Prepared in cooperation with the

Arkansas Department of Health

HYDROGEOLOGIC CHARACTERISTICS OF FOUR PUBLIC DRINKING-WATER SUPPLY SPRINGS IN NORTHERN ARKANSAS

Water-Resources Investigations Report 03-4307

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

Cover: Photograph of the outflow from the spring box of Hughes Spring near Zack, Arkansas. Photograph by Joel Galloway, U.S. Geological Survey.

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Little Rock, Arkansas
2004

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Denver, Colorado 80225

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Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
miles per day (mi/d)	1.609	kilometer per day (m/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.01093	cubic meter per second (m^3/s)
degree Celsius (°C)	1.8 x °C + 32	degree Fahrenheit

In this report, vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

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ABSTRACT

In October 2000, a study was undertaken by the U.S. Geological Survey (USGS) in cooperation with the Arkansas Department of Health to determine the hydrogeologic characteristics, including the extent of the recharge areas, for Hughes Spring, Stark Spring, Evening Shade Spring, and Roaring Spring, which are used for public-water supply in northern Arkansas. Information pertaining to each spring can be used to enable development of effective management plans to protect these water resources and public health.

An integrated approach to determine the ground-water characteristics and the extent of the local recharge areas of the four springs incorporated tools and methods of hydrology, structural geology, geomorphology, geophysics, and geochemistry. Analyses of discharge, temperature, and water quality were completed to describe ground-water flow characteristics, source-water characteristics, and connectivity of the ground-water system with surface runoff. Water-level contour maps were constructed to determine ground-water flow directions and ground-water tracer tests were conducted to determine the extent of the recharge areas and ground-water flow velocities.

Hughes Spring supplies water for the city of Marshall, Arkansas, and the surrounding area. The mean annual discharge for Hughes Spring was 2.9 and 5.2 cubic feet per second for water years 2001 and 2002, respectively. Recharge to the spring occurs mainly from the Boone Formation (Springfield Plateau aquifer). Ground-water tracer tests indicate the recharge area for Hughes Spring generally coincides with the surface drainage area (15.8 square miles) and that Hughes Spring is connected directly to the surface flow in Brush Creek.

The geochemistry of Hughes Spring demonstrated variations with flow conditions and the influence of surface-runoff in the recharge area. Calcite saturation indices, total dissolved solids concentrations, and hardness demonstrate noticeable differences with flow conditions reflecting the reduced residence time and interaction of water with the source rock within the ground-water system at higher discharges for Hughes Spring. Concentrations of fecal indicator bacteria also demonstrated a substantial increase during high-flow conditions, suggesting that a non-point source of bacteria possibly from livestock may enter the system. Conversely, nutrient concentrations did not vary with flow and were similar to concentrations reported for undeveloped sites in the Springfield Plateau and Ozark aquifers in northern Arkansas and southern Missouri. Deuterium and oxygen-18 data show that the Hughes Spring discharge is representative of direct precipitation and not influenced by water enriched in oxygen-18 through evaporation. Discharge data show that Hughes Spring is dominated by conduit type ground-water flow, but a considerable component of diffuse flow also exists in the ground-water system. Carbon-13 data indicate a substantial component of the recharge water interacts with the surface material (soil and regolith) in the recharge area before entering the ground-water system for Hughes Spring. Tritium data for Hughes Spring indicate that the discharge water is a mixture of recent recharge and sub-modern water (recharged prior to 1952).

Stark Spring supplies water for the city of Cushman, Arkansas, and the surrounding area.

The mean annual discharge for Stark Spring was 0.5 and 1.5 cubic feet per second for water years 2001 and 2002, respectively. The discharge and water-quality data show the ground-water system for Stark Spring is dominated by rapid recharge from surface runoff and mainly consists of a conduit-type flow system with little diffuse-type flow. Analyses of discharge data show that the estimated recharge area (0.79 square mile) is larger than the surface drainage area (0.34 square mile). Ground-water tracer tests and the outcrop of the Boone Formation indicate that most of the recharge area extends outside the surface drainage area.

Similar to Hughes Spring, the geochemistry of Stark Spring varied with flow conditions. Calcite saturation indices, total dissolved solids concentrations, and hardness demonstrate noticeable differences with flow conditions reflecting the reduced residence time and interaction of the recharge water with the source rock at higher discharges for Stark Spring. In contrast to Hughes Spring, concentrations of fecal indicator bacteria demonstrated a decrease during high-flow conditions, and this dilution effect may reflect the lack of pastureland or sources of non-point contamination in the recharge area. Nutrient concentrations did not vary with flow. Nitrite plus nitrate concentrations were less than concentrations reported for undeveloped sites in the Springfield Plateau and Ozark aquifers in northern Arkansas and southern Missouri, and concentrations of phosphorus and orthophosphorus were slightly higher. Tritium data show that the discharge water is a mixture of recent recharge and sub-modern water (recharged prior to 1952).

Recharge to Evening Shade and Roaring Springs originate from water entering geologic formations in the Ozark aquifer. The springs provide the water supply for the communities of Evening Shade and Cherokee Village, respectively, and the surrounding areas. The mean annual discharge for water years 2001 and 2002 for Evening Shade Spring was 1.44 and 1.24 cubic feet per second, respectively. Roaring Spring had an average flow of 5.7 cubic feet per second for the period of record (July 2001 to October 2002). Little variation in discharge and temperature was evident during high-flow events and throughout the monitoring period for both springs, reflecting the contribution of flow from the Ozark aquifer. As a result, a local recharge area could not be delineated, as the area could include relatively remote locations where geologic formations composing the Ozark aquifer are exposed and have sufficient porosity and hydraulic conductivity to convey water that falls as precipitation to the subsurface. Ground-water flow directions also demonstrated regional flow patterns in each study area from water-level contour maps.

Analyses of major ion concentrations for Evening Shade Spring and Roaring Spring indicated that the source water is a calcium bicarbonate type from a dolomitic mineralogy representative of the Ozark aquifer. Nutrient concentrations generally were lower than Hughes and Stark Springs. Fecal indicator bacteria were not detected at Evening Shade Spring and were detected in only one sample from Roaring Spring. Tritium data show that the discharge water for Evening Shade Spring is a mixture of recent recharge and sub-modern water (recharged prior to 1952) and the discharge water for Roaring Spring was of relatively modern age (recharge within less than 5 to 10 years).

INTRODUCTION

Hughes Spring, Stark Spring, Evening Shade Spring, and Roaring Spring are primary municipal water supplies for several communities in north-central Arkansas. However, the extent and location of the recharge areas that contribute water to these four public drinking-water supply springs were unknown. The hydrogeologic framework of the area contains karst terrain (Imes and Emmett, 1994). Springs located in karst regions are particularly vulnerable to contamination (White, 1988; Younos and others, 2001; Taylor and McCombs, 1998) and present great challenges concerning resource protection. The karst ground-water system can have a close connection with the surface, with short travel times and flow paths from recharge areas to discharge in springs. Shallow ground-water systems predominated by fracture or conduit flow can be extremely problematic in areas of urban and agricultural land use, and may be subject to rapid input of surface contaminants and rapid transport of these contaminants to wells and springs with little opportunity for natural attenuation processes to occur. Many communities and towns in Arkansas have lost the use of springs that discharge shallow ground water because of surface-derived contamination.

The problems of delineating the recharge area and determining ground-water characteristics of karstic systems are numerous. Unlike surface watersheds, which have boundaries defined by topography, ground-water basins in karst terrains are controlled by subsurface permeability distributions that are poorly characterized, difficult to predict, non-homogeneous, and anisotropic. In karst terrains, the position of subsurface ground-water divides, or recharge area boundaries, may depend on the hydraulic gradient and orientation of widened joints, fractures, and bedding planes in the bedrock, and may not correspond to topographic highs or surface-drainage boundaries. Furthermore, karst characteristics can develop at various depths and as a result, subsurface ground-water divides during high flows may not coincide with divides during base-flow conditions. Subsurface flow in karst terrain can vary between two types of flow regimes including conduit and diffuse flow types. Conduit flow refers to rapid ground-water flow through solution openings with diameters ranging from inches to tens of feet. Flow is usually turbulent and velocities are commonly on the order of feet per second. Diffuse flow refers to ground-water flow in small fractures and pores with small, interconnected openings. Diffuse flow can be described by Darcy's Law and has much lower velocities than conduit flow.

In October 2000, a study was begun by the U.S. Geological Survey (USGS) in cooperation with the Arkansas Department of Health to characterize the hydrogeology and extent of the recharge area for Hughes, Stark, Evening Shade, and Roaring Springs. Characterization of the recharge areas was important because of the karst terrain in northern Arkansas. Also, land use near the springs, including areas suspected to lie within the spring recharge areas, included activities with potentially harmful effects to spring water quality. Potential effects could result from urban development including leakage from underground fuel storage tanks, agricultural development including runoff from animal feeding operations, and domestic development including discharges from underground septic systems. Resource management needs, including preservation of the health and safety of the people who rely on the resource, dictate that the extent of the recharge area and approximate time of travel for constituents moving from the recharge area to the spring be characterized. These data will help water managers to develop plans to protect the recharge area from contamination related to land use and enable planned response to acute effects such as spills.

Hughes Spring, Stark Spring, Evening Shade Spring, and Roaring Spring supply the public drinking water to the communities of Marshall (population 1,313) in Searcy County, Cushman (population 461) in Independence County, and Evening Shade (population 465) in Sharp County, and Cherokee Village (population 4,648) in Sharp and Fulton Counties, respectively (fig. 1; Arkansas Institute for Economic Advancement, 2003). Including the surrounding area, the total population served by the four public supply springs is approximately 11,200. Between 2001 and 2012 the population is projected to increase 15 percent in Searcy County, 10 percent in Independence County, 15 percent in Sharp County, and 14 percent in Fulton County (Arkansas Institute for Economic Advancement, 2003). As growth continues, land-use changes may cause the threat to shallow ground water to intensify, and the protection of the limited water resources in the area will be increasingly critical to the health and safety of the local population.

Purpose and Scope

The purpose of this report is to describe the hydrogeologic characteristics, including the extent of the recharge areas, of Hughes, Stark, Evening Shade, and Roaring Springs. Information pertaining to each spring can be used to enable development of effective management plans to protect these water resources and public health. Continuous discharge, temperature, and precipitation data were collected at the four springs for a 2-year period (October 2000 to October 2002) to determine flow characteristics and recharge area. An assessment of the local geology through previous mapping, borehole geophysics, and field investigation was completed in each study area to determine controls on the ground-water flow. Water-level contour maps were constructed from well and spring data in each study area to show the configuration of the water table and determine ground-water flow directions. Qualitative dye tracing also was completed in 2002 to help define the recharge area and estimate ground-water flow velocities. Water-quality samples were collected dur-

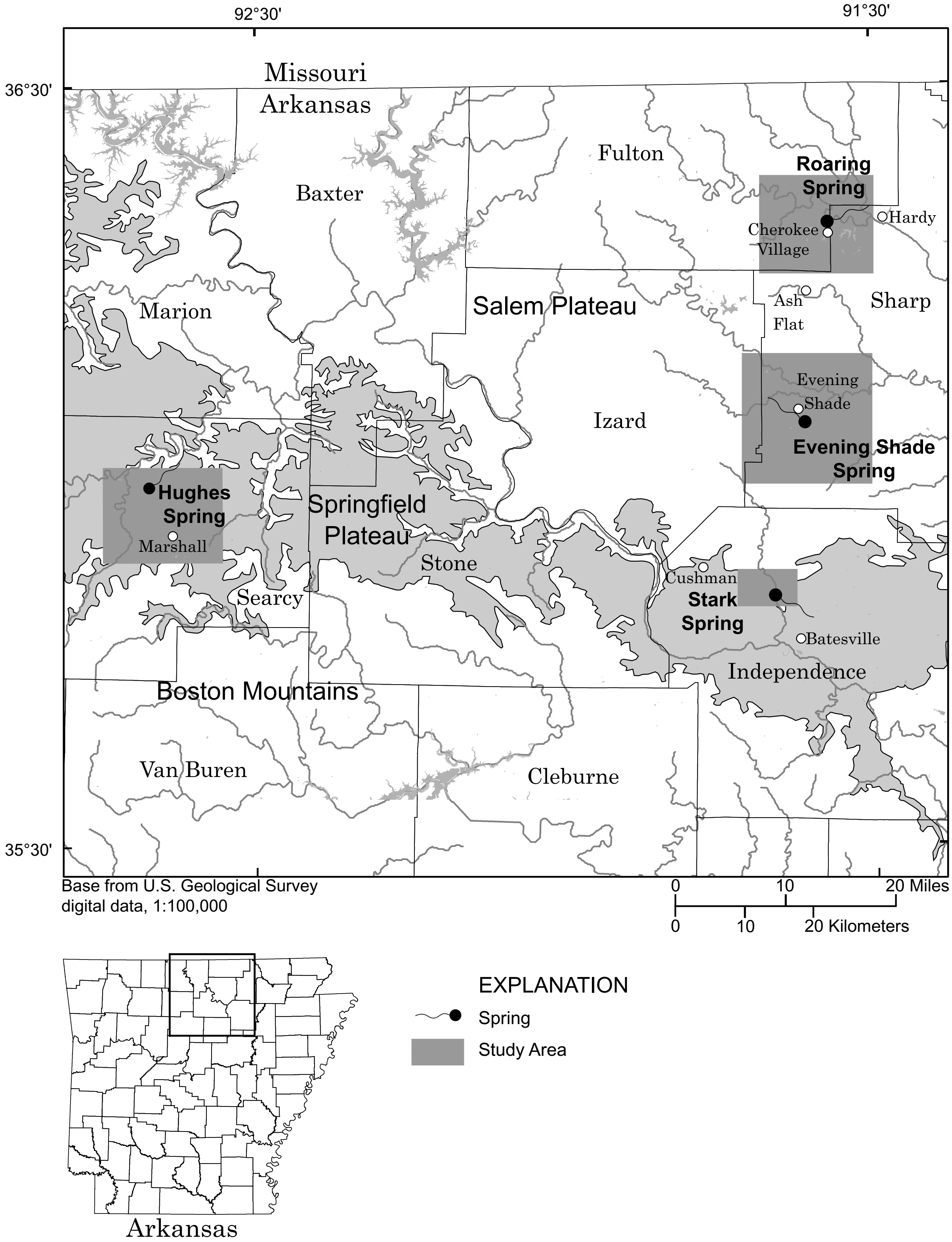


Figure 1. Locations of springs and study areas.

ing September 2001 through October 2002 at each spring to determine the geochemistry of the contributing geologic units, and the susceptibility of the springs to contamination.

Acknowledgments

The author would like to thank the operators of the public water systems examined in this report for their assistance and cooperation: Kevin Elliot, Marshall Water Works; Don Riley, Cushman Water Works; Pat Shell, Evening Shade Water Works; and Steve Rose, Cherokee Village Water Works. The author would like to especially thank the many residents that allowed access to their wells and springs used in this study.

METHODS OF INVESTIGATION

An integrated approach to determine the hydrogeologic characteristics and the extent of the local recharge areas of the four public water-supply springs incorporated methods of hydrology, structural geology, geomorphology, geophysics, and geochemistry. These independent methods of investigation are tools that can provide evidence for effectively describing the behavior of hydrologic systems.

Hydrogeologic Assessment

Several methods were used to determine the hydrogeologic characteristics of each study area. USGS 1:24,000-scale topographic maps were used to determine preliminary ground-water flow boundaries and recharge areas based solely on the configuration of the land-surface topography. Geologic maps created at a 1:24,000-scale (E.E. Glick, U.S. Geological Survey, unpub. data, 1973) were used to determine geologic units exposed in the study areas. Geomorphic and topographic data from existing maps were gathered and assessed to determine surficial controls on infiltration, ground-water flow pathways, and boundaries to ground-water flow.

A field inventory of karst features (caves, sinkholes, sinking streams, and enlarged vertical fractures and bedding planes), wells, and springs also was conducted in each study area. Karst features provided information on the connection of the ground-water system to the land surface. Water levels in wells and spring discharge altitudes were used to determine the configuration of the water table, flow characteristics in the recharge areas, and ground-water tracer injection and monitoring points.

In addition, several wells were used for borehole geophysical surveys. Borehole geophysical surveys conducted in 11 wells within the study areas provided information about the lithology, distribution of permeability, and nature of vertical flow within the ground-water system. All inventoried wells drilled to depths greater than 100 ft below land surface and not currently used for water supply were surveyed. A variety of geophysical parameters were measured including caliper measurements, fluid resistivity and temperature, natural gamma, long and short normal resistivity, and lateral and single-point resistivity. Heat-pulse flowmeter and acoustic televiewer tools also were used on several of the wells. Structural geology data from field investigation and geologic maps were inventoried, compiled, and reviewed along with the borehole geophysical data to characterize the distribution of conduits and configuration of the geologic units within the study areas.

Discharge, Temperature, and Precipitation Monitoring

To determine flow characteristics and aid in the estimate of the recharge area, the four springs were instrumented to measure discharge, water temperature, and precipitation. Each spring had a structure such as a springhouse or weir to control the stage-discharge relation. The stage (water-level elevation) was monitored and used in conjunction with periodic manual discharge measurements to define the stage-discharge relation for October 2001 to October 2002. For Stark Spring, discharge measurements were made only when the discharge was large enough to top the overflow weir that allows water to flow out of the springhouse. For most of the monitoring period, the discharge did not exceed the capacity of the withdrawal pumps and did not flow from the springhouse. During these periods, daily discharge was computed based on the volume of the springhouse holding tank at various stages and the withdrawal rates of the multiple pumps at the spring which were measured with a passive flow device. The passive flow device also was used at the three other springs to quantify the amount of water that was withdrawn at each spring.

The daily discharge was estimated for Hughes Spring for the period of November 2001 to September

2002. The weir constructed to control the stage-discharge relation was washed out twice by high-flow events (November 28, 2001 and January 31, 2002). The lack of a stable control structure prevented the development of a good stage-discharge relation. Therefore, the daily discharge was estimated using succeeding discharge measurements to develop a series of stage-discharge relations.

An analysis of base flow was conducted on the discharge data at each spring. Base flow was separated from excess runoff on a daily basis using the base flow index (BFI) program described in Wahl and Wahl (1995). The BFI program uses the Institute of Hydrology method of base flow separation, which divides the water year (October 1 to September 30) into 5-day increments and identifies the minimum flow for each increment. Minimum flow of each increment is compared to adjacent minimums to determine turning points on the base-flow hydrograph. If 90 percent of a given minimum is less than both adjacent minimums, then that minimum is a turning point. Straight lines are drawn between the turning points to define the base-flow hydrograph. The area beneath the hydrograph is the estimate of the volume of base flow for the period. The ratio of the base flow volume to total flow volume is the base flow index.

One method used to estimate the subsurface-flow regime (conduit or diffuse flow) in the aquifer system contributing to a spring is to calculate the ratio of the peak discharge to base-flow discharge. White (1988) presented a range of ratio values of 1 to 2 for slow-response (diffuse flow) springs; 7 to 10 for intermediate-response (diffuse and conduit flow) springs; and greater than 40 for fast-response (conduit flow) springs. The highest daily discharge for the year was chosen for the peak discharge and the lowest daily discharge was used for the base-flow discharge to calculate the ratio at each spring.

Because of the runoff characteristics and interactions of ground water and surface water in the Stark Spring study area, further analysis of discharge was conducted. The local-recharge area was estimated from the discharge record using a water-balance approach for individual storms. The water-balance approach accounts for the inputs, outputs, and storage of water in the system (White, 1988; Pavlicek, 1996; Vandike, 1994). Several storms were selected for analysis that had short intense precipitation events resulting in a substantial peak in the spring discharge. The volume of discharge attributed to the storm runoff was determined by removing the volume of base-flow discharge determined by the BFI program. Precipitation was monitored using a single automatic tipping bucket gage located at the spring. The volume of precipitation was determined by uniformly applying the recorded precipitation to the estimated recharge area (inflow) and then equating it to the volume of storm runoff discharging from the spring (outflow). Losses due to evapotranspiration, soil absorption, and interception were considered, but were not extensively quantified. A 10 percent reduction in recharge volume was used to estimate the losses. The 10 percent reduction was used based on field observations of little surface runoff during precipitation events, generally thin soil mantle on the bedrock, and the well-developed karst features (sinkholes, sinking streams, enlarged fractures) in the area. The greatest loss in recharge volume is probably because of interception by vegetation in the recharge area with minimal losses due to evapotranspiration because of the short duration of the storms. The calculated recharge area was adjusted using equation 1 until the inflow volume minus losses was equal to the outflow volume:

$$A = (4.3 \times 10^{-7})\frac{V_r}{(P-L)} \tag{1}$$

where A is the estimated recharge area, in square miles,
V_r is the total storm runoff volume from the spring discharge, in cubic feet,
P is the total storm precipitation, in inches, and
L is the total losses in the storm precipitation ($0.10 \times$ P), in inches.

Water temperature also was monitored at each spring to detect mixing of surface runoff and ground water in the spring discharge. While water temperatures during base-flow conditions may remain constant, inputs to the ground-water system during runoff events approximate the surface and air temperatures at the time of the event, and changes in water temperature provide an indicator of the connection with the surface-water system.

Water-Level Mapping

Water-level contour maps were constructed from ground-water level measurements and land-surface altitude data obtained from the wells and springs inventoried in each area. Well and spring altitudes were obtained from USGS 1:24,000-scale topographic maps. Wells inventoried for this study commonly were constructed with surface casing installed to a depth of 30 ft, with open borehole below that depth. Therefore, all the hydrogeologic units penetrated by the open borehole potentially contribute to water levels in the wells. The water-level contour maps were constructed using water-levels measured in the wells and altitudes of the spring discharge. The contour interval varied in each study area depending on the number of control points and range of altitude for each area. A water-level contour map of the Stark Spring study area was not constructed because of few control points.

Qualitative Ground-Water Tracing

The preliminary recharge area delineation was tested and improved using ground-water tracing techniques. Qualitative tracer tests were conducted from January to June 2002 during high-flow conditions to identify ground-water flow paths and velocities and confirm the locations of inferred ground-water-basin boundaries. Qualitative tests identify positive or negative detection of tracers at measured sites and do not quantify the concentrations of the tracers. In each ground-water tracer test, a fluorescent dye or optical brightener was injected into the aquifer using natural or induced flow into open sinkholes, swallow holes, sinking streams, or wells (fig. 2).

Four separate types of tracers were used including tinopal CBSX optical brightener (color index (C.I.) fluorescent brightener 351), eosine OJ (C.I. acid yellow), fluorescein (C.I. acid yellow 73), and rhodamine WT (C.I. acid red 388). Different tracers were used in the study to allow for multiple simultaneous injections. Resurgent tracers were recovered on passive charcoal detectors that generally were collected and exchanged at 1- to 7-day intervals. Tracers were input at various points inside and outside of the preliminary recharge areas. Collection sites were monitored until tracers were no longer observed at any of the sites. Background fluorescence was monitored at every collection site prior to each injection.

Figure 2. Injection of eosine OJ dye into a swallow hole in the Hughes Spring area (photograph by Jaysson Funkhouser, U.S. Geological Survey).

The passive dye detectors consisted of activated charcoal contained in a nylon mesh screen. The detectors were placed in the center of flow at springs or suspended in wells using a nylon line or wire. The dye was extracted from the passive detectors by elutriation in a 5 percent ammonium hydroxide and 70 percent propanol solution as described in Mull and others (1988). Positive or negative determination of tracer recovery was made using a scanning spectrofluorophotometer as described by Duley (1986).

Two tracer tests were conducted in the Hughes Spring study area that included a total of seven separate injections at different locations. One test also was conducted in the Stark Spring study area that included four injections and one test in the Evening Shade Spring study area that included three injections. Tracer tests were not conducted in the Roaring Spring study area because of the lack of injection sites.

Water Quality

Water-quality samples were collected at each spring to determine the geochemistry of the contributing geologic units and the susceptibility of the spring to contamination. Samples were collected during base-flow and high-flow conditions because ground-water quality in karst systems has been shown to be extremely variable, and dissolved constituent loads (including contaminants) during storm events can be orders of magnitude different than during base-flow conditions. Additional samples also were collected from several wells and springs in the Evening Shade and Roaring Springs areas to identify contributing aquifers to the springs through geochemical similarities.

All samples collected from the four springs were analyzed for major ions, selected trace constituents, nutrients, fecal indicator bacteria, wastewater constituents, stable isotopes, and radiogenic isotopes (table 1). Measurements of water temperature, dissolved oxygen, specific conductance, pH, and alkalinity also were completed during the collection of each sample. Samples were collected and measurements were made using protocols described in Wilde and Radke (1998), Wilde and others (1998a, 1998b, 1998c, 1999a, and 1999b), and Meyers and Wilde (1999).

The major ion and trace constituent data provided useful information in determining the type of source rock, and flow characteristics. Cation and anion concentrations are plotted as percentages of total milliequivalents per liter on trilinear diagrams to determine water composition type and to examine similarities between samples (Hem, 1989). Samples collected for this report were compared to other samples collected from previous studies in northern Arkansas and southern Missouri. Water-quality data for wells and springs identified as being contributed by water from the Springfield Plateau aquifer or Ozark aquifer were obtained from the USGS National Water Information System (NWIS) database. The ratio of calcium to magnesium, as molar equivalents per liter, was calculated to determine the mineralogy of the rocks that influence the ground-water chemistry. For waters in contact with dolomite, the molar ratio of calcium to magnesium is approximately 1. For water in contact with limestone, ratios have been observed to vary from 3 to greater than 10 (White, 1988).

Sample data also were analyzed using PHREEQC software, (Parkhurst and Appelo, 1999) to calculate calcite saturation indices ($SI_{calcite}$) using the following formula:

$$SI_{calcite} = \log(IAP/K_T) \qquad (2)$$

where IAP is the ion activity product of the mineral (calcite) and K_T is the thermodynamic equilibrium constant at a given temperature. A value of $SI_{calcite}$ equal to 0 indicates that the water sample is saturated with calcite. A value for $SI_{calcite}$ greater than 0 indicates that the sample is supersaturated with calcite and a value less than 0 would indicate a water sample was undersaturated with respect to calcite. The $SI_{calcite}$ can be used to determine hydrogeologic characteristics of the spring water. For example, water flowing diffusely through carbonate rocks or water flowing through small fractures quickly becomes saturated with respect to calcite. Conversely, water moving through large fractures and conduits requires longer flow paths and residence times to become saturated with respect to calcite (Adamski, 2000).

Samples were analyzed for several species of nitrogen and phosphorus (table 1) to determine potential contamination from local source water during different flow conditions. Nutrients in ground water occur naturally at low concentrations in northern Arkansas (Adamski, 1997). Anthropogenic sources of nutrients such as sewage discharge, fertilizers, animal waste, and septic tanks can increase concentrations of nitrogen and phosphorus above normal ambient levels. Species of nitrogen, such as nitrate, are undesirable in domestic

Table 1. List of water-quality properties and constituents collected and analyzed at Hughes, Stark, Evening Shade, and Roaring Springs

Field parameters	3-beta-Coprostanol	Isoquinoline
Water temperature	3-Methyl-1(H)-indole (Skatole)	Menthol
Dissolved oxygen	3-tert-Butyl-4-hydroxy anisole (BHA)	Metalaxyl
Specific conductance	4-Cumylphenol	Methyl salicylate
pH	4-n-Octylphenol	Metolachlor
Alkalinity	4-tert-Octylphenol	N,N-diethyl-meta-toluamide (DEET)
Major ions and trace constituents	5-Methyl-1H-benzotriazole	Naphthalene
Bicarbonate	Acetophenone	Nonylphenol, diethoxy- (total)
Calcium	Acetyl hexamethyl tetrahydronaphthalene (AHTN)	Octylphenol, diethoxy-
Magnesium	Anthracene	Octylphenol, monoethoxy-
Sodium	Anthraquinone	para-Nonylphenol (total)
Potassium	Benzo[a]pyrene	para-Nonylphenol (total)
Chloride	Benzophenone	Pentachlorophenol
Sulfate	beta-Stigmastanol	Phenanthrene
Silica	beta-Stigmastanol	Phenol
Bromide	Bisphenol A	Prometon
Fluoride	Bromacil	Pyrene
Iron	Bromoform	Tetrachloroethylene
Manganese	Caffeine	Tri(2-butoxyethyl)phosphate
Strontium	Camphor	Tri(2-chloroethyl)phosphate
Boron	Carbaryl	Tributyl phosphate
Nutrients	Carbazole	Triclosan
Ammonia	Chlorpyrifos	Triethyl citrate (ethyl citrate)
Ammonia plus organic nitrogen	Cholesterol	Triphenyl phosphate
Nitrite plus nitrate	Cotinine	Tris(dichlorisopropyl)-phosphate
Nitrite	d-Limonene	**Stable isotopes**
Phosphorus	Diazinon	Deuterium
Orthophosphorus	Dichlorvos	Oxygen-18
Fecal indicator bacteria	Equilenin	Carbon-13
Escherichia coli bacteria	Estrone	Strontium-87
Fecal coliform bacteria	Diazinon	**Radiogenic isotopes**
Fecal streptococci bacteria	Ethynyl estradiol	Tritium
Wastewater constituents	Fluoranthene	Carbon-14
1,4-Dichlorobenzene	Hexadydrohexamethyl-cyclopentabenzopyran (HHCB)	
1-Methylnaphthalene	Indole	
17-beta-Estradiol	Isoborneol	
2,6-Dimethylnaphthalene	Isophorone	
2-Methylnaphthalene	Isopropylbenzene	

or public-water supply at high concentrations because of the potential health hazards, particularly for infants (Davis and Bell, 1998). Because of the potential health risks associated with nitrate, the U.S. Environmental Protection Agency (USEPA) has established a Maximum Contaminant Level (MCL) of 10 milligrams per liter of nitrate as nitrogen in public-drinking water supplies (U.S. Environmental Protection Agency, 2002).

Samples were collected and analyzed for fecal indicator bacteria, which are measures of the sanitary quality of water. Indicator bacteria typically are not disease causing, but are correlated to the presence of water-borne pathogens. Sources of fecal indicator bacteria can include untreated municipal wastewater-treatment effluents; septic tanks; animal wastes from feedlots, barnyards, and pastures; and manure application areas. The fecal indicator bacteria used in this report are fecal coliform, fecal streptococci, and *Escherichia coli* (*E. coli*), all of which are restricted to the intestinal tracts of warm-blooded animals and can provide direct evidence of fecal contamination from warm-blooded animals and the possible presence of pathogens (Davis and Bell, 1998). The presence of fecal indicator bacteria would demonstrate a connection from the spring to local sources of the bacteria.

Samples also were collected and analyzed at each spring for a number of wastewater constituents (table 1). The wastewater constituents included a wide range of anthropogenic compounds that typically pass through conventional septic tanks or sewage- treatment systems. These compounds included fumigants, antioxidants, detergent metabolites, disinfectant antimicrobials, hormones, and caffeine.

Stable isotopes were used in the characterization of the geochemical evolution of the spring water. Deuterium and oxygen-18 ratios (δD and δ18O, respectively) were reported in per mil, or parts per thousand, relative to Vienna Standard Mean Ocean Water (VSMOW). The δD and δ18O data can be used to determine changes in the source water caused by evaporation between the time the precipitation fell on the ground surface and was discharged at each spring. For example, waters with δD and δ18O values that do not follow the δD and δ18O relation of the VSMOW can indicate that the source water resided at the land surface in lakes, ponds, and streams and were subjected to evaporation prior to infiltration into the aquifer system. Variations because of the isotopic composition of local precipitation also may cause the δD and δ18O to vary from the VSMOW and have a local meteoric water signature. δD and δ18O samples collected for this report were compared to a local meteoric line approximated by other samples collected from 160 wells and springs in northern Arkansas and southern Missouri for previous studies. These data were obtained from the USGS NWIS database.

Carbon-13 (δ13C) data were used to characterize the source water by examining the proportions of inorganically- and organically-derived carbon in the system. The proportions of inorganically- and organically-derived carbon in the spring discharge can be used to infer the path of water from the recharge source to the spring discharge. As recharge waters percolate through soils and regolith during infiltration into the ground-water system, soil CO_2 comprising organically-derived carbon from degradation of soil organic matter, is dissolved and increases the acidity of the water. As water enters the ground-water system, acidity is buffered as calcium carbonate from the source rock (limestone or dolomite) is dissolved, increasing the proportion of inorganically-derived carbon in the water. Typical δ13C values of organically-derived carbon found in soils or ground water in northern Arkansas are approximately -24 per mil (Clark and Fritz, 1997; P.D. Hays, U.S. Geological Survey, oral commun., 2003). The value of organically-derived δ13C for soils can be used to estimate the inorganically- and organically-derived carbon proportions in the spring discharge, assuming an initial value of 0 per mill for inorganic δ13C, using the following equations:

$$\%\delta C_{inorganic} = [1 - (\delta C_{measured} / \delta C_{organic})] \times 100\% \quad (3)$$

$$\%\delta C_{organic} = 100\% - \%\delta C_{inorganic} \quad (4)$$

where $\%\delta C_{inorganic}$ is the percentage of inorganically-derived δ13C,

$\%\delta C_{measured}$ is the δ13C value from sample analyses, and

$\%\delta C_{organic}$ is the percentage of organically-derived δ13C.

Samples were analyzed for radiogenic isotopes including tritium and carbon-14. These were used to determine the relative age of the water discharging from each of the springs. The age refers to the period of time that has elapsed since the water moved deep enough into the ground-water system to be isolated from the atmosphere. Tritium values, given in tritium units (TU) are used to age date more recent waters (less than 40 years) and carbon-14 data, given in percent modern carbon (PMC) are used to age date older waters (50 to 30,000 years). The tritium values were used to qualitatively date the discharge from each spring using ranges of age for given tritium values from Clark and Fritz (1997) (table 2).

Table 2. Tritium concentrations with relative ages (from Clark and Fritz, 1997)

[<, less than; >, greater than]

Tritium concentration, in tritium units	Relative age
<0.8	Sub-modern ground water recharged prior to 1952
0.8 - 4	Mixture between sub-modern waters and recent recharge
5 - 15	Modern water (<5 to 10 years)
15-30	Some “bomb” tritium present or some component of recharge from the 1960s or 1970s
>30	Considerable component of recharge from the 1960s or 1970s
>50	Dominantly recharged in the 1960s

SPRING CHARACTERIZATION

Hughes Spring

Study Area Description

The Hughes Spring study area lies in the Ozark Plateau, Salem Plateau, and Boston Mountains physiographic provinces (fig. 1). The area is dominated mainly by karstic limestones of Pennsylvanian to Ordovician age. The altitude of the study area ranges from 531 to 1,785 ft above NGVD of 1929. Land use in the area (Vogelmann and others, 2001) consists primarily of deciduous and evergreen forest (60 percent) and agricultural land (39 percent). Almost all of the agricultural land is utilized as pasture. Only a small portion of the study area is covered by urban land use (1 percent).

A humid, temperate climate is characteristic of the study area. The annual mean temperature recorded at Marshall (fig. 1) in calendar years 2001 and 2002 was 12 °C, which was below normal (-2 °C) based on a 30-year period from 1961 to 1990 (Hoare, 1996). The annual rainfall recorded at Marshall was 36 inches for 2001 and 58 inches for 2002 (National Oceanic and Atmospheric Administration, 2001; 2002). The average annual rainfall is 43 inches (Hoare, 1996).

Hydrogeology

The study area for Hughes Spring includes the Western Interior Plains confining system and the Springfield Plateau and Ozark aquifers. Exposures of geologic units of the Springfield Plateau aquifer dominate the area, smaller portions of the Ozark aquifer are exposed in the northern part of the study area, and portions of the Western Interior Plains confining system are exposed in the southern portion of the study area (figs. 3 and 4). Measurements of outcrop strike and dip (fig. 4) and geophysical logs indicate that units generally dip south-southeast by 3 to 12 degrees in the study area. The only large structural feature is a fault, located in the southern portion of the study area.

The Western Interior Plains confining system contains the youngest geologic units which are exposed in the southern portion of the study area at higher elevations. The units include the Pennsylvanian-age Bloyd Shale and Hale Formation, and Mississippian-age Pitkin Limestone, Fayetteville Shale, Batesville Sandstone, and Moorefield Formation including the Ruddell Shale Member (figs. 3 and 4).

The geologic units of the Springfield Plateau aquifer are extensively exposed in the study area and consist of the Mississippian-age Boone Formation including the St. Joe Limestone Member. The Springfield Plateau aquifer typically is separated from the underlying Ozark aquifer by the Ozark confining unit composed of Devonian-age Chattanooga Shale in areas of northern Arkansas (fig. 3). Borehole geophysical surveys in several wells (fig. 5) show the Chattanooga Shale (Ozark confining unit) was thin or absent in the study area.

The Ozark aquifer is exposed at low elevations in stream valleys in the northern portion of the study area. Geologic formations that compose the Ozark aquifer and are exposed in the study area include Devonian- and Silurian-age limestone units, and Ordovician-age Cason Shale, Fernvale, Kimmswick, and Plattin Limestones, Joachim Dolomite, St. Peter Sandstone, and Everton Formation.

Period		Geologic Unit Name: Formation	Geologic Unit Name: Member	Description	Thickness	Hydrogeologic unit or system	
Carboniferous	Pennsylvanian	Bloyd Shale		Black to dark-gray shale interbedded with limestone and some sandstones	0 -1,170 ft[1,3]	Western Interior Plains Confining System	
		Hale Formation	Prairie Grove	Dark-gray silty shales interbedded with siltstones and limy sandstones	0 - 980 ft[1,3]		
			Cane Hill				
	Mississippian	Pitkin Limestone		Fine- to coarse-grained, oolitic, bioclastic limestone	0 - 400 ft[1,3]		
		Fayetteville Shale		Black, fissile, concretionary, clay shale interbedded with fine-grained limestones	0 - 1,634 ft[1,3]		
		Batesville Sandstone		Fine- to coarse-grained sandstone with thin shales	0 - 200 ft[3]		
		Moorefield Formation	Ruddell Shale	Black calcareous and siliceous shale to a dark fissile clay shale	0 - 300 ft[3]		
		Boone Formation	St. Joe Limestone	Gray, fine- to coarse-grained fossiliferous limestone interbedded with chert	300 - 370 ft[1,3]	Springfield Plateau Aquifer	Ozark Plateaus Aquifer System
Devonian		Chattanooga Shale		Black, fissile clay shale that weathers into thin flakes	0 -85 ft[1,3]	Ozark Confining Unit	
		Clifty Limestone		Thin, very sandy limestone with few fossils	0 - 4 ft[3]	Ozark Aquifer	
		Penters Chert		Fine-grained, fossiliferous, dolomitic limestone with some chert	0 - 265 ft[1,3]		
Silurian		Lafferty Limestone		Gray-green to red micrite or sparsely fossiliferous biomicrite	5 - 20 ft[3]		
		St. Clair Limestone		Coarse-grained, highly fossiliferous limestone	0 -100 ft[3]		
		Cason Shale	Brassfield Limestone	Includes phosphatic sandstone and shale, oolitic limestone, fossiliferous limestone (Brassfield) and sandy calcareous shade	0 - 45 ft[1,3]		
Ordovician	Late	Fernvale Limestone		Massive, coarsely crystalline, crinoidal limestone	0 -100 ft[1,3]		
	Middle	Kimmswick Limestone		Thin to massive, fine- to coarse-grained, bioclastic limestone	0 -180 ft[1,3]		
		Plattin Limestone		Thin bedded, very fine-grained, micritic limestone	0 -367 ft[1,3]		
		Joachim Dolomite		Fine-grained dolostone and dolomitic limestone with thin beds of shale	0 -100 ft[1,3]		
		St. Peter Sandstone		Massive bedded, medium- to fine-grained, well-rounded, friable sandstone	0 -175 ft[1,3]		
		Everton Formation		Highly variable with mixtures of dolostone, sandstone, and limestone	0 -1,205 ft[1,3]		
	Early	Powell Dolomite		Fine-grained, limy argillaceous dolostone with thin beds of shale and sandstone	0 - 420 ft[1,2,3]		
		Cotter Dolomite		Two different types of dolostone	0 - 527 ft[1,2,3]		
		Jefferson City Dolomite		Fine-grained, crystalline dolostone and considerable chert	100 - 496 ft[1,2]		
		Roubidoux Formation		Cherty dolostone, dolomitic sandstone and scattered sandstone intervals	130 - 455 ft[1,2]		
		Gasconade Dolomite	Gunter Sandstone	Cherty dolostone, sandstone (Gunter)	300 - 600 ft[1,2]		

[1]Caplan (1957)
[2]Caplan (1960)
[3]McFarland (1998)

Figure 3. Stratigraphic column with descriptions of lithologic and geohydrologic properties of the Western Interior Plains confining system and the Ozark Plateaus aquifer system within Arkansas (modified from Pugh, 1998 and McFarland, 1998).

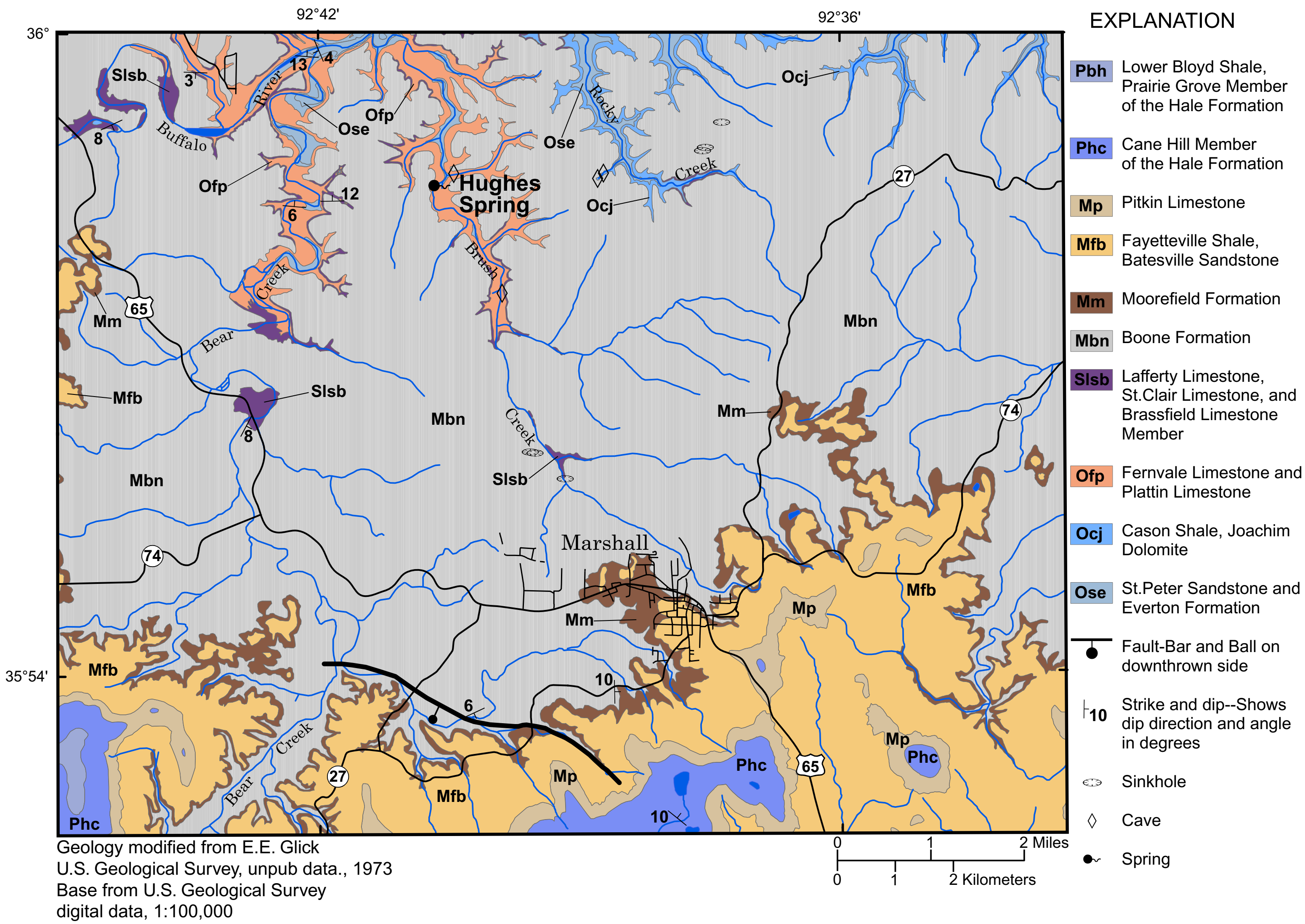


Figure 4. Geology of the Hughes Spring study area.

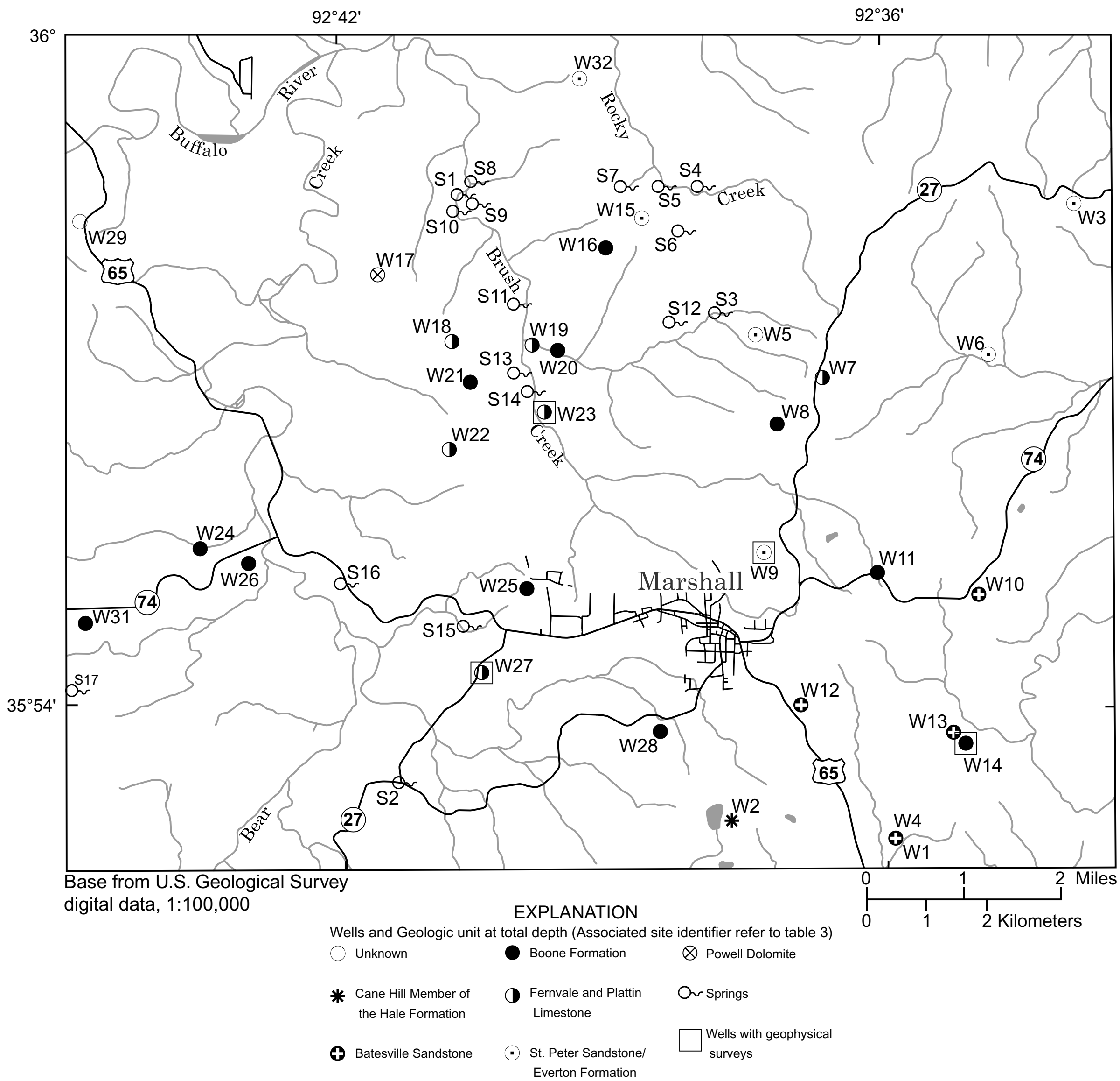


Figure 5. Distribution of wells and springs in the Hughes Spring study area.

Water-level data indicate a hydrologic connection exists between the Springfield Plateau aquifer and the Ozark aquifer because of the weak presence of the Ozark confining unit. Well-developed karstic features that provide vertical connection between the two aquifers also were observed in the study area. Hughes Spring discharges from fractures in units of the Ozark aquifer, although most of the water probably originates from the overlying Springfield Plateau aquifer (fig. 6).

The karst features observed in the Hughes Spring study area occur mainly in the Boone Formation. These features develop as ground water percolates through the limestone resulting in the enlargement of fractures through the dissolution of the carbonate rock (solution channels). Karst features present in the study area include solution channels, sinkholes, springs, sinking streams, and caves (fig. 4). Four caves and six sinkholes were inventoried and enlarged fracture openings were evident at the surface throughout the area. No surface streams were observed to have perennial flow throughout the year. Brush Creek was observed to have flow along its entire length in the study area only during periods of intense rainfall events. During the rest of the year, flow was evident only in the streambed near spring discharge points.

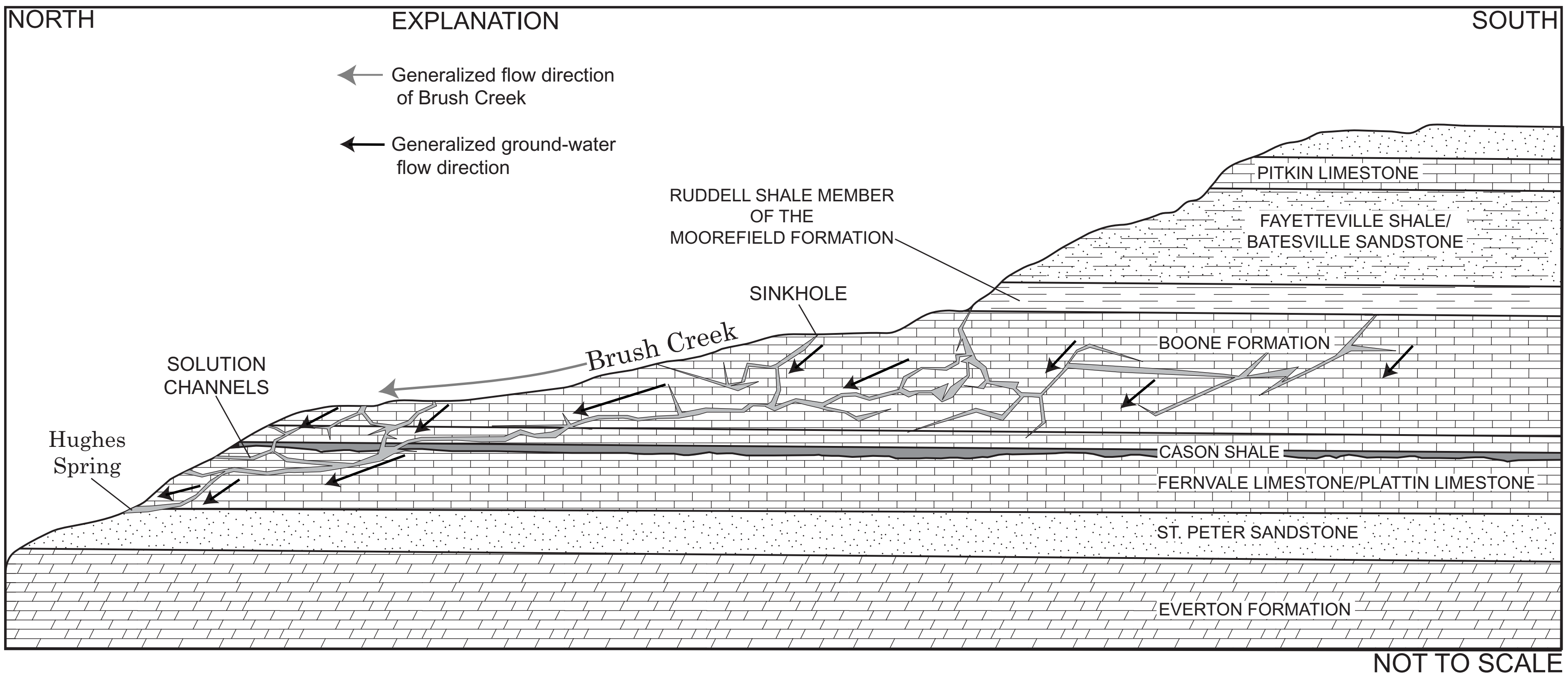


Figure 6. Conceptual model of ground-water flow to Hughes Spring.

Discharge, Temperature, and Precipitation

The discharge for Hughes Spring varied seasonally and temporally (fig. 7). The mean annual discharges for water years 2001 and 2002 were 2.0 and 5.2 cubic feet per second (ft^3/s), respectively (Brossett and Evans, 2003). Mean daily discharge ranged from approximately 0.5 to 14 ft^3/s for water years 2001 and 2002. The spring discharge generally followed precipitation patterns with the highest mean daily discharges in the months of December through May and the lowest mean daily discharges generally in the months of July through November.

Water temperature for Hughes Spring reflected seasonal variations throughout the monitoring period (fig. 7) and demonstrated considerable changes during summer high-flow events (fig. 8). Recorded water temperature ranged from 10.6 °C to 23.2 °C with a mean of 14.6 °C (fig. 7). The highest temperatures were recorded in the summer (June through August) and fall (September through November) with average temperatures at approximately 17 °C for both seasons. The winter (January, February, and December) and spring (March through May) had lower average temperatures of approximately 12 °C and 13 °C, respectively. Large water temperature variations corresponded to high-flow events (fig. 8).

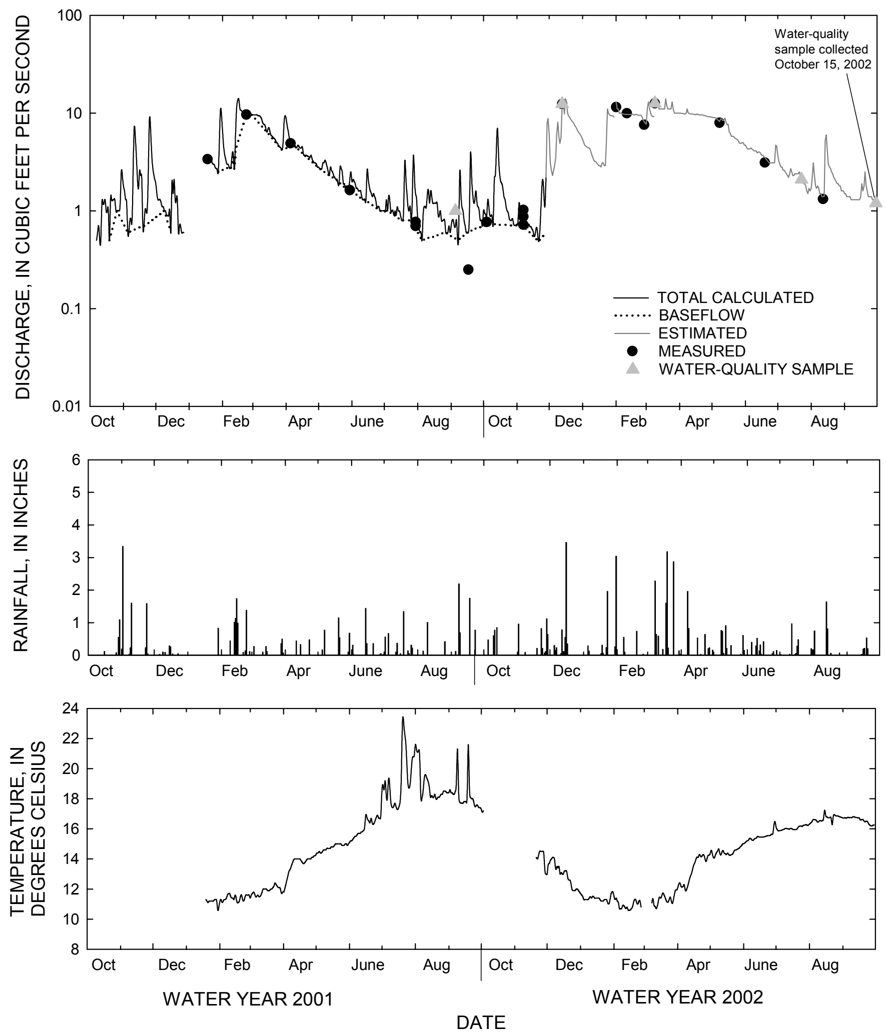


Figure 7. Daily discharge, rainfall, and water temperature recorded at Hughes Spring.

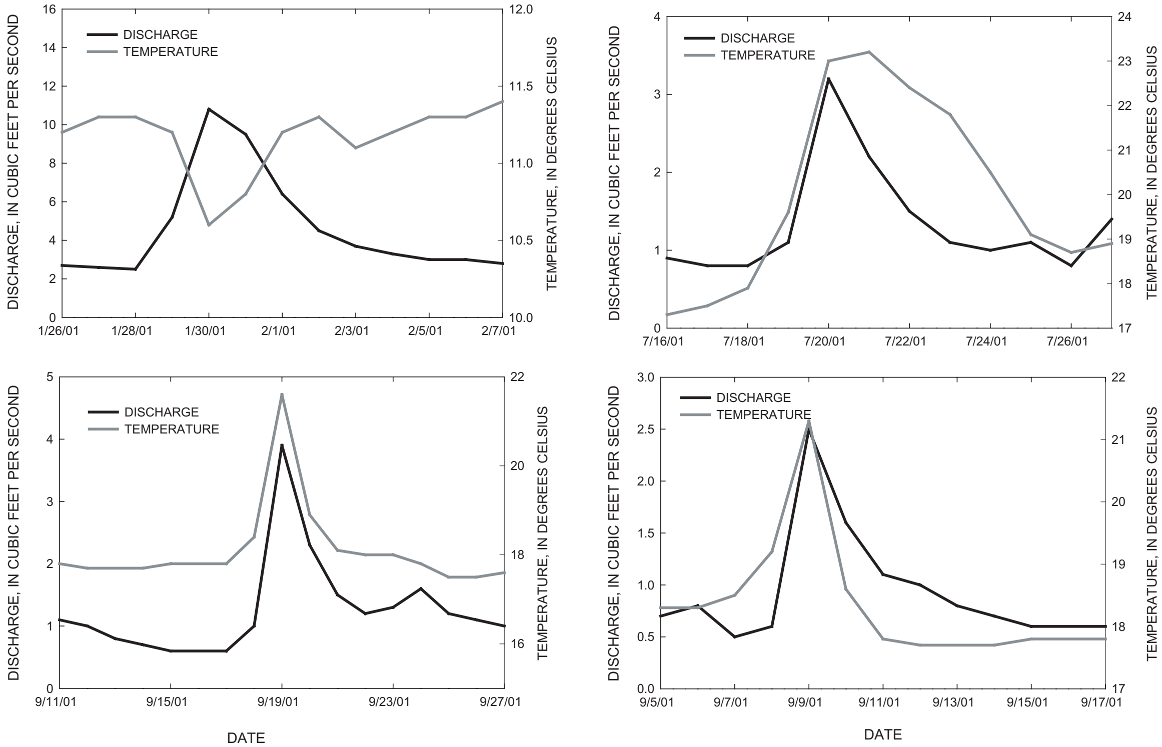


Figure 8. Discharge and water temperature data from Hughes Spring for four storm events.

Discharge data and base-flow separation analysis indicate that although the Hughes Spring discharge is dominated by base flow, it responds quickly to surface-runoff events. On average, the base flow composed approximately 67 percent of the discharge volume for the period of October 2000 through November 2001. However, discharge exceeded base flow by more than 5 percent during 75 percent of the monitoring period. The ratio of annual peak flow to base flow for Hughes Spring was calculated as 28 based on the 2001 water year data, indicating a fast-response spring (White, 1988). Further analysis of the discharge data for Hughes Spring using a water-balance calculation was not conducted because the runoff in Brush Creek was not measured. Because Hughes Spring lies within the Brush Creek drainage area, the runoff data would be required to determine the proportion of runoff discharging through Brush Creek and Hughes Spring to estimate the size of the recharge area contributing flow to Hughes Spring.

Water-Level Contours

Water-level contours constructed from static water levels measured in 27 wells and estimated at 15 springs representing units of the Springfield and Ozark aquifers in calendar year 2001(table 3) generally followed land-surface topography in the area and indicated ground-water flow is generally to the northwest towards the Buffalo River with the highest water-level elevations occurring in the southeast corner of the study area (fig. 9). There was one area of water-level depression in the north-central portion of the study area. The depression could reflect a zone of higher permeability in lower units penetrated by well W32 (fig. 5). A contour interval of 100 ft was used to account for the variations in water level because of the high topographic relief, extensive karst development, and the few data points in the study area (fig. 9).

Table 3. Wells and springs inventoried in the Hughes Spring study area

[Geologic unit name refers to the formation from which the spring discharges or the formation at the total depth of the well; USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds; --, no data;*, not located within study area boundary]

Site identifier (fig. 5)	Station identification number	USGS local number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface, in feet above NGVD of 1929	Site type	Well depth, in feet below land surface	Date of water-level measurement	Water level, in feet below land surface	Altitude of water-level, in feet above NGVD of 1929	Use	Geologic unit name
S1	07056545	Hughes Spring near Zack	355833	924036	620	Spring	--	--	--	620	Public water supply	Plattin Limestone
S2	355317092411601	14N16W04ACB1SP	355317	924116	860	Spring	--	--	--	860	Unused	Batesville Sandstone
S3	355729092374601	15N16W12ADC1SP	355729	923746	860	Spring	--	--	--	860	Residential	Boone Formation
S4	355837092375701	15N16W01ABC1SP	355837	923757	900	Spring	--	--	--	900	unused	Boone Formation
S5	355837092382301	15N16W01BBD1SP	355837	923823	718	Spring	--	--	--	718	Unused	Plattin Limestone
S6	355813092381001	15N16W01CAC1SP	355813	923810	840	Spring	--	--	--	840	Unused	St. Joe Limestone
S7	355837092384801	15N16W02AAC1SP	355837	923848	790	Spring	--	--	--	790	Unused	St. Joe Limestone
S8	355840092402701	15N16W03BBD1SP	355840	924027	630	Spring	--	--	--	630	Unused	Plattin Limestone
S9	355828092402601	15N16W03BCA1SP	355828	924026	700	Spring	--	--	--	700	Residential	Fernvale Limestone
S10	355824092403901	15N16W03BCD1SP	355824	924039	620	Spring	--	--	--	620	Unused	Fernvale Limestone
S11	355734092395901	15N16W10ACD1SP	355734	923959	680	Spring	--	--	--	680	Unused	Fernvale Limestone
S12	355724092381601	15N16W12CAB1SP	355724	923816	840	Spring	--	--	--	840	Residential	Boone Formation
S13	355657092395901	15N16W15ABD1SP	355657	923959	700	Spring	--	--	--	700	Livestock	Boone Formation
S14	355647092395001	15N16W15ADC1SP	355647	923950	700	Spring	--	--	--	700	Livestock	St. Joe Limestone
S15	355441092403301	15N16W27CBD1SP	355441	924033	800	Spring	--	--	--	800	Unused	Boone Formation
S16	355504092415401	15N16W29ADA1SP	355504	924154	740	Spring	--	--	--	740	Unused	Boone Formation
S17	355407092445201	15N17W36BCD1SP	355407	924452	897	Spring	--	--	--	897	Unused	Batesville Sandstone
W1	355245092355101	14N15W05DCD1	355245	923551	1,110	Well	18	5/09/01	10	1,100	Residential	Batesville Sandstone
W2	355256092374001	14N15W06CBC1	355256	923740	1,597	Well	35	5/10/01	7	1,590	Residential	Cane Hill Member
W3	355827092335201	15N15W03ACB1	355827	923352	1,180	Well	438	1/25/77	258	922	Unused	Everton Formation
W4	355247092355201	15N15W05DCA1	355247	923552	1,110	Well	70	5/09/01	25	1,085	Residential	Batesville Sandstone
W5	355717092372301	15N15W07CAC1	355717	923723	1,062	Well	500	6/07/01	213	849	Residential	Everton Formation
W6	355706092344901	15N15W09DDB1	355706	923449	960	Well	500	5/08/01	141	819	Residential	St. Peter Sandstone
W7	355654092363901	15N15W17BBB1	355654	923639	1,130	Well	500	5/08/01	210	920	Residential	Fernvale Limestone

Table 3. Wells and springs inventoried in the Hughes Spring study area--Continued

[Geologic unit name refers to the formation from which the spring discharges or the formation at the total depth of the well; USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds; --, no data;*, not located within study area boundary]

Site identifier (fig. 5)	Station identification number	USGS local number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface, in feet above NGVD of 1929	Site type	Well depth, in feet below land surface	Date of water-level measurement	Water level, in feet below land surface	Altitude of water-level, in feet above NGVD of 1929	Use	Geologic unit name
W8	355629092370901	15N15W18DBB1	355629	923709	1,130	Well	500	5/09/01	128	1,002	Residential	Boone Formation
W9	355520092371801	15N15W19CDD1	355520	923718	1,100	Well	550	7/09/01	344	756	Unused	Everton Formation
W10	355457092345601	15N15W28ACA1	355457	923456	1,180	Well	39	5/10/01	13	1,167	Residential	Batesville Sandstone
W11	355509092360301	15N15W29ABA1	355509	923603	1,120	Well	200	6/20/01	47	1,073	Residential	Boone Formation
W12	355358092365401	15N15W31ADD1	355358	923654	1,565	Well	285	6/05/01	88	1,478	Residential	Batesville Sandstone
W13	355343092351301	15N15W33DBC1	355343	923513	1,105	Well	19	5/09/01	11	1,094	Residential	Batesville Sandstone
W14	355337092350501	15N15W33DCB1	355337	923505	1,120	Well	300	5/09/01	103	1,017	Unused	Boone Formation
W15	355820092383801	15N16W02ADD1	355820	923838	1,030	Well	350	6/06/01	283	747	Residential	Everton Formation
W16	355804092390201	15N16W02DCB1	355804	923902	1,005	Well	140	5/08/01	58	947	Residential	Boone Formation
W17	355750092413301	15N16W09BBA1	355750	924133	925	Well	950	5/09/01	137	788	Residential	Powell Dolomite
W18	355714092404401	15N16W10CCB1	355714	924044	976	Well	300	6/06/01	219	757	Residential	Fernvale Limestone
W19	355712092395101	15N16W10DDB1	355712	923951	690	Well	35	5/08/01	23	667	Unused	Fernvale Limestone
W20	355709092393401	15N16W11CCB1	355709	923934	710	Well	unknown	6/28/01	39	671	Unused	Boone Formation
W21	355652092403201	15N16W15BBD1	355652	924032	985	Well	350	5/09/01	76	909	Unused	Boone Formation
W22	355616092404601	15N16W15CCC1	355616	924046	1,005	Well	355	6/05/01	247	758	Residential	Plattin Limestone
W23	355636092394301	15N16W15DAA1	355636	923943	720	Well	70	5/08/01	30	690	Unused	Fernvale Limestone
W24	355523092433101	15N16W19CDD1	355523	924331	695	Well	17	5/10/01	5	690	Unused	Boone Formation
W25	355501092395501	15N16W27ADB1	355501	923955	973	Well		6/05/01	87	886	Residential	Boone Formation
W26	355515092425901	15N16W30AAA1	355515	924259	676	Well	109	7/10/01	27	649	Residential	Boone Formation
W27	355416092402501	15N16W34BAD1	355416	924025	1,000	Well	485	5/09/01	187	813	Unused	Plattin Limestone
W28	355344092382701	15N16W36CCA1	355344	923827	960	Well	115	5/07/01	27	933	Unused	Boone Formation
W29	355819092445001	15N17W01CBA1	355819	924450	986	Well	1320	7/10/01	240	746	Public water supply	--
W30*	355719092450301	15N17W11DDA1	355719	924503	960	Well	825	6/26/01	110	850	Residential	Everton Formation
W31	355443092444701	15N17W25CAC1	355443	924447	940	Well	300	6/19/01	93	847	Residential	Boone Formation
W32	355935092391901	16N16W35BAB1	355935	923919	980	Well	550	7/09/01	397	583	Residential	Everton Formation

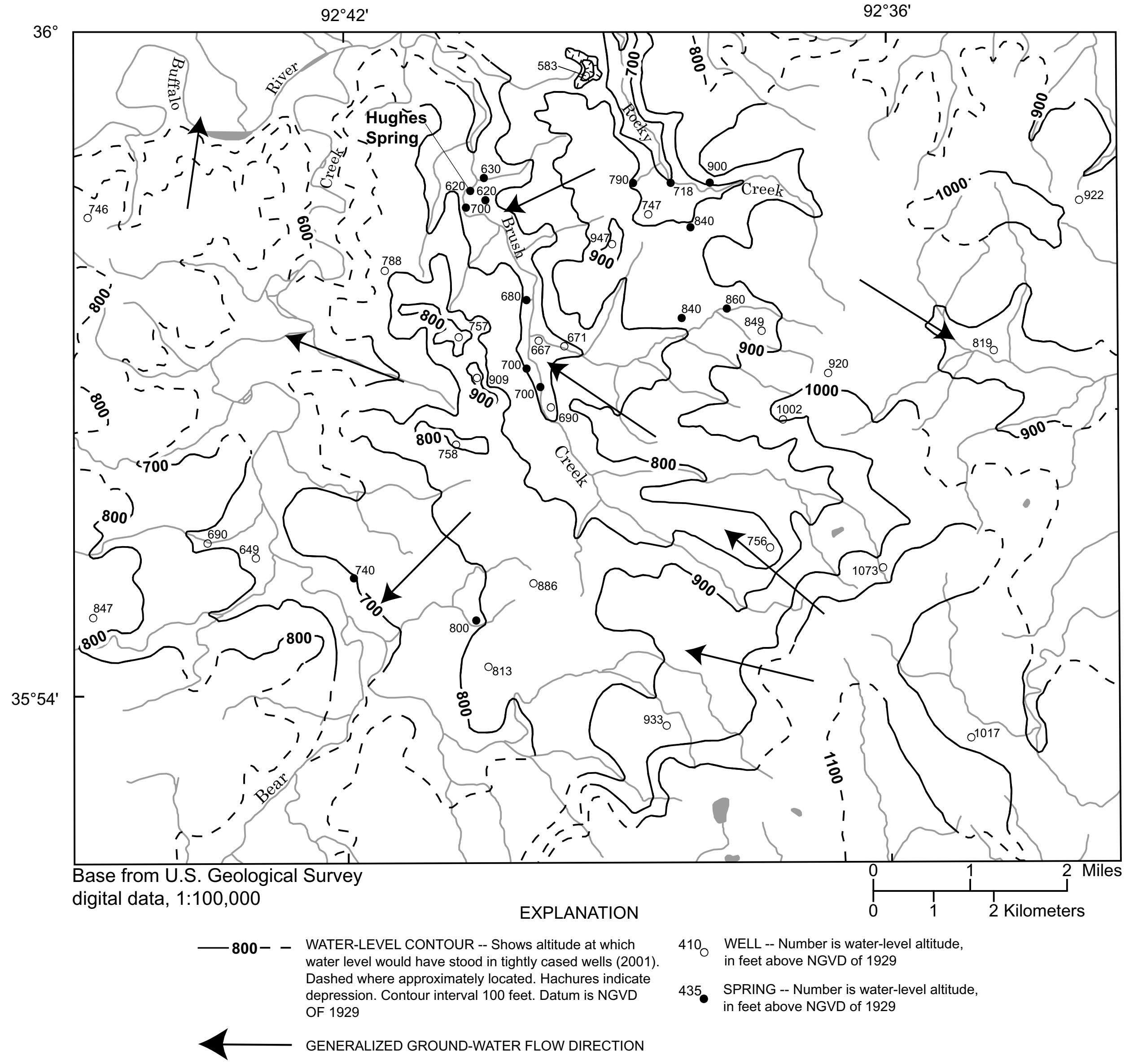


Figure 9. Water-level contours of the Hughes Spring study area.

Recharge Area Characterization

Based on the ground-water tracer test data and the spring discharge, it appears that the recharge area for Hughes Spring generally coincides with the surface drainage area, which is approximately 15.8 mi^2. Tracers injected outside the surface drainage area (sites 5-7) were not detected at Hughes Spring or other recovery sites within the surface drainage area (fig. 10). Tracers injected at two sites inside the surface drainage area (sites 2 and 3) were detected at Hughes Spring and at springs along Brush Creek and in Brush Creek itself, indicating a connection between the surface flow in the stream and Hughes Spring. The tracer-test data and spring-discharge data show that Hughes Spring may act like a distributary from Brush Creek during high-flow events, discharging a portion of runoff waters resulting from precipitation that occurs in the surface drainage area. More extensive ground-water tracer tests would be needed to further confirm whether the Hughes Spring recharge area is coincidental with the surface drainage area boundary.

Tracers injected at sites 1 and 4, located inside the surface drainage area, and at site 7 outside the surface drainage area, were not recovered at any of the monitored springs and wells located in the study area (fig. 10; table 4). Because multiple flow paths can exist that are not connected in karst areas, the tracers may have followed paths that did not coincide with any of the monitoring sites. The optical brightener injected at site 1 was not successfully recovered during any of the

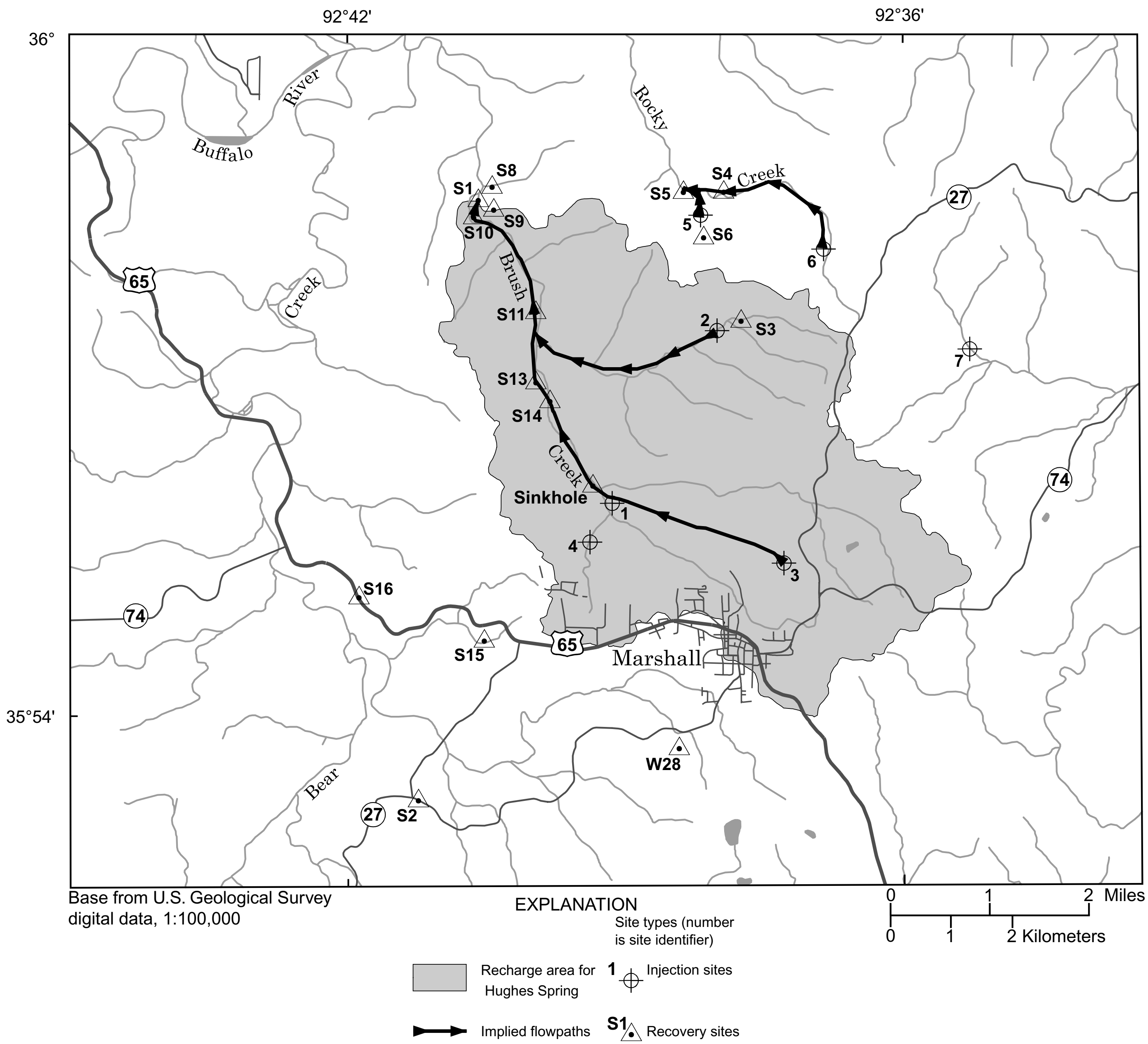


Figure 10. Locations of dye injection and recovery sites with implied flow paths of dyes and delineated recharge area for Hughes Spring.

tracer tests completed for this entire study and may not have been suitable for these hydrologic systems because of absorption properties of the tracer or because of flow characteristics of the ground-water systems.

Tracer tests demonstrated rapid ground-water flow velocities in the study area, which are characteristic of conduit-type flow often found in karst systems (White, 1988). Using distances measured along implied flow paths from injection sites to recovery sites (fig. 10), estimated minimum velocities ranged from 0.04 to 1.30 mi/d (table 4). The highest velocities were estimated for tracer tests conducted in January during high-flow conditions and for sites with the greatest elevation change. The estimated minimum flow velocities ranged from 0.42 to 1.30 mi/d for the January tracer test and from 0.04 to 0.27 mi/d for the tracer test conducted in May.

Geochemistry

The major ion analyses for five samples collected between September 2001 to October 2002 for Hughes Spring (table 5) show a chemistry that is a calcium bicarbonate type (Hem, 1989) and is indicative of waters from the Springfield Plateau aquifer (fig. 11). The calcium to magnesium ratio ranged from 26 to 38, indicating contribution from limestone mineralogy (White, 1988). Ratios of calcium to magnesium calculated for other samples collected from wells and springs representing the Springfield Plateau aquifer indicate ratios ranging from 3 to 70, with a median ratio value of 18, also indicating limestone mineralogy. Wells and springs representing units in the Ozark aquifer had values for calcium to magnesium ratios ranging from 1 to 3 with a median value of 1, indicating a dolomitic mineralogy.

Table 4. Results of ground-water tracer tests in the Hughes Spring study area

[*, Hughes Spring; --, no data]

Injection site identifier (fig. 10)	Injection site type	Tracer injected	Injection date	Sites where tracer was detected (fig. 10)	Date tracer was detected	Number of days from injection to detection	Distance from injection site to detection site (miles)	Apparent minimum velocity (miles per day)
1	Sinkhole	Optical brightener	1/10/02	None	--	--	--	--
2	Swallow hole	Eosine OJ	1/10/02	S1*	1/16/02	6	3.7	0.62
				S10	1/14/02	4	3.5	0.88
				S11	1/14/02	4	2.3	0.58
3	Well	Fluorescein	1/11/02	S1*	1/18/02	7	5.4	1.30
				S11	1/18/02	7	4.0	0.57
				S13	1/18/02	7	3.3	0.47
				S14	1/18/02	7	3.1	0.44
				Sinkhole	1/16/02	5	2.1	0.42
4	Swallow hole	Rhodamine WT	1/11/02	None	--	--	--	--
5	Swallow hole	Rhodamine WT	5/24/02	S5	5/31/02	7	0.4	0.06
6	Swallow hole	Eosine OJ	5/24/02	S1*	8/15/02	83	5.0	0.06
				S5	5/31/02	7	1.9	0.27
				S11	8/15/02	83	3.6	0.04
7	Swallow hole	Fluorescein	5/28/02	None	--	--	--	--

Table 5. Water-quality analyses from samples collected at Hughes Spring, 2001-2002

[ft^3/s, cubic foot per second; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; e, estimated; µg/L, micrograms per liter; <, less than; --, no data]

Constituent	Base-flow samples			High-flow event samples	
	Sept. 5, 2001	July 23, 2002	Oct. 15, 2002	Dec. 13, 2001	Mar. 9, 2002
Discharge, ft^3/s	1.0	2.1	1.2	12.4	12.6
Water temperature, °C	20	16	16	13	11
Dissolved oxygen, mg/L	--	8.46	7.41	--	13
Specific conductance, µS/cm	362	397	372	324	180
pH	7.8	7.7	7.8	7.8	7.8
Bicarbonate, dissolved, mg/L	210	224	205	179	106
Calcium, dissolved, mg/L	68.5	82	71.6	63.7	35.8
Magnesium, dissolved, mg/L	1.14	1.45	1.14	1.43	0.82
Sodium, dissolved, mg/L	3.29	3	3.15	2.64	1.37
Potassium, dissolved, mg/L	0.87	0.91	0.80	1.28	0.87
Chloride, dissolved, mg/L	6.3	5.8	5.8	4.6	2.5
Sulfate, dissolved, mg/L	3.85	5.87	3.67	8.98	5.21
Silica, dissolved, mg/L	9.63	9.83	9.46	8.22	6.59
Bromide, dissolved, mg/L	0.056	0.037	0.045	e0.019	<0.030
Fluoride, dissolved, mg/L	<0.1	<0.1	<0.1	e0.08	<0.1
Iron, dissolved, µg/L	<10	<10	<10	<10	<10
Manganese, dissolved, µg/L	<2	<2	e2.93	<2	<2
Total dissolved solids, calculated, mg/L	197	223	201	184	109
Calcite saturation index	0.47	0.40	0.40	0.29	-0.15
Hardness, mg/L as $CaCO_3$	176	211	180	165	92.8
Ammonia plus organic nitrogen, dissolved, mg/L as nitrogen	<0.1	<0.1	<0.1	e0.08	0.11
Nitrite, dissolved, mg/L as nitrogen	<0.008	<0.008	<0.008	<0.008	<0.008
Nitrite plus nitrate, dissolved, mg/L as nitrogen	e0.91	0.97	1.1	1.2	0.79
Phosphorus, dissolved, mg/L	e0.02	0.02	0.02	0.02	0.02
Orthophosphorus, dissolved, mg/L as phosphorus	e0.01	0.02	e0.01	0.02	0.02
Escherichia coli bacteria, colonies per 100 milliliters	150	e15	e34	150	680
Fecal coliform bacteria, colonies per 100 milliliters	e7	e5	68	110	e660
Fecal streptococci bacteria, colonies per 100 milliliters	e20	70	e58	360	e1,000
Deuterium, ratio per mil	-36.5	--	--	--	-36.8
Oxygen-18, ratio per mil	-6.18	--	--	--	-6.34
Carbon-13, ratio per mil	-13.27	--	--	--	-17.61
Tritium, tritium units	4.1	--	--	--	2.7
Carbon-14, percent modern carbon	88.3	--	--	--	93.66

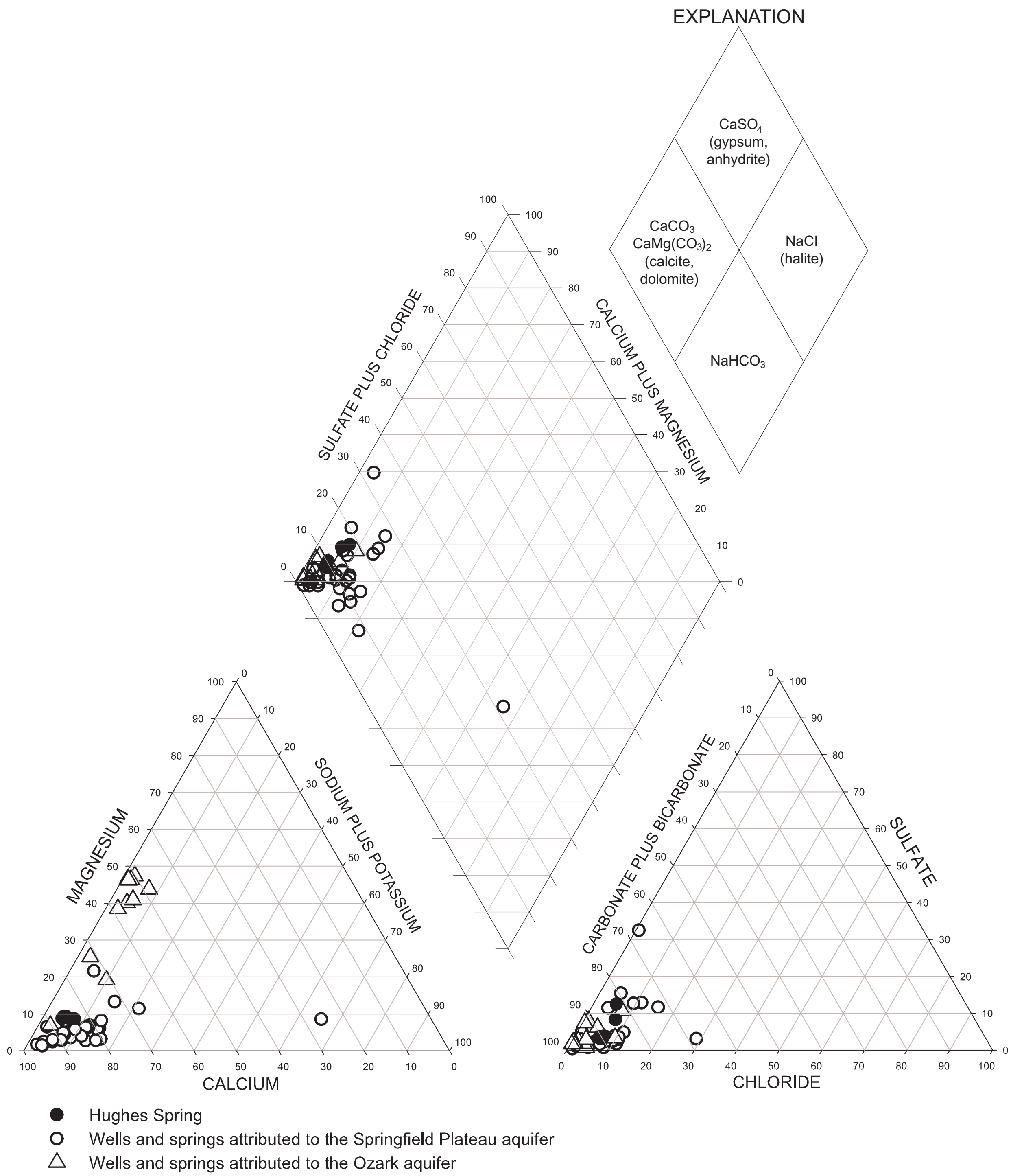


Figure 11. Relation of ground-water samples from Hughes Spring and other wells and springs in northern Arkansas and southern Missouri.

The geochemistry of Hughes Spring is characteristic of a conduit-dominated ground-water flow system. Samples were collected at Hughes Spring during base-flow and high-flow conditions and had calcite saturation indices ($SI_{calcite}$) values that were noticeably different with different flow conditions. Generally, the higher the spring discharge, the less saturated the water sample is with respect to calcite, which shows the effect of the residence time of the water with the aquifer material. Samples collected during base-flow conditions had $SI_{calcite}$ values near or greater than 0.4 (supersaturated with respect to calcite) while the high-flow samples had values of 0.3 and -0.15 (supersaturated to undersaturated with respect to calcite). Total dissolved solids (TDS) concentrations and hardness also changed with flow conditions. Both values decrease as discharge increases, reflecting the effects of reduced residence time of the water with the source rock at higher discharge, allowing for less dissolution (table 5).

Nutrient concentrations at Hughes Spring were similar to concentrations in samples collected from undeveloped (forest cover greater than or equal to 90 percent of land use) sites in the Springfield Plateau and Ozark aquifers in northern Arkansas and southern Missouri (Adamski, 1997). Nitrite and ammonia concentrations were below detection levels in all of the samples. Dissolved phosphorus concentrations were approximately 0.02 mg/L, which was mostly in the form of orthophosphorus. Nitrite plus nitrate concentrations ranged from 0.79 to 1.2 mg/L as nitrogen, and ammonia plus organic nitrogen concentrations were approximately 0.1 mg/L as nitrogen (table 5; fig. 12).

Although the nutrient data did not indicate elevated concentrations caused by surface influences, the fecal indicator bacteria demonstrated substantial increase in concentration during high-flow conditions. During base-flow conditions, concentrations for all of the indicator bacteria were below 200 colonies per 100 milliliters. During high-flow conditions, concentrations for *E. coli* and fecal coliform ranged from 110 to 680 colonies per 100 milliliters and fecal streptococci ranged from 360 to 1,000 colonies per 100 milliliters. The higher concentration during high-flow events indicates that a non-point source of bacteria such as from livestock may enter the system from surface-water runoff. One base-flow sample was analyzed for wastewater constituents to identify point source contamination; however, none of the constituents were above detection limits.

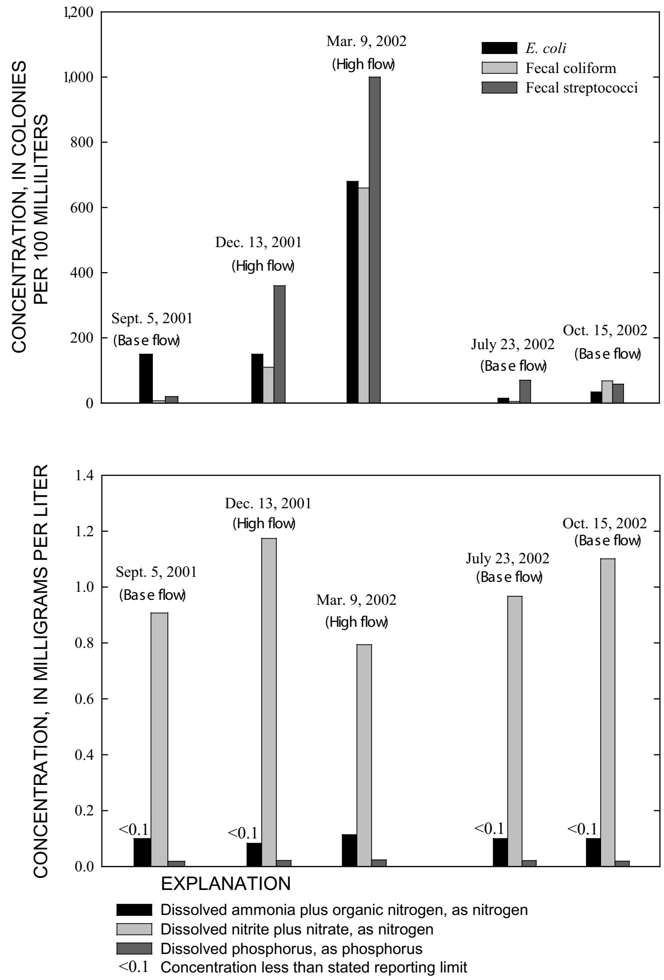


Figure 12. Fecal indicator bacteria and nutrient concentrations for samples collected from Hughes Spring.

δD and $\delta 18O$ values were -36.5 and -6.18 per mil, respectively, for the base-flow sample and -36.8 and -6.34 per mil, respectively, for the high-flow sample (table 5). The relation between δD and $\delta 18O$ of the samples are similar to that of the global meteoric line or VSMOW standard and generally followed the trend of the local meteoric line indicating the samples are representative of direct precipitation entering the aquifer system and not influenced by sources of water enriched in $\delta 18O$ through evaporation (fig. 13).

Stable isotopes of carbon ($\delta 13C$; table 5) in Hughes Spring indicate that although the ground-water system is dominated by conduit flow, a substantial component of the source water interacts with surface material, such as soils and regolith, before entering the ground-water system during high-flow events. Using a value of -24 per mil for organically-derived $\delta 13C$ in the ground-water (Clark and Fritz, 1997; P.D. Hays. U.S. Geological Survey, oral commun., 2003) and the mea-

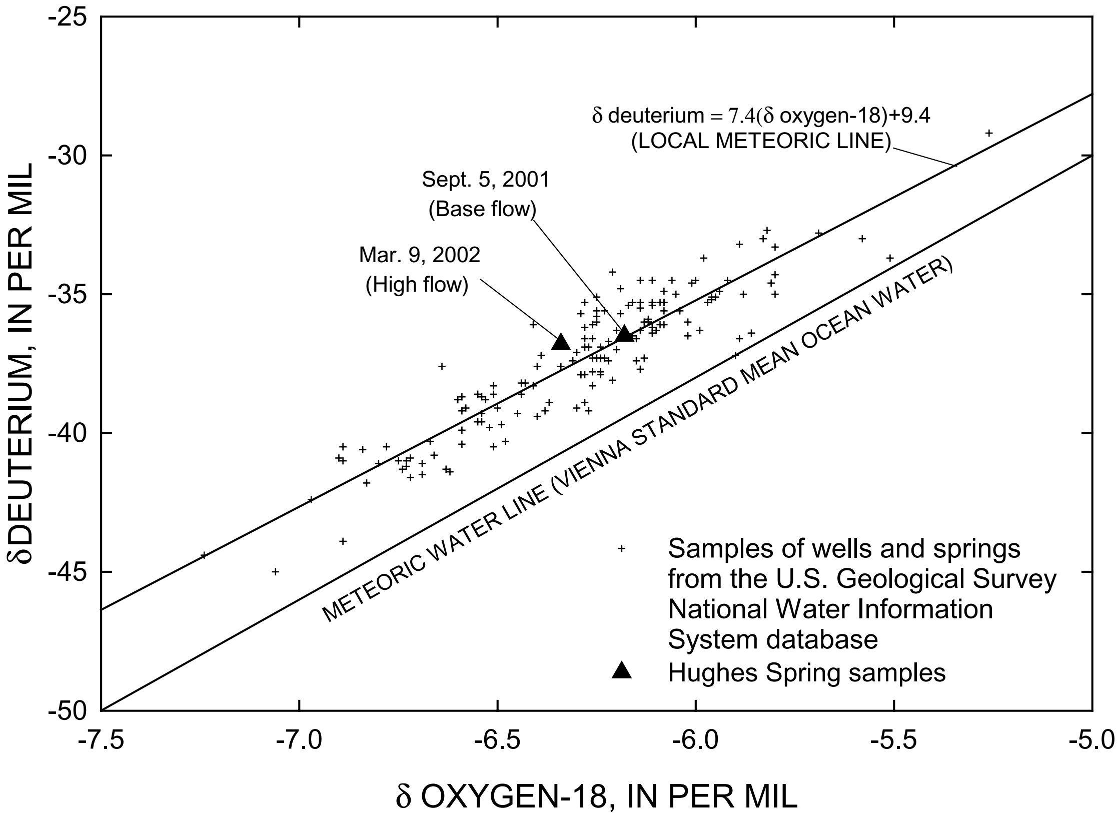


Figure 13. Relation of deuterium and oxygen-18 isotope ratios in ground-water samples from Hughes Spring and other wells and springs in northern Arkansas and southern Missouri.

sured value of -13.27 per mil for the base-flow sample collected from Hughes Spring, the proportion of inorganically-derived δ13C was calculated as 45 percent and the organically-derived δ13C was calculated as 55 percent. For the high-flow sample, a measured value of -17.61 per mil was used to calculate the proportion of inorganically-derived δ13C as 27 percent and the proportion of organically-derived δ13C as 73 percent. An enrichment of organically-derived carbon occurs in the Hughes Spring discharge during high-flow events from water infiltrating into soils in the recharge area before entering the aquifer system. The connection of Hughes Spring with Brush Creek, shown by the ground-water tracer tests, would provide pathways for water enriched in organically-derived carbon to reach the spring discharge. During base-flow conditions, water in the ground-water system that feeds the Hughes Spring discharge has a longer residence time in the system that allows it to approach equilibrium and maintains an even distribution of inorganically- and organically-derived carbon, caused by buffering (lowering the acidity) from carbonate dissolution. Most of the inorganically-derived carbon in the spring discharge is probably in the form of bicarbonate (HCO_3) in the ground-water system at the measured pH values, which also shows a substantially lower concentration during high-flow events (table 5).

Radiogenic isotopes (tritium and carbon-14) from Hughes Spring indicate that the discharge water is a mixture of recent recharge and sub-modern water (recharged prior to 1952; tables 2 and 5). The tritium values were 4.1 TU for the base-flow sample and 2.7 TU for the high-flow sample. The lower value for tritium collected at high-flow conditions may reflect the higher percentage of recently recharged water in the spring discharge. Because carbon-14 is used to date older water (50 to 30,000 years), further analysis of the data was not conducted.

Stark Spring

Study Area Description

The Stark Spring study area lies in the Springfield Plateau and Salem Plateau physiographic provinces (fig. 1) and is dominated by karstic limestones and dolomites of Mississippian to Ordovician age. The altitude of the study area ranges from 268 to 726 ft above NGVD of 1929. Land use in the area consists primarily of deciduous and evergreen forest (91 percent) and some pasture (9 percent). No urban areas are located in the study area (Vogelmann and others, 2001).

Annual mean temperatures recorded at Batesville (fig. 1) in calendar years 2001 and 2002 were 18 °C and 17 °C, respectively, which were near normal based on a 54-year period from 1932 to 1995 (Hoare, 1996). The annual rainfall recorded at Batesville was 36 inches for 2001and 55 inches for 2002 (National Oceanic and Atmospheric Administration, 2001; 2002). The average annual rainfall for Batesville is 52 inches (Hoare, 1996).

Hydrogeology

The Mississippian-age Boone Formation (fig. 3) is exposed throughout most of the study area at high altitudes with some small occurrences of the Moorefield Formation (fig. 14). Silurian- and Devonian-age units are present in the northern and western portions of the study area, but are absent in the area near Stark Spring, resulting in an unconformable contact of the Boone Formation and the Ordovician-age Cason Shale and Joachim Dolomite units (fig. 3).

Field observations in the area indicate that where the Boone Formation is exposed, surface runoff only occurs during periods of intense rainfall. Stark Spring occurs at the contact of the Boone Formation and the underlying less permeable and less karstic Cason Shale (fig. 15). Mill Spring (fig. 14) also appears to be a contact spring that discharges water from the Boone Formation in the study area.

Discharge, Temperature, and Precipitation

The discharge for Stark Spring varied seasonally and temporally with precipitation (fig. 16). The mean annual discharge for water years 2001 and 2002 were 0.5 and 1.5 ft^3/s, respectively (Brossett and Evans, 2003). Mean daily discharge ranged from approximately 0.1 to 23 ft^3/s for water year 2001 and from 0.1 to 49 ft^3/s for water year 2002. The spring discharge generally followed precipitation patterns with the highest mean daily discharges in the months of January through May and the lowest daily discharges generally in the months of July through November.

Water temperature recorded at Stark Spring had little seasonal variation for water years 2001 and 2002, although noticeable temperature fluctuations occurred during high-flow events. Recorded water temperature ranged from 13.5 °C to 14.7 °C with a mean of 14.5 °C (fig. 16). Unlike Hughes Spring, noticeable temperature fluctuations caused by high-flow events occurred mostly in the fall and winter months (figs. 16 and 17).

On average, the base flow accounted for approximately 40 percent of the discharge volume for the period of October 2000 through September 2002. Discharge exceeded the base condition by more than 5 percent during 55 percent of the monitoring period. The ratio of peak-flow to base-flow discharge (491) for Stark Spring (based on the entire period of record), indicates a fast-response spring (White, 1988).

Recharge Area Characterization

The recharge area computed from the recorded discharge indicated that the area approximated by the surface drainage was not large enough to produce the discharge observed at Stark Spring. The computed recharge area ranged from 0.39 to 0.86 mi^2 using a water-balance calculation of the discharge during five storms and assuming 100 percent of the rainfall entered the ground-water system (fig. 18; table 6). The surface drainage area was approximately 0.34 mi^2. Assuming a 10 percent reduction in the recharge volume from evapotranspiration, soil absorption, and vegetation interception, the computed recharge area ranged from 0.43 to 0.96 mi^2 (fig. 18; table 6). The January 22, 2002, storm resulted in the smallest computed recharge area (table 6) and may be attributed to how the rainfall was distributed across the recharge area during the event. An average computed recharge area of 0.79 mi^2 from the five storms, assuming a 10 percent reduction in recharge volume was used with ground-water tracer test data to delineate the recharge area for Stark Spring.

The configuration of the recharge area for Stark Spring was found to be considerably different than the surface drainage from tracer-test data and geologic characteristics of the area. The recharge area is controlled predominantly by the occurrence of the Boone Formation outcrop. No major structural features were observed from geologic mapping or field observations near the spring, and tracer-test results show that the recharge area extends outside the surface drainage area to the west of the spring surface drainage area (fig. 19).

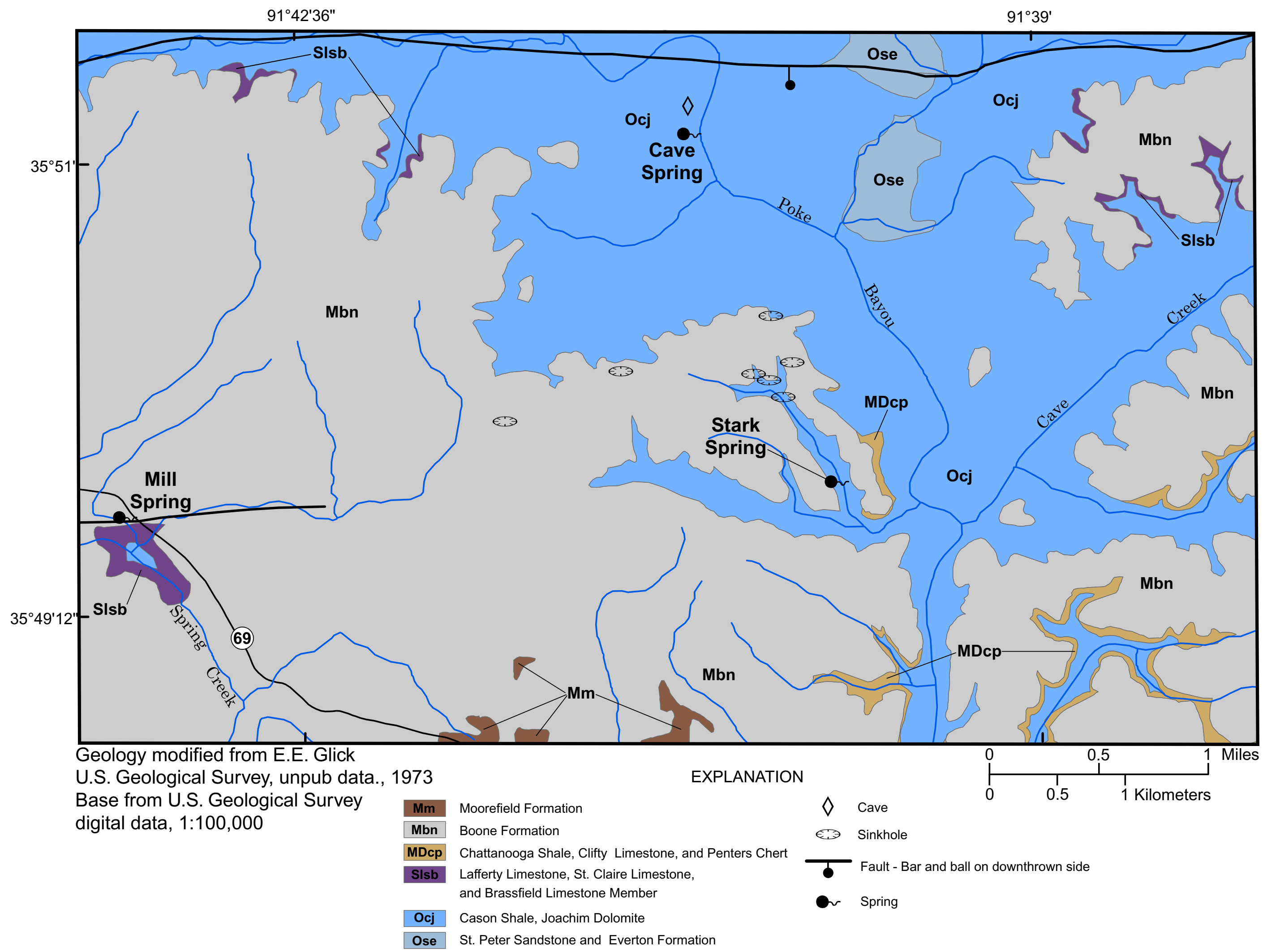


Figure 14. Geology of the Stark Spring study area.

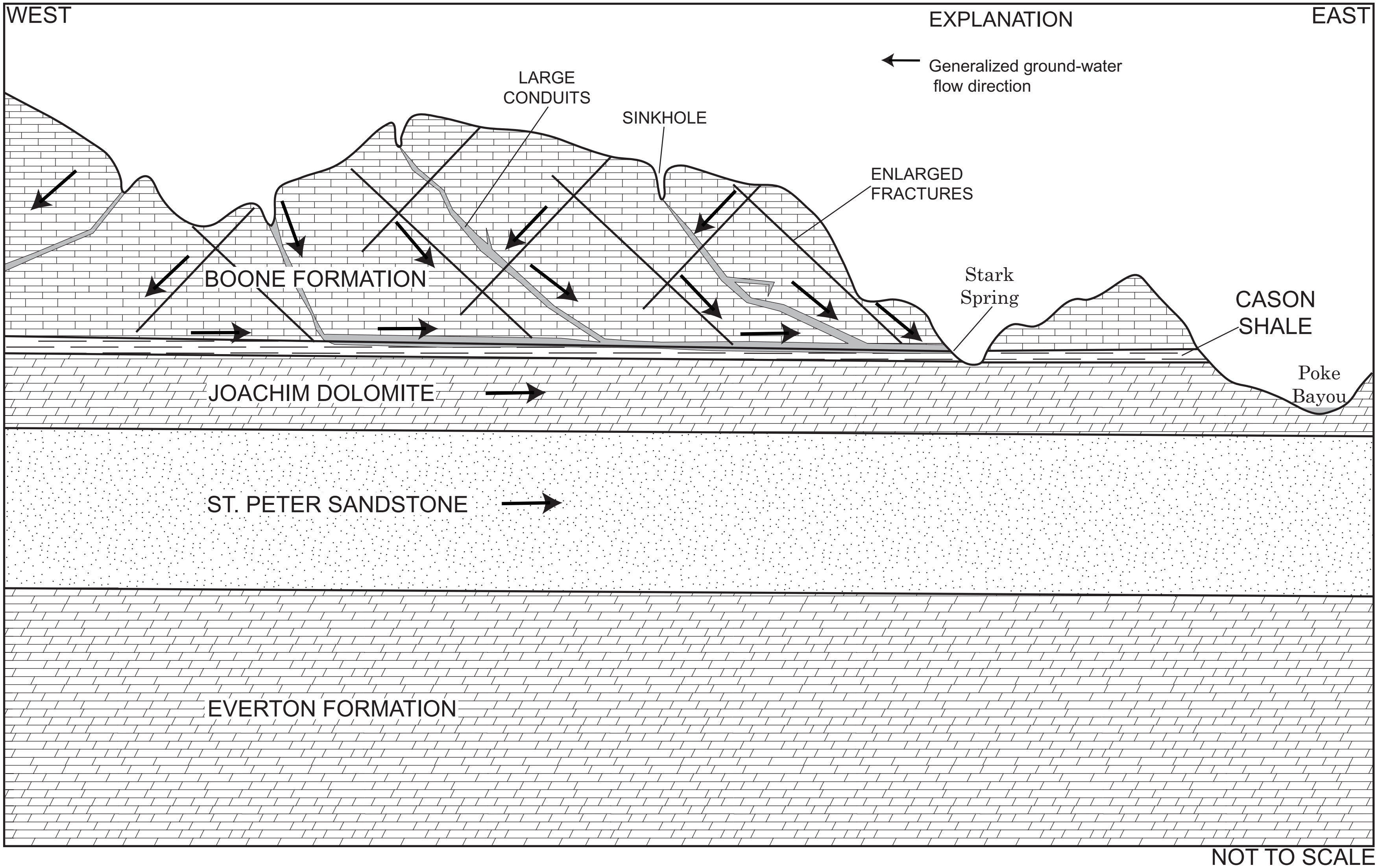


Figure 15. Conceptual model of ground-water flow to Stark Spring.

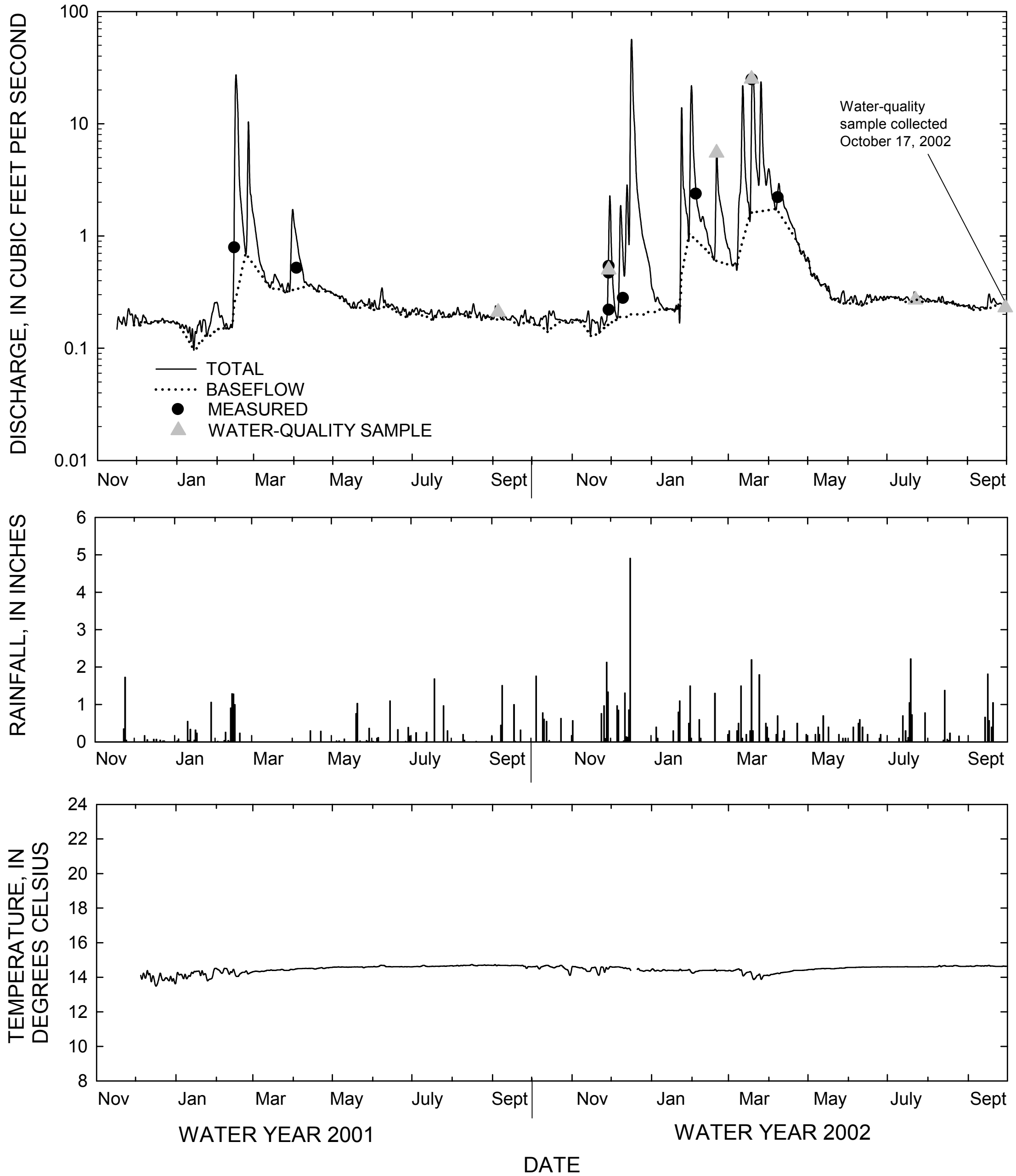


Figure 16. Daily discharge, rainfall, and water temperature recorded at Stark Spring.

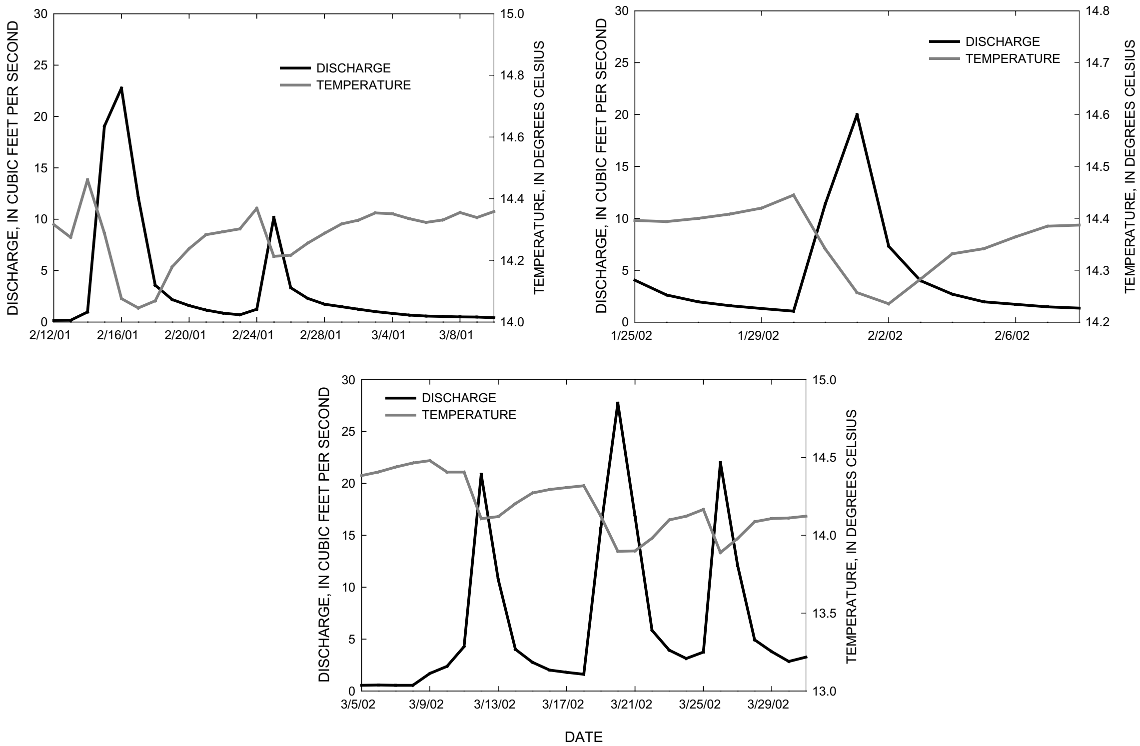


Figure 17. Discharge and water temperature data from Stark Spring for three storms.

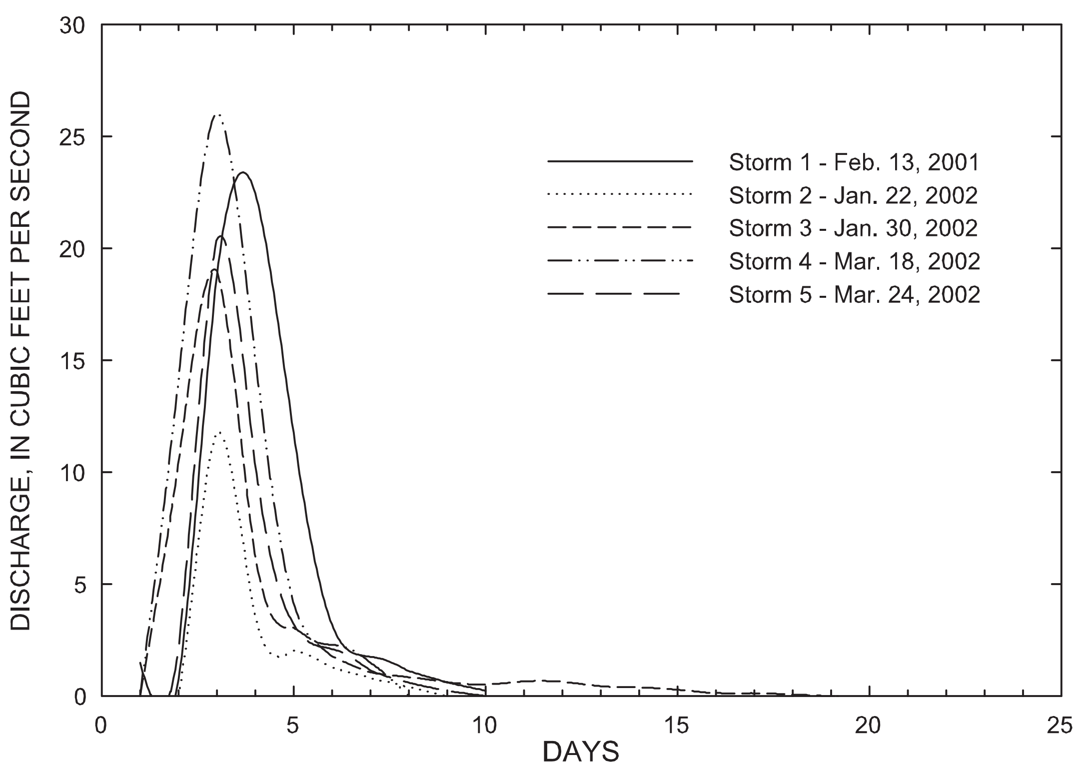


Figure 18. Runoff discharge for selected storms from Stark Spring.

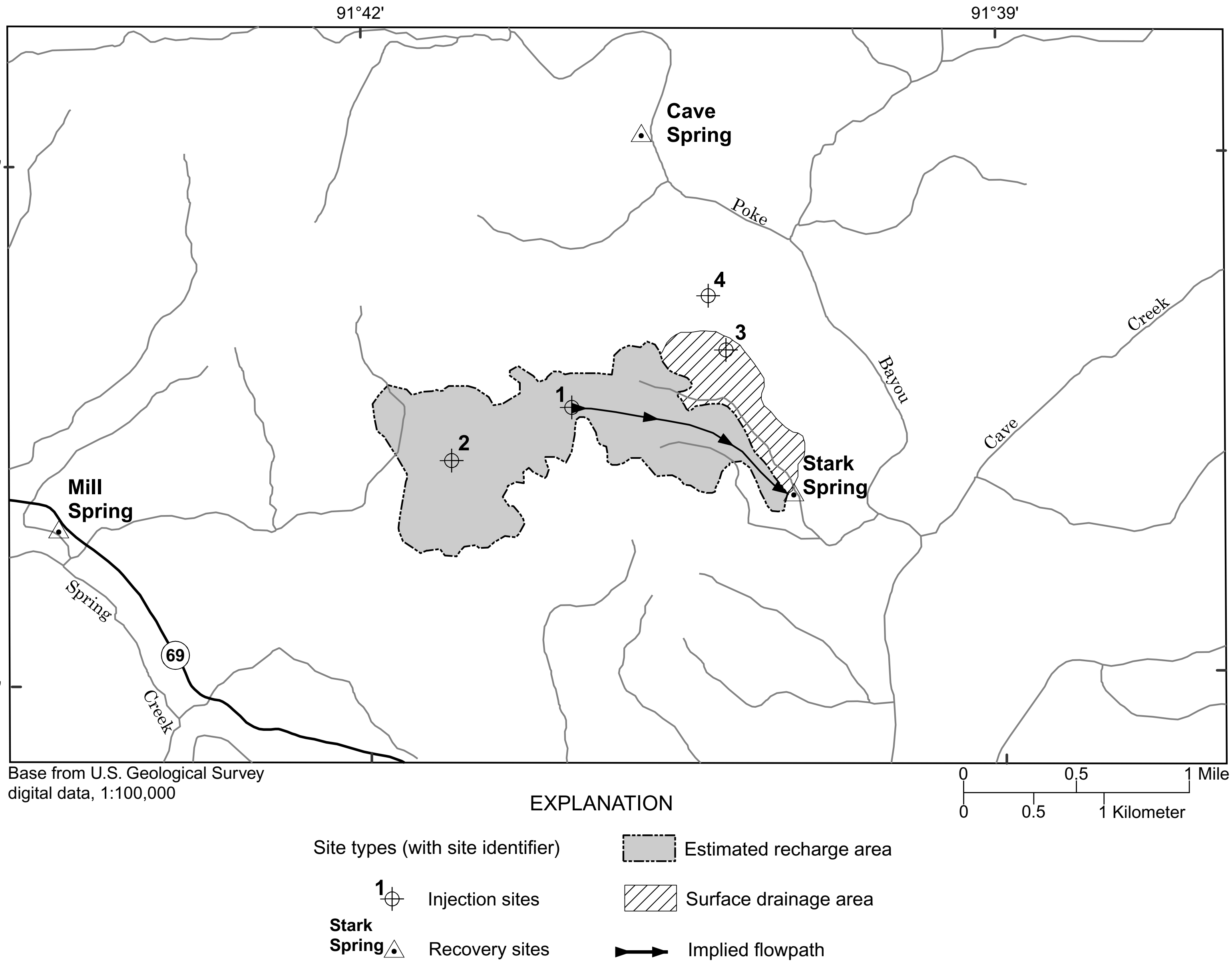


Figure 19. Locations of dye injection and recovery sites with implied flow path and the estimated local recharge area for Stark Spring.

Table 6. Storm events and calculated recharge areas for Stark Spring

Storm	Total storm runoff volume (cubic feet)	Total storm precipitation (inches)	Storm intensity (inches per day)	Calculated recharge area assuming all rainfall is recharge (square miles)	Calculated recharge area assuming 10 percent loss of recharge (square miles)
Feb. 13, 2001	5,241,000	3.5	1.3	0.65	0.72
Jan. 22, 2002	1,713,000	1.9	1.1	0.39	0.43
Jan. 30, 2002	4,001,000	2.0	1.5	0.86	0.96
Mar. 18, 2002	5,472,000	2.8	2.2	0.84	0.93
Mar. 24, 2002	3,402,000	1.8	1.8	0.81	0.90
			Average	**0.71**	**0.79**

Only one tracer was recovered in the study area. The tracer was injected into a sinkhole (site 1) in the Boone Formation located outside the surface drainage area and detected at Stark Spring (fig. 19; table 7). Although the tracer at site 2 was not detected at Stark Spring, it was considered to have originated within the recharge area based on the recharge area size estimated from the discharge data and extent of the Boone Formation. The negative detection of the tracer was probably caused by a large amount of organic debris in the sinkhole that may have absorbed enough of the tracer to prevent a detectable amount to enter the ground-water system. The recharge area boundary is very approximate, as the area may have a different configuration depending on the flow conditions. More extensive ground-water tracer tests would be needed to further confirm the location of the Stark recharge area boundary at different flow conditions.

Tracer tests demonstrated rapid ground-water flow velocities in the study area, which are characteristic of conduit-type flow often found in karst systems (White, 1988). A velocity of 0.06 mi/d was estimated from the tracer test using a distance measured along an implied flow path from injection site 1 to Stark Spring (fig. 19; table 7). Velocities are likely to be affected by the flow conditions and slope as was observed at Hughes Spring (table 4).

Geochemistry

The major ion analyses for six water samples collected between September 2001 and November 2002 from Stark Spring reflect a chemistry similar to Hughes Spring, and typical of waters from the Springfield Plateau aquifer (Boone Formation) (table 8; fig. 20). All samples collected from Stark Spring regardless of the flow condition had calculated calcium to magnesium ratio values of 9 or 10, indicating contribution from a limestone mineralogy (White, 1988) similar to other sample data representative of the Springfield Plateau aquifer found in the USGS NWIS database.

Samples collected at Stark Spring had $SI_{calcite}$ values that were considerably different with different flow conditions. Generally, the higher the discharge, the less saturated the water sample was with respect to calcite, which shows the effect of the residence time with the aquifer material. Samples taken during base-flow conditions had $SI_{calcite}$ values ranging from -0.12 to 0.16 while high-flow samples had values ranging from -1.05 to 0.34. The two samples collected on February 20 and March 19, 2002, had discharges of 5.5 and 25 ft^3/s, respectively, and $SI_{calcite}$ values of -0.4 and -1.05 ft^3/s, respectively. The other samples were collected at discharges less than or equal to 0.5 ft^3/s and had $SI_{calcite}$ values ranging from -0.12 to 0.34. The discharge for the high-flow event sampled on November 29, 2001, although about twice as large as for base-flow samples, was substantially less than that for the other two high-flow event samples.

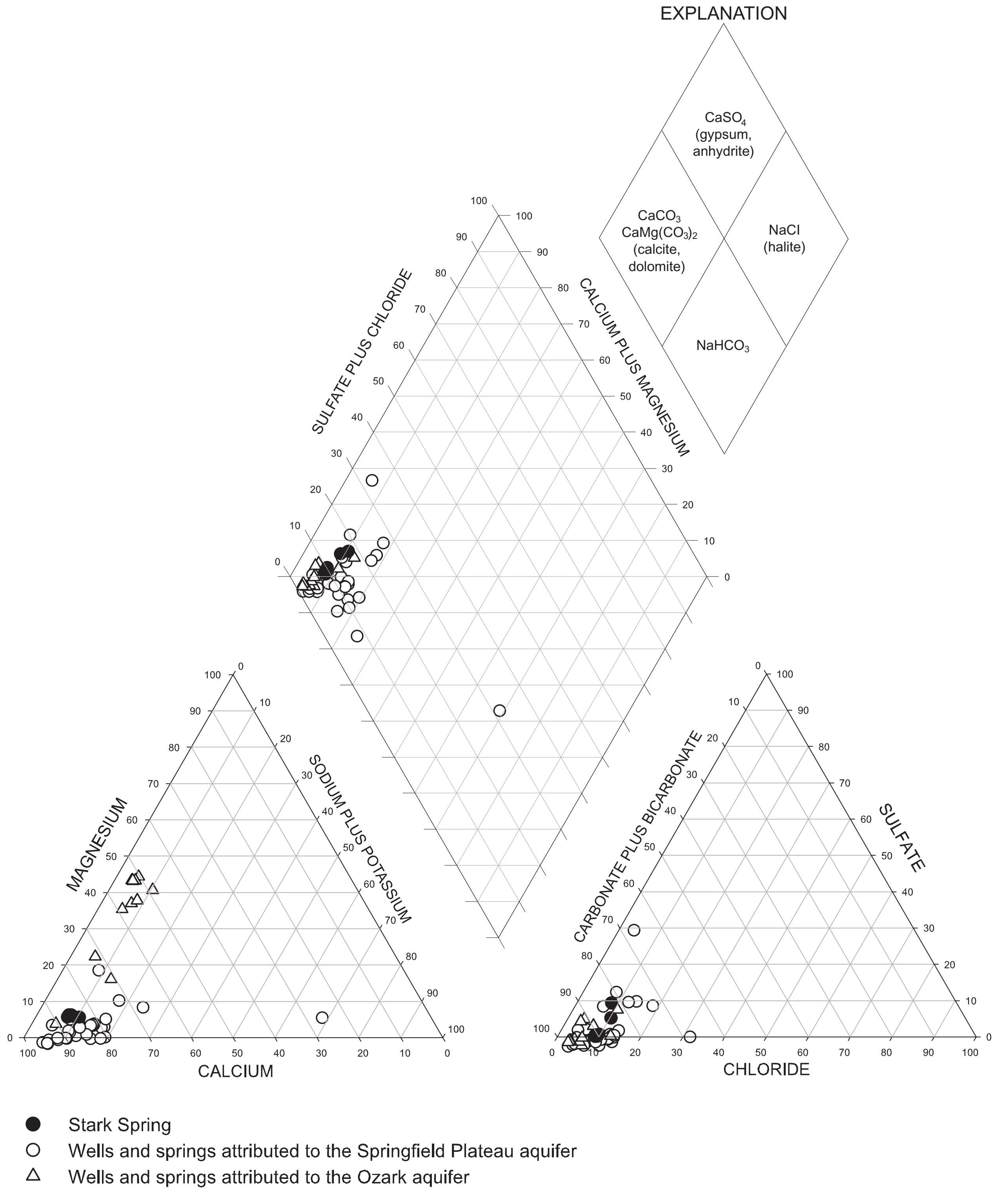


Figure 20. Relation of ground-water samples from Stark Spring and other wells and springs in northern Arkansas and southern Missouri.

Table 7. Results of ground-water tracer tests in the Stark Spring study area

[--, no data]

Injection site identifier	Injection site type	Tracer injected	Injection date	Sites where tracer was detected	Dates tracer was first detected	Number of days from injection to detection	Distance from injection site to detection site (miles)	Apparent minimum velocity (miles per day)
1	Sinkhole	Eosine OJ	4/23/02	Stark	5/11/02	19	1.1	0.06
2	Sinkhole	Fluorescein	4/23/02	None	--	--	--	--
3	Sinkhole	Optical brightener	4/24/02	None	--	--	--	--
4	Well	Rhodamine WT	4/24/02	None	--	--	--	--

Total dissolved solids (TDS) and hardness also demonstrated noticeable differences depending on the discharge. Both values decreased as discharge increased, reflecting the effects of reduced residence time of the water with the source rock at higher discharge, allowing for less dissolution (table 8).

Unlike major ion concentrations, nutrient concentrations for Stark Spring did not vary with different flow conditions (fig. 21). Dissolved nitrite plus nitrate concentrations ranged from 0.29 mg/L to 0.74 mg/L as nitrogen. Adamski (1997) presented nitrite plus nitrate concentrations of 0.98 mg/L as nitrogen for the 90th percentile of samples collected from 25 undeveloped sites (forest cover greater than 90 percent) in areas overlying the Springfield Plateau and Ozark aquifers. Dissolved phosphorus and orthophosphorus concentrations for Stark Spring ranged from 0.03 to 0.06 mg/L. These concentrations were higher than the 90th percentile concentrations for undeveloped sites (0.02 mg/L for phosphorus and 0.01mg/L for orthophosphorus; Adamski, 1997).

Concentrations of fecal indicator bacteria in samples collected at Stark Spring generally were higher in samples collected during base-flow conditions than in samples collected during high-flow conditions (fig. 21). Lower concentrations during high-flow conditions may be caused by dilution effects from the large inflow of runoff water and attributed to the land use in the recharge area. Petersen and others (1999) noted higher concentrations of bacteria in areas with predominately agricultural land use. The land use of the Stark Spring area is only 9 percent pasture, while the area near Hughes Spring, which had higher concentrations of bacteria at high flows, is composed of 38 percent pasture, a possible source of bacteria.

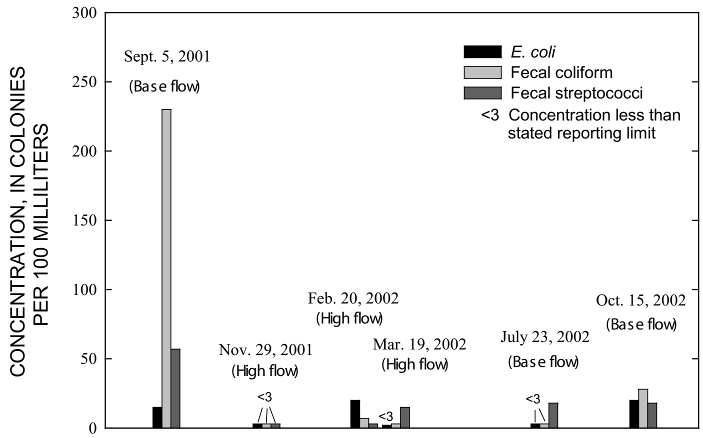
Stable isotopes (δD and δ18O) for Stark Spring generally followed the trend of the local meteoric line and were similar to that of the global meteoric line (VSMOW) indicating that they are representative of direct precipitation entering the aquifer system and not influenced by sources of water enriched in δ18O through evaporation (fig. 22). Values for δD and δ18O were -36.7 and -6.22 per mil, respectively, for the base-flow sample and -37.9 and -6.29 per mil, respectively, for the high-flow sample.

δ13C data show that the recharge water for Stark Spring has less interaction with the soil and regolith before entering the ground-water system than observed at Hughes Spring. The high-flow sample collected from Stark Spring had a δ13C value of -12.13 per mil, yielding an estimated 39 percent inorganically-derived δ13C and 61 percent organically-derived δ13C. The base-flow sample collected from Stark Spring had a δ13C of -14.62 per mil indicating an even distribution of 50 percent organically- and inorganically-derived δ13C. Unlike Hughes Spring, where the percentages of organically-derived carbon increased during high flow, Stark Spring displayed a decrease in the calculated percentage of organically-derived carbon during high-flow conditions. These data indicate that runoff enters the ground-water system at a more rapid rate near Stark Spring than near Hughes Spring, and does not allow sufficient interaction with surface material in the recharge area for the transport of organically-derived carbon into the ground-water system.

Table 8. Water-quality analyses from samples collected at Stark Spring, 2001-2002

[ft^3/s, cubic foot per second; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; <, less than; e, estimated; --, no data]

Constituent	Base-flow samples			High-flow event samples		
	Sept. 5, 2001	July 23, 2002	Oct. 15, 2002	Nov. 29, 2001	Feb. 20, 2002	Mar. 19, 2002
Discharge, ft^3/s	0.21	0.27	0.23	0.5	5.5	25
Water temperature, °C	17	15	15	14	14	14
Dissolved oxygen, mg/L	--	10.1	7.6	10	11.4	12.6
Specific conductance, µS/cm	256	261	269	255	161	109
pH	7.8	7.9	7.6	8.1	7.8	7.5
Bicarbonate, dissolved, mg/L	149	135	144	144	80.5	48.8
Calcium, dissolved, mg/L	43.3	47.4	48.0	44.9	27.1	17.8
Magnesium, dissolved, mg/L	2.86	2.91	2.99	2.95	1.72	1.12
Sodium, dissolved, mg/L	2.52	2.43	2.52	2.39	1.65	1.32
Potassium, dissolved, mg/L	0.98	0.89	0.89	0.84	0.97	0.90
Chloride, dissolved, mg/L	5.80	6.01	5.54	5.80	4.12	1.91
Sulfate, dissolved, mg/L	4.34	4.51	4.69	3.94	6.25	5.81
Silica, dissolved, mg/L	9.30	9.91	9.83	9.33	9.23	9.25
Bromide, dissolved, mg/L	0.061	0.040	0.045	0.047	0.019	<0.030
Fluoride, dissolved, mg/L	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Iron, dissolved, µg/L	<10	<10	<10	<10	<10	<10
Manganese, dissolved, µg/L	<2	<2	e2.17	<2	<2	e0.95
Total dissolved solids, calculated, mg/L	142	143	149	144	93	62
Calcite saturation index	0.08	0.16	-0.12	0.34	-0.4	-1.05
Hardness, mg/L as $CaCO_3$	120	130	130	124	75	49
Ammonia plus organic nitrogen dissolved, mg/L as nitrogen	<0.1	<0.1	<0.1	<0.1	<0.1	e0.07
Nitrite, dissolved, mg/L as nitrogen	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008
Nitrite plus nitrate, dissolved, mg/L as nitrogen	e0.56	0.59	0.74	0.59	0.53	0.29
Phosphorus, dissolved, mg/L	e0.05	0.05	0.05	0.06	0.04	0.03
Orthophosphorus, dissolved, mg/L as phosphorus	e0.04	0.06	0.04	0.05	0.03	0.03
Escherichia coli bacteria, colonies per 100 milliliters	15	<3	e20	<3	e20	e20
Fecal coliform bacteria, colonies per 100 milliliters	230	<3	e28	<3	e7	<3
Fecal streptococci bacteria, colonies per 100 milliliters	57	e18	e18	<3	<3	e15
Deuterium, ratio per mil	-36.7	--	--	--	-37.9	--
Oxygen-18, ratio per mil	-6.22	--	--	--	-6.29	--
Carbon-13, ratio per mil	-14.62	--	--	--	-12.13	--
Tritium, tritium units	3.5	--	--	--	3.2	--
Carbon-14, percent modern carbon	103.6	--	--	--	87.8	--



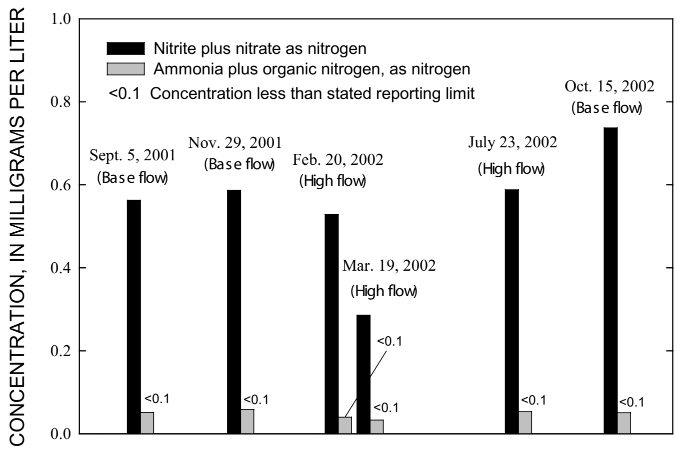


Figure 21. Fecal indicator bacteria and nutrient concentrations for samples collected at Stark Spring.

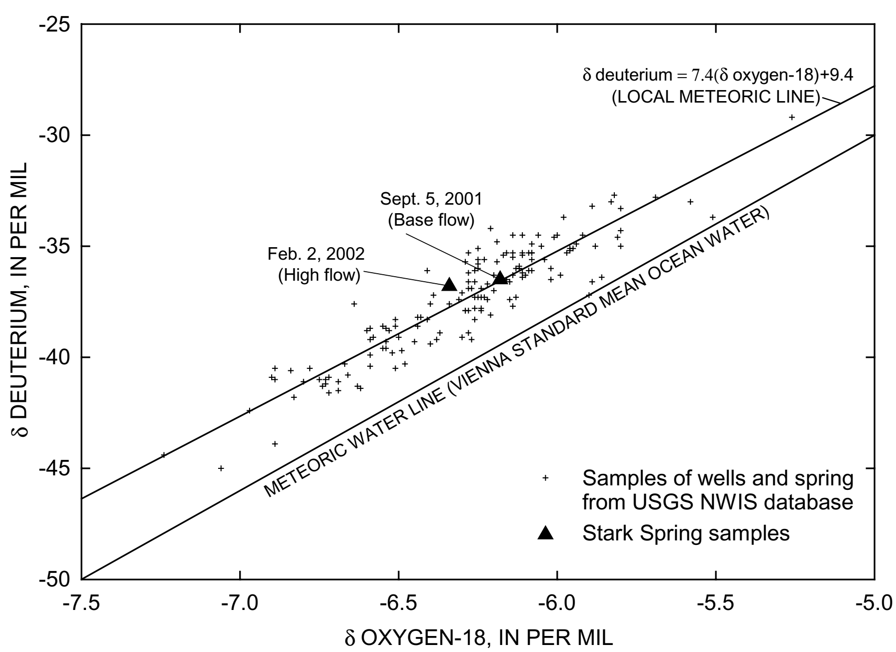


Figure 22. Relation of deuterium and oxygen-18 isotope ratios in ground-water samples from Stark Spring and other wells and springs in northern Arkansas and southern Missouri.

Radiogenic isotopes (tritium and carbon-14) from Stark Spring indicated that the discharge water is a mixture of recent recharge and sub-modern water (recharged prior to 1952; tables 2 and 8). The tritium values were 3.5 TU for the base-flow sample and 3.2 TU for the high-flow sample. Because carbon-14 is used to date older water (50 to 30,000 years), further analysis of the data was not conducted.

Evening Shade

Study Area Description

The Evening Shade Spring study area lies in the Salem Plateau physiographic province (fig. 1). The altitude of the study area ranges from 303 to 805 ft above NGVD of 1929. Land use in the area consists primarily of deciduous and evergreen forest land (74 percent) and agricultural land (25 percent). Urban land use consists of less than 1 percent of the study area (Vogelmann and others, 2001).

Annual mean temperatures recorded at Evening Shade (fig. 23) for calendar years 2001 and 2002 were 16 °C and 15 °C, respectively, which were near normal based on a 34-year period from 1939 to 1995 (Hoare, 1996). The annual rainfall recorded at Evening Shade was 48 inches for 2001 and 61 inches for 2002 (National Oceanic and Atmospheric Administration, 2001; 2002). The average annual rainfall for Evening Shade is 44 inches (Hoare, 1996).

Hydrogeology

The predominant surficial bedrock units exposed in the Evening Shade study area include Ordovician-aged limestone, dolomite, and sandstone formations that compose the Ozark aquifer. These formations include (from youngest to oldest) the St. Peter Sandstone, Everton Formation, Powell Dolomite, and Cotter Dolomite (figs. 3 and 23). Other important formations that are not exposed but occur in the subsurface include the Jefferson City Dolomite, Roubidoux Formation, and Gasconade Dolomite. The units generally have a slight dip to the south-southeast with an angle of less than 1 degree estimated from geophysical logs. No major structural features were evident in the study area from field observations and geophysical logs. Few vertical fractures were observed in geophysical logs, but horizontal bedding planes were observed and likely provide the preferred pathways for dissolution.

The St. Peter Sandstone unconformably overlies the Everton Formation. These units are not differentiated from each other in the study area. Thickness of the two units ranged from 0 to 488 ft from geophysical logs of wells in the study area (fig. 24), although thicknesses of as much as 1,380 ft have been reported in other areas of northern Arkansas (Caplan, 1957) (fig. 3). The outcrop of the St. Peter Sandstone/Everton Formation covers most of the study area south of the Strawberry River (fig. 23). Several karst features such as sinkholes and a cave were observed on the outcrop of the St. Peter Sandstone/Everton Formation.

The Powell Dolomite is exposed across the northern portion of the study area (fig. 23). The range of thickness has been reported from 0 to 420 ft in northern Arkansas (Caplan, 1960) and was observed to be at least 107 ft thick in the study area from geophysical logs. The Cotter and Jefferson City Dolomites generally are undifferentiated in the subsurface. The range of thickness of the Cotter Dolomite has been reported from 0 to 527 ft and the Jefferson City dolomite had a reported thickness ranging from 100 to 496 ft (Caplan, 1957; 1960; McFarland, 1998) (fig. 3).

The Roubidoux Formation unconformably overlies the Gasconade Dolomite and ranges in thickness from 130 to 455 ft and is exposed across a large area in southeastern Missouri (Caplan, 1957; 1960) (fig. 3). The Gasconade Dolomite is mainly composed of cherty dolostone, but contains a sandstone unit in its lowermost part designated as the Gunter Sandstone Member. The thickness of the Gasconade ranges from 300 to 600 ft (fig. 3).

Evening Shade Spring discharges through two main discharge points in the Everton Formation outcrop. One has been enclosed by a springhouse for utilization as a public- water supply for the city of Evening Shade and the surrounding area. The other resurgent point is in the stream channel of Mill Creek near the springhouse. The location of Evening Shade Spring may be caused by a set of enlarged vertical fractures or conduits not readily visible at the surface that may concentrate and convey flow to the surface from fractures and conduits in multiple formations composing the Ozark aquifer (fig. 25).

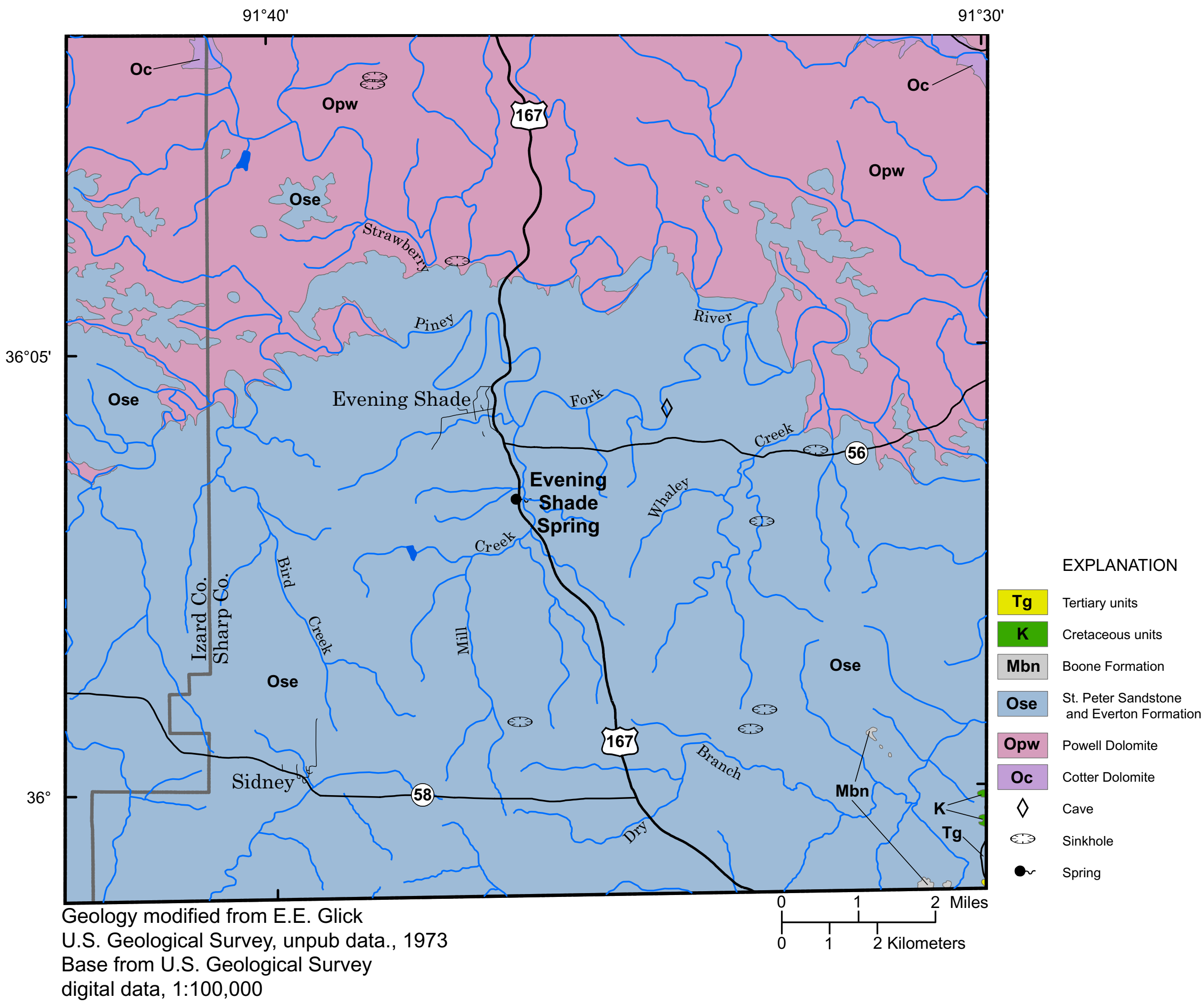


Figure 23. Geology of the Evening Shade Spring study area.

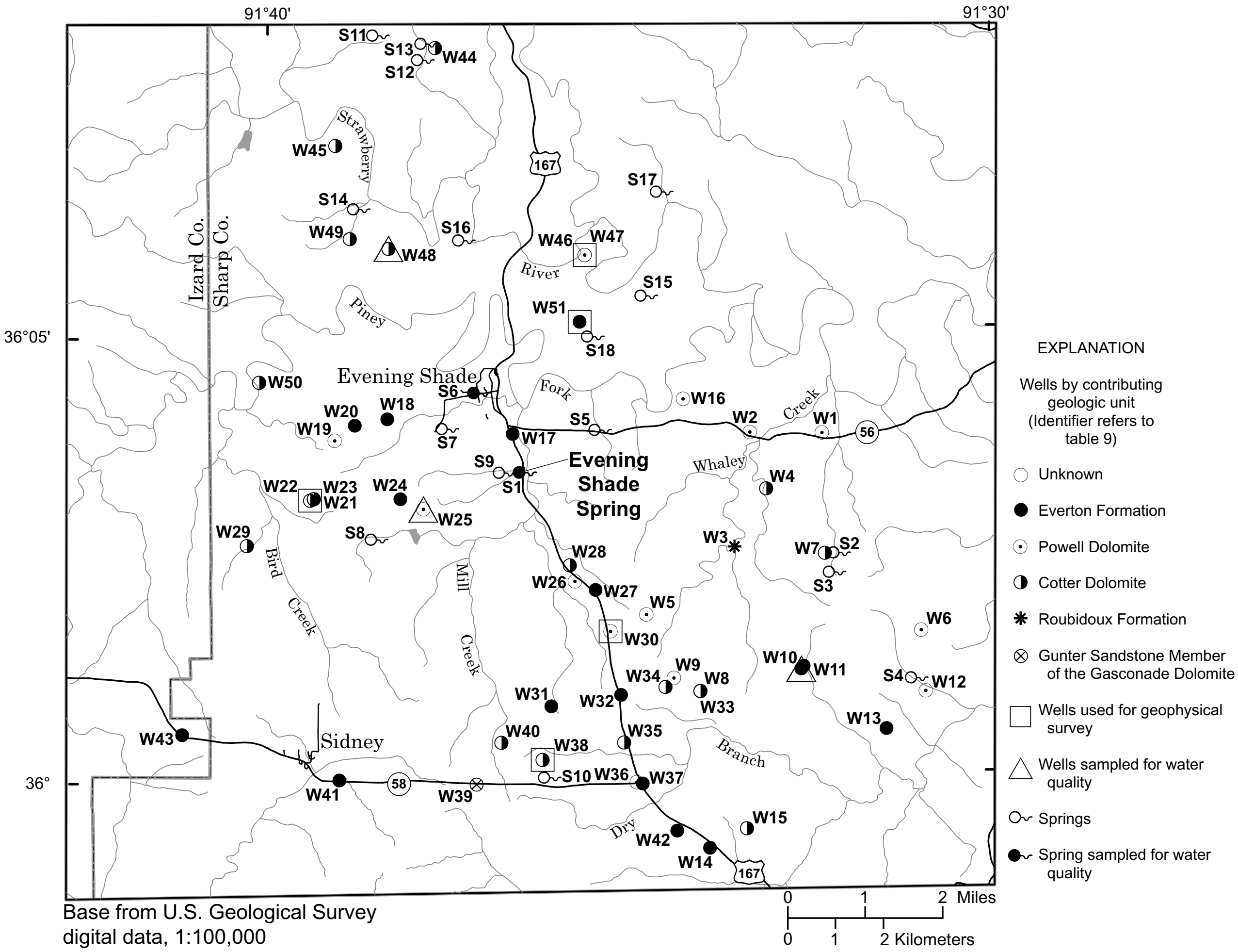


Figure 24. Distribution of wells and springs in the Evening Shade Spring study area.

Discharge, Temperature, and Precipitation

The discharge for Evening Shade Spring remained fairly constant with time. The mean daily discharge computed from the springhouse ranged from 0.88 to 2.29 ft^3/s for water year 2001 and from 0.76 to 2.25 ft^3/s for water year 2002. The mean annual discharge for water years 2001 and 2002 was 1.44 and 1.24 ft^3/s, respectively (Brossett and Evans, 2003) (fig. 26). The mean annual discharge for 2001 may be underestimated because of missing data during the period of December 2000 and January 2001. The spring discharge periodically measured in the channel of Mill Creek ranged from 3.6 to 9.0 ft^3/s during water years 2001 and 2002 (fig. 26).

On average, the base-flow discharge for Evening Shade Spring accounted for approximately 95 percent of the total discharge volume for the monitoring period. The largest base-flow component occurred during the period of June through September for both water years 2001 and 2002 (fig. 26). Small peaks were evident during periods of intense rainfall that indicated a small component of local recharge. The local recharge may occur immediately adjacent to the spring as infiltration through the shallow subsurface, but not at substantial volumes (<5 percent of flow on average). Discharge exceeded base flow by more than 5 percent during less than 40 percent of the monitoring period. The ratio of base flow to peak flow for Evening Shade Spring ranged from 2.6 to 3.0 indicating a slow-response spring (White, 1988). The discharge for Evening Shade Spring contrasts with the fast response, storm input type of discharge that was observed at Hughes and Stark Springs.

Water temperature recorded at Evening Shade Spring remained fairly constant with time. The recorded temperature ranged from 16.7 to 16.8 °C from February 2001 to July 2002 (fig. 26). The relatively stable discharge and temperature suggest that the Evening Shade Spring discharge probably is representative of a regional ground-water system.

Water-Level Contours

Water-level contours constructed from static water levels measured in 51 wells and 18 springs in calendar year 2001 (table 9) generally follow land surface topography in the area and indicate that ground water flows toward the Strawberry River and the Piney Fork in the northern portion of the study area (fig. 27). The contours follow a similar pattern to the regional flow of the Ozark aquifer constructed by Pugh (1998) and Schrader (2001). An area of higher water-level altitude was evident in the central portion of the study area between the Piney Fork and Strawberry River in an area referred to as “The Backbone.” This mounding of the water level may be caused by a restriction or isolation of the water table from the surrounding system by a layer of low permeability limestone or shale observed in geophysical logs (figs. 25 and 27).

Recharge Area Characterization

The discharge, geochemical, and hydrogeologic data indicate that the discharge for Evening Shade Spring is mostly representative of a regional ground-water flow system (Ozark aquifer) and does not allow for a distinct boundary to be delineated for the recharge area contributing to the spring. Ground-water tracer tests conducted in the study area to identify a connection between Evening Shade Spring and local ground-water flow systems resulted in the negative recovery of the three tracers injected into two wells and a sinkhole (fig. 24). Although the tracer tests did not establish that a local recharge area does not exist conclusively, they lend support that the Evening Shade Spring is mainly recharged from the Ozark aquifer. The recharge area could include relatively remote locations where hydrogeologic units composing the Ozark aquifer are exposed and have sufficient porosity and hydraulic conductivity to convey water that falls as precipitation to the subsurface.

Geochemistry

The major ion analyses from Evening Shade Spring (table 10) and from wells and springs in the study area (table 11) demonstrate a calcium bicarbonate type water typical of the Ozark aquifer (fig. 28). All samples collected from Evening Shade Spring had calcium to magnesium ratio values of 1.3, indicating contribution from a dolomitic mineralogy (White, 1988) that also is representative of formations of the Ozark aquifer. The ratios of the other wells and spring had similar values ranging from 0.8 to 1.2.

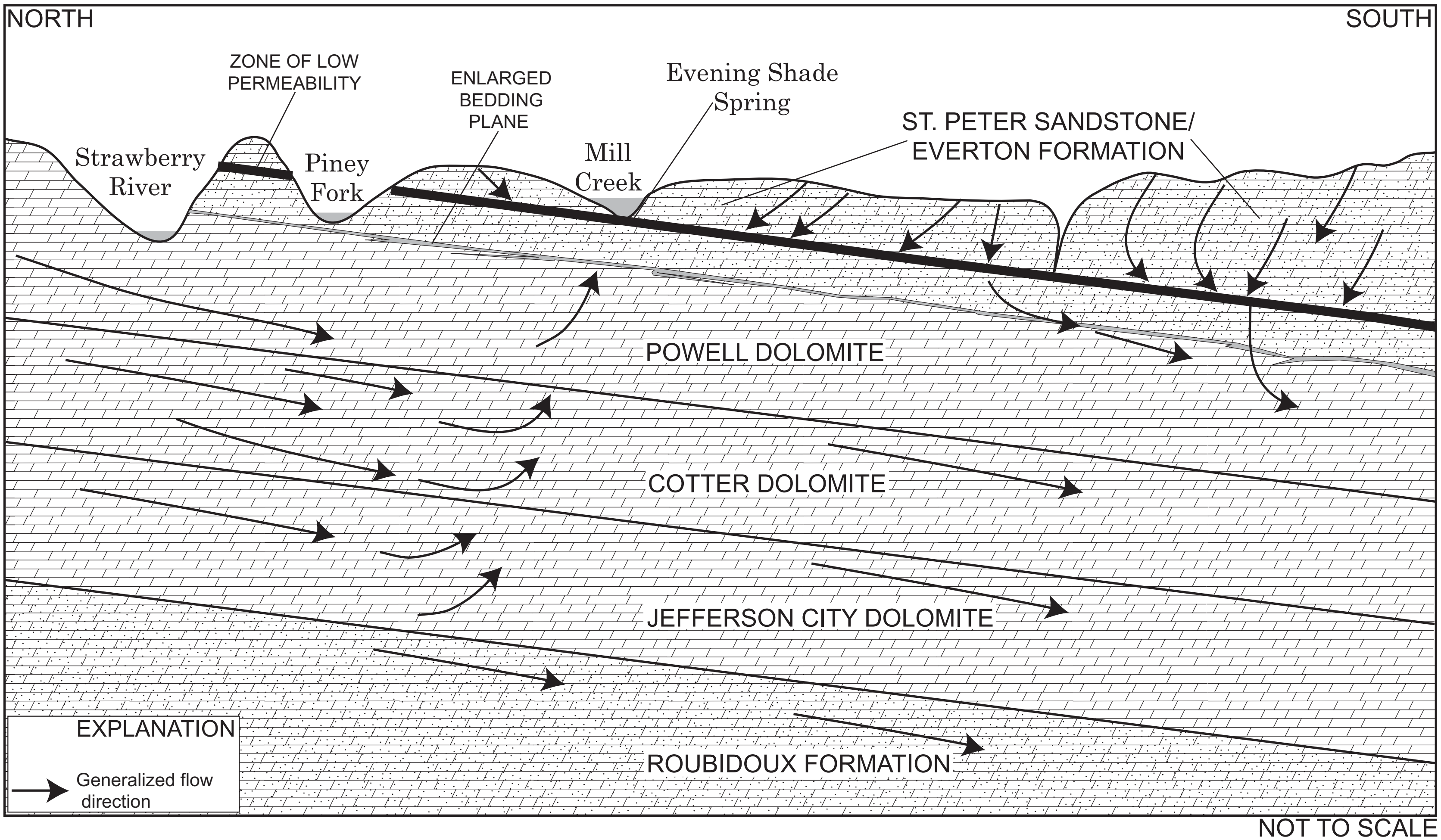


Figure 25. Conceptual model of ground-water flow to Evening Shade Spring.

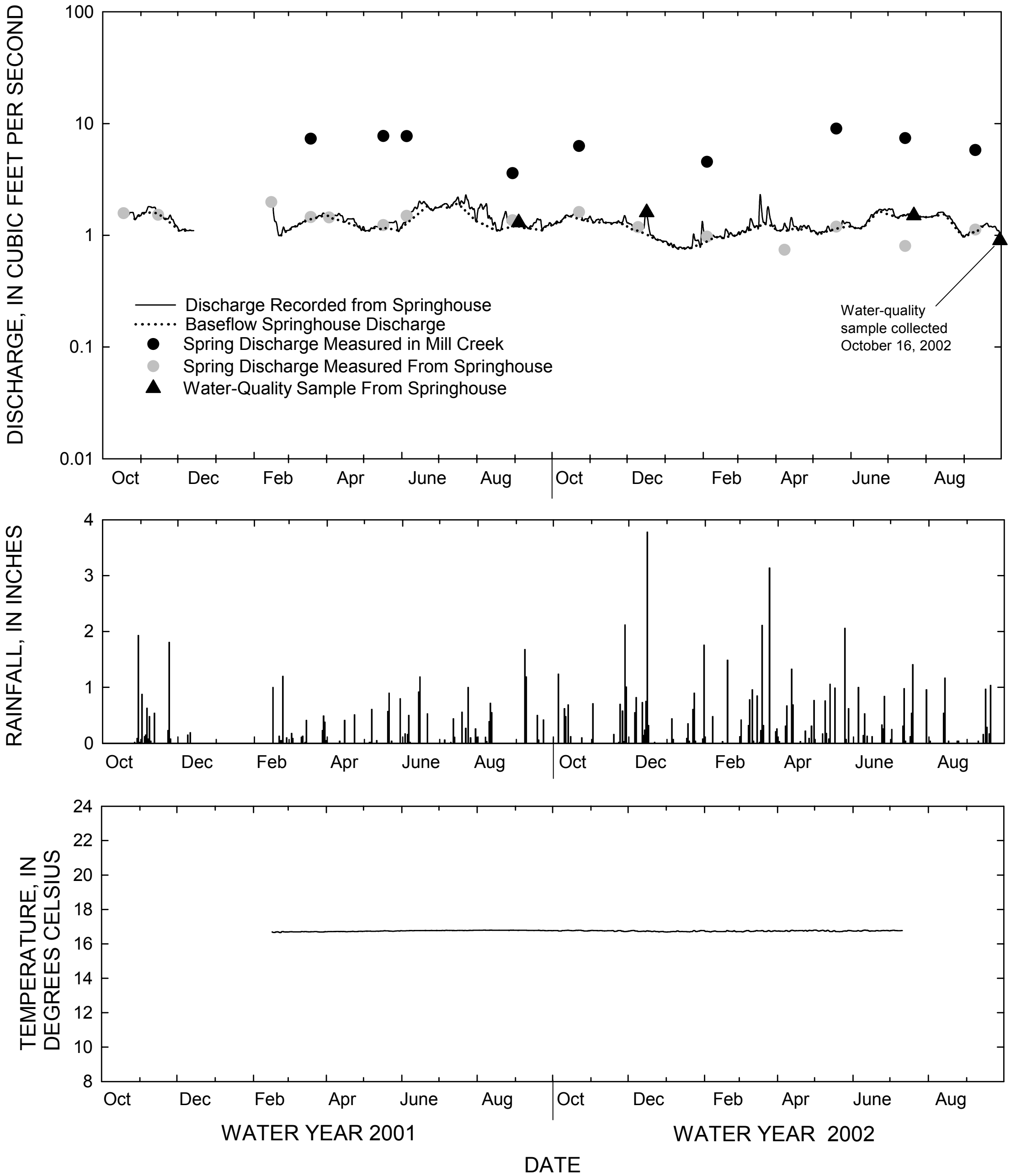


Figure 26. Daily discharge, rainfall, and water temperature recorded at Evening Shade Spring.

Table 9. Wells and springs inventoried in the Evening Shade Spring study area

[Geologic formation refers to the formation from which the spring discharges or the formation at the total depth of the well; USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds; --, no data]

Site identi-fier (fig. 24)	Station identification number	USGS local number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface, in feet above NGVD of 1929	Site type	Well depth, in feet below land surface	Date of water-level measure-ment	Water level, in feet below land surface	Altitude of water-level, in feet above NGVD of 1929	Use	Geologic unit name
S1	07073595	Evening Shade Spring near Evening Shade	360325	913631	435	Spring	--	--	--	435	Public water supply	Everton Formation
S2	360228091321101	16N05W17AAB1SP	360228	913211	495	Spring	--	--	--	495	Unused	Everton Formation
S3	360215091321501	16N05W17ADB1SP	360215	913215	550	Spring	--	--	--	550	Unused	Everton Formation
S4	360103091310801	16N05W21DAA1SP	360103	913108	485	Spring	--	--	--	485	Unused	Everton Formation
S5	360353091352801	16N06W02ADC1SP	360353	913528	455	Spring	--	--	--	455	Unused	Everton Formation
S6	360419091370801	16N06W03BAB1SP	360419	913708	460	Spring	--	--	--	460	Unused	Everton Formation
S7	360355091373501	16N06W04ADC1SP	360355	913735	500	Spring	--	--	--	500	Unused	Everton Formation
S8	360241091383501	16N06W09CCC1SP	360241	913835	545	Spring	--	--	--	545	Unused	Everton Formation
S9	360325091364801	16N06W10ABB1SP	360325	913648	455	Spring	--	--	--	455	Unused	Everton Formation
S10	355959091361401	16N06W26CBA1SP	355959	913614	660	Spring	--	--	--	660	Unused	Everton Formation
S11	360821091382801	17N06W08DAA1SP	360821	913828	680	Spring	--	--	--	680	Unused	Powell Dolomite
S12	360804091375101	17N06W09CDC1SP	360804	913751	538	Spring	--	--	--	538	Unused	Powell Dolomite
S13	360815091374801	17N06W09DBC1SP	360815	913748	557	Spring	--	--	--	557	Unused	Powell Dolomite
S14	360624091384601	17N06W20DCA1SP	360624	913846	457	Spring	--	--	--	457	Unused	Powell Dolomite
S15	360523091344801	17N06W25CDA1SP	360523	913448	460	Spring	--	--	--	460	Unused	Everton Formation
S16	360602091371901	17N06W27BBC1SP	360602	913719	460	Spring	--	--	--	460	Unused	Powell Dolomite
S17	360633091343401	17N06W24DBB1SP	360633	913434	405	Spring	--	--	--	405	Unused	Powell Dolomite

Table 9. Wells and springs inventoried in the Evening Shade Spring study area--Continued

[Geologic formation refers to the formation from which the spring discharges or the formation at the total depth of the well; USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds; --, no data]

Site identi-fier (fig. 24)	Station identification number	USGS local number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface, in feet above NGVD of 1929	Site type	Well depth, in feet below land surface	Date of water-level measure-ment	Water level, in feet below land surface	Altitude of water-level, in feet above NGVD of 1929	Use	Geologic unit name
S18	360456091353301	17N06W35ACA1SP	360456	913533	490	Spring	--	--	--	490	Unused	Everton Formation
W1	360349091322401	16N05W05DBA1	360349	913224	440	Well	unknown	6/5/01	83	357	Residential	Powell Dolomite
W2	360350091332401	16N05W06ACD1	360350	913324	400	Well	110	6/7/01	32	368	Residential	Powell Dolomite
W3	360233091333801	16N05W06DCC1	360233	913338	450	Well	1110	3/30/01	42	408	Livestock	Roubidoux Formation
W4	360312091331101	16N05W07AAD1	360312	913311	435	Well	300	3/29/01	34	401	Residential	Powell Dolomite
W5	360148091345201	16N05W13CDD1	360148	913452	660	Well	225	3/20/01	158	502	Residential	Everton Formation
W6	360135091310401	16N05W16DDD1	360135	913104	625	Well	240	3/29/01	170	455	Residential	Everton Formation
W7	360228091322301	16N05W17ABA1	360228	913223	535	Well	400	1/1/01	60	475	Residential	Cotter Dolomite
W8	360056091340801	16N05W19CCB1	360056	913408	610	Well	514	3/29/01	142	468	Residential	Powell Dolomite
W9	360056091340802	16N05W19CCB2	360056	913408	610	Well	540	3/29/01	131	479	Unused	Powell Dolomite
W10	360112091324201	16N05W20BDD1	360112	913242	555	Well	32	3/28/01	12	543	Unused	Everton Formation
W11	360110091324401	16N05W20BDD2	360110	913244	565	Well	119	3/28/01	72	493	Residential	Everton Formation
W12	360054091310101	16N05W21DAD1	360054	913101	482	Well	140	3/29/01	16	466	Residential	Everton Formation
W13	360029091313401	16N05W28ABC1	360029	913134	590	Well	150	3/29/01	98	492	Residential	Everton Formation
W14	355910091340201	16N05W31CCA1	355910	913402	615	Well	173	6/6/01	100	515	Residential	Everton Formation
W15	355923091333101	16N05W31DBA1	355923	913331	607	Well	600	6/9/75	111	496	Residential	Powell Dolomite
W16	360413091341901	16N06W01AAD1	360413	913419	430	Well	112	1998	18	412	Residential	Everton Formation
W17	360351091364101	16N06W03DBA1	360351	913641	460	Well	55	3/30/01	19	441	Residential	Everton Formation

Table 9. Wells and springs inventoried in the Evening Shade Spring study area--Continued

[Geologic formation refers to the formation from which the spring discharges or the formation at the total depth of the well; USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds; --, no data]

Site identi-fier (fig. 24)	Station identification number	USGS local number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface, in feet above NGVD of 1929	Site type	Well depth, in feet below land surface	Date of water-level measure-ment	Water level, in feet below land surface	Altitude of water-level, in feet above NGVD of 1929	Use	Geologic unit name
W18	360402091382501	16N06W04BCC1	360402	913825	527	Well	78	6/7/01	19	508	Residential	Everton Formation
W19	360348091390901	16N06W05CAD1	360348	913909	603	Well	263	6/12/97	80	523	Residential	Everton Formation
W20	360358091385201	16N06W05DBA1	360358	913852	605	Well	125	3/30/01	95	510	Residential	Everton Formation
W21	360308091393001	16N06W08BCD1	360308	913930	638	Well	413	5/16/01	87	551	Unused	Everton Formation
W22	360309091392701	16N06W08BCD2	360309	913927	642	Well	400	5/16/01	73	569	Residential	Everton Formation
W23	360309091392702	16N06W08BCD3	360309	913927	642	Well	610	7/1/94	78	564	Residential	Cotter Dolomite
W24	360308091381501	16N06W09BDB1	360308	913815	630	Well	165	5/14/01	159	471	Residential	Everton Formation
W25	360300091380001	16N06W09DBB1	360301	913756	630	Well	236	5/14/01	137	494	Public water supply	Everton Formation
W26	360211091355101	16N06W14ACD1	360211	913551	570	Well	428	1/15/75	70	500	Residential	Powell Dolomite
W27	360205091353401	16N06W14ADC1	360205	913534	570	Well	165	3/28/01	91	479	Residential	Everton Formation
W28	360222091355501	16N06W14BAD1	360222	913555	560	Well	300	6/6/01	88	472	Residential	Everton Formation
W29	360238091402301	16N06W18BAA1	360238	914023	582	Well	985	6/7/01	95	487	Residential	Cotter Dolomite
W30	360137091352201	16N06W23AAA1	360137	913522	600	Well	302	3/28/01	75	525	Residential	Everton Formation
W31	360047091361201	16N06W23CCD1	360047	913612	590	Well	50	5/15/01	19	571	Residential	Everton Formation
W32	360054091351402	16N06W24CCB2	360054	913514	640	Well	unknown	5/15/01	18	623	Residential	Everton Formation
W33	360105091343001	16N06W24DAC1	360105	913430	615	Well	157	3/28/01	138	477	Residential	Everton Formation
W34	360059091343701	16N06W24DCA1	360059	913437	645	Well	360	3/28/01	156	489	Residential	Everton Formation

Table 9. Wells and springs inventoried in the Evening Shade Spring study area--Continued

[Geologic formation refers to the formation from which the spring discharges or the formation at the total depth of the well; USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds; --, no data]

Site identi-fier (fig. 24)	Station identification number	USGS local number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface, in feet above NGVD of 1929	Site type	Well depth, in feet below land surface	Date of water-level measure-ment	Water level, in feet below land surface	Altitude of water-level, in feet above NGVD of 1929	Use	Geologic unit name
W35	360022091352601	16N06W25BCD1	360022	913512	600	Well	303	6/6/01	38	562	Residential	Everton Formation
W36	355955091350201	16N06W25CDC1	355955	913502	635	Well	525	6/6/01	101	534	Residential	Powell Dolomite
W37	355954091345701	16N06W25CDC2	355954	913457	620	Well	unknown	6/6/01	42	578	Residential	Everton Formation
W38	360011091362001	16N06W26CBC1	360011	913620	650	Well	800	5/14/01	105	545	Residential	Cotter Dolomite
W39	355945091391501	16N06W34BAB1	355955	913715	740	Well	2700	5/16/01	230	510	Public WS	Gunter SS
W40	360023091365401	16N06W27ACC1	360023	913654	650	Well	1000	5/15/01	93	557	Residential	Cotter Dolomite
W41	355959091390901	16N06W29DCC1	355959	913909	650	Well	252	5/16/01	64	586	Residential	Everton Formation
W42	355922091342901	16N06W36DAC1	355922	913429	660	Well	190	6/6/01	37	623	Residential	Everton Formation
W43	360031091411901	16N07W25ACD1	360031	914119	670	Well	unknown	6/6/01	133	537	Residential	Everton Formation
W44	360812091374101	17N06W09DBD1	360812	913741	700	Well	375	6/5/01	161	539	Residential	Cotter Dolomite
W45	360707091390501	17N06W17CDD1	360707	913905	540	Well	unknown	6/5/01	79	461	Residential	Cotter Dolomite
W46	360551091353901	17N06W26ACB1	360551	913539	440	Well	1200	5/17/01	30	410	Residential	Roubidoux Formation
W47	360551091353902	17N06W26ACB2	360551	913539	440	Well	107	5/17/01	32	408	Residential	Powell Dolomite
W48	360557091382201	17N06W28BBC1	360557	913822	620	Well	375	5/17/01	153	467	Residential	Cotter Dolomite
W49	360604091385401	17N06W29ABC1	360604	913854	525	Well	900	5/16/01	80	445	Residential	Jefferson City Dolomite
W50	360428091401101	17N06W31DCC1	360428	914011	520	Well	700	4/18/01	96	424	Residential	Cotter Dolomite
W51	360506091354401	17N06W35ABC1	360506	913544	570	Well	170	4/18/01	25	545	Residential	Everton Formation

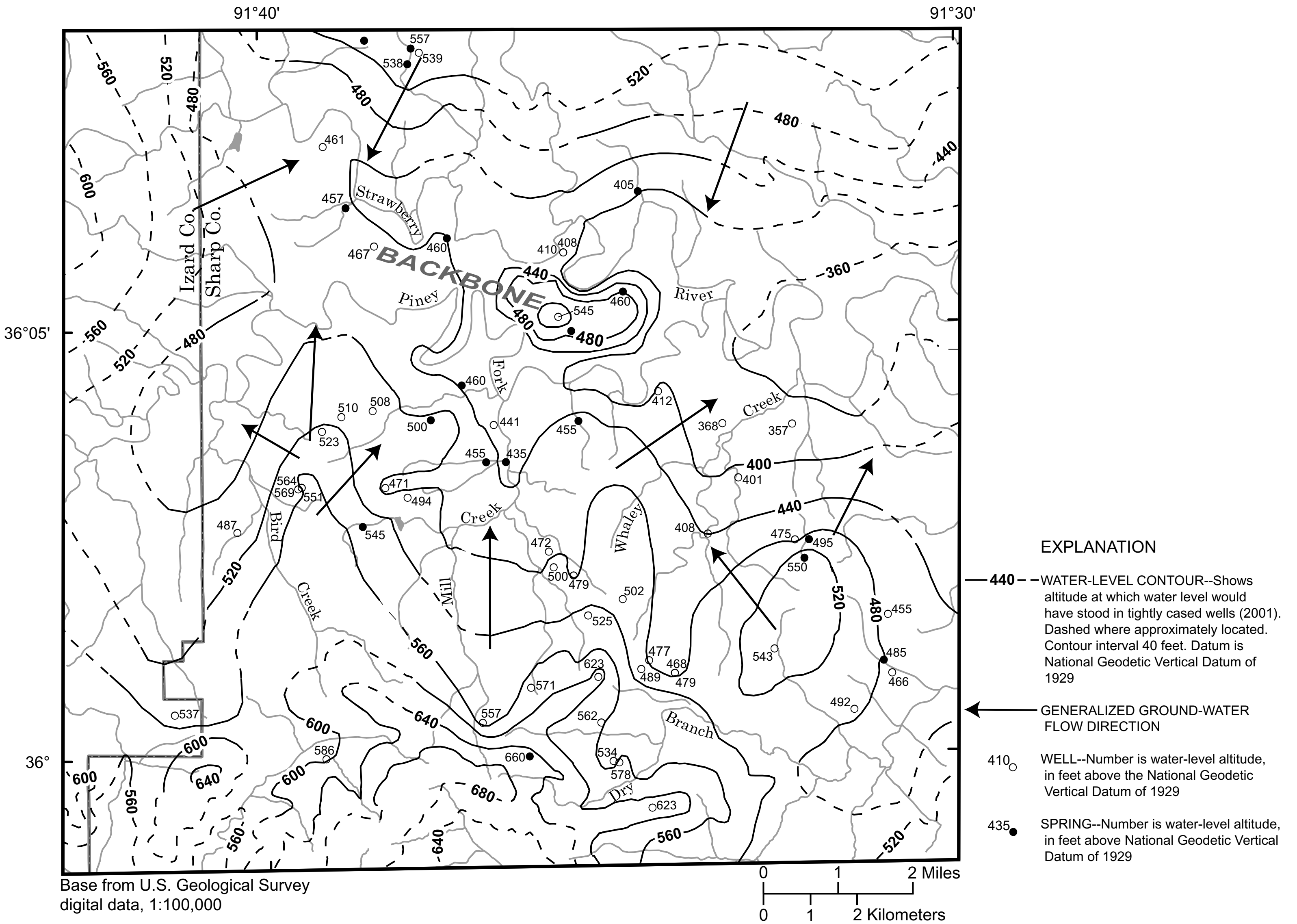


Figure 27. Water-level contours of the Evening Shade Spring study area.

Samples collected at Evening Shade Spring had $SI_{calcite}$ values ranging from 0.48 to 0.12, showing the waters are supersaturated with calcite. Values for $SI_{calcite}$ appeared to have an inverse relation with the quantity of discharge at the time the sample was collected. At higher discharges, the $SI_{calcite}$ decreased and at lower discharges the value increased (table 10). Although it has been shown that there is not a large variation in spring discharge during precipitation events, flow velocities in the ground-water system during periods of high precipitation (late winter, early spring) may increase enough to decrease the contact time of the water with the rock because of a steepening of the ground-water gradient.

Nutrient concentrations at Evening Shade Spring generally were less than concentrations at Hughes Spring and Stark Spring and concentrations reported for undeveloped sites in the Springfield Plateau and Ozark aquifers (Adamski, 1997). Ammonia, ammonia plus organic nitrogen, nitrite, and orthophosphorus concentrations were below detection limits in all of the samples from Evening Shade Spring. Dissolved nitrite plus nitrate concentrations ranged from 0.44 to 0.52 mg/L as nitrogen and dissolved phosphorus concentrations were 0.01 mg/L (table 10).

The relation between δD and $\delta 18O$ for Evening Shade Spring is similar to that of the global meteoric line (VSMOW) and followed the trend of the local meteoric line indicating that samples are representative of direct precipitation entering the aquifer system and not influenced by sources of water enriched in $\delta 18O$ through evaporation (fig. 29). Samples from wells W11 and W48 had similar isotopic chemistries as Evening Shade Spring. Values for δD in W11 and W48 were -35.08 and -36.32 per mil, respectively, and for $\delta 18O$ were -6.06 and -6.11 per mil, respectively. Spring S6 and well W25 demonstrated an enrichment of $\delta 18O$ and δD because of the effects of evaporation. Spring S6 is an extreme example of the effects of evaporation with values of 2.84 and 3.92 per mil for δD and $\delta 18O$, respectively. Other constituents such as sodium, chloride, sulfate, and bromide had high concentrations in Spring S6 compared to other samples in the area (table 11), indicating the chemistry may be influenced by a contamination source.

The $\delta 13C$ data show the water discharging from Evening Shade Spring reflects near-equilibrium conditions between the ground water and the aquifer material. The estimated proportions of organically- and inorganically-derived carbon from $\delta 13C$ data for Evening Shade Spring were calculated to be 58 percent and 42 percent, respectively (table 10). Similar values were found for the base-flow sample collected from Hughes Spring.

Radiogenic isotopes (tritium and carbon-14) from Evening Shade Spring indicated that the discharge water is a mixture of recent recharge and submodern water (recharged prior to 1952; table 2 and 10). Tritium measured at Evening Shade Spring was 2.3 TU and the carbon-14 was 46.9 percent modern carbon. Although the tritium value is similar to values measured at Hughes and Stark Spring (influenced by local recharge), the carbon-14 value is approximately half. This would indicate that the water that discharges from Evening Shade Spring has less influx of modern carbon and is more indicative of a regional ground-water source.

Table 10. Water-quality analyses from samples collected at Evening Shade Spring, 2001-2002

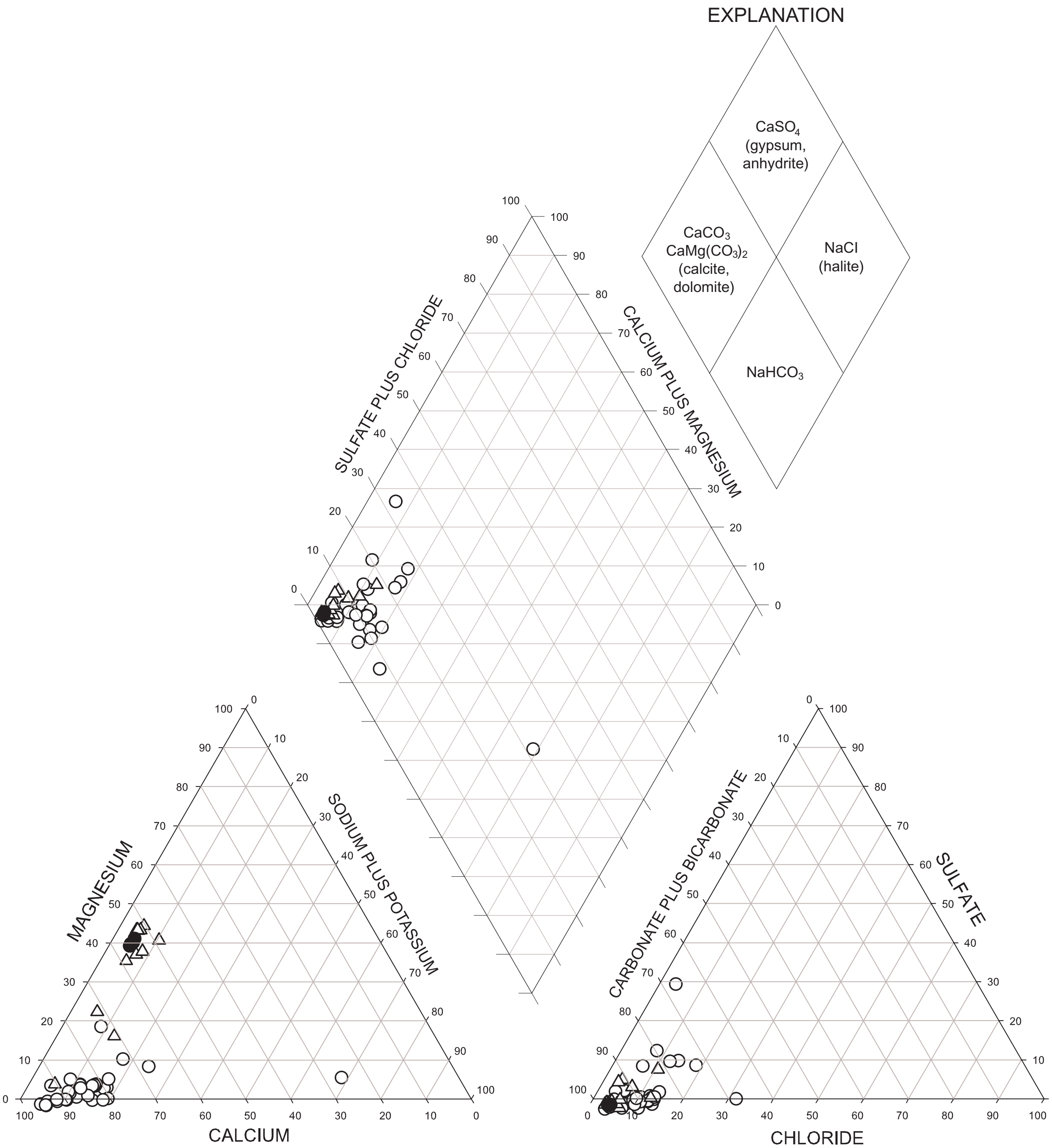
[ft^3/s, cubic foot per second; °C, degrees Celsius; mg/L, milligrams per liter; μS/cm, microsiemens per centimeter at 25 degrees Celsius; e, estimated; <, less than; μg/L, micrograms per liter; --, no data]

Constituent	Sept. 4, 2001	Dec. 17, 2001	July 22, 2002	Oct. 16, 2002
Discharge, ft^3/s	1.3	1.6	1.5	0.9
Water temperature, °C	17	17	17	16
Dissolved oxygen, mg/L	7.8	6.4	8.6	2.6
Specific conductance, μS/cm	352	348	355	348
pH	8.0	7.7	7.9	8.1
Bicarbonate, dissolved, mg/L	221	213	207	211
Calcium, dissolved, mg/L	40.0	41.7	42.9	43.1
Magnesium, dissolved, mg/L	19.8	19.9	20.1	19.8
Sodium, dissolved, mg/L	1.23	1.38	1.22	1.22
Potassium, dissolved, mg/L	0.66	0.68	0.60	0.61
Chloride, dissolved, mg/L	1.87	1.62	2.28	1.82
Sulfate, dissolved, mg/L	2.50	2.57	2.69	2.85
Silica, dissolved, mg/L	8.56	8.64	9.01	8.95
Bromide, dissolved, mg/L	0.037	e0.027	e0.021	0.021
Fluoride, dissolved, mg/L	<0.1	e0.082	<0.1	<0.1
Iron, dissolved, μg/L	<10	<10	<10	<10
Manganese, dissolved, μg/L	<2	e1.61	<2	e0.89
Total dissolved solids, calculated, mg/L	183	184	183	184
Calcite saturation index	0.43	0.12	0.27	0.48
Hardness, mg/L as $CaCO_3$	181	186	190	190
Ammonia plus organic nitrogen dissolved, mg/L as nitrogen	<0.1	<0.1	<0.1	<0.1
Nitrite, dissolved, mg/L as nitrogen	<0.008	<0.008	<0.008	<0.008
Nitrite plus nitrate, dissolved, mg/L as nitrogen	e0.49	0.44	0.48	0.52
Phosphorus, dissolved, mg/L	e0.01	0.01	0.01	0.01
Orthophosphorus, dissolved, mg/L as phosphorus	<0.02	<0.02	<0.02	<0.02
Escherichia coli bacteria, colonies per 100 milliliters	<1	<1	<3	<3
Fecal coliform bacteria, colonies per 100 milliliters	<1	<1	<3	<3
Fecal streptococci bacteria, colonies per 100 milliliters	<1	<1	<3	<3
Deuterium, ratio per mil	-36.1	--	--	--
Oxygen-18, ratio per mil	-6.08	--	--	--
Carbon-13, ratio per mil	-14.05	--	--	--
Tritium, tritium units	2.3	--	--	--
Carbon-14, percent modern carbon	46.9	--	--	--

Table 11. Water-quality analyses of samples collected from three wells and one spring in the Evening Shade Spring study area on October 16 and 17, 2002

[° C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; <, less than; µg/L, micrograms per liter]

	Site identifier (fig. 24)			
Constituent	**S6**	**W11**	**W25**	**W48**
Site type	Spring	Well	Well	Well
Contributing geologic unit	Everton Formation	Everton Formation	Everton Formation	Cotter Dolomite
Water temperature, ° C	18	18	15	16
Dissolved oxygen, mg/L	5.6	4.5	3.4	3.6
Specific conductance, µS/cm	574	89	365	555
pH	8.8	6.4	7.4	7.8
Bicarbonate, dissolved, mg/L	250	43	228	339
Calcium, dissolved, mg/L	46.8	7.26	42.1	62.9
Magnesium, dissolved, mg/L	34.2	3.91	20.5	33.5
Sodium, dissolved, mg/L	15.7	1.80	1.26	1.98
Potassium, dissolved, mg/L	11.0	0.43	0.62	0.98
Chloride, dissolved, mg/L	20.6	2.62	2.33	15.0
Sulfate, dissolved, mg/L	33.2	0.53	1.13	4.30
Silica, dissolved, mg/L	0.13	12.35	11.36	9.89
Bromide, dissolved, mg/L	15.7	e0.015	0.030	0.018
Fluoride, dissolved, mg/L	<0.1	<0.1	<0.1	<0.1
Iron, dissolved, µg/L	<10	24.08	e7.12	<10
Manganese, dissolved, µg/L	<2	4.42	<2	e1.19
Total dissolved solids, calculated, mg/L	285	50.1	192	295
Calcite saturation index	0.88	-2.37	-0.17	0.55
Hardness, mg/L as $CaCO_3$	258	34.3	190	295
Deuterium, ratio per mil	2.84	-36.32	-26.41	-35.08
Oxygen-18, ratio per mil	3.92	-6.11	-4.04	-6.06



● Evening Shade Spring

○ Wells and springs attributed to the Springfield Plateau aquifer

△ Wells and springs attributed to the Ozark aquifer

Figure 28. Relation of ground-water samples from Evening Shade Spring and other wells and springs in northern Arkansas and southern Missouri.

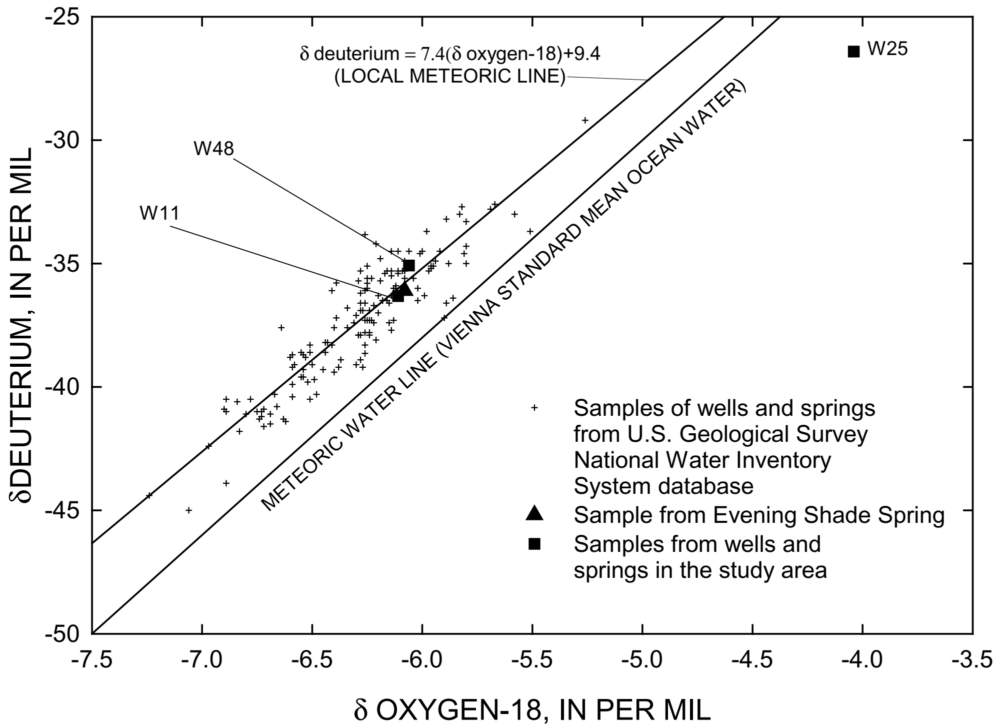


Figure 29. Relation of deuterium and oxygen-18 isotope ratios in ground-water samples from Evening Shade Spring and other wells and springs in northern Arkansas and southern Missouri.

Roaring Spring

Study Area Description

The Roaring Spring study area lies in the Salem Plateau physiographic province (fig. 1) and occurs largely within dolomites of Ordovician age. The altitude of the study area ranges from 325 to 928 ft above NGVD of 1929. Land use in the area consists primarily of deciduous and evergreen forest land (82 percent) and agricultural land (14 percent). Urban land use consists of less than 2 percent of the study area. Water and transitional land uses consists of 2 percent of the study area (Vogelmann and others, 2001).

Annual mean temperatures recorded at Hardy (fig.1) for calendar years 2001 and 2002 were 17 °C and 16 °C, respectively, which were above normal (+4 °C and +3 °C, respectively) based on a 54-year period from 1948 to 2002 (National Oceanic and Atmospheric Administration, 2002). The annual rainfall recorded at Hardy was 42 inches for 2001 and 62 inches for 2002 (National Oceanic Atmospheric Administration, 2001; 2002). The average annual rainfall for Hardy is 45 inches (Hoare, 1996).

Hydrogeology

The Cotter Dolomite and the Jefferson City Dolomite are the major geologic formations exposed in the Roaring Spring study area. There also are some small areas of the Powell Dolomite and Everton Formation in the southwestern corner of the study area (fig. 30). At depth, the geology is similar to the Evening Shade Spring study area, with the Roubidoux Formation and Gasconade Dolomite present as formations that are commonly used for higher yield water-supply wells. Many of the residential wells in the study area are completed in the Cotter Dolomite and the Jefferson City Dolomite (table 12; fig. 31). All of the formations in the study area are considered part of the Ozark aquifer.

Roaring Spring discharges near the contact between the Cotter Dolomite and the Jefferson City Dolomite. Similar to Evening Shade Spring, the location of the Roaring Spring discharge may be from the concentration of regional flow in formations composing the Ozark aquifer through enlarged conduits or fractures (fig. 32). Raccoon Spring (S2) near Roaring Spring has similar characteristics (fig. 31).

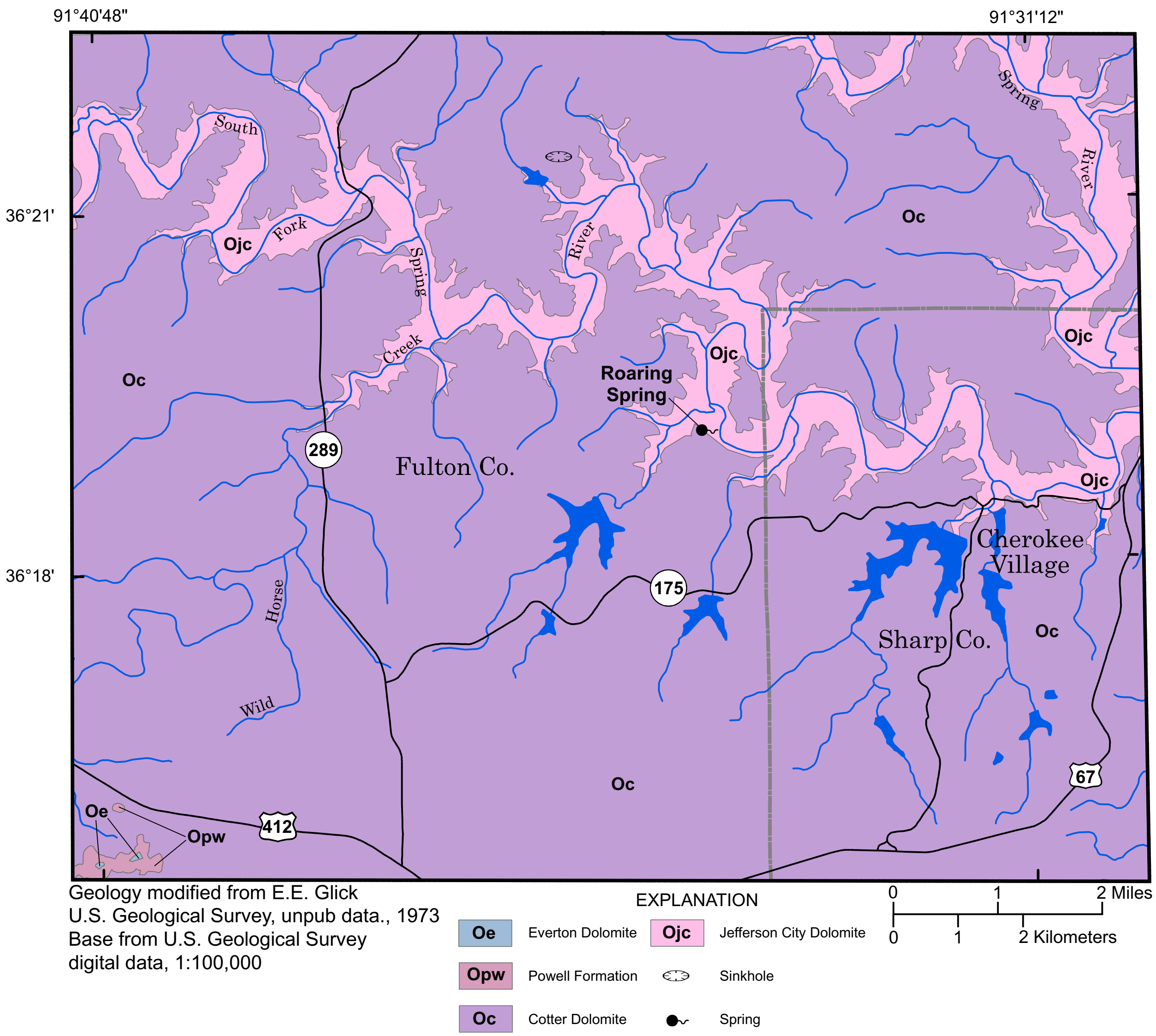


Figure 30. Geology of the Roaring Spring study area.

Table 12. Wells and springs inventoried in the Roaring Spring study area

[Geologic formation refers to the formation from which the spring discharges or the formation at the total depth of the well; USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds; --, no data]

Site identifier (fig. 31)	Station identification number	USGS local number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface, in feet above NGVD of 1929	Site type	Well depth, in feet below land surface	Date of water-level measurement	Water level, in feet below land surface	Altitude of water-level, in feet above NGVD of 1929	Use	Geologic formation
S1	07069297	19N06W12BDA1SP	361908	913431	400	Spring	--	--	--	400	Public water supply	Roubidoux Formation
S2	361857091325701	19N05W08BCD1SP	361857	913237	400	Spring	--	--	--	400	Irrigation	Roubidoux Formation
S3	361617091344201	19N06W25CAB1SP	361617	913442	697	Spring	--	--	--	697	Unused	Cotter Dolomite
S4	361545091342101	19N06W36ABD1SP	361545	913421	635	Spring	--	--	--	635	Unused	Cotter Dolomite
S5	362122091352201	20N06W26DCD1SP	362122	913522	500	Spring	--	--	--	500	Unused	Cotter Dolomite
W1	361945091312401	19N05W04BCD1	361945	913124	700	Well	Unknown	7/26/01	167	533	Unused	Cotter Dolomite
W2	361944091312101	19N05W04CAB1	361944	913121	690	Well	1,420	10/2/01	183	507	Unused	Gunter Sandstone
W3	361855091333101	19N05W07BDC1	361855	913331	490	Well	Unknown	3/22/01	74	416	Residential	Cotter Dolomite
W4	361854091333201	19N05W07BDC2	361854	913332	505	Well	77	3/22/01	71	434	Unused	Cotter Dolomite
W5	361826091301701	19N05W10CDC1	361826	913017	500	Well	1,100	8/24/01	96	404	Commercial	Gunter Sandstone
W6	361644091304001	19N05W21DDD1	361644	913040	700	Well	Unknown	7/25/01	128	572	Unused	Unknown
W7	361926091345901	19N06W01CCC1	361926	913459	560	Well	360	6/20/01	103	457	Residential	Jefferson City Dolomite
W8	362009091354301	19N06W02BDB1	362009	913543	440	Well	42	3/22/01	11	429	Residential	Jefferson City Dolomite
W9	361844091334701	19N06W07CBC1	361844	913347	440	Well	100	6/21/01	35	405	Residential	Jefferson City Dolomite
W10	361917091354701	19N06W11BAC1	361917	913547	608	Well	269	7/26/01	157	451	Residential	Jefferson City Dolomite
W11	361832091345101	19N06W12CCD1	361832	913451	602	Well	Unknown	7/25/01	179	423	Residential	Jefferson City Dolomite
W12	361853091341601	19N06W12DBA1	361853	913416	520	Well	160	3/22/01	113	407	Residential	Jefferson City Dolomite
W13	361809091384201	19N06W17DBB1	361809	913842	560	Well	65	6/19/01	31	529	Residential	Cotter Dolomite
W14	361803091383601	19N06W17DBD1	361803	913836	607	Well	180	6/19/01	63	544	Residential	Cotter Dolomite
W15	361707091383101	19N06W20DCA1	361707	913831	825	Well	158	1/4/01	89	736	Monitoring	Cotter Dolomite
W16	361629091352001	19N06W26ACA1	361629	913520	780	Well	261	6/20/01	90	690	Residential	Cotter Dolomite

Table 12. Wells and springs inventoried in the Roaring Spring study area

[Geologic formation refers to the formation from which the spring discharges or the formation at the total depth of the well; USGS, U.S. Geological Survey; ddmmss, degrees, minutes, seconds; --, no data]

Site identifier (fig. 31)	Station identification number	USGS local number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude of land surface, in feet above NGVD of 1929	Site type	Well depth, in feet below land surface	Date of water-level measurement	Water level, in feet below land surface	Altitude of water-level, in feet above NGVD of 1929	Use	Geologic formation
W17	361621091353801	19N06W26CAA1	361621	913538	750	Well	400	7/25/01	124	626	Residential	Jefferson City Dolomite
W18	361644091360701	19N06W27AAA1	361644	913607	750	Well	150	6/20/01	73	677	Residential	Cotter Dolomite
W19	361639091363101	19N06W27ABC1	361639	913631	700	Well	173	6/20/01	42	658	Residential	Cotter Dolomite
W20	361646091364001	19N06W27BAA1	361646	913640	720	Well	323	6/20/01	60	660	Residential	Jefferson City Dolomite
W21	361628091364001	19N06W27BDD1	361628	913640	690	Well	280	6/20/01	56	634	Residential	Cotter Dolomite
W22	361616091365401	19N06W27CBD1	361616	913654	670	Well	280	6/20/01	43	627	Residential	Jefferson City Dolomite
W23	361647091381601	19N06W29AAD1	361647	913816	770	Well	128	7/5/01	39	731	Monitoring	Cotter Dolomite
W24	361548091351801	19N06W35ABD1	361548	913518	682	Well	520	6/21/01	60	622	Residential	Jefferson City Dolomite
W25	361549091344401	19N06W36BAB1	361549	913444	665	Well	70	6/20/01	28	637	Residential	Cotter Dolomite
W26	362107091311701	20N05W28CDC1	362107	913117	540	Well	Unknown	7/26/01	36	504	Unused	Cotter Dolomite
W27	362151091320001	20N05W29AAC1	362151	913200	600	Well	Unknown	7/26/01	149	451	Unused	Cotter Dolomite
W28	362046091331501	20N05W31ACD1	362046	913315	680	Well	Unknown	7/26/01	165	515	Residential	Cotter Dolomite
W29	362128091363101	20N06W27DBC1	362128	913631	550	Well	165	3/21/01	65	485	Public water supply	Jefferson City Dolomite
W30	362045091352801	20N06W35DBB1	362045	913528	505	Well	180	3/21/01	67	438	Public water supply	Jefferson City Dolomite
W31	362118091381201	20N06W33BBB1	362118	913812	498	Well	42	8/24/01	7	491	Residential	Cotter Dolomite
W32	361849091300301	19N05W10CAA1	361849	913003	395	Well	150	10/12/01	8	387	Residential	Jefferson City Dolomite

Roaring Spring discharges near the contact between the Cotter Dolomite and the Jefferson City Dolomite. Similar to Evening Shade Spring, the location of the Roaring Spring discharge may be from the concentration of regional flow in formations of the Ozark aquifer through enlarged conduits or fractures (fig. 32). Raccoon Spring (S2) near Roaring Spring has similar characteristics (fig. 31).

Discharge, Temperature, and Precipitation

The discharge for Roaring Spring did not vary in response to precipitation events but did increase through time for the period of record (June 29, 2001 to October 1, 2002) (fig. 33) The mean daily discharge computed from the springhouse ranged from 4.8 to 7.2 ft^3/s and the mean discharge was 5.7 ft^3/s for the period of record (Brossett and Evans, 2003).

On average, the base-flow discharge for Roaring Spring accounted for approximately 99 percent of the total discharge volume for the period. The lowest base-flow discharge occurred during the period of September through December of 2001 and steadily increased and remained high for the remainder of the monitoring period (fig. 33). The increase in discharge appears to be a reflection of the increase in precipitation during the period of December 2001 to June 2002. Discharge exceeded base flow by more than 5 percent during only 2 percent of the monitoring period (June 29, 2001 to October 1, 2002). The small peaks that were evident during periods of intense rainfall indicated a small component of local recharge. The local recharge may occur immediately adjacent to the spring as infiltration through the shallow subsurface, but not at substantial volumes. The ratio of peak flow to base flow for Roaring Spring was calculated as 1.5 based on the entire period of record, indicating a slow-response spring (White, 1988). The discharge characteristics were similar to Evening Shade Spring and contrasted with the fast response, storm input type of discharge that was observed at Hughes and Stark Springs.

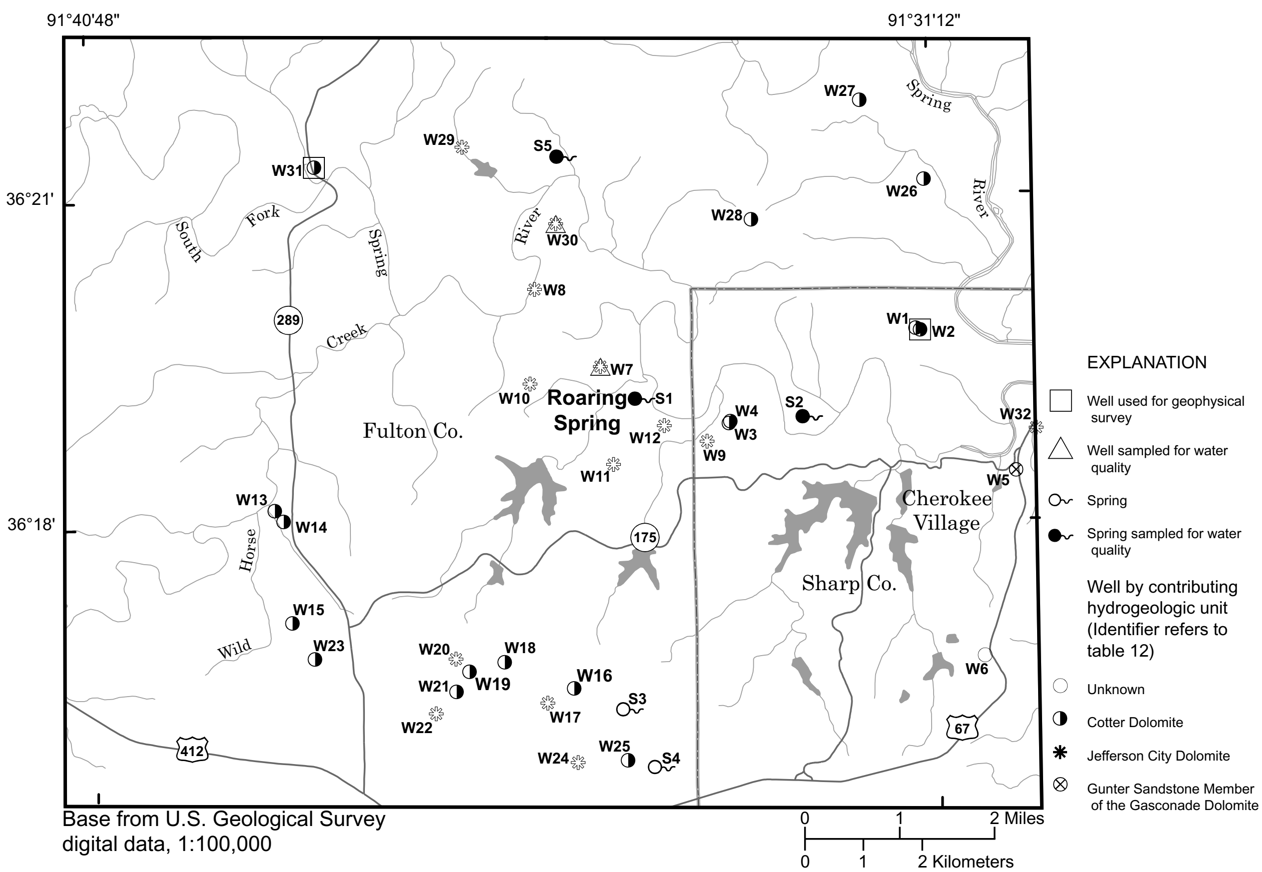


Figure 31. Distribution of wells and springs in the Roaring Spring study area.

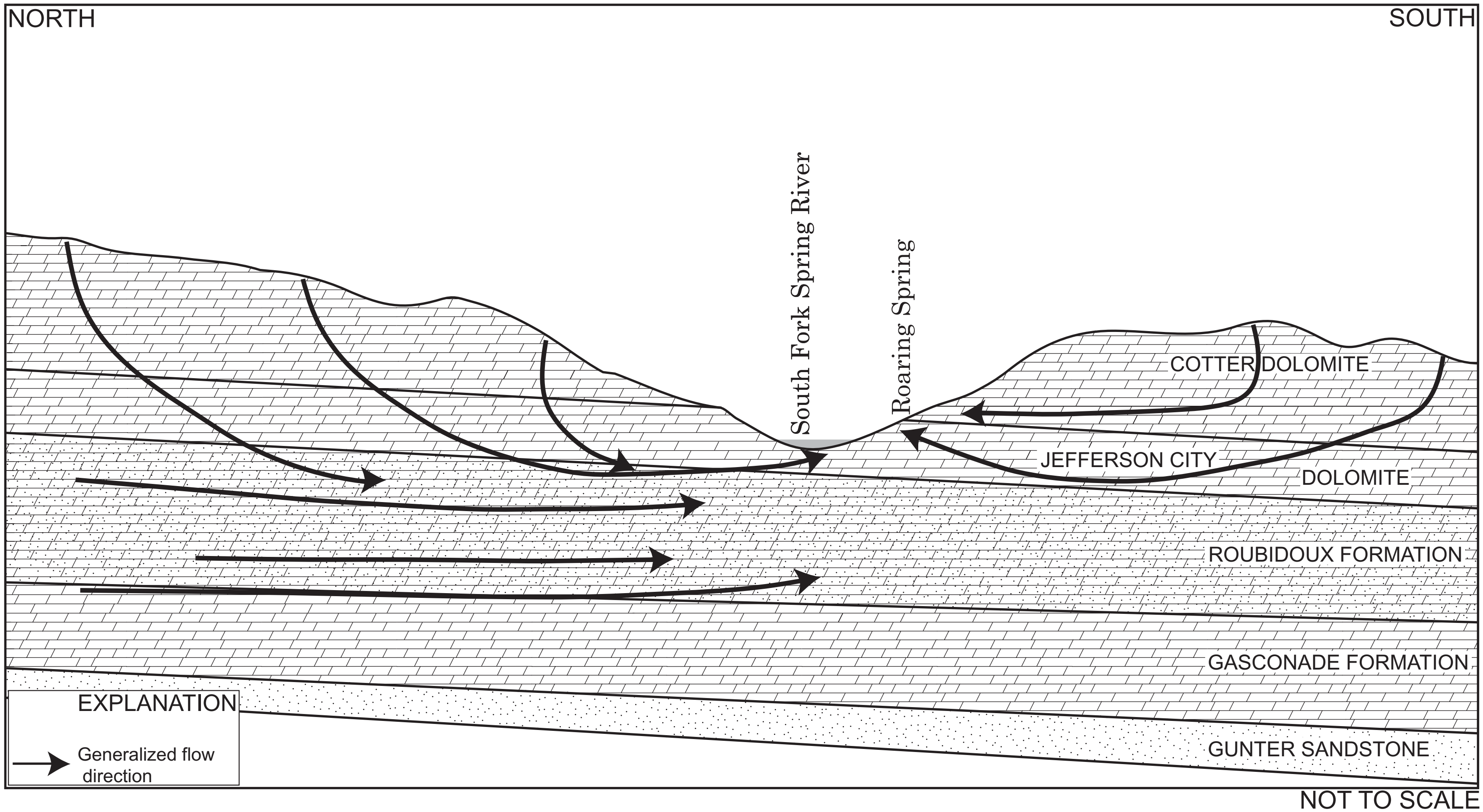


Figure 32. Conceptual model of ground-water flow to Roaring Spring.

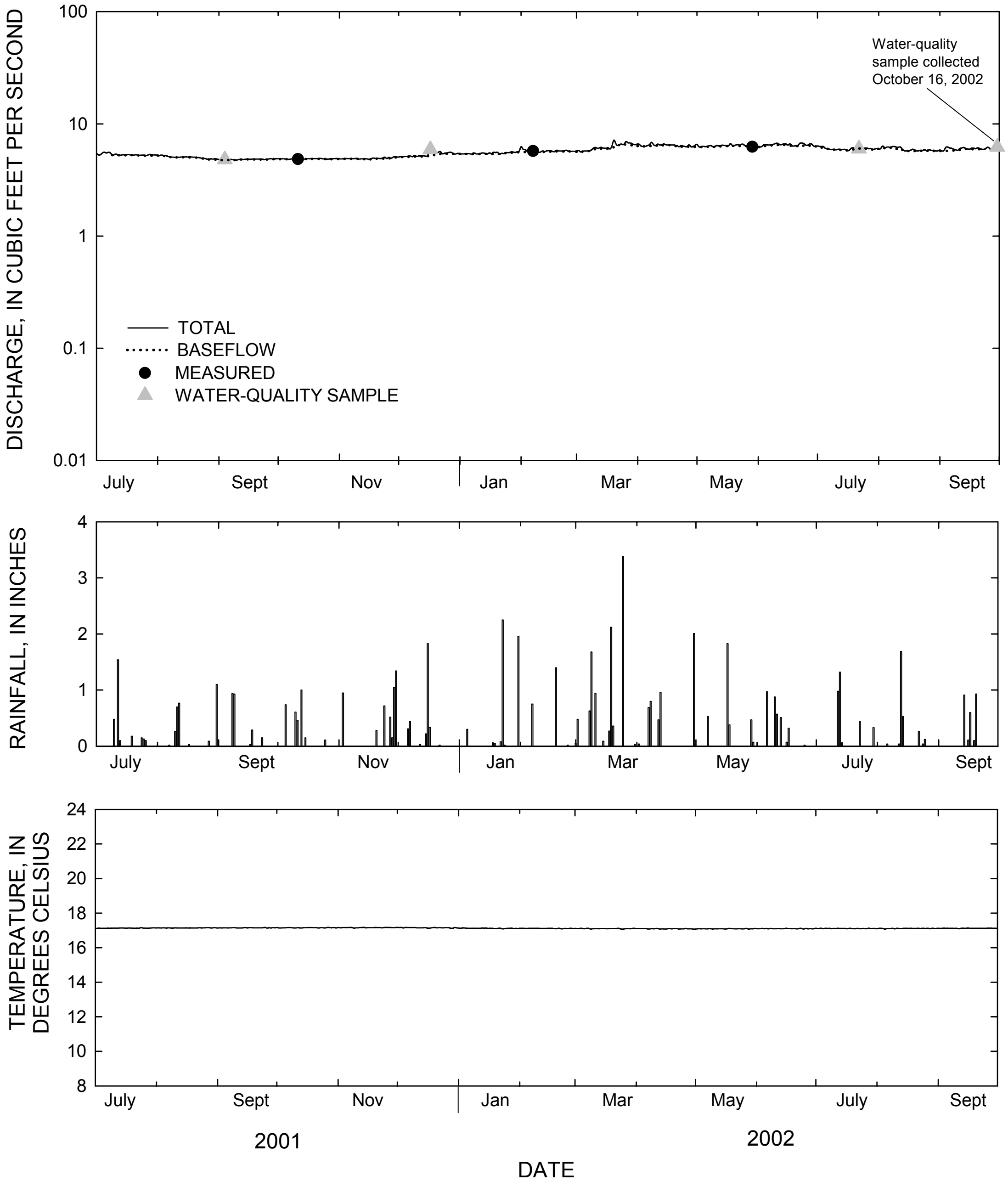


Figure 33. Daily discharge, rainfall, and water temperature recorded at Roaring Spring.

The water temperature recorded at Roaring Spring ranged from 17.1 to 17.2 °C for the period of record (fig. 33). The relatively stable discharge and temperature recorded for Roaring Spring indicates a large, steady, regional source of water.

Water-Level Contours

Water-level contours constructed from static water levels measured in 32 wells and 5 springs in 2001 (table 13) generally followed land-surface topography in the area and indicate that ground water flows towards the South Fork Spring River in the central portion of the study area and the Spring River in the northeast (fig. 34). The highest water levels were found in the south-western portion of the study area. The linear depression in the water-level altitude that occurs in the central and eastern parts of the study area indicates an area of ground-water discharge and corresponds with the location of Roaring (S1) and Raccoon (S2) Springs. The contours in the study area follow a similar pattern to the regional flow of the Ozark aquifer constructed by Pugh (1998) and Schrader (2001).

Recharge Area Characterization

The discharge, geochemical, and hydrogeologic data indicate that the discharge for Roaring Spring mostly is representative of a regional ground-water flow system (Ozark aquifer) and does not allow for a distinct boundary to be delineated for the recharge area contributing to the spring. The recharge area could include relatively remote locations where hydrogeo-logic units composing the Ozark aquifer are exposed

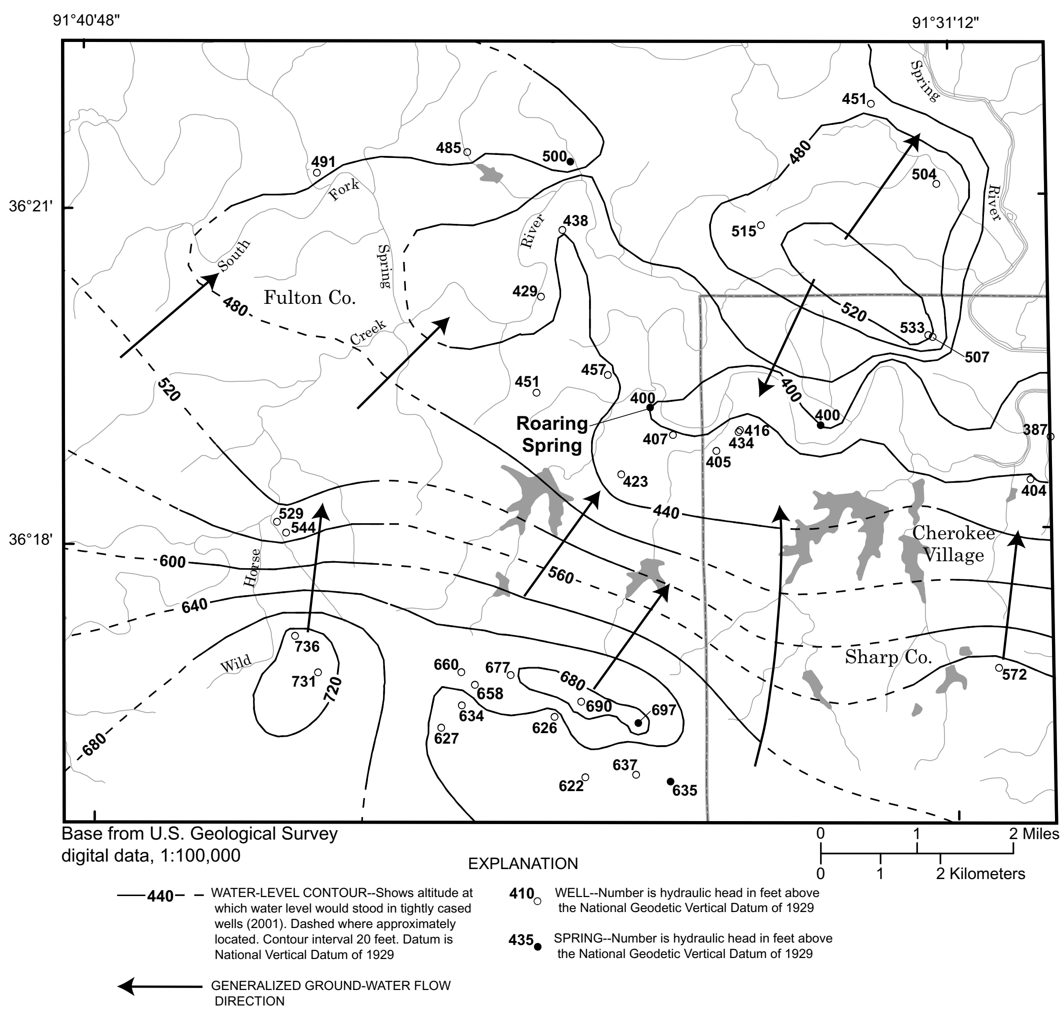


Figure 34. Water-level contours of the Roaring Spring study area.

Table 13. Water-quality analyses from samples collected at Roaring Spring, 2001-2002

[ft^3/s, cubic foot per second; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; e, estimated; <, less than; µg/L, micrograms per liter; --, no data]

Constituent	Sept. 4, 2001	Dec. 17, 2001	July 22, 2002	Oct. 16, 2002
Discharge, ft^3/s	4.8	5.9	6.0	6.2
Water temperature, °C	17	16	17	17
Dissolved oxygen, mg/L	5.4	5.2	5.2	3.4
Specific conductance, µS/cm	491	483	491	493
pH	7.7	7.7	7.6	7.7
Bicarbonate, dissolved, mg/L	315	317	305	335
Calcium, dissolved, mg/L	53.1	54.2	55.9	56.2
Magnesium, dissolved, mg/L	31.7	31.0	31.3	31.0
Sodium, dissolved, mg/L	1.42	1.38	1.40	1.39
Potassium, dissolved, mg/L	1.02	1.04	0.97	0.94
Chloride, dissolved, mg/L	2.02	1.48	2.54	1.22
Sulfate, dissolved, mg/L	3.43	3.26	2.95	2.93
Silica, dissolved, mg/L	9.16	9.02	9.58	9.50
Bromide, dissolved, mg/L	0.040	e0.024	e0.022	e0.022
Fluoride, dissolved, mg/L	<0.1	<0.1	<0.1	<0.1
Iron, dissolved, µg/L	<10	<10	<10	<10
Manganese, dissolved, µg/L	<2	<2	e1.19	4.42
Total dissolved solids, calculated, mg/L	257	258	255	269
Calcite saturation index	0.33	0.31	0.21	0.35
Hardness, mg/L as $CaCO_3$	263	163	269	270
Ammonia plus organic nitrogen dissolved, mg/L as nitrogen	<0.1	<0.1	0.38	<0.1
Nitrite, dissolved, mg/L as nitrogen	<0.008	<0.008	<0.008	<0.008
Nitrite plus nitrate, dissolved, mg/L as nitrogen	e0.17	0.15	0.16	0.18
Phosphorus, dissolved, mg/L	e0.005	e0.004	e0.004	0.006
Orthophosphorus, dissolved, mg/L as phosphorus	<0.02	<0.02	<0.02	<0.02
Escherichia coli bacteria, colonies per 100 milliliters	--	<1	76	<1
Fecal coliform bacteria, colonies per 100 milliliters	--	<1	61	<1
Fecal streptococci bacteria, colonies per 100 milliliters	--	<1	258	<1
Deuterium, ratio per mil	-38.1	--	--	--
Oxygen-18, ratio per mil	-6.21	--	--	--
Carbon-13, ratio per mil	-13.17	--	--	--
Tritium, tritium units	5.1	--	--	--
Carbon-14, percent modern carbon	53.1	--	--	--

and have sufficient porosity and hydraulic conductivity to convey water that falls as precipitation to the subsurface. However, the discharge data and fecal indicator bacteria samples did show that some local influences may affect the spring discharge, but probably reflect conditions immediately adjacent to the location of Roaring Spring.

Geochemistry

The major ion analyses from Roaring Spring (table 13) and from wells and springs in the study area (table 14) demonstrate calcium bicarbonate type water typical of the Ozark aquifer (fig. 35). All samples collected from Roaring Spring and from the other wells and springs in the study area had calcium to magnesium ratio values of 1.1, indicating contribution from a dolomitic mineralogy (White, 1988) that is representative of units of the Ozark aquifer and similar to Evening Shade Spring. The chemistry of Raccoon Spring (S2) was similar to Roaring Spring with respect to the field parameter values (pH, specific conductance, and temperature) and major ion concentrations (tables 13 and 14). The samples collected from other springs and wells in the study area also were similar, but generally had higher total dissolved solid concentrations and hardness values.

Samples collected at Roaring Spring had $SI_{calcite}$ values ranging from 0.21 to 0.35, indicating the waters are supersaturated with calcite, regardless of the flow conditions. The other wells and springs, except for Raccoon Spring (S2), had waters more saturated with respect to calcite, ranging in value from 0.60 to 0.71 (table 14).

Nutrient concentrations at Roaring Spring were lower than concentrations for all of the other springs sampled for this study. Concentrations of ammonia, nitrite, and orthophosphorus were below detection limits (table 13). Concentrations of ammonia plus organic nitrogen were below detection levels except for one sample that had a concentration of 0.38 mg/L as nitrogen. Concentrations of dissolved nitrate plus nitrite ranged from 0.15 to 0.18 mg/L as nitrogen and dissolved phosphorus concentrations were all equal to or less than 0.006 mg/L.

Wastewater constituents analyzed for Roaring Spring did not indicate any influence from contamination sources. However, fecal indicator bacteria indicated some local influence on the spring. Wastewater constituents analyzed from one sample did not have any constituents with concentrations greater than the detection levels. Fecal indicator bacteria were found only in one sample collected during a period of no precipitation from Roaring Spring (table 13).

The relation between δD and $\delta 18O$ of the Roaring Spring is similar to that of the global meteoric line (VSMOW) and generally followed the trend of the local meteoric line indicating that samples are representative of direct precipitation entering the aquifer system and not influenced by sources of water enriched in $\delta 18O$ through evaporation. The δD and $\delta 18O$ values for Roaring Spring were -38.10 and -6.21 per mil, respectively (table 13). Some variation was evident between other sites sampled in the study area (fig. 36 and table 14). Well W30 had the most similar isotopic signature as Roaring Spring with δD and $\delta 18O$ values of -38.64 and -6.26 per mil, respectively. Samples from spring S5 and well W7 demonstrated source waters that were more enriched in δD and $\delta 18O$. Raccoon Spring (S2) was more enriched in $\delta 18O$, although the isotopic signature was similar to the local meteoric line.

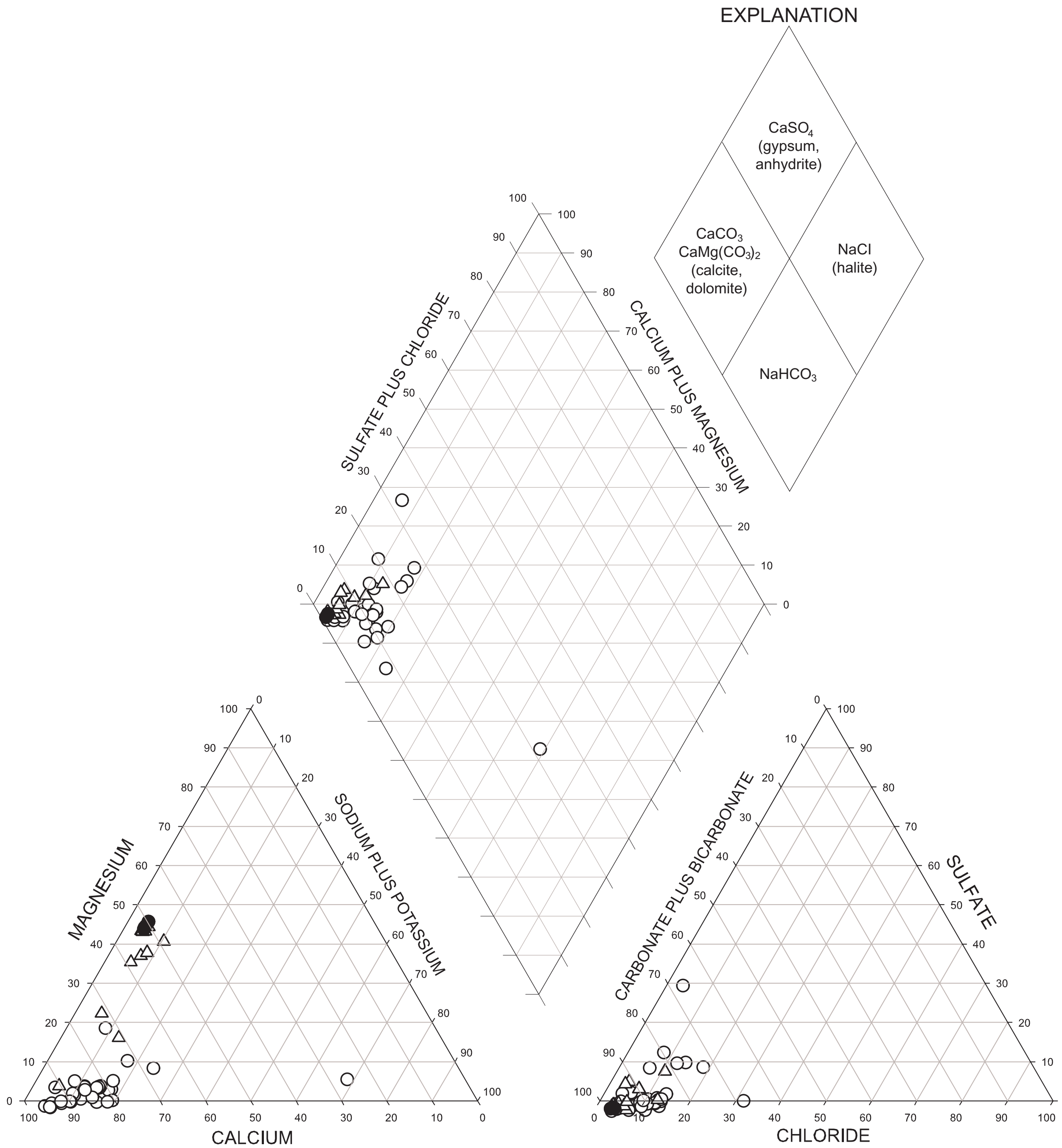
The $\delta 13C$ data show the water discharging from Roaring Spring reflect near-equilibrium conditions between the ground water and the aquifer material. Inorganically-derived $\delta 13C$ was estimated at 45 percent of the total $\delta 13C$ content and organically-derived $\delta 13C$ constituted 55 percent. Proportions of inorganically- and organically-derived carbon at Roaring Spring were similar to Evening Shade Spring sample and the base-flow sample collected from Hughes Spring.

Radiogenic isotopes (tritium and carbon-14) from Roaring Spring indicated that the discharge water is of relatively modern age (recharged within less than 5 to 10 years; tables 2 and 13). Tritium measured at Roaring Spring was 5.1 TU and the carbon-14 was 53.1 percent modern carbon. The tritium value was greater than values measured at Hughes and Stark Spring (influenced by local recharge), and the carbon-14 value was approximately half. This would indicate that the water that discharges from Roaring Spring has less influx of modern carbon and is more indicative of a regional ground-water source.

Table 14. Water-quality analyses of samples collected from two wells and two springs in the Roaring Spring study area on October 16 and 17, 2002

[°C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, microgram per liter; <, less than; --, no data; e, estimated]

	Site identifier (fig. 31)			
Constituent	**S2**	**S5**	**W7**	**W30**
Site type	Spring	Spring	Well	Well
Contributing geologic unit	Roubidoux Formation	Cotter Dolomite	Jefferson City Dolomite	Jefferson City Dolomite
Water temperature, °C	18	15	16	15
Dissolved oxygen, mg/L	2.1	4.76	--	--
Specific conductance, µS/cm	497	630	720	749
pH	7.6	7.7	7.8	7.8
Bicarbonate, dissolved, mg/L	334	433	482	438
Calcium, dissolved, mg/L	56.6	73.6	84.7	75.1
Magnesium, dissolved, mg/L	31.2	41.2	45.0	40.0
Sodium, dissolved, mg/L	1.47	1.32	0.87	1.51
Potassium, dissolved, mg/L	0.9	0.96	0.93	1.06
Chloride, dissolved, mg/L	1.79	1.08	1.68	2.30
Sulfate, dissolved, mg/L	3.00	2.81	6.11	1.30
Silica, dissolved, mg/L	9.36	11.02	10.83	13.77
Bromide, dissolved, mg/L	0.025	0.022	0.020	0.021
Fluoride, dissolved, mg/L	<0.1	<0.1	<0.1	<0.1
Iron, dissolved, µg/L	<10	<10	<10	<10
Manganese, dissolved, µg/L	3.62	3.30	e1.29	e2.42
Total dissolved solids, calculated, mg/L	269	345	387	350
Calcite saturation index	0.31	0.60	0.71	0.63
Hardness, mg/L as $CaCO_3$	270	353	397	352
Deuterium, ratio per mil	-32.60	-35.79	-33.83	-38.64
Oxygen-18, ratio per mil	-5.67	-6.39	-6.26	-6.26



● Roaring Spring
○ Wells and springs attributed to the Springfield Plateau aquifer
△ Wells and springs attributed to the Ozark aquifer

Figure 35. Relation of ground-water samples from Roaring Spring and other wells and springs in northern Arkansas and southern Missouri.

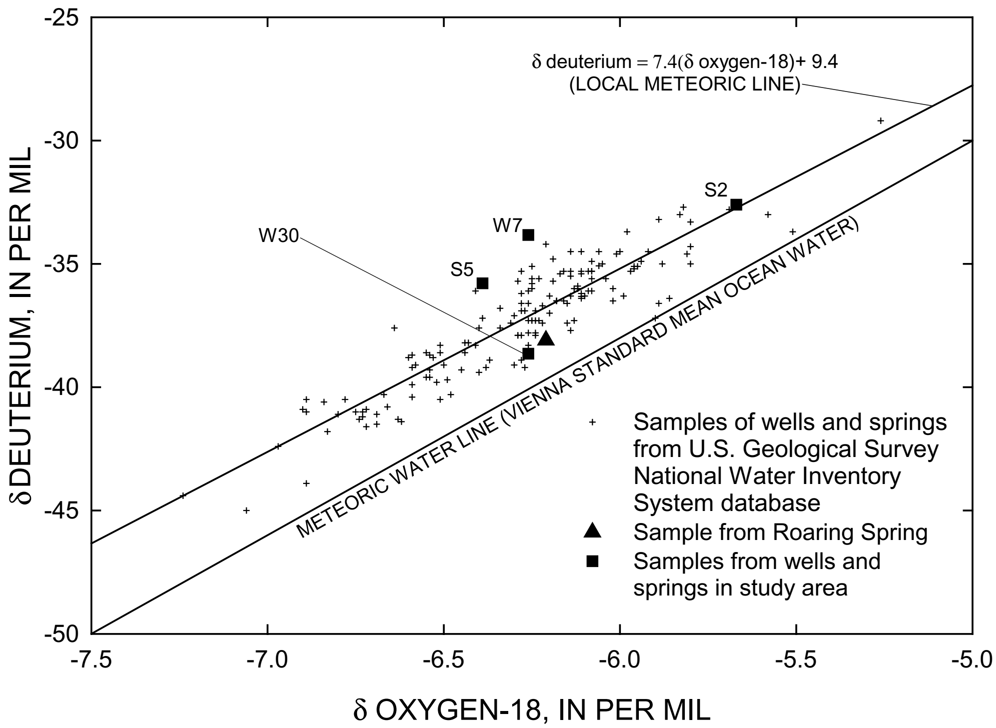


Figure 36. Relation of deuterium and oxygen-18 isotope ratios in the ground-water sample from Roaring Spring and other wells and springs in northern Arkansas and southern Missouri.

SUMMARY

In October 2000, a study was undertaken by the U.S. Geological Survey (USGS) in cooperation with the Arkansas Department of Health to determine the hydrogeologic characteristics, including the extent of the local recharge area, for four springs used for public-water supply in northern Arkansas. The four springs included in the study are Hughes Spring, Stark Spring, Evening Shade Spring, and Roaring Spring. Characterization of the recharge areas is important because of the karst terrain common in northern Arkansas and because land use proximal to the springs included activities with potentially harmful impacts to spring-water quality.

An integrated approach to determine the hydrogeologic characteristics, including the extent of the local recharge area, of the four springs incorporated tools and methods of hydrology, structural geology, geomorphology, geophysics, and geochemistry. An assessment of the local geology through previous mapping, borehole geophysics, and field investigation was completed in each study area to develop a conceptual model of the local ground-water flow system. An analysis of continuous discharge, water temperature, and precipitation was completed to determine the local recharge area size and characteristics of the flow system. Discharge and precipitation data for selected storms were used to determine the local recharge area through a water-balance approach for Stark Spring. Water-level contour maps were constructed from well and spring data to show the configuration of the water table and determine ground-water flow directions. Qualitative ground-water tracer tests also were completed to determine recharge area boundary locations and to estimate ground-water flow velocities for Hughes and Stark Springs. Water-quality samples were collected at each spring to determine the geochemistry of the contributing geologic units and the susceptibility of the springs to contamination. Samples were analyzed for major ions, nutrients, fecal indicator bacteria, wastewater constituents, and stable and radiogenic isotopes.

Hughes Spring supplies water for the city of Marshall, Arkansas, and the surrounding area. Recharge to the spring occurs mainly from the Boone Formation that comprises the Springfield Plateau aquifer. The mean annual discharge for Hughes Spring was 2.9 ft^3/s for water year 2001 and 5.2 ft^3/s for water year

2002. Water-level contours show that ground-water generally follows the land-surface topography and flows generally to the northwest in the study area. Ground-water tracer tests indicate that the recharge area for Hughes Spring generally coincides with the surface drainage area (15.8 mi^2) and that Hughes Spring is directly connected to the surface flow in Brush Creek.

The geochemistry of Hughes Spring demonstrated variations with flow conditions and the influence of surface-runoff in the recharge area. Calcite saturation indices, total dissolved solids concentrations, and hardness demonstrate noticeable differences with flow conditions reflecting the reduced residence time and interaction of water with the source rock at high-flow conditions for Hughes Spring. Concentrations of fecal indicator bacteria also demonstrated a substantial increase during high-flow conditions, indicating that a non-point source of bacteria possibly from livestock may enter the system. Conversely, nutrient concentrations did not vary with flow and were similar to concentrations reported for undeveloped sites in the Springfield Plateau and Ozark aquifers (Adamski, 1997). δD and $\delta 18O$ data show that the Hughes Spring discharge is representative of direct precipitation and not influenced by water enriched in $\delta 18O$ through evaporation. $\delta 13C$ data show an enrichment of organically-derived carbon during high-flow conditions, indicating a substantial component of the recharge water interacts with the surface material (soil and regolith) in the recharge area before entering the ground-water system for Hughes Spring. Tritium data for Hughes Spring indicate that the water discharging from the spring is a mixture of recent recharge and sub-modern water (recharged prior to 1952).

Stark Spring discharges at land surface from the Boone Formation and supplies water for the city of Cushman, Arkansas, and the surrounding area. The mean annual discharge for Stark Spring was 0.5 ft^3/s for water year 2001 and 1.5 ft^3/s for water year 2002. Analyses of discharge data show that Stark Spring has a fast response to surface runoff and the estimated recharge area (0.79 mi^2) is larger than the surface drainage area (0.34 mi^2). Ground-water tracer tests and the outcrop of the Boone Formation indicate that most of the recharge area extends outside the surface drainage area.

Similar to Hughes Spring, the geochemistry of Stark Spring varied with flow conditions. Calcite saturation indices, total dissolved solids concentrations, and hardness demonstrate noticeable differences with flow conditions reflecting the reduced residence time and interaction of water with the source rock at high discharges for Stark Spring. In contrast to Hughes Spring, concentrations of fecal indicator bacteria demonstrated a decrease during high-flow conditions, and may reflect dilution and the lack of pastureland or other sources of non-point contamination in the Stark Spring recharge area. Nitrite plus nitrate concentrations did not vary with flow and were less than concentrations reported for undeveloped sites in the Springfield Plateau and Ozark aquifers (Adamski, 1997). Concentrations of phosphorus and orthophosphorus were slightly higher than concentrations reported for undeveloped sites in the Springfield Plateau and Ozark aquifers (Adamski, 1997). δD and $\delta 18O$ data show that the Stark Spring discharge is representative of direct precipitation and not influenced by water enriched in $\delta 18O$ through evaporation. $\delta 13C$ data indicate that the recharge has little interaction with the soils and regolith in the recharge area before entering the ground-water system for Stark Spring. Tritium data for Stark Spring indicate that the water discharging from the spring is a mixture of recent recharge and sub-modern water (recharged prior to 1952).

Evening Shade and Roaring Springs originate from geologic formations composing the Ozark aquifer. The springs provide the water supply for the communities of Evening Shade and Cherokee Village, respectively, and the surrounding areas. The mean annual discharge for Evening Shade Spring was 1.44 ft^3/s for water year 2001 and 1.24 ft^3/s for water year 2002. Roaring Spring had a mean discharge of 5.7 ft^3/s for the period of record (July 2001 to October 2002). Little variation in discharge and temperature was evident during high-flow events and throughout the monitoring period indicating that spring discharge is dominated by regional ground-water flow with small portions of local recharge. As a result, a local recharge area could not be delineated, as the area could include relatively remote locations where geologic formations composing the Ozark aquifer are exposed and have sufficient porosity and hydraulic conductivity to convey water that falls as precipitation to the subsurface. Water-level contours showed ground-water flow predominately towards the major rivers in each study area, similar to regional flow patterns.

Analyses of major ion concentrations for Evening Shade Spring and Roaring Spring indicated that the source water is a calcium bicarbonate type from a dolomitic mineralogy representative of the Ozark aquifer. Nutrient concentrations generally were lower than at Hughes and Stark Springs. Fecal indicator bacteria were not detected at Evening Shade Spring and were detected in only one sample from Roaring Spring. δD and δ18O data show that the discharge from Evening Shade Spring and Roaring Spring is representative of direct precipitation and not influenced by water enriched in δ18O through evaporation. Tritium data for Evening Shade Spring indicate that the discharge water is a mixture of recent recharge and submodern water (recharged prior to 1952). Discharge water for Roaring Spring was determined to be of relatively modern age (recharged less than 5 to 10 years).

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