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Assessment of Local Recharge Area Characteristics of Four Caves in Northern Arkansas and Northeastern Oklahoma, 2004–07

Scientific Investigations Report 2009–5118

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

Cover photograph. Nesbitt Spring Cave in north-central Arkansas. Photograph by Scott Ausbrooks, Arkansas Geological Survey.

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile (ft^3/s/mi^2)	0.0109	cubic meter per second per square kilomter (m^3/s/km^2)

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

°F = (1.8×°C) + 32

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

°C = (°F - 32)/1.8

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

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

Altitude, as used in this report, refers to distance above the vertical datum, and is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929).

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

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

Assessment of Local Recharge Area Characteristics of Four Caves in Northern Arkansas and Northeastern Oklahoma, 2004-07

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Abstract

A study was conducted from 2004 to 2007 by the U.S. Geological Survey in cooperation with the U.S. Fish and Wildlife Service to assess the characteristics of the local recharge areas of four caves in northern Arkansas and northeastern Oklahoma that provide habitat for a number of unique organisms. Characterization of the local recharge areas are important because the caves occur in a predominately karst system and because land use proximal to the caves, including areas suspected to lie within the local recharge areas, may include activities with potentially deleterious effects to cave water quality.

An integrated approach was used to determine the hydrogeologic characteristics and the extent of the local recharge areas of Civil War Cave, January-Stansbury Cave, Nesbitt Spring Cave, and Wasson's Mud Cave. This approach incorporated methods of hydrology, structural geology, geomorphology, and geochemistry. Continuous water-level and water-temperature data were collected at each cave for various periods to determine recharge characteristics. Field investigations were conducted to determine surficial controls affecting the groundwater flow and connections of the groundwater system to land-surface processes in each study area. Qualitative groundwater tracing also was conducted at each cave to help define the local recharge areas. These independent methods of investigation provided multiple lines of evidence for effectively describing the behavior of these complex hydrologic systems.

Civil War Cave is located near the city of Bentonville in Benton County, Arkansas, and provides habitat for the Ozark cavefish. Civil War Cave is developed entirely within the epikarst of the upper Boone Formation, and recharge to Civil War Cave occurs from the Boone Formation (Springfield Plateau aquifer). The daily mean discharge for the period of study was 0.59 cubic feet per second and ranged from 0.19 to 2.8 cubic feet per second. The mean water temperature for Civil War Cave was 14.0 degrees Celsius. The calculated recharge area for Civil War Cave ranged from 0.13 to 2.5 square miles using the water-balance equation to 3.80 square miles using a normalized base-flow method. Tracer tests indicated a portion of the water within Civil War Cave was from across a major topographic divide located to the southwest.

January-Stansbury Cave is located in Delaware County in northeastern Oklahoma, and provides habitat for the Oklahoma cave crayfish and the Ozark cavefish. January-Stansbury Cave is developed in the St. Joe Limestone member of the Boone Formation. The daily mean discharge for the period of study was 1.0 cubic foot per second and ranged from 0.35 to 8.7 cubic feet per second. The mean water temperature for January-Stansbury Cave was 14.3 degrees. The calculated recharge area for January-Stansbury Cave using the water-balance equation ranged from approximately 0.04 to 0.83 square miles. Tracer tests generally showed water discharging from January-Stansbury Cave during high flow originates from within the topographic drainage area and from an area outside the topographic drainage area to the southwest.

Nesbitt Spring Cave is located near the city of Mountain View in north-central Arkansas and provides habitat for the Hell Creek cave crayfish. Nesbitt Spring Cave is developed in the Plattin Limestone (Ozark aquifer) and is recharged through the Boone Formation (Springfield Plateau aquifer). The mean daily discharge for the period of study was 4.5 cubic feet per second and ranged from 0.39 to 70.7 cubic feet per second. The mean water temperature for Nesbitt Spring Cave was 14.2 degrees Celsius. The calculated recharge area for Nesbitt Spring Cave using the water-balance equation ranged from 0.49 square mile to 4.0 square miles. Tracer tests generally showed a portion of water discharging from Nesbitt Spring during high flow originates from outside the topographic drainage area.

Wasson's Mud Cave is located near the city of Springtown in Benton County, Arkansas, and provides habitat for the Ozark cavefish. Wasson's Mud Cave consists of solutionally enlarged passages along fractures and bedding planes within the epikarst of the upper Boone Formation, and recharge to Wasson's Mud Cave occurs from the Boone Formation (Springfield Plateau aquifer). No flow was observed although the water level did fluctuate. Fluctuation in water level can be attributed to changes in the water level of the shallow ground-

water system.Because there was no detectable flow and tracer tests proved ineffective, the recharge area for Wasson's Mud Cave could not be calculated. The immediate topographic recharge area consists of less than 0.01 square mile around the opening of the cave. The location of the cave indicates that the cave is associated with the shallow groundwater system within the Flint Creek Basin. Therefore, the entire basin potentially contributes recharge to the cave.

Introduction

Several caves in the Ozark Plateaus physiographic province in Missouri, Arkansas, and Oklahoma (Fenneman, 1938) provide habitat to a number of unique organisms. The Ozark cavefish (*Amblyopsis rosae*) is distributed through areas of Arkansas, Missouri, and Oklahoma, with two of Arkansas' caves containing two-thirds of the known individuals (Romero, 1998). Civil War and Wasson's Mud caves (fig. 1) are home to the Ozark cavefish, which was Federally listed as a threatened species in 1984 because of threats from human disturbance and decreased water quality (Brown and Willis, 1984). The Ozark cavefish range includes 41 sites, including Civil War and Wasson's Mud caves, occurring in the Springfield Plateau of the Ozark Plateaus in northwestern Arkansas, southwestern Missouri, and northeastern Oklahoma (Brown and Willis, 1984; Willis and Brown, 1985; Noltie and Wicks 2001). Most of the 28 known populations are considered marginal (Romero, 1998). January-Stansbury Cave (fig. 1) is also home to the Ozark cavefish, as well as the endangered Oklahoma cave crayfish (*Cambarus tartarus*), known at only two sites globally, both located in the Spavinaw Creek watershed in Delaware County, Oklahoma (Graening and others, 2006a). January-Stansbury Cave is the most species-rich cave in Oklahoma and one of the most biologically important caves in the Ozark Highlands ecoregion (Graening and others, 2006a). Threats to these species include development, agriculture, and human disturbance. The endangered Hell Creek cave crayfish (*Cambarus zophonastes*) is restricted to two caves, including Nesbitt Spring Cave in Stone County, Arkansas (Graening and others, 2006b) (fig. 1). The Hell Creek cave crayfish was listed as an endangered species in April 1987 because of its limited range and threats by potential point and nonpoint source pollutants within the basin (Hobbs and Brown, 1987). Because of the installation of cave gates, public acquisition of one of the caves, and cooperation by private landowners, direct human impacts have been reduced. Although human disturbances have been reduced, land-use activities within the recharge area (the area that contributes water to a cave) remain an ongoing threat.

Characterization of the local recharge areas that contribute water to caves and provide habitat for endangered or threatened aquatic organisms is important because these areas occur in a predominately karst system and because land use proximal to the caves, including areas suspected to lie within the local recharge areas, may include activities with potentially deleterious impacts on cave water quality. In karst groundwater systems, recharge can be in close connection with the local surface drainage and can lead to rapid transport of precipitation and runoff derived contaminants to the subsurface with little attenuation, or can be mostly, or entirely, from a deeper, regional groundwater flow system with a source of water many miles away in a different drainage basin. The hydrogeologic framework of the area for each cave consists of karst terrain; hence, these caves are highly susceptible to contamination from surface sources within and outside their surface-water drainage area. Potential impacts could result from urban development including underground septic and fuel storage tanks, and agricultural development, which may be associated with animal feeding operations. Information pertaining to the local recharge area characteristics of a cave would enable resource managers to focus conservation efforts, develop plans that would provide resource managers and landowners with ways to protect cave water quality from contamination related to land use in the area, and enable planned responses to acute impacts such as spills.

A study was conducted from October 2004 to July 2007 by the U.S. Geological Survey (USGS) in cooperation with the U.S. Fish and Wildlife Service (USFWS) to assess the characteristics of the local recharge areas of four caves in northern Arkansas and northeastern Oklahoma (fig. 1). Galloway (2004) used an integrated approach incorporating tools and methods of hydrology, structural geology, geomorphology, geophysics, and geochemistry to determine the hydrogeologic characteristics and the extent of the local recharge areas of four springs in northern Arkansas. That approach demonstrated that changes in spring discharge and water temperature in conjunction with field reconnaissance of the hydrogeology and an appropriate number of groundwater tracer tests can be used to estimate local recharge characteristics. This approach was used to assess the characteristics of the local recharge areas of Civil War Cave, January-Stansbury Cave, Nesbitt Spring Cave, and Wasson's Mud Cave as described in this report.

The purpose of this report is to assess the characteristics of the local recharge areas of Civil War Cave, January-Stansbury Cave, Nesbitt Spring Cave, and Wasson's Mud Cave in northern Arkansas and northeastern Oklahoma (fig. 1). Data were collected for various periods at the four caves between October 2004 and July 2007. Continuous water-level and water-temperature data were collected at each cave for various periods to determine flow characteristics. Field investigations were conducted to determine surficial controls affecting the groundwater flow and connections of the groundwater system to land-surface processes in each study area. Qualitative groundwater tracing also was conducted at each cave to help characterize the local recharge areas.

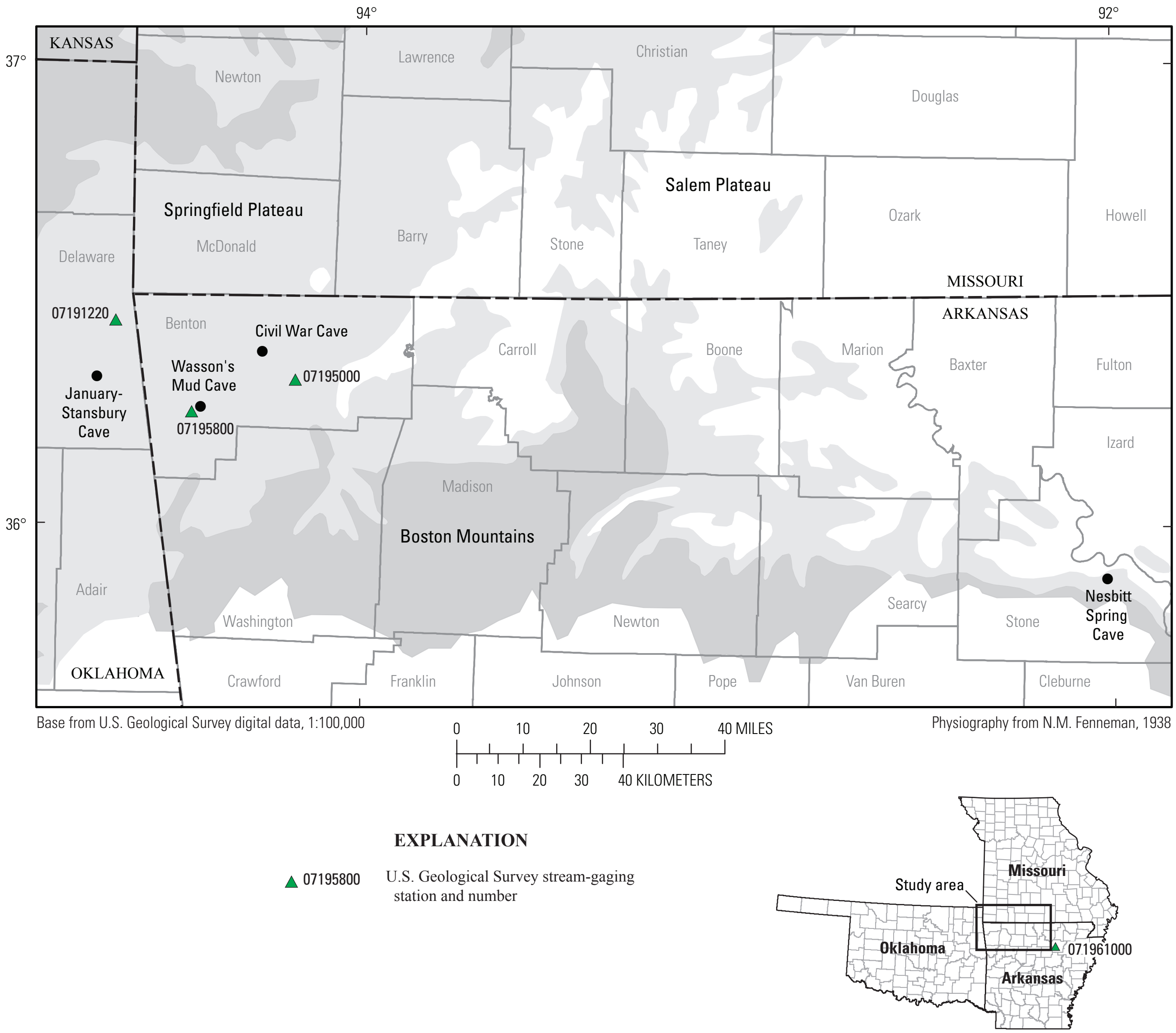

Figure 1. Location of four caves in northern Arkansas and northeastern Oklahoma.

Assessment Methods

An integrated approach to determine the hydrogeologic characteristics and the extent of the local recharge areas of the four caves incorporated methods of hydrology, structural geology, geomorphology, and geochemistry. These independent methods of investigation are tools that can provide evidence for effectively describing the behavior of complex 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 surface-water boundaries and projected groundwater 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, 1974) were used to identify geologic units exposed in the study areas (Caplan, 1957, 1960; McFarland, 1998). Geomorphic data were derived from county-scale soil surveys (U.S. Department of Agriculture, 1970, 1977, 1983). Geomorphic and topographic data from existing maps were gathered and assessed to determine surficial controls on infiltration, potential groundwater flow directions, and boundaries to groundwater flow.

A field inventory of karst features (caves, sinkholes, sinking streams, and enlarged vertical fractures and bedding planes), wells, and springs were conducted in each study area. Karst features provide information on the connection of the groundwater system to the land surface. Water levels in wells and altitudes for springs were used to determine flow directions in the recharge areas and to locate groundwater tracer injection and monitoring points. Structural geology data from field investigation and geologic maps were inventoried, compiled, and reviewed to characterize the distribution of conduits and configuration of the geologic units within the study areas.

Discharge, Precipitation, and Water Temperature Monitoring and Analysis

To determine flow characteristics and aid in the estimation of the local recharge areas, the four caves were instrumented to measure continuous water-level stage and water temperature. The stage was monitored and used in conjunction with periodic instantaneous discharge measurements to define the stage-discharge relation for various periods and to develop continuous discharge data for the cave using methods described in Rantz and others (1982). Discharge data were used to estimate contributions from local recharge areas and from large regional aquifer sources. Hydrographs also provide an indication of the response a spring to a storm event, and therefore, an indication of the flow system. For example, for a fast-response cave system, individual storm pulses have a similar shape as surface stream hydrographs, with a steep rising limb, a crest, and a slower recession limb (White, 2002). Wasson's Mud Cave did not have any measurable discharge, so a stage-discharge relation was not developed.

Base flow was calculated from the discharge data at each spring to determine the contribution of the local recharge and regional aquifer sources. 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 2-day increments and identifies the minimum flow for each increment. Minimum flow of each increment was compared to adjacent minimums to determine turning points on the base-flow hydrograph. If 90 percent of a given minimum was less than both adjacent minimums, then that minimum was a turning point. Straight lines were 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 BFI.

To determine the dominant hydrogeologic subsurface-flow regime (conduit or diffuse flow) in the aquifer system contributing to the spring, the ratio of peak discharge to base-flow discharge was calculated. Conduit flow is described as water flow through large solution cavities and diffuse flow as flow through low-permeability rock and unmodified fissures (Bartodziej and Perry, 1990). In general, springs that have a large peak to base-flow discharge ratio are considered conduit-dominated systems, whereas, springs with small ratios are diffuse-flow dominated systems. 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 (White, 1988). Conduit flow springs commonly discharge from open cave systems, display temperatures that vary seasonally, have chemical compositions that respond rapidly to storm events, and are recharged from internal runoff into sinkholes and from a large component of diffuse infiltration (White, 2002).

The local recharge area was estimated from the discharge record using a water-balance approach at Civil War Cave, January-Stansbury Cave, and Nesbitt Spring Cave and the normalized base-flow approach at Civil War Cave. 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 estimated by removing the volume of base-flow discharge determined by the BFI program. The normalized base-flow method compares discharge observations under base-flow conditions with the discharges of well delineated basins with similar characteristics (Brahana, 1997). With flow dependant approximations, a range of recharge areas is estimated with no constraint on the geometry of the recharge area. The recharge areas resulting from these methods are approximate and dependant on estimates of unknown hydrogeologic properties. The recharge area may vary with different magnitudes of storm events than those observed.

Precipitation was monitored using a single automatic tipping-bucket gage located at nearby USGS streamgages. For Civil War Cave, the Osage Creek near Elm Springs, Ark. (07195000) streamgage was used. For January-Stansbury Cave, the Spavinaw Creek near Sycamore, Okla. (07191220) streamgage was used. For Nesbitt Spring Cave, the White River at Batesville, Ark. (07061000) streamgage was used. For Wasson's Mud Cave, the Flint Creek at Springtown, Ark. (07195800) streamgage was used. Data are available from the USGS National Water Information System (http://waterdata.usgs.gov/nwis). The volume of precipitation inflow was determined by uniformly applying the recorded precipitation to the estimated recharge area and then equating it to the volume of storm runoff discharging from the cave (outflow) and water losses. Losses because of evapotranspiration, soil absorption, and runoff were considered, but were not quantified. The percent reduction of water losses was based on field observations such as surface runoff during precipitation events, thickness of soil (regolith), structural features, and karst features (sinkholes, sinking streams, enlarged fractures) in the area. Additionally, the recharge area was calculated assuming all rainfall as recharge, which would be indicative of the minimum groundwater recharge area.

The greatest losses in recharge volume is probably caused by impermeable soils with minimal losses associated with evapotranspiration because of the short durationof the storms. An 80 percent reduction in recharge volume was used to estimate the losses for Civil War and January-Stansbury Caves because of thicker regolith, and a 50 percent reduction in recharge volume was used to estimate the losses for Nesbitt Spring because of thinner regolith. The recharge area was calculated using the following equation:

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

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.

An approximation of the recharge area based on normalized base flow was calculated for Civil War Cave. Brahana (1997) documented a normalized base flow range of 0.14 to 0.29 cubic feet per second per square mile ($ft^3/s/mi^2$) for springs and caves in northwestern Arkansas in the Springfield Plateau aquifer. The normalized base-flow values are only accurate for this area because they are influenced by the local hydraulic properties of the aquifer. Civil War Cave falls in this geographic area, and the characteristics of the cave are similar to springs and caves included in Brahana's study. To estimate recharge area from normalized base flow, it was necessary to consider some controlling factors such as lithology, stratigraphy, geomorphology, and topography. This method is an approximation based on choosing a value within the range documented based on hydrologic judgment of the system after examining conditions in the field. Applying a second method of recharge area approximation to Civil War Cave provided a check of the accuracy of the methods.

Water temperature was monitored at each cave to detect mixing of surface runoff and groundwater in the spring discharge. While water temperatures during base-flow conditions may remain relatively constant, inputs to the groundwater 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. The elapsed time between the start of percipitaion and a change in the ambient cave water temperature is indicative of the time it takes for surface water to reach the cave.

Qualitative Groundwater Tracing

Preliminary recharge area delineation was tested and improved using groundwater tracing techniques. Qualitative tracer tests were conducted during high-flow conditions to identify groundwater flow paths and confirm the locations of inferred groundwater 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 groundwater tracer test, a fluorescent dye was injected into the aquifer using natural or induced flow into open sinkholes, swallow holes, sinking streams, or wells.

Three separate types of tracers were used including eosine OJ (C.I. Acid Red 87), 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. Tracers were input at various points inside and outside of the preliminary recharge areas. Resurgent tracers were recovered from water by passive charcoal detectors. These passive charcoal detectors contained activated carbon derive-from coconut shell charcoal placed in fiberglass screen with openings of 0.05 to 0.06 inches (Aley, 1999). The activated carbon samplers were collected and exchanged at 1- to 14-day intervals, until tracers were no longer observed at any of the sites. Background fluorescence was monitored at every collection site prior to each injection.

The passive charcoal detectors were placed in the cave discharge, as well as springs, wells, and surface waters downstream from injection points and in adjacent surface-water basins to detect possible interbasin flow. The detectors were placed in the center of flow at springs and suspended in wells using nylon-clad copper 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).

Assessment of Local Recharge Area Characteristics

The four caves described in this report—Civil War Cave and Wasson's Mud Cave, located in northwestern Arkansas, January-Stansbury Cave located in northeastern Oklahoma, and Nesbitt Spring Cave, located in north-central Arkansas (fig. 1)—had different hydrogeologic settings, recharge characteristics, and land use. This section describes the study area; hydrogeology; continuous discharge, precipitation, water temperature data; and local recharge area characteristics; and tracer test results for each cave.

Civil War Cave

Study Area Description

Civil War Cave is a privately-owned cave located near Bentonville in Benton County, Arkansas, and provides habitat for the Ozark cavefish. The cave entrance is through a sinkhole in the Mississippian Boone Formation (Springfield Plateau aquifer). The sinkhole is approximately at the midpoint of the open cave passage. Water enters the cave through a breakdown feature upstream from the sinkhole entrance. Because Civil War Cave is contained entirely in the Springfield Plateau aquifer, additional inflow from the aquifer is possible. The cave stream meanders irregularly through highly weathered Boone Formation, exits the open cave passage through a sump, and discharges from the cave at an unknown point. The length of total passable cave stream is approximately 640 ft.

In the area of Civil War Cave, water from the Springfield Plateau aquifer is withdrawn primarily by domestic and stock wells. Historically the major land use in the area has been agricultural (Adamski, 1997). Although agricultural practices continue, mainly confined poultry and cattle grazing operations, much of the land has recently become residential, with mostly single-family home dwellings. A very small amount of undeveloped hardwood forest currently (2007) remains.

Hydrogeology

Civil War Cave is developed entirely within the epikarst of the Springfield Plateau (fig. 2) and is recharged through the Springfield Plateau aquifer, which crops out over the entire recharge area of the cave. Approximately 1,000 ft to the southeast of Civil War Cave is the Bella Vista Fault (Glick, 1974), which is a normal fault trending northeast/southwest; Civil War Cave lies on the upthrown side of the fault. The Boone Formation dips gently to the south in the Civil War Cave area, and the measured dip of the Boone Formation ranged from 0 to 5 degrees with a dominant dip of between 0 and 1 degrees

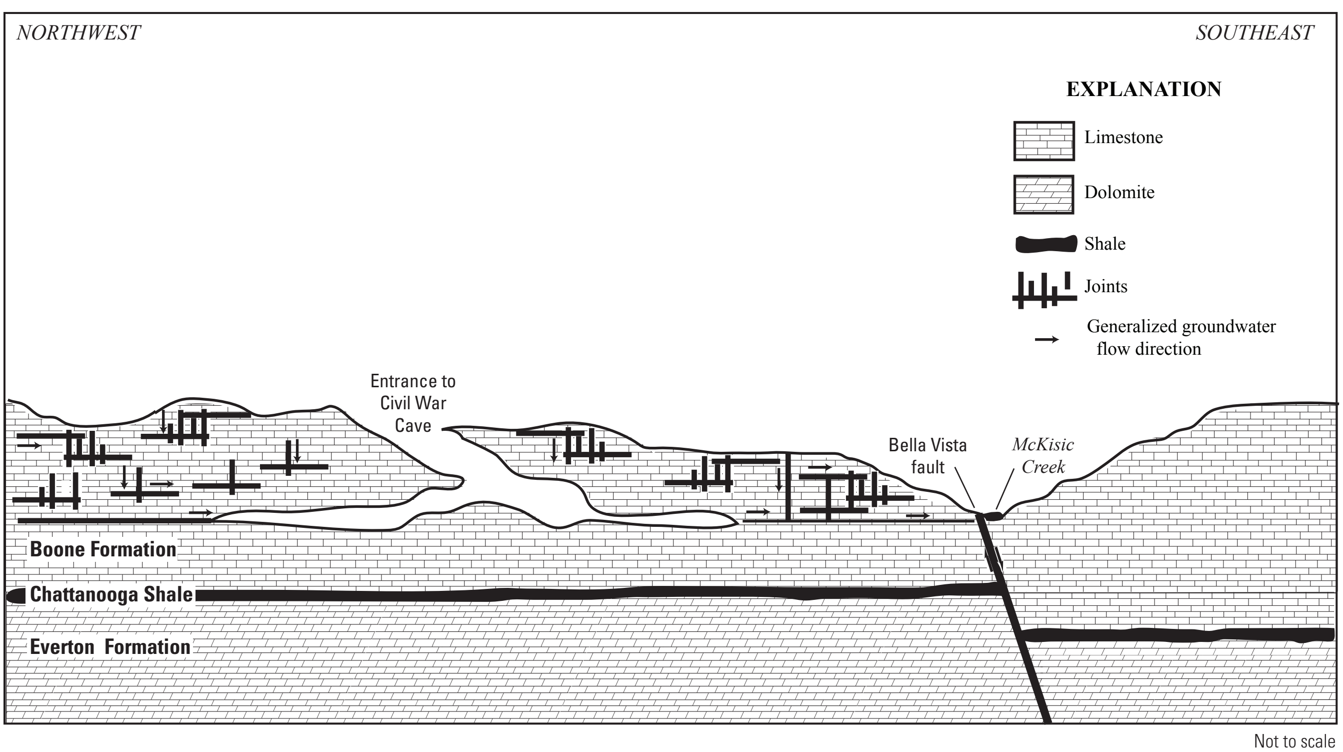

Figure 2. Conceptual model of groundwater flow to Civil War Cave, northwestern Arkansas.

with the greater dips occurring near the fault. In the area of Civil War Cave, the Chattanooga Shale of Devonian age (Ozark confining unit) underlies the Springfield Plateau aquifer, and the Ozark confining unit crops out approximately 3.5 miles southeast of the cave along the Bella Vista Fault. At this outcropping, the altitude of the top of the Ozark confining unit is 1,160 ft, and the surface altitude at Civil War Cave is 1,315 ft, indicating a thickness for the Springfield Plateau aquifer of approximately 150 ft at this location. This coincides with an isopach map of the Springfield Plateau aquifer described in Imes and Emmett (1994).

The chert content of the Springfield Plateau aquifer is highly variable in the area of Civil War Cave. Within Civil War Cave, the chert content visible in the cave walls varies from less than 10 percent to more than 80 percent with the greatest chert content in the upper reaches of the cave (Gillip, 2007). This high chert content, in general, prevents well developed karst features. In addition, the high chert content has resulted in a mantle of regolith. The regolith immediately above Civil War Cave is less than 6.5 ft thick, but regolith in excess of 30 ft thick was observed nearby. The thick regolith decreases the amount of surface-water infiltration. The Bella Vista Fault located to the southeast of Civil War Cave seems to serve as a groundwater conduit (Gillip, 2007). Locations of springs along the fault indicate local groundwater flow direction is toward the fault. McKisic Creek also is located to the southeast of Civil War Cave and drains to the northeast.

Water-quality data showed water discharging through Civil War Cave originated from the Springfield Plateau aquifer (Gillip, 2007). Gillip (2007) described six water-quality samples and field measurements (pH, water temperature, and specific conductance) collected from the upper level of Civil War Cave and nine from the lower level of Civil War Cave during base-flow conditions during 2006. The samples were analyzed for nutrients, metals, and major anions and cations. Major anions and cations measured at base-flow conditions on December 18, 2006, indicated a calcium-bicarbonate water type (Gillip, 2007), typical of a limestone aquifer such as the Springfield Plateau aquifer (Imes and Emmett, 1994; Petersen and others, 1999; Adamski, 2000) (fig. 3). The calcium to magnesium weight ratios for the upper and lower levels of Civil War Cave were 31 and 26, respectively, indicating a limestone aquifer (Hem, 1998), typical of the Springfield Plateau aquifer. The calcite saturation indices calculated for water from Civil War Cave showed the samples for the upper and lower levels of Civil War Cave were undersaturated with calcium carbonate ($CaCO_3$) (Gillip, 2007). The water in Civil War Cave was undersaturated because of the high chert content of the Springfield Plateau aquifer or because of a short residence time. The high chert content decreases the interaction between $CaCO_3$ and the water. Rapid infiltration also results in less rock-water interaction, resulting in less dissolution of $CaCO_3$.

Discharge, Water Temperature, and Precipitation

The discharge of Civil War Cave, as well as the water temperature, was measured at a temporary gage installed near the middle of the cave where the most discharge appeared to be present. The discharge data from Civil War Cave show the cave is heavily influenced by surface water for the period of study, February 2005 to May 2006 and from November 2006 to September 2007. The mean daily discharge for the period of study was 0.59 cubic foot per second (ft^3/s) and ranged from 0.19 ft^3/s to 2.8 ft^3/s (fig. 4). Base flow accounted for 83 percent of the total flow for the entire period. The ratio of base flow to peak flow ranged from 4.0 to 7.8 indicating diffuse and conduit flow (White, 1988; Galloway, 2004). The highest mean daily discharges occurred during the spring and summer and the lowest daily discharges during the fall.

Typical of conduit-dominated systems, the discharge for Civil War Cave was closely related to precipitation events. A major precipitation event occurred on August 14, 2005, and precipitation tracked closely to the peak discharge event for Civil War Cave. Three major storm events and one minor storm event occurred during the period of study and were used to approximate the recharge area of the cave (fig. 4, table 1).

The water temperature reflected seasonal changes and distinct changes after precipitation events (fig. 4). The maximum recorded water temperature at Civil War Cave was 17.0°C and the minimum recorded temperature was 11.3°C with a mean water temperature of 14.0°C. Seasonal variations in temperature were small because of the bedrock warming and cooling very slowly. During a storm event, water temperature increased as flow increased if the atmospheric temperature was greater than the temperature of the cave. A precipitation event at low temperatures decreased the water temperature in the cave. Temperature data indicated that the waters discharging through Civil War Cave mixes with runoff from the land surface. The lag time from the precipitation event until the water temperature increased or decreased was approximately 1 to 2 days after a major storm event. This is indicative of a conduit-dominated system (White, 1988).

Local Recharge Area Characterization

Civil War Cave is recharged through the Springfield Plateau aquifer, which crops out over the entire study area of the cave. The apparent topographic recharge area of Civil War Cave is approximately 0.08 mi^2. A base-flow discharge of 0.53 ft^3/s and dye trace results indicate that Civil War Cave receives water from across the major topographic divides.

The local recharge area for Civil War Cave was estimated using the water-balance equation described previously. Three major storm events and one minor storm event occurred from February 2005 to May 2006 (table 1). The calculated recharge

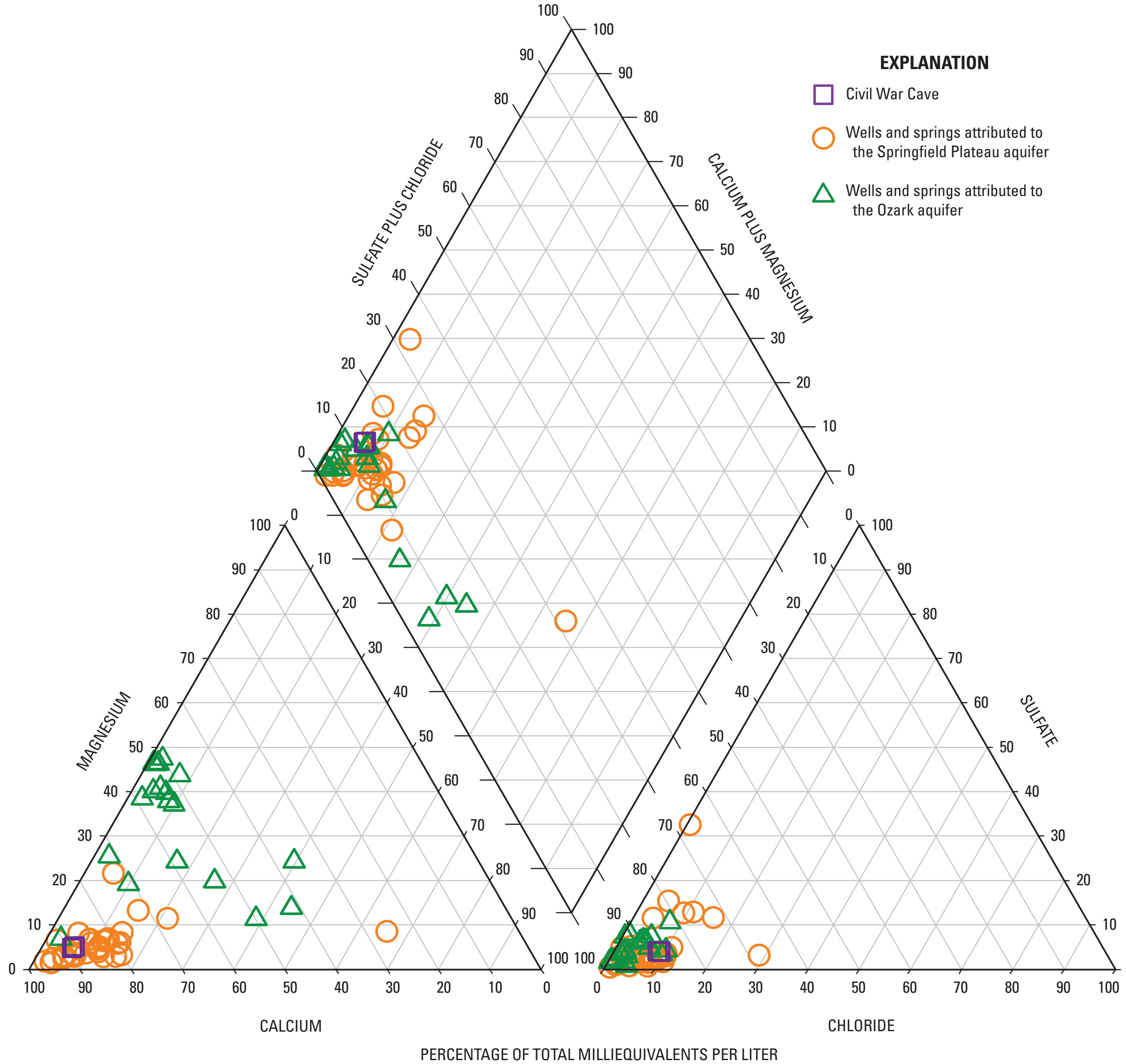

Figure 3. Relation of groundwater samples from Civil War Cave and other wells and springs in northern Arkansas and southern Missouri.

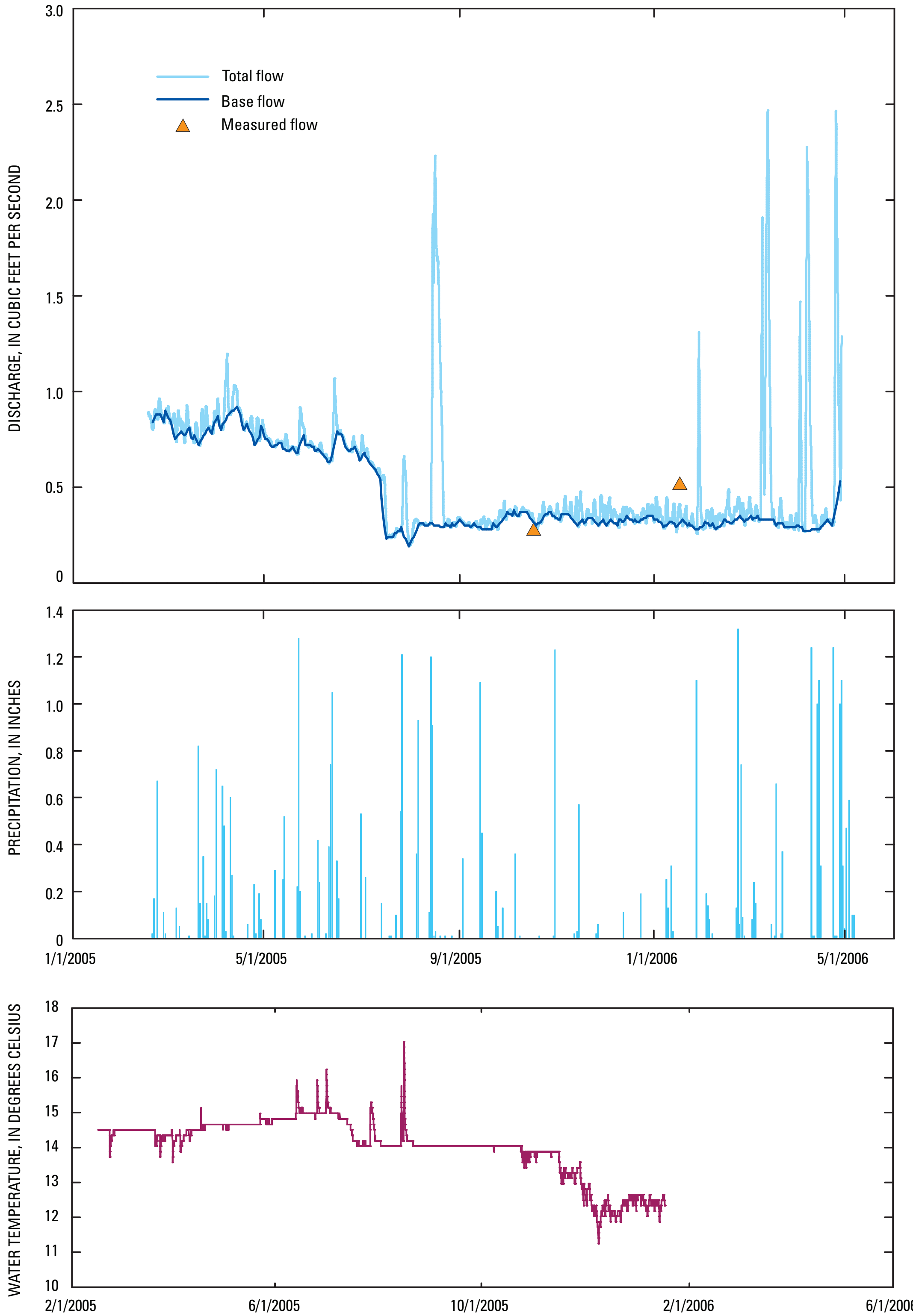

Figure 4. Discharge, water temperature, and precipitation recorded at Civil War Cave, northwestern Arkansas.

Table 1. Storm events and calculated recharge areas for Civil War Cave.

Storm Date	Total storm runoff volume (cubic feet)	Total storm precipitation (inches)	Calculated recharge area assuming all rainfall is recharge (square miles)	Calculated recharge area assuming 80 percent loss of recharge (square miles)
August 14, 2005	709,530.28	2.27	0.13	0.67
January 28, 2006	93,626.36	1.10	0.04	0.18
March 10-13, 2006	551,750.17	0.47	0.50	2.52
April 2-7, 2006	457,494.79	1.12	0.18	0.88
		Average	**0.21**	**1.06**

area using the water-balance equation ranged from 0.13 mi^2 to 0.50 mi^2 assuming all rainfall is recharge, with an average recharge area of 0.21 mi^2 under this condition. Assuming 80 percent loss of rainfall to evapotranspiration, soil moisture storage, and runoff, the estimated local recharge area using the water-balance equation ranged from 0.18 mi^2 to 2.5 mi^2 with an average local recharge area of 1.06 mi^2 assuming this condition (table 1). The topographic drainage area for Civil War Cave is approximately 0.016 mi^2 and is confined to a small area between two drainages northeast and southwest of the cave.

Brahana (1997) established that discharge at normalized base flow for the Springfield Plateau aquifer in northwestern Arkansas ranges from 0.14 to 0.29 $ft^3/s/mi^2$. An evaluation of the geology, structure, geomorphology, and hydrology of the Civil War Cave area suggests the lower range is more appropriate because of high chert content, thick regolith that decreases infiltration, groundwater drainage by other springs, and regional drainage by McKisic Creek, which acts as a groundwater-flow boundary. High nitrate concentrations suggest concentrated recharge (Gillip, 2007). Therefore, a median discharge value of those specified for the area (Brahana, 1997) of 0.17 $ft^3/s/mi^2$ was used for calculating recharge to Civil War Cave using the normalized base-flow method. Based on the discharge measurements made under base-flow conditions on January 17, 2006 (0.51ft^3/s), and October 3, 2006 (0.54 ft^3/s), the normalized base flow was approximated to be 0.53 ft^3/s for Civil War Cave. Using a normalized base flow of 0.53 ft^3/s and the value of 0.17 $ft^3/s/mi^2$, the recharge area of Civil War Cave is estimated to be 3.1 mi^2. Using the normalized base-flow range of 0.14 to 0.29 $ft^3/s/mi^2$ established by Brahana (1997), the recharge area of Civil War Cave could range from 1.8 to 3.8 mi^2. This method yields a larger recharge area than the water-balance equation. However, the ranges of the two recharge estimation methods overlap.

To estimate the geometry of the recharge area of Civil War Cave and determine if a larger recharge area contributes to the cave at high flow, a groundwater tracing study was completed. On April 21, 2005, rhodamine WT, fluorescein, and eosine dyes were injected into three losing streams near Civil War Cave that were in the McKisic Creek drainage. All of these losing streams were located outside the apparent topographic recharge area of Civil War Cave. The passive charcoal detectors were collected until August 9, 2005. The tracer tests indicated water entered Civil War Cave from across a major topographic divide located to the southwest. The tracers injected at the other two locations (fig. 5) were not recovered in Civil War Cave.

On April 11, 2007, Rhodamine WT and fluorescein were injected into two wells in an area to the north and west of the previous injection sites thought to be in the recharge area of Civil War Cave (fig. 5). The rhodamine WT was injected into an abandoned well completed in the Springfield Plateau aquifer approximately 1.5 mi northwest of Civil War Cave. The fluorescein was placed in a dry abandoned dug well approximately 2 mi west of Civil War Cave. Passive charcoal detectors were placed in a radial pattern around and within the suspected recharge area. The Rhodamine WT was not recovered. The fluorescein was recovered at a spring approximately 2 mi northwest of the injection site but not at Civil War Cave.

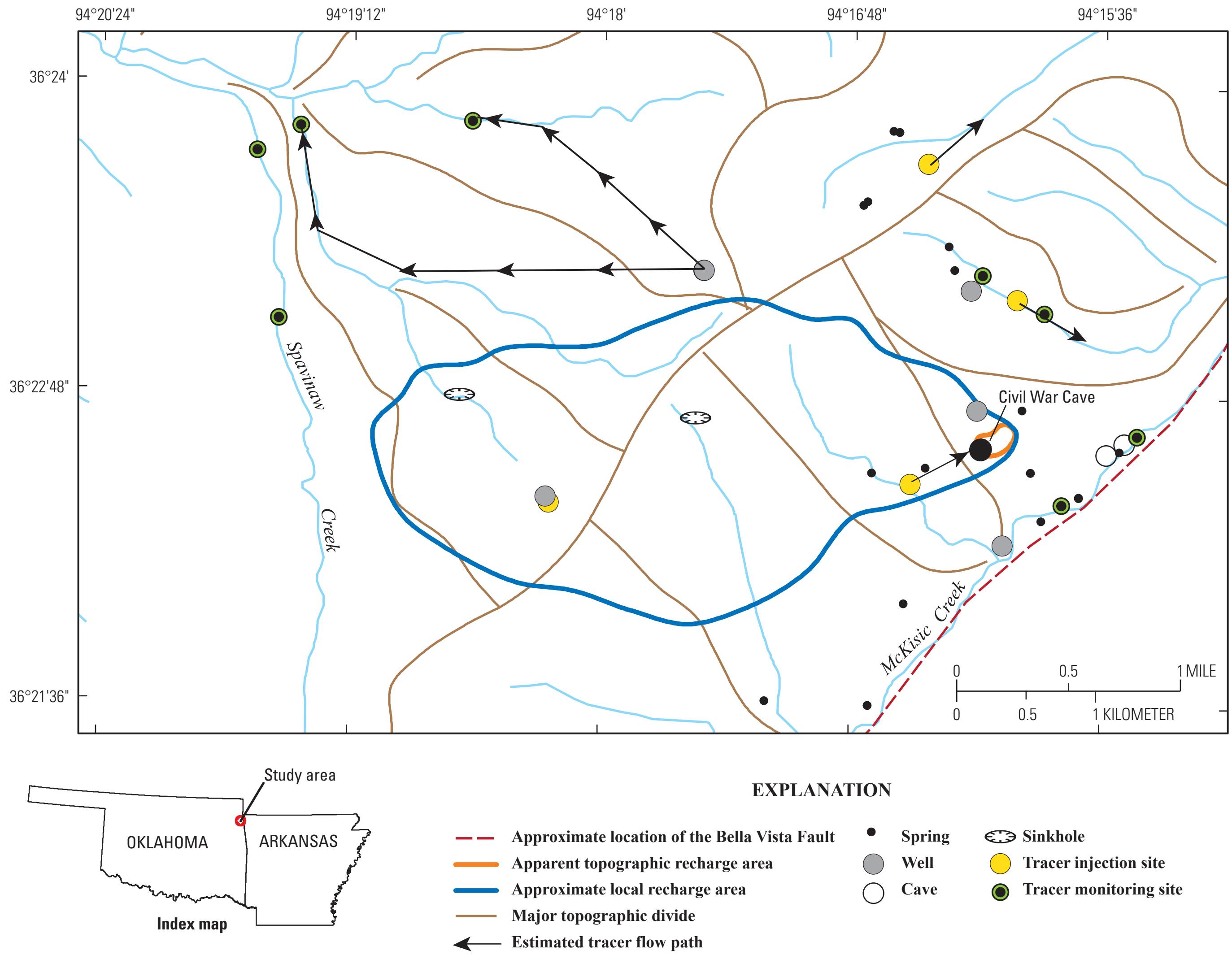

Figure 5. Approximate groundwater recharge area and groundwater tracing results, Civil War Cave, northwestern Arkansas.

January-Stansbury Cave

Study Area Description

January-Stansbury Cave is located in Delaware County in northeastern Oklahoma in the Ozark Plateau National Wildlife Refuge and provides habitat for the endangered Oklahoma cave crayfish and the threatened Ozark cavefish. The cave entrance is through the St. Joe Member of the Boone Formation and has an average passage of 16 ft wide and 6.5 ft high. January-Stansbury Cave has a total mapped passage length over 5,900 ft (Fenolio and others, 2006) and is formed by dissolution along a fracture. The January-Stansbury Spring discharges through the open cave passage in the St. Joe Limestone and Reed Springs Limestone members of the Boone Formation with a higher entrance through the Reeds Spring Limestone member of the Boone Formation. The water from the spring flows at the surface for approximately 985 ft to the confluence with Spavinaw Creek. The predominant substrate for January-Stansbury Cave is chert cobbles from the Reeds Spring Limestone member of the Boone Formation.

In the area of January-Stansbury Cave, water from the Springfield Plateau aquifer is withdrawn primarily by domestic and stock wells. January-Stansbury Cave is in a relatively undeveloped area of mixed forest and agriculture, mainly confined poultry and cattle grazing operations.

Hydrogeology

January-Stansbury is a phreatic conduit approximately 5,900 ft long with secondary vadose development. Primary karst development occurs along a well-developed fracture system. The cave is formed dominantly in the St. Joe Member of the Boone Formation (Springfield Plateau aquifer). In the area of January-Stansbury Cave, the Chattanooga Shale (Ozark confining unit) underlies the Springfield Plateau aquifer. The Ozark confining unit crops out approximately 1 mi to the west-northwest along Spavinaw Creek (fig. 6).

Discharge, Water Temperature, and Precipitation

The discharge and water temperature of January-Stansbury Cave were measured at a temporary gage installed at the spring outlet of the cave. The discharge from January-Stansbury Cave was highly variable during the period of study, February 2005 to January 2006. The daily mean discharge for the period of study was 1.0 ft^3/s and ranged from 0.35 ft^3/s to 8.7 ft^3/s (fig. 7). Base flow accounted for 78 percent of the total flow, and the ratio of base flow to peak flow ranged from 1.8 to 3.4 indicating diffuse flow (White, 1988; Galloway, 2004). The greatest discharge occurred in the spring months and steadily decreased for the remainder of the period.

The discharge corresponded to rainfall events. Larger peaks in discharge occurred with less rainfall in the late winter and spring (February through May) compared to the summer months when relatively smaller peaks in discharge occurred with greater rainfall events. This probably occurred because in the summer months there is more vegetative growth, increasing the plant uptake, rainfall interception, and evapotranspiration, resulting in drier antecedent conditions. In the winter months, minimal vegetative growth occurs, which allows rainfall to infiltrate more readily into the groundwater system. The highest mean daily discharges were during the months of April through May 2005, and the lowest daily discharges during the months of August through September 2005. A major precipitation event occurred on April 2-7, 2005, and precipitation tracked closely to the peak discharge events for January-Stansbury Cave (fig. 7). One major storm event and two minor storm events occurred during the period of study (fig. 7, table 2) and were used to estimate the recharge area.

Water temperature recorded for January-Stansbury Cave reflected seasonal changes and demonstrated little reaction to individual rainfall events. The maximum recorded water temperature at January-Stansbury Cave was 16.4°C and the minimum recorded temperature was 11.6°C with a mean water temperature of 14.3°C (fig. 7). Temperature data indicated that the waters discharging from January-Stansbury Cave mixed with runoff from the land surface during the late spring and early summer months. The lag time for the water temperature increase was approximately 3 to 4 days after a major storm event.

Table 2. Storm events and calculated recharge areas for January-Stansbury Cave.

Storm Date	Total storm runoff volume (cubic feet)	Total storm precipitation (inches)	Calculated recharge area assuming all rainfall is recharge (square miles)	Calculated recharge area assuming 80 percent loss of recharge (square miles)
April 2-7, 2005	2,283,143.74	2.94	0.33	0.83
May 23, 2005	170,859.88	1.71	0.04	0.11
June 18, 2005	365,809.46	0.50	0.31	0.79
		Average	**0.23**	**0.58**

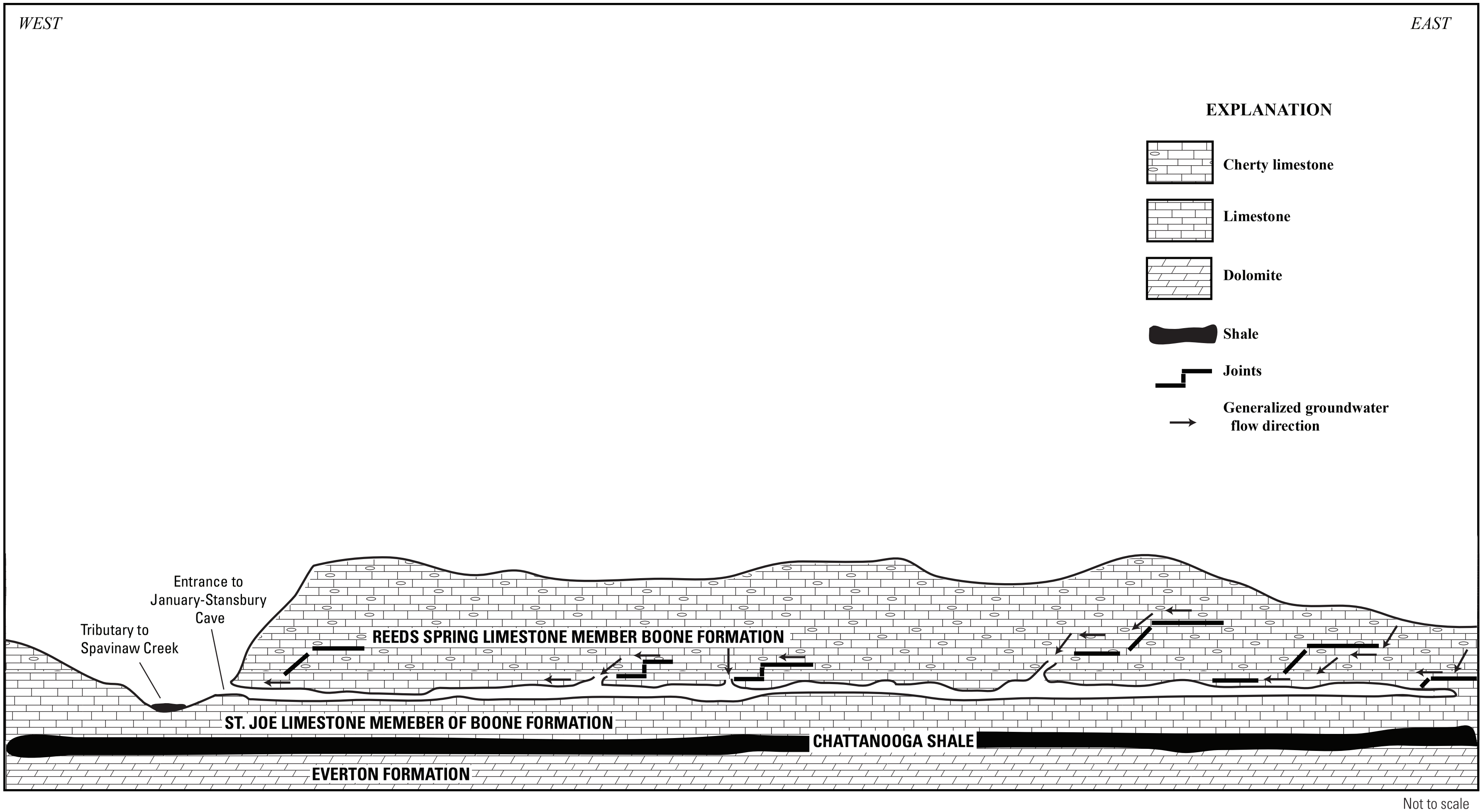

Figure 6. Conceptual model of groundwater flow to January-Stansbury Cave, northeastern Oklahoma.

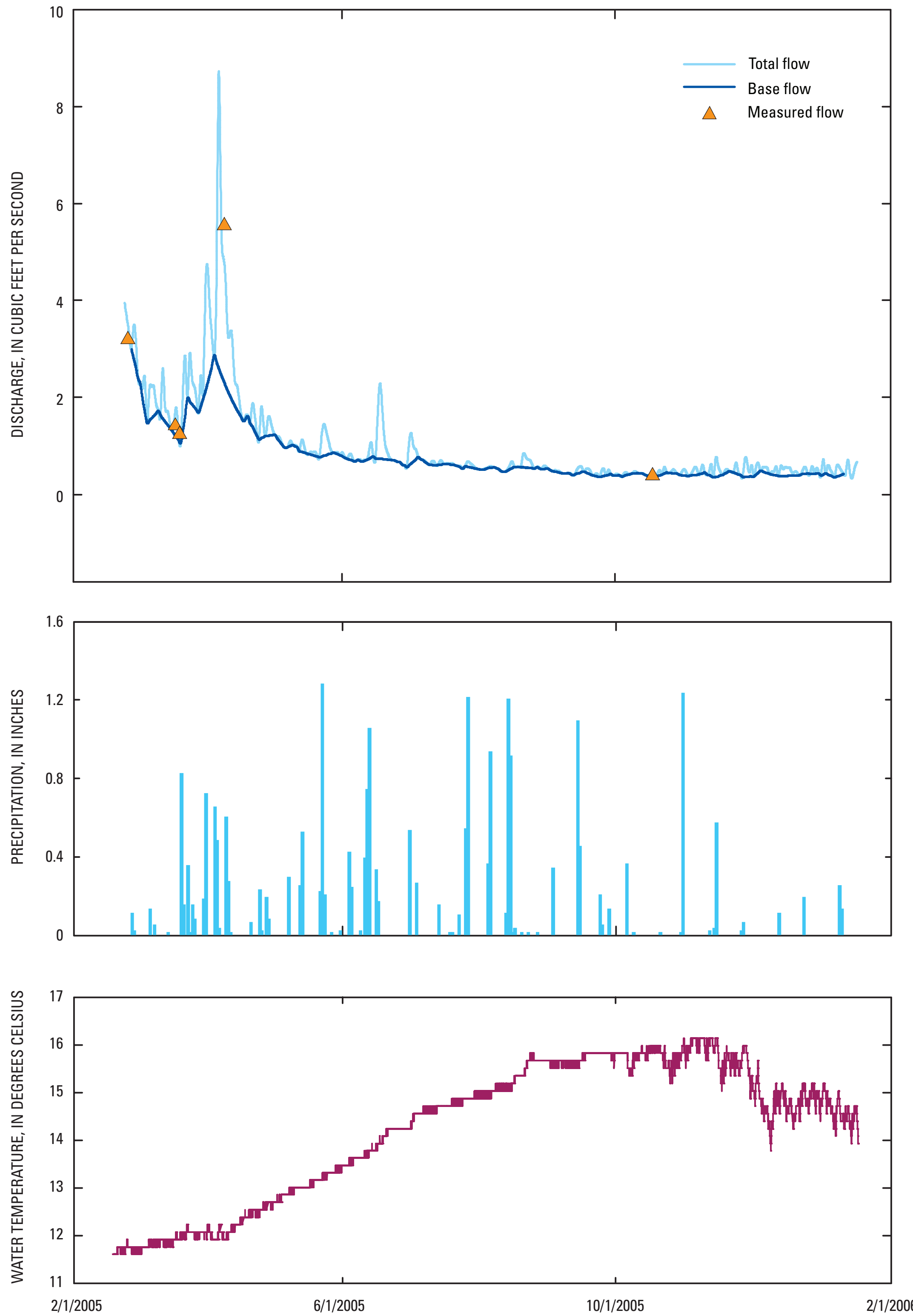

Figure 7. Discharge, water temperature, and precipitation recorded at January-Stansbury Cave, northeastern Oklahoma.

Local Recharge Area Characterization

Discharge data and groundwater tracer tests showed that the local recharge area for January-Stansbury Cave extends across the topographic drainage area. The recharge area for January-Stansbury Cave was determined using the water-balance equation described previously. One major storm event and two minor storm events occurred from February 2005 to January 2006 at January-Stansbury Cave (table 2). The calculated recharge area using the water-balance equation ranged from 0.04 mi^2 to 0.33 mi^2 assuming all rainfall is recharge, with an average recharge area of 0.23 mi^2 under this condition. Assuming 80 percent loss of rainfall to evapotranspiration, soil moisture storage, and runoff, the calculated recharge area ranged from 0.11 to 0.83 mi^2 with the average recharge area of 0.58 mi^2 with this condition (table 2). The apparent topographic recharge area for January-Stansbury Cave is very small and is located in the immediate vicinity of the cave.

To estimate the geometry of the recharge area of January-Stansbury Cave and determine if a larger recharge area contributes to the cave at high flow, a groundwater tracing study was completed. The groundwater tracer test showed that water entered January-Stansbury Cave from within the apparent topographic recharge area and across a major topographic divide to the southwest (fig. 8). On April 21, 2005, rhodamine WT, fluorescein, and eosine dyes were injected into a sinkhole and two losing streams near January-Stansbury Cave. All of these losing features were located outside the topographic recharge area of January-Stansbury Cave. Passive charcoal detectors were collected until August 9, 2005. The tracer injected into a losing stream approximately 1.3 mi southeast of January-Stansbury Cave (fig. 8) was not recovered.

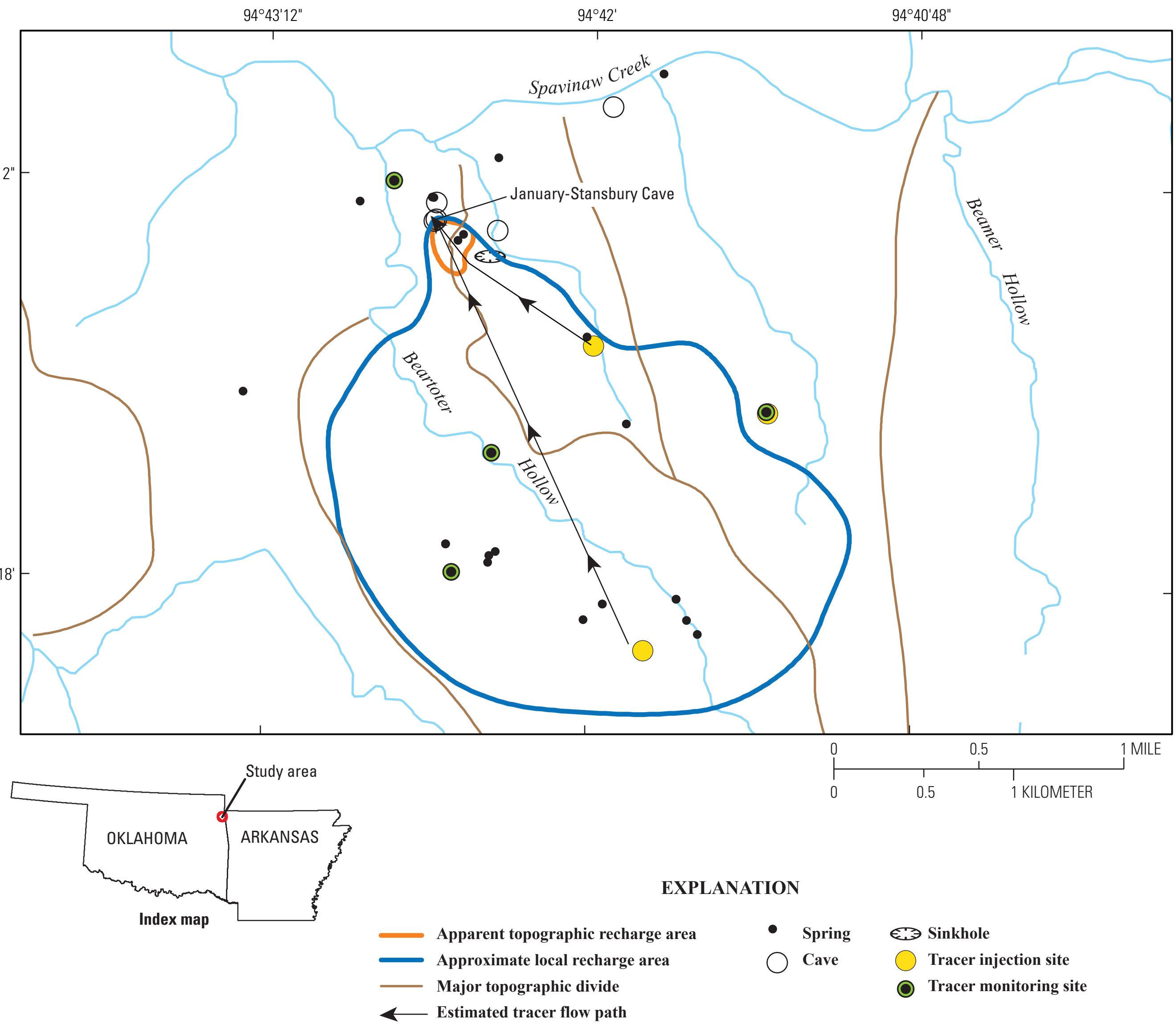

Figure 8. Approximate groundwater recharge area and groundwater tracing results, January-Stansbury Cave, northeastern Oklahoma.

Nesbitt Spring Cave

Study Area Description

Nesbitt Spring Cave, a privately owned karst spring located near the city of Mountain View in north-central Arkansas, provides habitat for the Hell Creek cave crayfish, a Federally endangered species, and is one of only two locations where the rare crayfish is found (Graening and others, 2006b). Nesbitt Spring Cave discharges from the Ordovician Plattin Limestone (Ozark aquifer) and the overlying Ordovician Fernvale/Kimmswick Limestone (Ozark aquifer) and the Mississippian Boone Formation (Springfield Plateau aquifer). The Springfield Plateau aquifer is used primarily as a source of water for domestic and stock-watering wells (Renken, 1998). The dominant land use within the Nesbitt Spring study area is agriculture (cattle and poultry) and mixed forest.

Hydrogeology

The geology within the Nesbitt Spring area is predominantly Ordovician- through Mississippian-age limestone with some shale and chert. Dominant structural features include caves, sinkholes, and enlarged vertical fractures. The land surface consists of a thin soil layer developed predominantly on the Boone Formation. Nesbitt Spring Cave discharges from the Ozark aquifer and is recharged through the Springfield Plateau aquifer (fig. 9). The discharging spring and accompanying creek flows approximately 0.25 mi from the mouth of the cave to the confluence with Rocky Bayou. Nesbitt Spring Cave has an opening that is approximately 40 ft wide and 10 ft high. The accessible part of the cave passage, which trends around 105 degrees, extends approximately 0.125 mi to the east-southeast before becoming impassible.

Water-quality data indicated water discharging from Nesbitt Spring Cave originated from the Springfield Plateau aquifer (Scheiderer, 2007). Scheiderer (2007) described two water-quality samples and field measurements (pH, water temperature, and specific conductance) collected during base-flow conditions on February 2, 2006, and July 21, 2006. The samples were analyzed for major anions and cations, which indicated a calcium-bicarbonate water type, typical of a limestone aquifer (Hem, 1989) such as the Springfield Plateau aquifer (Imes and Emmett, 1994; Petersen and others, 1999; Adamski, 2000) (fig. 10). The calcium to magnesium weight ratios ranged from 16.3 to 24.3, also indicating dissolution of limestone rock

Discharge, Water Temperature, and Precipitation

The discharge and water temperature of Nesbitt Spring Cave were measured at a temporary gage installed a short distance inside the cave where all discharge appeared to be present. Discharge for Nesbitt Spring Cave responded rapidly to precipitation for the period of study from February 2006 to December 2006. The daily mean discharge for the period of

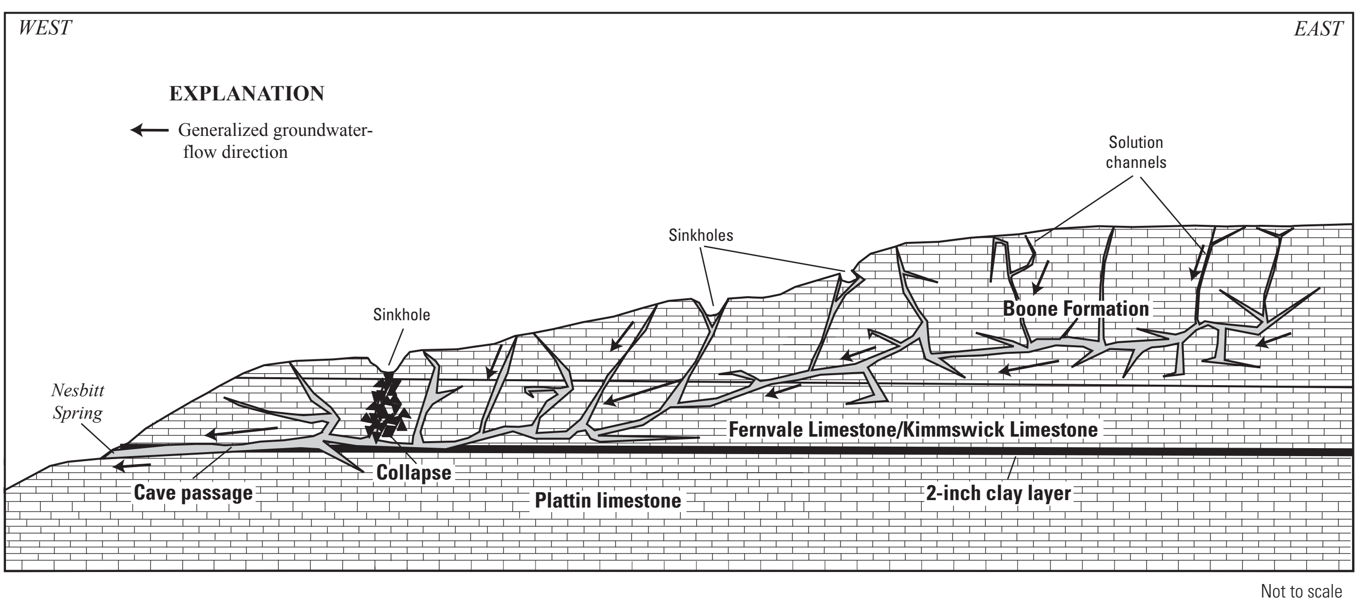

Figure 9. Conceptual model of groundwater flow to Nesbitt Spring Cave, north-central Arkansas.

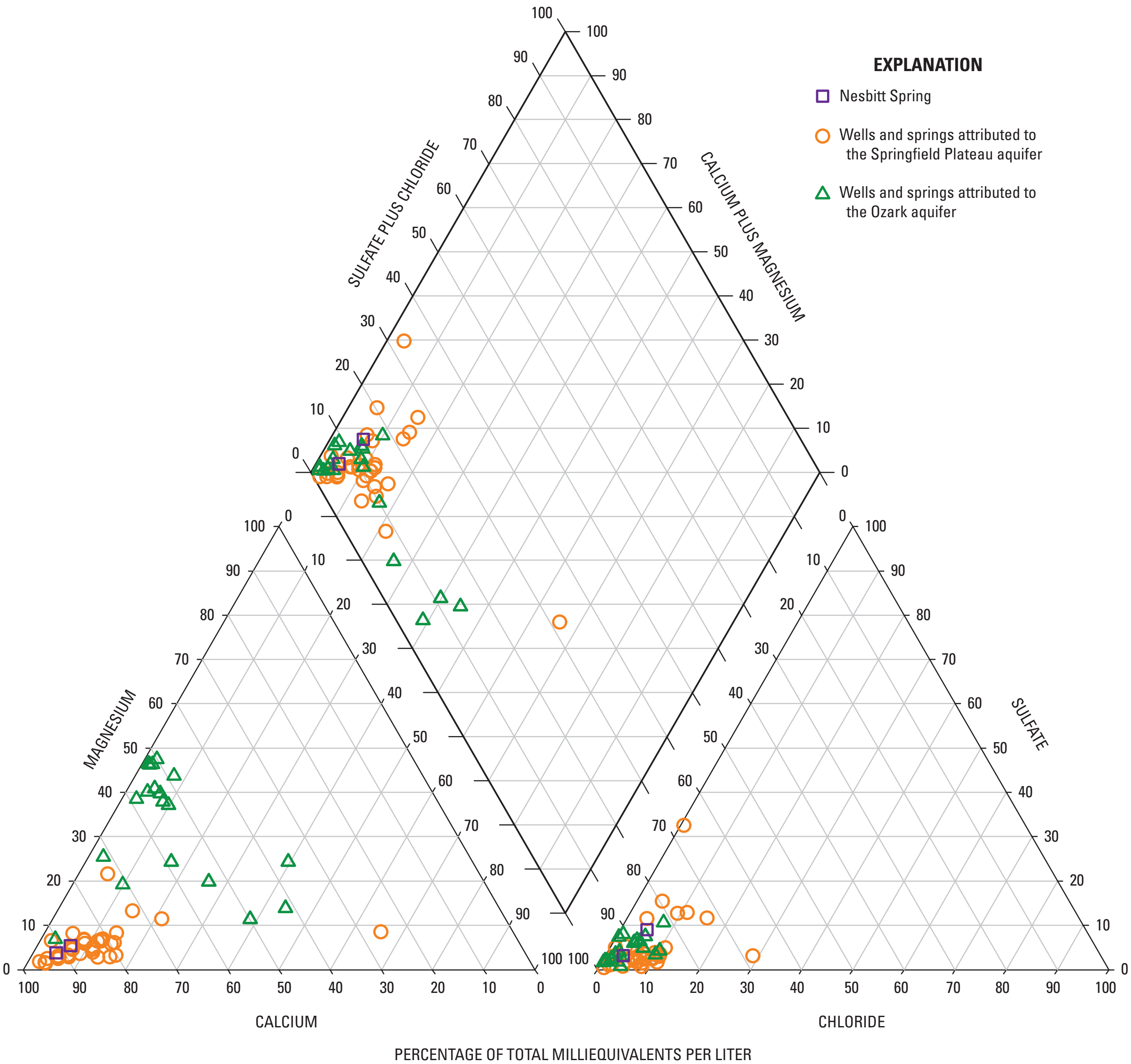

Figure 10. Relation of groundwater samples from Nesbitt Spring Cave and other wells and springs in northern Arkansas and southern Missouri.

study was 4.5 ft^3/s and ranged from 0.39 ft^3/s to 70.7 ft^3/s (fig. 11). Discharge was highly variable and base flow accounted for 47 percent of the total flow. The ratio of base flow to peak flow ranged from 6.0 to 11.8 indicating diffuse and conduit flow (White, 1988; Galloway, 2004). The highest mean daily discharges were during the months of April 2006 through May 2006 and the lowest mean daily discharges were during the months of August 2006 through September 2006.

Typical of conduit-dominated systems, the discharge for Nesbitt Spring closely followed precipitation events. Four major storm events (2.45-2.90 inches) and four minor storm events (1.03-1.89 inches) occurred during the study (fig. 11; table 3). A major storm event occurred on March 9, 2006, and was followed by the largest spring discharge of 97.5 ft^3/s, although the storm event did not have the greatest amount of precipitation of all storm events (fig. 11). This is probably because precipitation is measured by a tipping-bucket rain gage, which does not accurately measure the rainfall acorss the entire basin. Intense local rainfall at the gage location may not have occurred in the vicinity of the cave.

The maximum recorded water temperature at Nesbitt Spring was 14.9°C and the minimum recorded temperature was 13.4°C with a mean water temperature of 14.2°C from February 2006 to December 2006 (fig. 11). Water temperature recorded for Nesbitt Spring Cave showed variation among seasons and showed noticeable fluctuations during storm events (fig. 11). Changes in water temperature reflected the temperature of precipitation, and there was a slight increase in overall temperature from the winter/spring months to the summer months. Temperature data indicated that the waters discharging from Nesbitt Spring Cave mixed with runoff from the land surface. The lag time for the water temperature increase was approximately 1 to 2 days after a major storm event.

Local Recharge Area Characterization

The discharge from Nesbitt Spring Cave is representative of the regional groundwater flow paths. The recharge area for Nesbitt Spring was determined using the water-balance equation described previously using the four major and four minor storm events that occurred during from February 2006 to December 2006 at Nesbit Spring Cave. The calculated recharge area using the water-balance equation ranged from 0.49 mi^2 to 2.0 mi^2 assuming all rainfall is recharge with an average recharge area of 1.3 mi^2 under this condition. Assuming 50 percent loss of rainfall to evapotranspiration, soil moisture storage, and runoff, the calculated recharge area ranged from 0.98 mi^2 to 4.0 mi^2 and averaged 2.6 mi^2 with this condition (table 3). The topographic recharge area for Nesbitt Spring Cave is 0.02 mi^2 and located in the immediate vicinity of the cave (fig. 12).

To estimate the geometry of the recharge area of Nesbitt Spring Cave and determine if a larger recharge area contributes to the cave at high flow, a groundwater tracing study was completed. On March 15, 2007, rhodamine WT, fluorescein, and eosine dyes were injected into three sinkholes near Nesbitt Spring Cave. The passive charcoal detectors were collected until May 25, 2007. One tracer was injected at a location within the apparent topographic recharge area, and the other two tracers were injected outside the topographic recharge area. The tracer injected within the apparent topographic recharge area was detected in the cave, while the other tracers were not recovered (fig. 12).

Ground-water discharge showed that a portion of the water discharging from Nesbitt Spring Cave during high flow was received from outside the topographic recharge area. The chemical makeup of the water indicated that the flow path may be confined within the Springfield Plateau aquifer. Therefore, the estimated recharge area is bounded by the outcrop of the Springfield Plateau aquifer.

Table 3. Storm events and calculated recharge areas for Nesbitt Spring Cave.

Storm Date	Total storm runoff volume (cubic feet)	Total storm precipitation (inches)	Calculated recharge area assuming all rainfall is recharge (square miles)	Calculated recharge area assuming 50 percent loss of recharge (square miles)
March 9, 2006	8,318,417.03	2.45	1.46	2.92
March 21, 2006	4,086,960.65	1.03	1.71	3.42
April 30, 2006	6,499,964.21	2.66	1.05	2.10
May 4, 2006	11,407,137.54	2.45	2.00	4.01
May 10, 2006	1,802,962.16	1.49	0.52	1.04
November 6, 2006	2,169,529.25	1.89	0.49	0.98
November 16, 2006	6,668,993.55	1.51	1.90	3.80
December 1, 2006	8,650,496.78	2.90	1.28	2.57
		Average	**1.30**	**2.61**

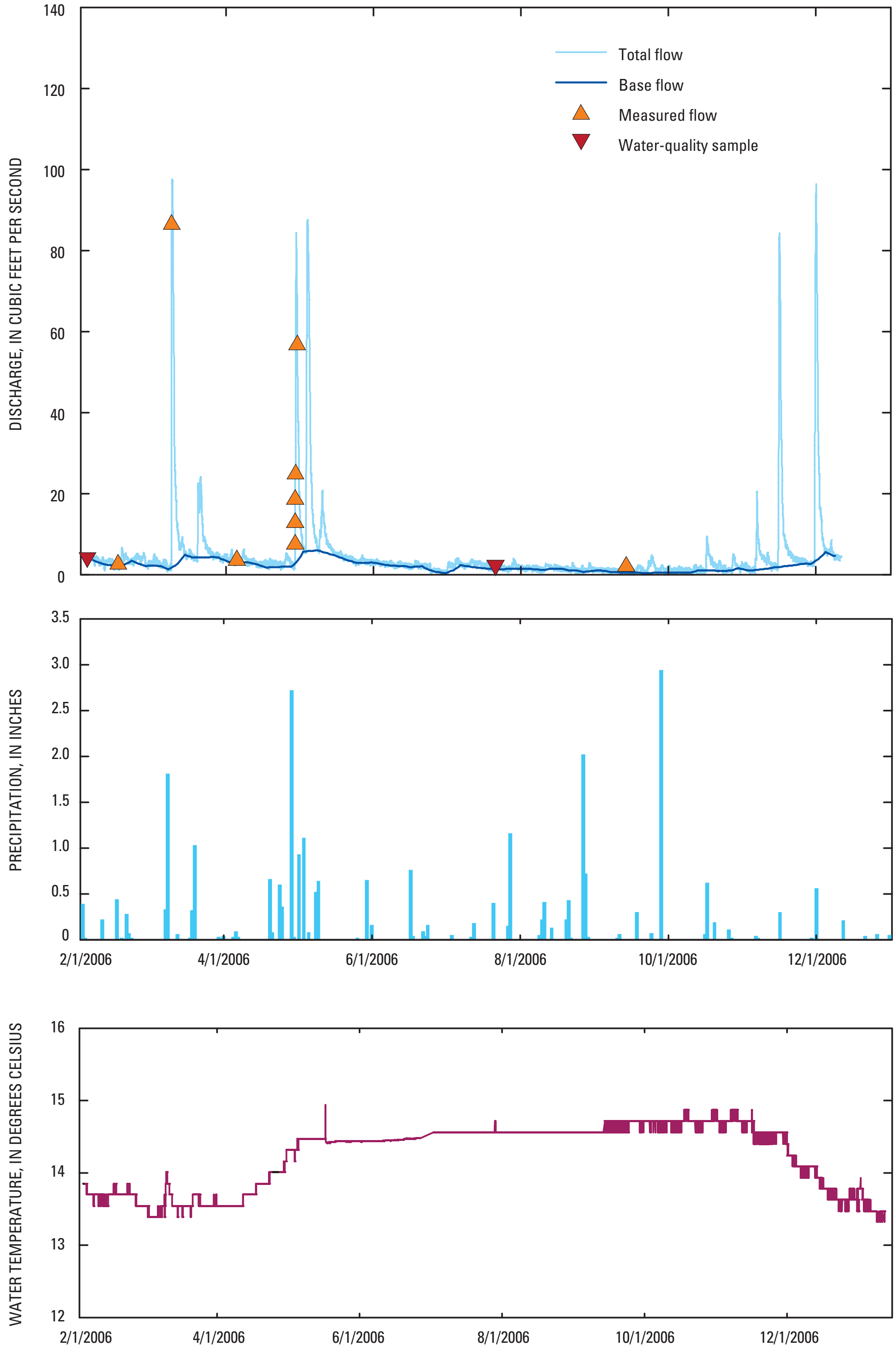

Figure 11. Discharge, water temperature, and precipitation recorded at Nesbitt Spring Cave, north-central Arkansas.

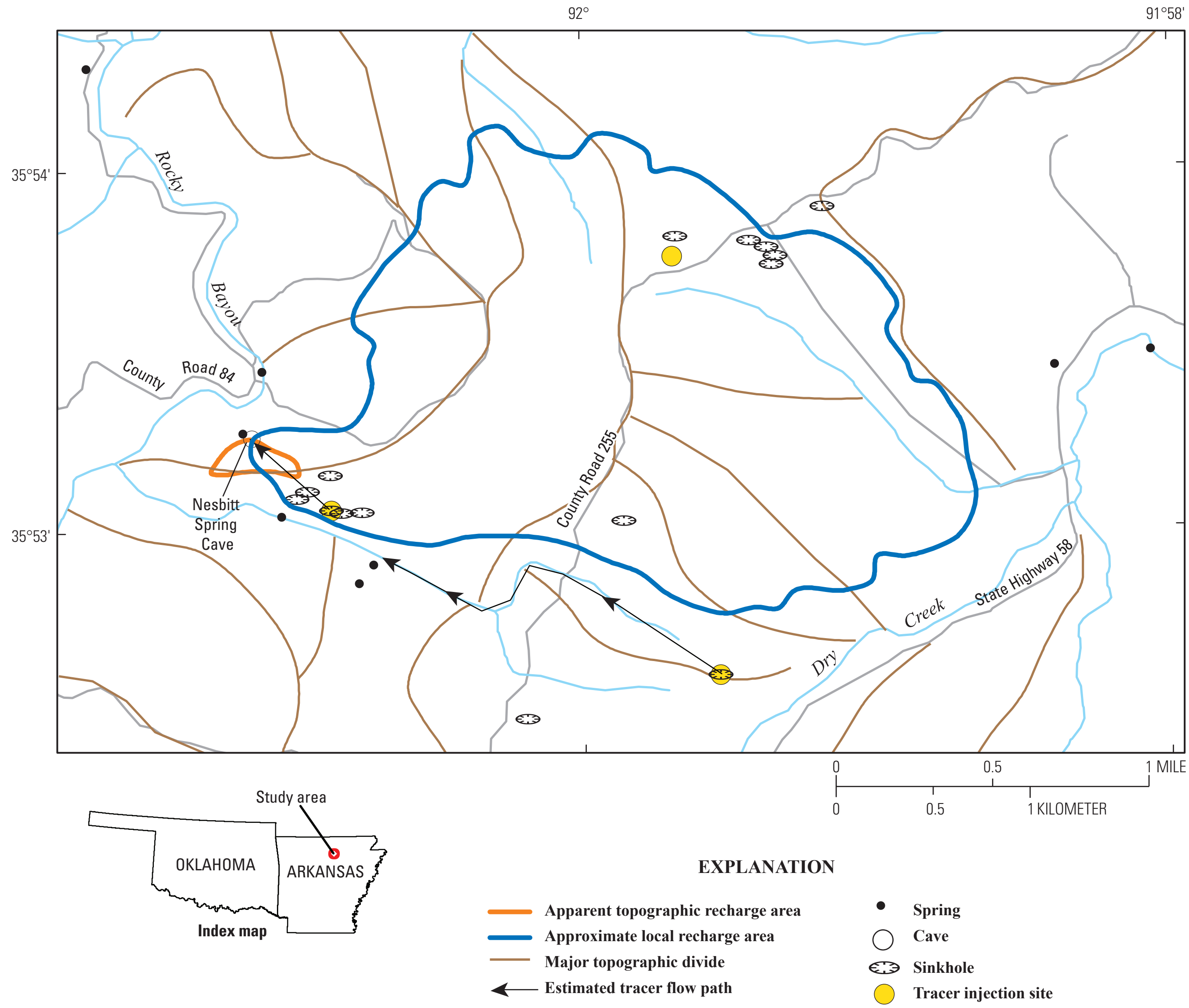

Figure 12. Approximate groundwater recharge area and groundwater tracing results, Nesbitt Spring Cave, north-central Arkansas.

Wasson's Mud Cave

Study Area

Wasson's Mud Cave is a privately owned cave located near the town of Springtown in Benton County, Arkansas. The cave entrance is through a sinkhole in the Boone Formation near Flint Creek. The cave is mantled by alluvial deposits from Flint Creek. The slope above the sinkhole is unstable, frequently collapsing, and blocking the entrance of the cave. The cave is formed by solutional enlargement along a fracture and bedding planes in the Boone Formation. The cave is very shallow with very little rock over the top of the cave. At the entrance and other locations, the cave is open to the overlying regolith and alluvial deposits (fig. 13).

Hydrogeology

Wasson's Mud Cave is developed along a fracture and bedding plane in the Boone Formation. The observable part of Wasson's Mud Cave is contained in the epikarst of the Boone Formation (Springfield Plateau aquifer) at a shallow depth (less than 8 ft) and is near Flint Creek. The immediate topographic recharge area consists of less than 0.01 mi^2 around the opening of the cave. Direct recharge to Wasson's Mud Cave occurs by surface water entering the sinkhole entrance and the thin epikarst of the Springfield Plateau aquifer. Previous studies suggest zones of high transmissivity in the valleys concurrent with observed photolineaments, indicating a structural control (Martin, 1999). The water-level altitude in the cave is similar to the water level in Flint Creek. Flint Creek is strongly connected to the shallow groundwater system in the area (Martin, 1999). The similar water-level altitude indicates Wasson's Mud Cave also is tied to the shallow groundwater system and Flint Creek. Along Flint Creek groundwater flows to the southeast as indicated by the many springs that discharge along Flint Creek upstream from the cave. These springs contribute a substantial amount of flow to Flint Creek.

Water Temperature, Precipitation, and Water Levels

No measureable flow was observed in Wasson's Mud Cave, although water level and water temperature were monitored from February 2005 to January 2006 at a temporary gage established in the main pool of Wasson's Mud Cave. The water-level and water-temperature monitors frequently were out of the water because of fluctuations in the water level. The maximum recorded water temperature at Wasson's Mud Cave was 17.8°C and the minimum recorded temperature was 7.6°C with a mean temperature of 13.6°C (fig. 14). Temperature

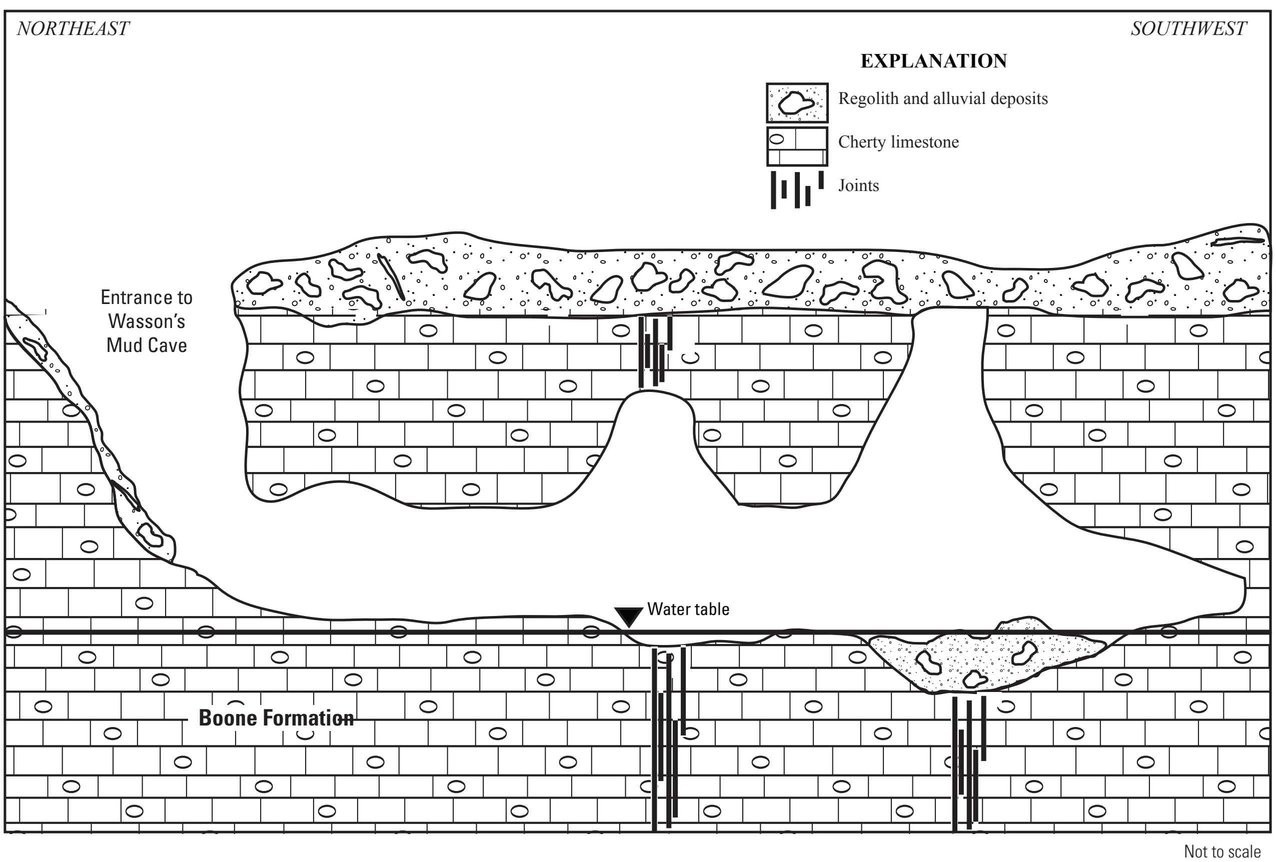

Figure 13. Conceptual model of groundwater flow to Wasson's Mud Cave, northwestern Arkansas.

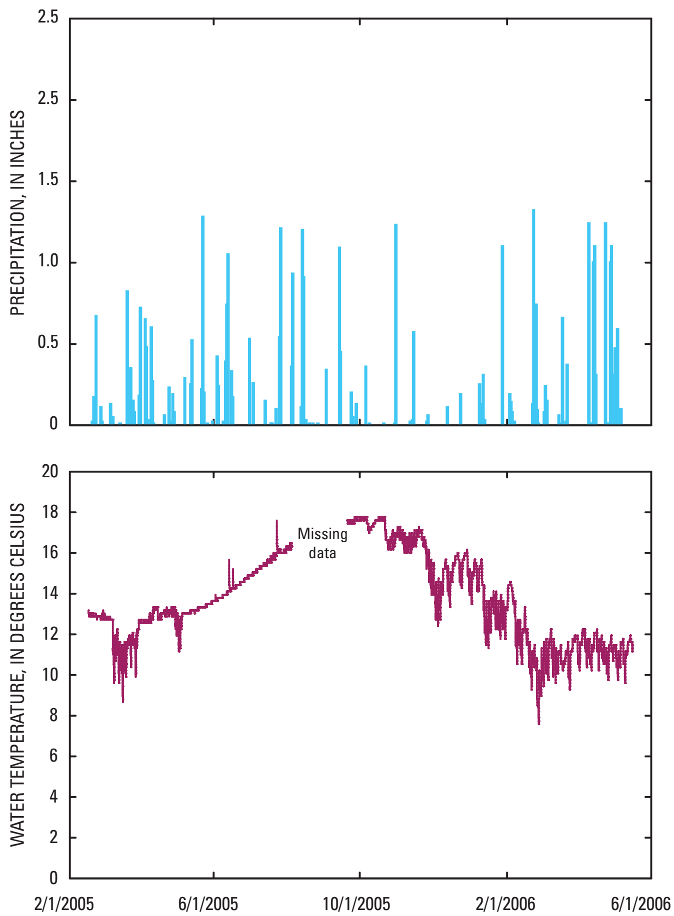

Figure 14. Water temperature, precipitation, and water levels recorded at Wasson's Mud Cave, northwestern Arkansas.

recorded for Wasson's Mud Cave showed noticeable variation among seasons, indicating a strong connection to surface conditions. Slow response to changes in the temperature and stage data recorded at a nearby gage on Flint Creek shows that Wasson's Mud Cave is not directly connected to Flint Creek (fig.14).

Local Recharge Area Characterization

A small area, less than 0.01 mi^2, drains directly into the sinkhole entrance of Wasson's Mud Cave. A groundwater tracing study was attempted with dyes being injected within the Flint Creek Basin and in adjacent drainages. Tracers were injected into streams 0.4 mi and 0.5 mi south of Wasson's Mud Cave, across a major topographic divide, and 1.0 mi upstream (northeast) of Wasson's Mud Cave into a dry tributary of Flint Creek. Passive charcoal collectors were sampled for 3 months. No dye was recovered, therefore, this study proved ineffective in delineating the recharge area of Wasson's Mud Cave.

A previous study used groundwater-level measurements from the USGS National Water Information System (NWIS) database and land-surface altitude data to create a potentiometric-surface map for the Flint Creek Basin (Martin, 1999). Water levels were obtained in wet and dry seasons. The dry-season levels were measured on September 12 and 13, 1994, and the wet-season levels were measured from May 15 through 18, 1995. A comparison of the water levels showed little difference between water levels measured during wet and dry conditions (Martin, 1999). Wet-season water levels were used to create the potentiometric surface because they would be indicative of the maximum groundwater contribution to the basin. In addition to the wells, the water level in Flint Creek and the altitudes of springs also were used to construct the potentiometric surface.

The potentiometric-surface map (Martin, 1999) indicates that the groundwater surface is a subdued reflection of the topography and shows little change in observed water levels along the valleys in the Flint Creek Basin. This lack of increased water-level altitudes despite increased recharge indicates zones of high transmissivity in the valleys, which are concurrent with observed photolineaments (Martin, 1999). Structure, therefore, probably is the main control of groundwater flow in the Flint Creek Basin. Wasson's Mud Cave is developed along a fracture and bedding plane in the Boone Formation. The groundwater in Flint Creek Basin flows downgradient to Flint Creek and towards the cave. This indicates that recharge to Wasson's Mud Cave includes a small topographic area within the Flint Creek Basin in the immediate vicinity of the cave along with potential recharge from portions of the Flint Creek Basin upstream from the cave. The possibility of water crossing major topographic divides, especially under high-flow conditions, cannot be eliminated. The low gradient of the potentiometric surface along Flint Creek is consistent with the observation of no flow in Wasson's Mud Cave.

Summary

A study was conducted from October 2004 to July 2007 by the U.S. Geological Survey in cooperation with the U.S. Fish and Wildlife Service to characterize the local recharge areas of four caves in northern Arkansas and northeastern Oklahoma that provide habitat to a number of unique organisms. Characterization of the local recharge areas that contribute water to caves and provide habitat for endangered or threatened aquatic organisms is important because of their occurrence in a predominately karst system, and because land use proximal to the cave, including areas suspected to lie within the cave's local recharge area, may include activities with potentially deleterious impacts on cave water quality.

An integrated approach was used to determine the hydrogeologic characteristics and the extent of the local recharge areas of Civil War Cave, January-Stansbury Cave, Nesbitt Spring Cave, and Wasson's Mud Cave. This approach incorporated methods of hydrology, structural geology, geomorphology, and geochemistry. Continuous water-level and water-temperature data were collected at each cave and precipitation data from the area of the cave were collected for various periods to determine flow characteristics and recharge areas. Field investigations were conducted to determine surficial controls affecting the groundwater flow and connections of the groundwater system to land-surface processes in each study area. Qualitative groundwater tracing studies were conducted at each cave to help characterize the local recharge areas. These independent methods of investigation are tools that can provide evidence for effectively describing the behavior of these complex hydrologic systems.

Civil War Cave is located near Bentonville in Benton County, Arkansas, and provides habitat for the Ozark cavefish. Civil War Cave is developed entirely within the epikarst of the upper Boone Formation (Springfield Plateau aquifer) and recharge to Civil War Cave occurs through the Springfield Plateau aquifer. The mean daily discharge at the gage for the period of study was 0.59 ft^3/s and ranged from 0.19 ft^3/s to 2.8 ft^3/s. The mean water temperature for Civil War Cave was 14.0°C and water temperature increased approximately 1 to 2 days after a major storm event. The topographic drainage area for Civil War Cave is very small and located in the immediate vicinity of the cave. The calculated recharge area using the water-balance equation ranged from 0.13 mi^2 to 2.5 mi^2. The average local recharge area was 0.21 mi^2 assuming all rainfall as recharge, and 1.06 mi^2 assuming 80 percent loss to evapotranspiration, soil moisture storage, and runoff. Using the normalized base flow approximation method, the recharge area of Civil War Cave could range from 1.8 mi^2 to 3.8 mi^2. Tracer tests indicate water entered Civil War Cave from across a major topographic divide located to the southwest.

January-Stansbury Cave is located in Delaware County in northeastern Oklahoma, and provides habitat for the Oklahoma cave crayfish and the Ozark cavefish. January-Stansbury Cave is developed in the St. Joe Limestone and Reeds Springs Limestone members of the Boone Formation (Springfield Plateau aquifer) and recharge to January-Stansbury Cave occurs through the Springfield Plateau aquifer. The daily mean discharge for the period of study was 1.0 ft^3/s and ranged from 0.35 ft^3/s to 8.7 ft^3/s. The mean water temperature for January-Stansbury Cave was 14.3°C and water temperature increased approximately 3 to 4 days after a major storm event. The topographic drainage area for January-Stansbury Cave is very small and located in the immediate vicinity of the cave. The calculated recharge area for January-Stansbury Cave using the water-balance equation ranged from 0.04 mi^2 to 0.83 mi^2. The average local recharge area was 0.23 mi^2 assuming all rainfall as recharge, and 0.58 mi^2 assuming 80 percent loss to evapotranspiration, soil moisture storage, and runoff. Tracer tests showed, in general, water discharging from January-Stansbury Cave during high flow was received from within the topographic drainage area and from an area outside the topographic drainage area to the southwest.

Nesbitt Spring Cave is located near the city of Mountain View in north-central Arkansas, and provides habitat for the Hell Creek cave crayfish. Nesbitt Spring Cave is developed in the Plattin Limestone (Ozark aquifer) and is recharged through the Springfield Plateau aquifer. The mean daily discharge for the period of study was 4.5 ft^3/s and ranged from 0.39 ft^3/s to 70.7 ft^3/s. The mean water temperature for Nesbitt Spring Cave was 14.2°C and water temperature increased approximately 1 to 2 days after a major storm event. The topographic recharge area for Nesbitt Spring Cave is very small and located in the immediate vicinity of the cave. The calculated recharge area for Nesbitt Spring Cave using the water-balance equation ranged from 0.49 mi^2 to 4.0 mi^2. The average local recharge area was 1.3 mi^2 assuming all rainfall as recharge, and 2.6 mi^2 assuming 50 percent loss to evapotranspiration, soil moisture storage, and runoff. Tracer tests showed, in general, water discharging from Nesbitt Spring during high flow was received from outside the topographic drainage area.

Wasson's Mud Cave is located near the town of Springtown in Benton County, Arkansas, and provides habitat for the Ozark cavefish. Wasson's Mud Cave consists of solutionally enlarged passages along a fracture and bedding plane, within the epikarst of the upper Boone Formation (Springfield Plateau aquifer) and recharge to Wasson's Mud Cave occurs directly by surface water entering the sinkhole entrance and from the epikarst of the Springfield Plateau aquifer. No flow was observed although the water level did fluctuate. The immediate topographic recharge area is less than 0.01 mi^2 and located in the immediate vicinity of the cave. A potentiometric-surface map created from previous work indicated that the groundwater surface in the Flint Creek Basin is a subdued reflection of the topography. This indicates that recharge to Wasson's Mud Cave includes the small topographic recharge area in the immediate vicinity of the cave along with potential recharge from the parts of the Flint Creek Basin upstream from the cave, and potentially groundwater from across major topographic divides.

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