6. Concentrations of dissolved gases in water samples from Big Spring and Greer Spring, 2001–03.—Continued

[°C, degrees Celsius; mg/L, milligrams per liter; CH₄, methane; CO₂, carbon dioxide; N₂, nitrogen; O₂, oxygen; Ar, argon; cc/kg, cubic centimeters per kilogram of water; for each date there was only one sample collected but there were multiple analyses]

Spring name	Date collected	Time collected	Field temperature (°C)	Dissolved gas in mg/L				Ar	Recharge temperature (°C)	Average calculated recharge temperature (°C)	Excess air (cc/kg)	Average calculated excess air (cc/kg)
				CH ₄	CO ₂	N ₂	O ₂					
Big Spring (recharge elevation 750 feet above National Geodetic Vertical Datum of 1929)—Continued												
Big Spring	02/12/2003	1730	14.5	0	14.620	23.250	7.670	0.755	11.0	11.0	6.059	5.7
			14.5	0	14.560	22.910	7.590	0.749	11.1		5.735	
			14.5	0	14.650	22.620	7.530	0.743	11.1		5.469	
			14.5	0	14.300	22.770	7.770	0.747	10.9		5.536	
	03/17/2003	1130	14.4	0	14.850	22.260	8.330	0.723	12.8	12.8	5.694	5.7
				0	14.970	22.490	8.440	0.729	12.5		5.822	
				0	15.000	22.230	8.330	0.723	12.8		5.648	
				0	14.900	22.020	8.280	0.717	13.0		5.529	
	04/17/2003	1700	14.4	0	15.590	21.960	8.040	0.723	12.2	12.0	5.174	5.2
				0	15.540	21.920	8.050	0.722	12.2		5.152	
				0	15.490	22.010	8.070	0.726	11.9		5.124	
				0	15.790	22.170	8.100	0.730	11.7		5.221	
	05/21/2003	1730	14.2	0	17.570	21.450	8.020	0.722	11.3	11.3	4.309	4.2
				0	17.530	21.260	7.830	0.719	11.3		4.123	
				0	17.520	21.340	7.770	0.720	11.3		4.217	
				0	17.570	21.370	7.990	0.721	11.2		4.187	
	06/17/2003	830	14.3	0	16.420	21.790	7.970	0.716	12.7	12.9	5.169	5.1
				0	16.160	21.420	8.020	0.705	13.2		4.971	
				0	16.350	21.730	7.960	0.711	13.1		5.269	
				0	16.470	21.620	8.010	0.713	12.7		5.007	
	07/18/2003	1400	14.8	0	15.340	22.530	7.370	0.731	12.3	12.3	5.805	6.2
				0	15.710	22.920	7.080	0.740	12.1		6.117	
				0	15.550	23.280	7.490	0.744	12.4		6.583	

Table 6. Concentrations of dissolved gases in water samples from Big Spring and Greer Spring, 2001–03.—Continued

[°C, degrees Celsius; mg/L, milligrams per liter; CH₄, methane; CO₂, carbon dioxide; N₂, nitrogen; O₂, oxygen; Ar, argon; cc/kg, cubic centimeters per kilogram of water; for each date there was only one sample collected but there were multiple analyses]

Spring name	Date collected	Time collected	Field temperature (°C)	Dissolved gas in mg/L				Ar	Recharge temperature (°C)	Average calculated recharge temperature (°C)	Excess air (cc/kg)	Average calculated excess air (cc/kg)
				CH ₄	CO ₂	N ₂	O ₂					
Big Spring (recharge elevation 750 feet above National Geodetic Vertical Datum of 1929)—Continued												
Big Spring	08/13/2003	830	14.6	0	16.710	22.960	5.940	0.744	11.7	11.4	6.017	6.0
				0	16.460	22.750	6.200	0.744	11.3		5.649	
				0	17.330	23.250	5.600	0.753	11.2		6.145	
				0	16.560	23.180	6.210	0.751	11.3		6.092	
	09/11/2003	1800	14.8	0	15.680	19.640	7.090	0.670	13.8	14.0	3.372	2.8
				0	15.770	18.500	6.830	0.648	14.1		2.291	
				0	15.780	18.910	6.820	0.655	14.2		2.728	
				0	15.650	18.980	6.760	0.657	14.0		2.730	
Greer Spring (recharge elevation 900 feet above National Geodetic Vertical Datum of 1929)												
Greer Spring	08/28/2001	1630	14.8	0	15.320	20.570	6.400	0.701	11.7	11.8	3.686	3.5
				0	15.730	20.200	5.940	0.694	11.8		3.319	
	02/01/2002	1000	14.2	0	17.860	20.750	5.270	0.706	11.5	11.6	3.782	3.7
				0	16.810	20.600	6.270	0.703	11.6		3.652	
	02/08/2002	1030	14.3	0	17.230	20.310	5.510	0.701	11.2	11.3	3.204	3.2
				0	16.140	20.180	6.160	0.697	11.4		3.160	
	04/12/2002	1300	13.7	0	17.320	18.710	7.400	0.667	11.9	12.1	1.848	1.8
				0	16.710	18.590	7.160	0.664	12.2		1.805	

Table 7. Summary of average chlorofluorocarbon (CFC) concentrations, CFC apparent ages, and CFC-113/CFC-11 binary mixing model results from Big Spring and Greer Spring, 2001–03.

[pg/kg, picograms per kilogram of water; °C, degrees Celsius; pptv, parts per trillion by volume; Contam., contaminated]

Spring name	Date collected	Time collected	Recharge temperature °C	Average CFC concentration in pg/kg			Average CFC concentration in pptv		
				CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113
Big Spring (recharge elevation 750 feet above National Geodetic Vertical Datum of 1929)									
Big Spring	08/27/2001	1740	10.4	204.9	98.6	21.5	75.14	157.88	18.76
	02/01/2002	1730	11.4	315.4	167.8	37.3	122.14	282.07	34.49
	02/07/2002	1530	10.4	497.0	235.9	63.6	182.23	377.68	55.45
	10/11/2002	1430	11.6	282.3	161.3	40.0	108.94	259.54	35.80
	11/15/2002	1100	10.8	259.8	153.1	36.6	96.05	237.44	31.25
	12/17/2002	1300	10.9	230.9	141.4	30.3	85.82	220.36	26.05
	01/17/2003	1300	11.2	323.5	179.9	36.5	122.20	284.24	31.91
	02/12/2003	1730	11.0	240.5	170.3	34.4	90.07	268.89	29.99
	03/17/2003	1130	12.9	334.7	205.8	44.3	138.63	354.50	43.02
	04/17/2003	1700	12.0	360.9	224.3	47.0	142.60	370.83	43.34
	05/21/2003	1730	11.2	371.7	198.3	49.4	140.98	318.16	43.74
	06/17/2003	830	12.7	298.6	152.1	38.9	122.40	259.53	37.34
	07/18/2003	1400	12.3	235.9	128.2	30.6	94.45	212.97	28.45
	08/13/2003	830	11.5	226.4	122.2	28.3	87.09	197.41	25.35
	09/11/2003	1800	13.9	249.9	135.2	26.6	109.65	248.92	27.77
Greer Spring (recharge elevation 900 feet above National Geodetic Vertical Datum of 1929)									
Greer Spring	08/28/2001	1655	11.8	201.7	144.3	31.3	80.27	248.77	29.86
	02/01/2002	1000	11.6	327.8	179.1	42.6	129.05	305.75	40.14
	02/08/2002	1030	11.3	348.1	196.1	43.1	135.05	326.63	40.13
	04/12/2002	1300	12.1	652.8	310.9	87.6	263.97	543.68	84.99

Table 7. Summary of average chlorofluorocarbon (CFC) concentrations, CFC apparent ages, and CFC-113/CFC-11 binary mixing model results from Big Spring and Greer Spring, 2001-03.—Continued

[pg/kg, picograms per kilogram of water; °C, degrees Celsius; pptv, parts per trillion by volume; Contam., contaminated]

Spring name	Date collected	Time collected	Average piston-flow recharge date				Average piston-flow age in years				Binary mixing of young and old water			
			CFC-11	CFC-12	CFC-113	CFC-113	CFC-11	CFC-12	CFC-113	CFC-113	Recharge date	Age in years	Percent young water in mixture	
Big Spring (recharge elevation 750 feet above National Geodetic Vertical Datum of 1929)														
Big Spring	08/27/2001	1740	1971.5	1971.7	1978.2	30.2	30.0	23.5	1987.7	14.0	31.3			
	02/01/2002	1730	1975.0	1978.2	1983.0	27.1	23.9	19.1	1989.7	12.4	46.7			
	02/07/2002	1530	1981.5	1984.2	1986.7	20.6	17.9	15.4	1992.3	9.8	66.7			
	10/11/2002	1430	1974.3	1976.8	1983.3	28.4	25.9	19.4	1997.0	5.8	42.9			
	11/15/2002	1100	1973.1	1975.6	1982.3	29.7	27.2	20.6	1994.0	8.9	35.1			
	12/17/2002	1300	1972.5	1974.7	1980.7	30.5	28.3	22.3	1993.2	9.8	31.9			
	01/17/2003	1300	1975.2	1978.3	1982.3	27.9	24.7	20.7	1988.3	14.7	49.2			
	02/12/2003	1730	1972.7	1977.5	1982.0	30.5	25.6	21.1	1991.5	11.6	32.3			
	03/17/2003	1130	1976.5	1982.5	1984.7	26.7	20.7	18.5	1994.8	8.4	51.5			
	04/17/2003	1700	1976.8	1983.7	1984.7	26.5	19.6	18.6	1990.0	13.3	52.3			
	05/21/2003	1730	1976.5	1980.5	1984.8	26.9	22.9	18.6	1993.8	9.6	52.7			
	06/17/2003	830	1975.2	1976.8	1983.7	28.3	26.6	19.8	1993.0	10.5	46.0			
	07/18/2003	1400	1973.0	1974.3	1981.3	30.5	29.2	22.2	1991.5	12.0	35.0			
	08/13/2003	830	1972.5	1973.7	1980.5	31.1	30.0	23.1	1990.3	13.3	32.8			
	09/11/2003	1800	1974.2	1976.2	1981.2	29.5	27.5	22.5	1988.0	15.7	44.5			
Greer Spring (recharge elevation 900 feet above National Geodetic Vertical Datum of 1929)														
Greer Spring	08/28/2001	1655	1972.0	1976.3	1982.0	29.7	25.3	19.7	Contam.	Contam.	Contam.			
	02/01/2002	1000	1975.7	1979.8	1984.2	26.4	22.3	17.9	1994.5	7.6	47.7			
	02/08/2002	1030	1976.2	1981.5	1984.0	25.9	20.6	18.1	1990.7	11.4	50.6			
	04/12/2002	1300	1989.2	2001.0	1992.0	13.1	1.3	10.3	1997.0	5.3	99.4			

Table 8. Summary of sulfur hexafluoride (SF₆) and tritium (³H) data from Big Spring and Greer Spring, 2001–03.

[°C, degrees Celsius; cc/kg, cubic centimeters per kilogram of water; fMol/L; femtomoles per liter; pptv, parts per trillion by volume; TU, tritium unit; nd, not determined]

Spring name	Date collected	Time collected	Recharge temperature (°C)	Excess air (cc/kg)	Data uncorrected for excess air				Data corrected for excess air			
					SF ₆ concentration		Piston flow		SF ₆ concentration		Piston flow	
					(fMol/L)	(pptv)	apparent recharge date	apparent recharge date	apparent recharge date	apparent recharge date		
Big Spring (recharge elevation 750 feet above National Geodetic Vertical Datum of 1929)												
Big Spring	08/27/2001	1715	10.4	6.7	0.92	2.35	1989.8	1.3	1983.5	18.2	2.2	
	02/01/2002	1730	11.4	5.7	1.20	3.22	1994.0	1.9	1987.5	14.6	3.3	
	02/07/2002	1530	10.4	4.1	1.74	4.48	1998.8	3.1	1993.3	8.9	3.3	
	10/11/2002	1430	11.6	6.1	1.11	3.06	1993.0	1.7	1986.3	16.5	nd	
	11/15/2002	1100	10.7	6.0	1.15	3.07	1993.3	1.8	1986.8	16.1	nd	
	12/17/2002	1300	10.9	6.5	1.10	2.97	1992.8	1.6	1985.8	17.2	nd	
	01/17/2003	1300	11.3	5.1	1.44	3.93	1996.8	2.4	1990.0	13.0	nd	
	02/12/2003	1730	11.0	5.7	1.03	2.77	1991.8	1.6	1985.8	17.4	nd	
	03/17/2003	1130	12.8	5.7	1.45	4.19	1997.5	2.4	1990.0	13.2	nd	
	04/17/2003	1700	12.0	5.7	1.49	4.17	1997.5	2.4	1990.0	13.3	nd	
	05/21/2003	1730	11.3	4.2	1.49	4.06	1997.0	2.7	1991.5	11.9	nd	
	06/17/2003	830	12.9	6.1	1.24	3.59	1995.5	1.9	1987.5	16.0	nd	
	07/18/2003	1400	12.3	6.2	.99	2.81	1992.1	1.5	1985.1	18.4	nd	
	08/13/2003	830	11.4	6.0	.73	2.00	1988.0	1.1	1982.5	21.1	nd	
	09/11/2003	1800	14.0	2.8	1.44	4.36	1998.3	3.2	1993.5	10.2	nd	
Greer Spring (recharge elevation 900 feet above National Geodetic Vertical Datum of 1929)												
Greer Spring	08/28/2001	1630	11.8	3.5	1.06	2.88	1992.5	2.0	1988.0	13.7	1.7	
	02/01/2002	1000	11.2	3.7	1.37	3.68	1995.8	2.6	1990.8	11.3	2.9	
	02/08/2002	1030	11.3	3.2	1.27	3.39	1994.8	2.5	1990.3	11.9	2.8	

Table 9. Concentrations of selected chemical constituents, calcium and magnesium ratios and loads, bicarbonate loads, and calcite saturation index for water samples collected from Big Spring under various flow conditions, 2000–02.

[ft³/s, cubic feet per second; μ S/cm, microsiemens per centimeter at 25 degrees Celsius; $^{\circ}$ C, degrees Celsius; mg/L, milligram per liter; μ g/L, microgram per liter; kg/s, kilogram per second; S.L., saturation index; --, no data]

Date	Time	Discharge (ft ³ /s)	pH	Specific conductance (μ S/cm)	Temperature at ($^{\circ}$ C)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Silicon (mg/L)	Strontium (μ g/L)	Total dissolved solids (mg/L)
03/22/2000	1450	323	7.2	272	15.0	31.7	18.0	1.9	0.47	--	--	151
08/09/2000	1500	302	7.2	333	14.8	38.2	22.4	2.0	.38	--	--	179
03/14/2001	0900	383	7.5	241	14.0	26.2	14.9	2.2	.48	--	--	120
08/14/2001	1015	276	7.5	351	15.0	39.8	23.2	2.1	.29	--	--	182
08/27/2001	1700	278	7.5	346	14.8	40.5	23.0	1.7	1.00	--	29.0	--
08/27/2001	1715	287	7.5	346	14.8	40.5	23.0	1.7	1.00	4.0	29.0	--
10/02/2001	1700	269	7.5	355	14.8	38.6	22.7	1.7	.72	8.7	29.1	191
11/01/2001	1240	265	7.6	360	15.3	40.1	23.4	1.6	.76	8.2	30.6	194
12/03/2001	1425	267	7.5	350	14.8	37.6	21.8	1.5	.10	8.0	30.0	--
01/07/2002	1200	331	7.5	276	14.4	31.3	17.4	1.3	.79	8.0	24.1	148
03/05/2002	1310	388	7.4	293	14.3	32.9	18.9	1.3	.14	--	--	151
03/07/2002	1400	384	7.5	299	14.6	31.9	18.8	1.4	.79	7.6	26.2	158
03/19/2002	1415	800	7.3	212	13.7	23.0	13.5	1.2	.81	6.9	20.9	113
03/19/2002	1416	800	7.3	212	13.7	22.3	12.9	1.1	.81	7.1	20.0	110
03/19/2002	1417	800	7.4	212	13.7	22.4	13.1	1.2	.83	7.4	20.4	110
03/20/2002	0645	1,020	7.3	204	13.6	21.8	12.7	1.1	.84	7.1	19.9	108
03/20/2002	1750	984	7.3	198	13.5	20.9	12.1	1.1	.79	7.1	18.9	103
03/21/2002	1100	1,070	7.2	183	13.3	19.2	11.2	1.1	.83	6.9	18.2	96
03/27/2002	1200	889	7.1	171	13.0	18.7	10.2	1.0	.91	7.3	18.0	92
07/10/2002	1300	509	7.7	318	14.5	34.5	19.5	1.3	.84	8.0	27.6	163
08/08/2002	1300	500	7.4	325	14.3	34.3	19.2	1.3	.89	8.0	26.7	159
08/19/2002	1230	347	7.4	323	14.7	36.9	20.6	1.4	.80	--	--	164

Table 9. Concentrations of selected chemical constituents, calcium and magnesium ratios and loads, bicarbonate loads, and calcite saturation index for water samples collected from Big Spring under various flow conditions, 2000–02.—Continued

[ft³/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligram per liter; µg/L, microgram per liter; kg/s, kilogram per second; S.I., saturation index; --, no data]

Date	Time	Discharge (ft ³ /s)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Calcium - Magnesium ratio	Calcium load (kg/s)	Magnesium load (kg/s)	Bicarbonate load (kg/s)	Calcite S.I.	Dolomite S.I.
03/22/2000	1450	323	177	4.5	4.2	1.068	0.290	0.165	1.619	-0.61	-1.25
08/09/2000	1500	302	225	2.2	1.9	1.034	.327	.192	1.924	-.44	-.91
03/14/2001	0900	383	137	3.1	2.9	1.066	.284	.162	1.486	-.50	-1.06
08/14/2001	1015	276	227	2.0	1.9	1.040	.311	.181	1.774	-.12	-.27
08/27/2001	1700	278	232	2.2	2.1	1.068	.319	.181	1.826	-.11	-.25
08/27/2001	1715	287	234	2.2	2.1	1.068	.329	.187	1.899	-.11	-.26
10/02/2001	1700	269	233	1.8	1.9	1.031	.294	.173	1.775	-.13	-.28
11/01/2001	1240	265	234	2.3	2.0	1.039	.301	.176	1.756	-0	-.03
12/03/2001	1425	267	227	3.5	2.2	1.046	.284	.165	1.716	-.15	-.32
01/07/2002	1200	331	170	2.5	2.8	1.091	.293	.163	1.593	-.34	-.73
03/05/2002	1310	388	184	2.9	2.4	1.056	.361	.208	2.022	-.39	-.82
03/07/2002	1400	384	189	2.0	2.3	1.029	.347	.204	2.055	-.29	-.60
03/19/2002	1415	800	128	1.9	2.5	1.033	.521	.306	2.900	-.78	-1.61
03/19/2002	1416	800	124	1.8	2.5	1.048	.505	.292	2.809	-.81	-1.67
03/19/2002	1417	800	123	2.0	2.5	1.037	.507	.297	2.786	-.71	-1.47
03/20/2002	0645	1,020	122	1.9	2.5	1.041	.630	.367	3.524	-.83	-1.70
03/20/2002	1750	984	116	1.7	2.6	1.047	.582	.337	3.232	-.86	-1.78
03/21/2002	1100	1,070	106	1.7	2.7	1.040	.582	.339	3.212	-1.04	-2.13
03/27/2002	1200	889	100	1.7	2.7	1.112	.471	.257	2.517	-1.18	-2.44
07/10/2002	1300	509	193	2.0	2.0	1.073	.497	.281	2.782	-.05	-.15
08/08/2002	1300	500	186	2.0	1.8	1.083	.486	.272	2.633	-.37	-.79
08/19/2002	1230	347	201	1.8	1.9	1.086	.363	.202	1.975	-.30	-.65

Table 10. Suspended sediment concentrations and sediment load of water discharging from Big Spring, 2001–04.[ft³/s, cubic feet per second; mg/L, milligram per liter; EWI, equal width increment; TDS, total dissolved solids; --, no data]

Date	Time	Discharge (ft ³ /s)	Total dissolved solids ¹ (mg/L)	EWI collection method (corrected for TDS where necessary)			Point sampler collection method (corrected for TDS where necessary)		
				Sediment concentration (mg/L)	Sediment concentration ² (mg/L)	Sediment load (tons/day)	Sediment concentration (mg/L)	Sediment concentration ² (mg/L)	Sediment load (tons/day)
02/07/2001	1300	294	184	24	7	6	--	--	--
02/08/2001	1400	295	183	--	--	--	19	2	2
02/24/2001	1902	479	158	--	--	--	17	3	4
02/26/2001	1520	730	143	29	16	32	24	11	22
02/26/2001	1902	720	143	--	--	--	22	9	18
02/28/2001	1529	650	137	--	--	--	19	7	12
03/02/2001	1340	539	133	--	--	--	20	8	12
03/07/2001	1400	430	116	--	--	--	16	6	6
09/11/2001	1315	283	185	35	18	14	--	--	--
10/02/2001	1700	264	184	31	14	10	--	--	--
11/01/2001	1240	272	185	29	12	9	--	--	--
12/17/2001	1330	800	179	42	26	56	--	--	--
12/18/2001	1230	750	159	38	24	48	--	--	--
01/07/2002	1200	330	145	16	3	3	--	--	--
03/07/2002	1540	383	158	26	12	12	16	2	2
03/19/2002	1415	812	111	16	6	13	12	2	4
03/19/2002	1926	999	111	21	11	30	17	7	19
03/20/2002	0326	1010	109	--	--	--	22	12	33
03/20/2002	0645	1020	107	27	17	48	24	14	39
03/20/2002	1239	1000	106	31	21	58	29	19	52
03/20/2002	1724	1020	103	31	22	60	32	23	62
03/20/2002	2149	1050	101	--	--	--	26	17	48
03/20/2002	2324	1050	101	--	--	--	30	21	59
03/21/2002	0524	1060	101	--	--	--	29	20	57
03/21/2002	1123	1070	96	33	24	70	32	23	67
03/21/2002	1723	1040	93	--	--	--	29	21	58
03/21/2002	2323	1020	91	--	--	--	30	22	60
03/22/2002	0523	1010	91	--	--	--	26	18	49
03/22/2002	1045	1000	89	30	22	59	--	--	--
03/27/2002	1142	900	89	21	13	32	19	11	27
03/28/2002	1746	815	87	--	--	--	17	9	20
04/03/2002	2346	586	97	--	--	--	14	5	8
04/07/2002	1746	576	106	--	--	--	13	3	5
04/08/2002	2346	790	114	--	--	--	19	9	19
04/10/2002	0546	940	115	--	--	--	17	7	17
04/11/2002	1146	803	106	--	--	--	17	7	16
04/12/2002	1746	685	107	--	--	--	17	7	14
04/13/2002	2346	708	105	--	--	--	17	8	14
04/15/2002	0546	900	103	--	--	--	15	6	14
04/17/2002	1400	770	97	25	16	34	16	7	15
04/18/2002	1746	699	100	--	--	--	13	4	8
04/23/2002	1939	613	108	--	--	--	14	4	7

Table 10. Suspended sediment concentrations and sediment load of water discharging from Big Spring, 2001–04.—Continued[ft³/s, cubic feet per second; mg/L, milligram per liter; EWI, equal width increment; TDS, total dissolved solids; --, no data]

Date	Time	Discharge (ft ³ /s)	EWI collection method (corrected for TDS where necessary)				Point sampler collection method (corrected for TDS where necessary)		
			Total dissolved solids ¹ (mg/L)	Sediment concentration (mg/L)	Sediment concentration ² (mg/L)	Sediment load (tons/day)	Sediment concentration (mg/L)	Sediment concentration ² (mg/L)	Sediment load (tons/day)
04/25/2002	0139	750	113	--	--	--	15	5	10
04/27/2002	1339	668	115	--	--	--	20	10	17
04/28/2002	1939	629	117	--	--	--	15	4	8
05/06/2002	0739	552	132	--	--	--	47	35	52
05/07/2002	1339	557	133	--	--	--	16	4	6
05/13/2002	1430	1100	107	31	21	63	--	--	--
06/11/2002	0830	635	140	31	18	31	3	3	5
06/20/2002	0043	570	--	--	--	--	6	6	9
07/08/2002	1843	509	--	--	--	--	2	2	3
07/10/2002	1130	514	--	2	2	3	5	5	7
07/19/2002	0530	517	--	--	--	--	9	9	13
07/20/2002	1130	527	--	--	--	--	9	9	13
07/21/2002	1730	532	--	--	--	--	4	4	6
07/22/2002	2330	499	--	--	--	--	11	11	15
07/30/2002	1130	482	--	--	--	--	5	5	6
08/08/2002	1300	458	--	5	5	6	12	12	15
08/13/2002	1110	456	--	--	--	--	1	1	1
08/14/2002	1710	461	--	--	--	--	14	14	17
08/23/2002	1110	444	--	--	--	--	17	17	20
08/27/2002	1330	440	--	--	--	--	2	2	2
09/05/2002	1400	435	--	--	--	--	6	6	7
09/05/2002	1210	435	--	--	--	--	1	1	1
10/03/2002	1345	358	--	2	2	2	1	1	1
10/18/2002	2245	348	--	--	--	--	2	2	2
10/30/2002	0445	342	--	--	--	--	4	4	4
11/15/2002	0845	344	--	1	1	1	--	--	--
11/22/2002	2002	338	--	--	--	--	2	2	2
12/04/2002	0202	342	--	--	--	--	12	12	11
12/17/2002	1130	338	--	2	2	2	9	9	8
12/23/2002	1730	335	--	--	--	--	3	3	3
12/31/2002	0530	364	--	--	--	--	1	1	1
01/01/2003	1130	600	--	--	--	--	1	1	2
01/02/2003	1730	500	--	--	--	--	2	2	3
01/03/2003	2330	442	--	--	--	--	2	2	2
01/10/2003	0530	367	--	--	--	--	10	10	10
01/16/2003	1415	352	--	1	1	1	15	15	14
01/22/2003	2253	333	--	--	--	--	4	4	4
02/01/2003	2253	325	--	--	--	--	1	1	1
02/09/2003	1053	318	--	--	--	--	1	1	1
02/12/2003	1600	314	--	1	1	1	1	1	1
02/15/2003	0306	381	--	--	--	--	2	2	2
02/16/2003	0906	401	--	--	--	--	1	1	1

Table 10. Suspended sediment concentrations and sediment load of water discharging from Big Spring, 2001–04.—Continued[ft³/s, cubic feet per second; mg/L, milligram per liter; EWI, equal width increment; TDS, total dissolved solids; --, no data]

Date	Time	Discharge (ft ³ /s)	EWI collection method (corrected for TDS where necessary)			Point sampler collection method (corrected for TDS where necessary)			
			Total dissolved solids ¹ (mg/L)	Sediment concentration (mg/L)	Sediment concentration ² (mg/L)	Sediment load (tons/day)	Sediment concentration (mg/L)	Sediment concentration ² (mg/L)	Sediment load (tons/day)
02/18/2003	2106	354	--	--	--	--	1	1	1
02/20/2003	0306	419	--	--	--	--	1	1	1
02/21/2003	0906	460	--	--	--	--	3	3	4
02/25/2003	0306	425	--	--	--	--	2	2	2
03/04/2003	1506	379	--	--	--	--	1	1	1
03/09/2003	1506	358	--	--	--	--	2	2	2
03/14/2003	0830	352	--	1	1	1	2	2	2
04/06/2003	0705	367	--	--	--	--	2	2	2
04/07/2003	1305	412	--	--	--	--	3	3	3
04/08/2003	0405	437	--	--	--	--	2	2	2
04/10/2003	1605	419	--	--	--	--	1	1	1
04/13/2003	1905	388	--	--	--	--	1	1	1
04/17/2003	1305	377	--	1	1	1	1	1	1
04/23/2003	2010	369	--	--	--	--	2	2	2
04/25/2003	1710	403	--	--	--	--	1	1	1
04/26/2003	0810	560	--	--	--	--	2	2	3
04/26/2003	2310	550	--	--	--	--	2	2	3
04/28/2003	2010	430	--	--	--	--	4	4	5
05/10/2003	0011	449	--	--	--	--	2	2	2
05/16/2003	0011	426	--	4	4	5	1	1	1
05/17/2003	1211	506	--	--	--	--	0	0	0
05/22/2003	0820	477	--	--	--	--	2	2	3
05/31/2003	0820	390	--	--	--	--	3	3	3
06/10/2003	2330	362	--	--	--	--	1	1	1
06/13/2003	0530	379	--	--	--	--	6	6	6
06/13/2003	2330	394	--	--	--	--	1	1	1
06/16/2003	1747	369	--	2	2	2	1	1	1
06/28/2003	1747	346	--	--	--	--	2	2	2
07/08/2003	0605	331	--	--	--	--	1	1	1
08/12/2003	1730	312	--	1	1	1	1	1	1
08/22/2003	1730	306	--	--	--	--	1	1	1
08/28/2003	2330	298	--	--	--	--	1	1	1
08/31/2003	1130	335	--	--	--	--	1	1	1
09/02/2003	2330	421	--	--	--	--	1	1	1
09/11/2003	1630	342	--	2	2	2	--	--	--
11/13/2003	1545	306	178	14	-2	-2	--	--	--
11/18/2003	1300	776	183	31	14	30	--	--	--
11/20/2003	1500	859	151	44	30	70	--	--	--
02/06/2004	0930	442	232	--	--	--	25	4	5

¹ TDS values are estimated from a linear regression relation of laboratory TDS values and specific conductance measurements. Values are entered only where TDS estimates are used to correct evaporation method laboratory analyses.

² Sediment analyses using the evaporation method (before June 20, 2002 and from November 2003 to February 2004) are corrected for the effect of TDS.

For more information concerning the research described
in this report, contact:

U.S. Geological Survey
Missouri Water Science Center
1400 Independence Road
Rolla, MO 65401
(573) 308-3667

<http://mo.water.usgs.gov>

