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Geohydrologic Investigations and Landscape Characteristics of Areas Contributing Water to Springs, the Current River, and Jacks Fork, Ozark National Scenic Riverways, Missouri

Scientific Investigations Report 2009–5138

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

Cover photograph. Big Spring branch looking downstream from spring orifice, September, 2001 (photograph courtesy of Jeffrey L. Imes, U.S. Geological Survey).

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By Douglas N. Mugel, Joseph M. Richards, and John G. Schumacher

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Conversion Factors, Abbreviations, and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Length	
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)

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

$$°F=(1.8\times°C)+32$$

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

$$°C=(°F-32)/1.8$$

Altitude and elevation data are referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)

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

Altitude and elevation, as used in this report, refer to distance above the vertical datum.

Geohydrologic Investigations and Landscape Characteristics of Areas Contributing Water to Springs, the Current River, and Jacks Fork, Ozark National Scenic Riverways, Missouri

By Douglas N. Mugel, Joseph M. Richards, and John G. Schumacher

Abstract

The Ozark National Scenic Riverways (ONSR) is a narrow corridor that stretches for approximately 134 miles along the Current River and Jacks Fork in southern Missouri. Most of the water flowing in the Current River and Jacks Fork is discharged to the rivers from springs within the ONSR, and most of the recharge area of these springs is outside the ONSR. This report describes geohydrologic investigations and landscape characteristics of areas contributing water to springs and the Current River and Jacks Fork in the ONSR.

The potentiometric-surface map of the study area for 2000–07 shows that the groundwater divide extends beyond the surface-water divide in some places, notably along Logan Creek and the northeastern part of the study area, indicating interbasin transfer of groundwater between surface-water basins. A low hydraulic gradient occurs in much of the upland area west of the Current River associated with areas of high sinkhole density, which indicates the presence of a network of subsurface karst conduits. The results of a low base-flow seepage run indicate that most of the discharge in the Current River and Jacks Fork was from identified springs, and a smaller amount was from tributaries whose discharge probably originated as spring discharge, or from springs or diffuse groundwater discharge in the streambed.

Results of a temperature profile conducted on an 85-mile reach of the Current River indicate that the lowest average temperatures were within or downstream from inflows of springs. A mass-balance on heat calculation of the discharge of Bass Rock Spring, a previously undescribed spring, resulted in an estimated discharge of 34.1 cubic feet per second (ft^3/s), making it the sixth largest spring in the Current River Basin.

The 13 springs in the study area for which recharge areas have been estimated accounted for 82 percent (867 ft^3/s of 1,060 ft^3/s) of the discharge of the Current River at Big Spring during the 2006 seepage run. Including discharge from other springs, the cumulative discharge from springs was over 90 percent of the river discharge at most of the spring locations, and was 92 percent at Big Spring and at the lower end of the ONSR. The discharge from the 1.9-mile long Pulltite Springs Complex measured in the 2006 seepage run was 88 ft^3/s. Most of this (77 ft^3/s) was from the first approximately 0.25 mi of the Pulltite Springs Complex. It has been estimated that the annual mean discharge from the Current River Springs Complex is 125 ft^3/s, based on an apparent discharge of 50 ft^3/s during a 1966 U.S. Geological Survey seepage run. However, a reinterpretation of the 1966 seepage run data shows that the discharge from the Current River Springs Complex instead was about 12.6 ft^3/s, and the annual mean discharge was estimated to be 32 ft^3/s, substantially less than 125 ft^3/s. The 2006 seepage run showed a gain of only 12 ft^3/s from the combined Round Spring and Current River Springs Complex from the mouth of Sinking Creek to 0.7 mi upstream from Root Hollow. The 2006 temperature profile measurements did not indicate any influx of spring discharge throughout the length of the Current River Springs Complex.

The spring recharge areas with the largest number of identified sinkholes are Big Spring, Alley Spring, and Welch Spring. The spring recharge areas with the largest number of sinkholes per square mile of recharge area are Alley Spring, Blue Spring (Jacks Fork), Welch Spring, and Round Spring and the Current River Springs Complex. Using the currently known locations of losing streams, the Big Spring recharge area has the largest number of miles of losing stream, and the Bass Rock Spring recharge area has the largest number of miles of losing stream per unit recharge area. The spring recharge areas with the most open land and the least forested land per unit recharge area are Blue Spring (Jacks Fork), Welch Spring, Montauk Springs, and Alley Spring. The spring recharge areas with the least amount of publicly owned land per unit recharge area are Montauk Springs, Blue Spring (Jacks Fork), Cave Spring, Welch Spring, and the Pulltite Springs Complex.

Introduction

The Ozark National Scenic Riverways (ONSR) was established as a national park in 1964 to preserve the Current River and Jacks Fork in southern Missouri, and is

administered by the National Park Service (NPS). The park is a narrow corridor that stretches for approximately 134 miles (mi) along the two rivers, encompassing 80,785 acres (fig. 1). The park is mostly in Shannon and Carter Counties, but also in small parts of Dent and Texas Counties. The park contains numerous caves and springs, including four first magnitude springs [average daily flow greater than 65 Mgal/d (million gallons per day; National Park Service, 2008)]. About 1.5 million people visit the ONSR each year for canoeing, hiking, camping, fishing, horseback riding, and other recreational activities.

The ONSR is a narrow corridor, but the sources of water to the ONSR cover a large area outside that corridor. Most of the water flowing in the Current River and Jacks Fork is discharged to the rivers from springs within the ONSR, and most of the recharge area of these springs is outside the ONSR. Surface water is a large component of river discharge during runoff events, and most of the drainage areas of the Current River and Jacks Fork are outside the ONSR. An understanding of the geohydrology outside the ONSR, therefore, is important to manage the water resources of the ONSR. Certain landscape characteristics are important because they affect how precipitation falling on the land surface moves from areas outside the park to the park. These characteristics vary throughout the area contributing water to the ONSR, and knowledge of this variation allows for a better understanding of where, for example, precipitation is likely to recharge the groundwater system and later discharge at springs along the ONSR. To improve understanding of the geohydrology and landscape characteristics in and outside the ONSR, the U.S. Geological Survey (USGS) conducted a study during 2006–08 in cooperation with the National Park Service.

Description of the Study Area

The study area (fig. 1) was selected to encompass the ONSR and any surrounding land that could conceivably contribute water to the ONSR by surface runoff or groundwater flow. The study area is the Current River surface-water basin upstream from the lower boundary of the ONSR, expanded to include an approximately 2-mi wide buffer around the groundwater divide for groundwater flowing to the Current River and Jacks Fork and spring recharge areas that extend outside the groundwater or surface-water divides. Also included is the drainage area of the losing reach of the Eleven Point River in the southwestern part of the study area. This area is not in the Big Spring recharge defined by Imes and others (2007) because they did not consider two dye traces from this area to Big Spring (Aley and Aley, 1987) to be conclusive. Because a conservative approach was taken to include any area that could conceivably contribute water to the ONSR, this area is included in the study area for the cooperative study.

The ONSR is located within the Salem Plateau of the Ozark Plateaus Physiographic Province (Fenneman, 1938). The Salem Plateau is a large area of uplifted Cambrian- and Ordovician-age sedimentary strata in southern Missouri and northern Arkansas. It is characterized by rolling hills and rugged terrain, with narrow steep-walled valleys and generally thin soils. The Current River, Jacks Fork and their tributaries have incised deep valleys into the generally gently rolling upland terrain, with as much as several hundred feet of local relief.

The core of the uplifted Salem Plateau is the St. Francois Mountains in southeastern Missouri, an area of exposed Precambrian-age intrusive and volcanic igneous rocks (figs. 1, 2, and 3). Precambrian volcanic rocks also are exposed in the study area within and near the ONSR, including along the Current River (fig. 3). Younger, Paleozoic sedimentary rocks were deposited on the Precambrian surface, beginning with the Cambrian-age Lamotte Sandstone. The Lamotte Sandstone is exposed at the surface surrounding Precambrian knobs in the St. Francois Mountains northeast of the study area, but is not exposed in the study area, and is present only in the subsurface. The overlying Cambrian-age Bonneterre Formation, Davis Formation, and Derby-Doerun Dolomite also are exposed at the land surface in the St. Francois Mountains but are present only in the subsurface in the study area.

The Cambrian-age Potosi Dolomite overlies the Derby-Doerun Dolomite and is the oldest Paleozoic formation to crop out in the study area. It is exposed in places along the Current River and its tributaries and can be more than 400 ft (feet) thick in the subsurface (Orndorff and others, 1999; Weary and Schindler, 2004; Weary and McDowell, 2006). The Potosi Dolomite is a massive bedded, vuggy dolostone with quartz druse and chert (Thompson, 1995).

The Cambrian-age Eminence Dolomite overlies the Potosi Dolomite and is a massive bedded dolostone with small amounts of chert and quartz druse. It ranges in thickness up to 270 ft or more (Orndorff and others, 1999) and locally is as thick as 350 ft in south-central Missouri (Thompson, 1995). Many of the bluffs along the Current River and its tributaries are formed by the Eminence Dolomite.

The Ordovician-age Gasconade Dolomite overlies the Eminence Dolomite. It is a dolostone with variable amounts of chert and has a sandstone to sandy dolostone basal unit (Gunter Sandstone Member). It averages about 300 ft thick in south-central Missouri (Thompson, 1995). The Gasconade Dolomite forms many of the bluffs along the Current River and its tributaries and also underlies upland regions in the study area. Erosion of bedrock units that dip peripherally away from the St. Francois Mountains has resulted in an outcrop pattern of progressively younger bedrock units from the northeast to the southwest in the study area (fig. 3). It is for this reason that the Gasconade Dolomite underlies more of the land surface on the northeastern side of the Current River, and younger formations underlie a larger portion of the land surface on the southwestern side of the Current River (fig. 3).

Overlying the Gasconade Dolomite is the Ordovician-age Roubidoux Formation. The lithology of the Roubidoux Formation ranges from dolostone to cherty dolostone to sandy dolostone to sandstone. Its thickness ranges from about 100 to

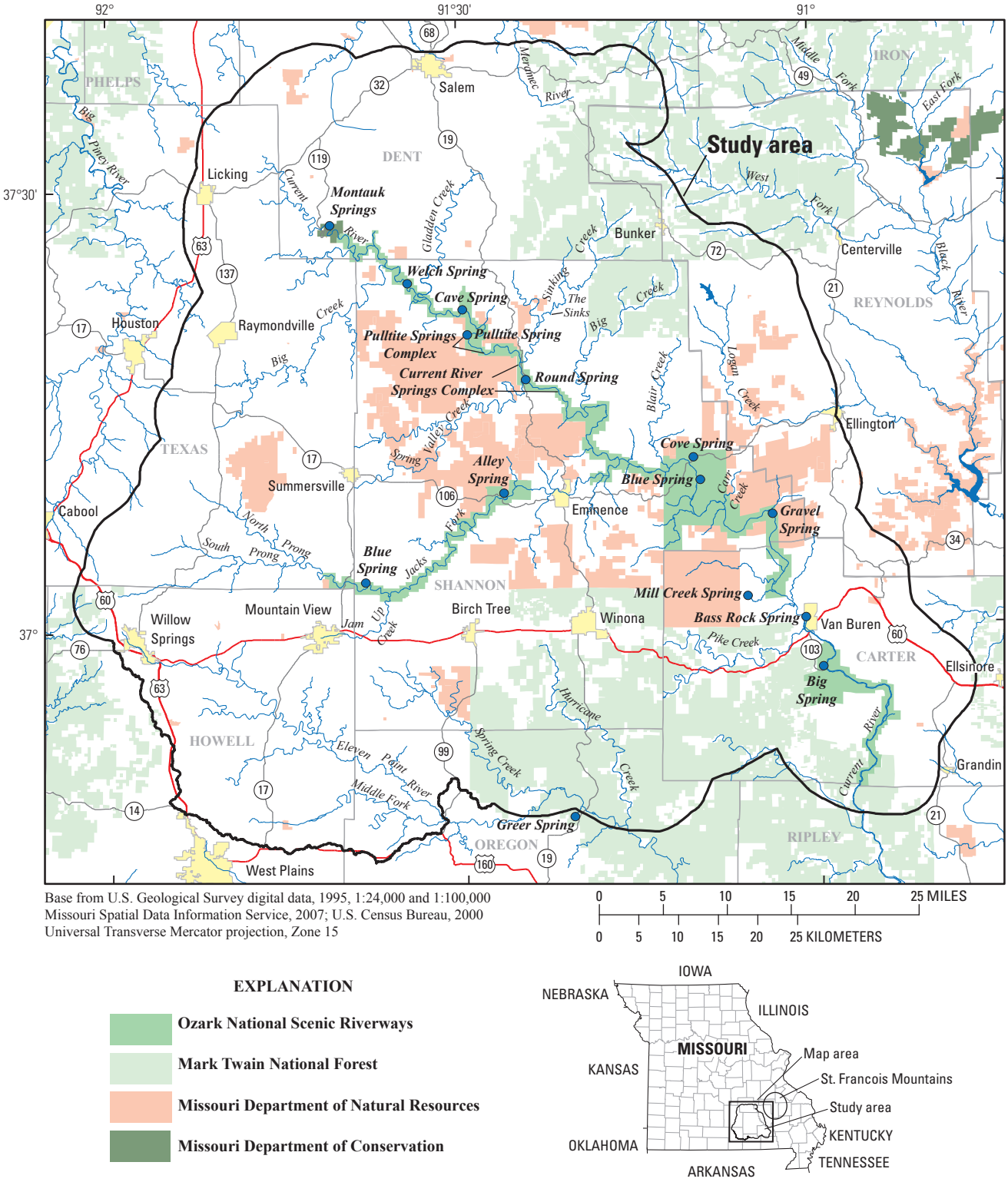

Figure 1. Study area showing locations of streams, selected springs, and public land ownership.

TIME-STRATIGRAPHIC UNIT		ROCK-STRATIGRAPHIC UNIT	REGIONAL GEOHYDROLOGIC UNIT
ERA	SYSTEM		
PALEOZOIC	ORDOVICIAN	Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite	Ozark aquifer
	CAMBRIAN	Eminence Dolomite Potosi Dolomite	
		Elvins Group Derby-Doerun Dolomite Davis Formation	St. Francois confining unit
		Bonneterre Formation Lamotte Sandstone	St. Francois aquifer
PRECAMBRIAN		Precambrian intrusive and volcanic igneous rocks	Basement confining unit

Modified from Imes, 1990a; Geologic nomenclature follows that of the Missouri Division of Geology and Land Survey (Missouri Department of Natural Resources, 2003)

Figure 2. Hydrostratigraphic units in the study area.

250 ft (Weary and Schindler, 2004). The Roubidoux Formation underlies upland areas, particularly in the northwestern part of the study area and southwest of the Current River, and also underlies the upper reaches of some of the tributaries of the Current River.

The Jefferson City Dolomite overlies the Roubidoux Formation and is the youngest formation in the study area. It is a dolostone with chert, and may contain lenses of orthoquartzite, conglomerate, and shale. The Jefferson City Dolomite can be as much at 350 ft thick in Missouri (Thompson, 1991), but its full thickness is not preserved anywhere in the study area because its upper part has been eroded. The Jefferson City Dolomite underlies upland areas in the western part of the study area (fig. 3).

Faults shown on figure 3 are reproduced from those shown at 1:500,000 scale on the State geologic map (Missouri Department of Natural Resources, 2003). Detailed geologic mapping in parts of the study area at 1:24,000 scale (for example, Orndorff and others, 1999) has revealed more faults than are shown on figure 3. Faults are generally steep and most have a northwest or northeast trend (Orndorff and others, 2001). Normal, strike-slip, and reverse faults have been identified (Ordorff and others, 1999). Vertical joints occur in two dominant sets: 340° to 0° and 70° to 90° (Orndorff and others, 2001). Structural control of some stream locations is suggested by straight-line stream segments and alluvial valleys.

Geologic formations have been grouped into regional geohydrologic units depending on relative rock permeability and well yield (Imes, 1990a; fig. 2). The Basement confining unit consists of Precambrian igneous rocks, and has a low permeability except where faults and fractures are present or where weathering at the land surface has increased rock permeability. Wells in the Basement confining unit yield less than 10 gal/min (gallons per minute; Imes and others, 2007). The overlying St. Francois aquifer consists of the Lamotte Sandstone and the Bonneterre Formation. Wells open to these units yield sufficient water for domestic or small-capacity public-supply wells (Imes and others, 2007), but the St. Francois aquifer generally is used where overlying, more productive units are not present. The overlying St. Francois confining unit consists of the low-permeability Davis Formation and Derby-Doerun Dolomite, and restricts groundwater flow between the St. Francois aquifer and the overlying Ozark aquifer. The Ozark aquifer consists of the Potosi Dolomite, Eminence Dolomite, Gasconade Dolomite, Roubidoux Formation, and Jefferson City Dolomite, and is as much as about 1,500 ft thick in the southwestern part of the study area (Imes, 1990b). It is the major supplier of water throughout much of Missouri. The Potosi Dolomite is the most permeable formation in the Ozark aquifer, and wells open to this unit can yield from several hundred to 1,000 gal/min (Fuller and others, 1967; Imes and Emmett, 1994). Although the Eminence Dolomite contains caves and some of the larger springs in the study area, regionally it has less secondary porosity and permeability than the Potosi Dolomite (Imes and Emmett, 1994), and in places may form a weak barrier to groundwater flow between the overlying Gasconade Dolomite and the underlying Potosi Dolomite (Mugel and Imes, 2003). The Gasconade Dolomite and the Roubidoux Formation commonly yield from several tens to several hundred gallons per minute of water (Melton, 1976). The Jefferson City Dolomite is less permeable region-

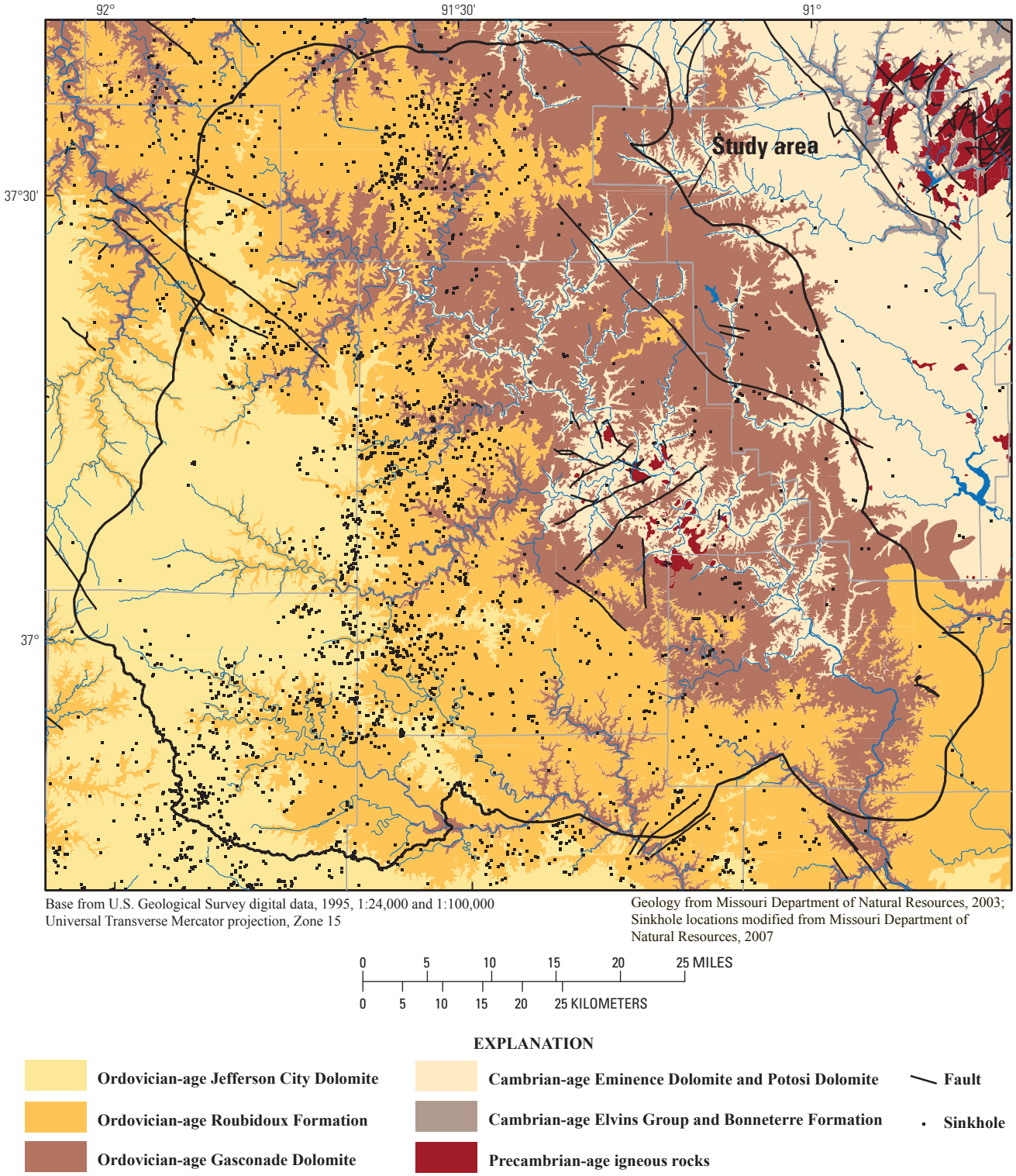

Figure 3. Bedrock geology of the study area and locations of faults and sinkholes.

ally than underlying units in the Ozark aquifer (Imes and Emmett, 1994).

The karst terrain of the study area is characterized by many sinkholes, springs, caves, and losing streams, which are linked by a complex and poorly understood underground drainage system of fractures and conduits (Imes and others, 2007). Over 2,000 sinkholes have been identified in the study area by the Missouri Division of Geology and Land Survey (DGLS; Missouri Department of Natural Resources, 2007; fig. 3). Sinkholes vary in size and character from small (20 ft or

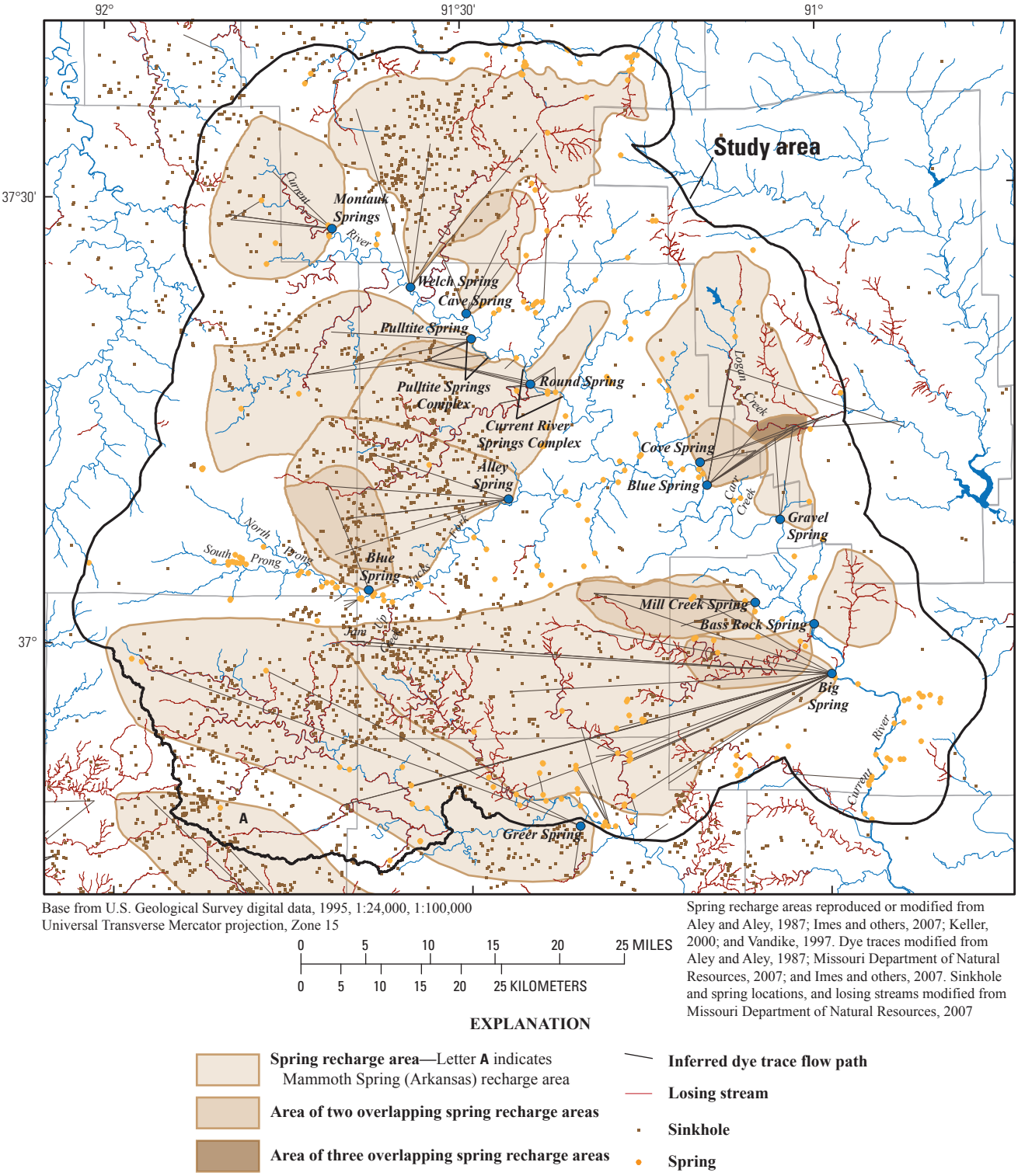

Figure 4. Locations of dye traces, spring recharge areas, sinkholes, springs, and losing streams.

less) circular depressions that are only a few feet deep, to large [up to 0.25 square miles (mi²)] circular or irregular-shaped sinkholes that are up to several tens of feet deep, and are the result of the coalescence of several sinkholes. Most sinkholes in the study area occur in the outcrop area of the Roubidoux Formation, with a lesser number in the outcrop area of the Jefferson City Dolomite (and most of these occurring close to the contact with the Roubidoux Formation), and fewer in the outcrop area of the Gasconade Dolomite (fig. 3). The result is a concentration of sinkholes north and southwest of the Current River, and fewer on the northeastern side of the Current River where the Gasconade Dolomite crops out in most places.

This pattern breaks down somewhat in the far southwestern part of the study area and south of the study area, where sinkholes are abundant in the outcrop area of the Jefferson City Dolomite. Two large topographic depressions in creeks (The Sinks on Sinking Creek, and Jam Up Creek; fig. 1) were removed from the DGLS sinkhole coverage for this study and are not shown on figure 3 because they are not sinkholes but are streams that flow through natural tunnels and emerge on the other side of the tunnel.

Losing streams are common in the study area. Those losing streams identified as such by the DGLS (Missouri Department of Natural Resources, 2007) are shown in figure 4, with modification to four streams based on seepage runs performed by the USGS (Kleeschulte, 2000; Kleeschulte, 2008; Schumacher, 2008). The DGLS determines that a stream is losing on the basis of a Missouri Clean Water Commission regulation that defines a losing stream as a stream that loses 30 percent or more of its flow during low-flow conditions into a bedrock aquifer within 2 mi of an existing or proposed discharge (Missouri Department of Natural Resources, 1996), and uses geomorphic criteria to make a determination when flow data are not available. Other losing stream segments probably exist but are not identified on figure 4 because specific studies have not been performed. Losing streams occur where areas of high streambed hydraulic conductivity exist in combination with groundwater levels below the streambed altitude (Imes and others, 2007). During periods of intense or extended precipitation resulting in a large amount of runoff, the capacity of the losing stream to capture water can be exceeded, and some stream discharge can continue downstream. This is characteristic of an overflow allogenic karst drainage basin (Ray, 2001), where a surface overflow channel is maintained (further evolution of a subsurface conduit system can result in an underflow allogenic basin where surface-water channels are no longer maintained – this does not appear to be the case of karst in the Current River Basin).

Over 270 springs have been identified in the study area (Missouri Department of Natural Resources, 2007; fig. 4). Springs range in size from small springs that may flow intermittently, to Big Spring, the largest spring in Missouri (Vineyard and Feder, 1982) with an annual mean discharge of 446 ft^3/s (cubic feet per second; U.S. Geological Survey, 2008a). Greer Spring, the second largest spring in Missouri, is a short distance south of the study area (fig. 4).

Land use/land cover (fig. 5) is based on interpretation of spectral reflectance data by the University of Missouri, School of Natural Resources, Missouri Resource Assessment Partnership (Missouri Spatial Data Information Service, 2007). Four types of land use/land cover are shown in figure 5 as the dominant land use/land cover in 200-m (meter) cells: forested, open, cultivated, and urban. Forests cover the largest part of the study area, including most of the ONSR and nearby lands, while upland areas away from the Current River and its tributaries as well as some land along streams are open. Cultivated land is shown in only a few places in the study area. A few towns are located in the study area, mostly in upland areas. Areas between towns are sparsely to nonpopulated. The pattern of land use/land cover reflects public and private land ownership to a large extent, but not completely. Much of the land in the study area is owned by public entities — NPS, U.S. Forest Service (USFS), Missouri Department of Conservation (MDC), Missouri Department of Natural Resources (MDNR) (fig. 1), and these lands are mostly forested. However, much of the privately owned land also is forested.

Activities on the land surface vary throughout the study area. The Current River, Jacks Fork, and Eleven Point River are used largely for canoeing and other recreational uses. While some of the forested land is designated as wilderness or is otherwise not used commercially, logging is still an important industry on private and public lands, and saw mills (past and present) occur throughout the study area. Most of the open ground is pasture, with cattle operations a major land use. Mining is an important industry in southern Missouri, particularly large-scale lead and zinc mining in the Viburnum Trend. One Viburnum Trend mine and tailings lake is located along the upper reaches of Logan Creek, immediately inside the study area boundary, and part of another tailings lake from another mine also is just inside the study area. Small-scale gravel-mining in streams also occurs. A series of roads cross the study area, including Federal, State, and County roads. Most of the roads shown on figure 1 are two-lane blacktop, with four-lane divided highway being less common. Many unimproved roads exist in the study area but are not shown on figure 1.

Purpose and Scope

This report was written to describe geohydrologic investigations and landscape characteristics of areas contributing water to springs and the Current River and Jacks Fork in the ONSR. The geohydrologic investigations are a compilation of existing information and the addition of new information collected during 2006–07. A potentiometric-surface map is presented that combines newly acquired and interpreted data in the northern part of the study area with a previously published potentiometric map in the southern part of the study area. Data for a low base-flow seepage run of the Current River, Jacks Fork, and Sinking Creek conducted for this investigation are presented, as well as the results of a temperature profile of the Current River conducted at the same time to detect inflow of spring water in the streambed. Spring discharge data are presented and spring recharge areas are compiled from previously published studies, with slight modification based on the newly interpreted potentiometric surface. The results of previously conducted dye traces and two new dye tracer tests for this investigation are presented. A series of maps at locations along the Current River and Jacks Fork show the surface-water and groundwater basins and spring recharge areas, which together provide water to the ONSR. Also shown are a series of maps that depict the variation of landscape characteristics relevant to surface-water or groundwater flow to the ONSR.

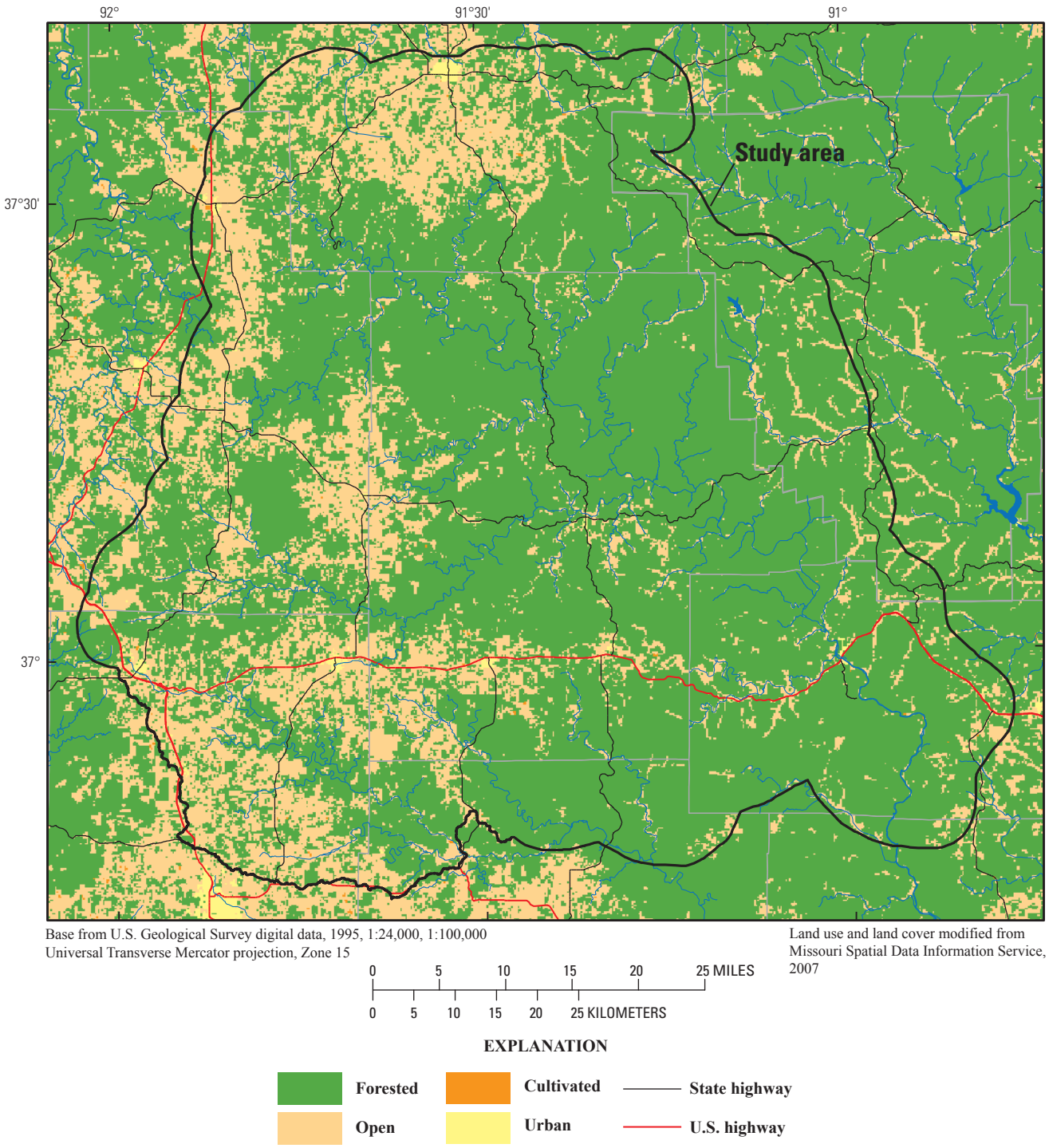

Figure 5. Land use/land cover in the study area.

Previous Investigations

Potentiometric-surface maps have been prepared for areas south of Jacks Fork using groundwater measurements in wells collected beginning in 1992 (Imes and Kleeschulte, 1995; Imes and others, 2007). The potentiometric-surface map in Imes and others (2007) covers the approximately southern one-half of the study area for this investigation, and was used to construct a potentiometric-surface map for this study. Potentiometric-surface maps also were constructed for areas overlapping and east of the study area (Kleeschulte, 2001) and west of the study area (Mugel and Imes, 2003).

Stream gages are maintained by the USGS at locations along the Current River and Jacks Fork (Current River at

Montauk State Park, USGS station number 0706440; Current River above Akers, USGS station number 07064533; Current River at Van Buren, USGS station number 07066700; Big Spring near Van Buren, USGS station number 07067500; Current River at Doniphan, USGS station number 07068000; Jacks Fork near Mountain View, USGS station number 07065200; Jacks Fork at Alley Spring, USGS station number 07065495; Jacks Fork at Eminence, USGS station number 07066000). Some gages have a long period of record (for example, Current River at Van Buren, since 1921) while others have a shorter period of record (for example, the Current River at Montauk State Park gage was installed in 2007). Wilson (2001) discusses some streamflow statistics for these gages. Other gages have been operated in the past. A gage was located at Round Spring (USGS station number 07065000) from 1928 to 1939 and from 1965 to 1979. A gage also was located at Alley Spring (USGS station number 07065500) from 1928 to 1939 and from 1965 to 1979. A gage also was located at the Current River near Eminence (USGS station number 07066500) from 1921 to 1975, at Montauk Springs (station number 07064400) in 1965 and from 1967 to 1968, and at Blue Spring (Current River; USGS station number 07066550) for about a year from 1970 to 1971.

USGS annual data reports (for example, U.S. Geological Survey, 2008a) contain summary statistics, including annual mean discharge, for active gages. An annual mean discharge is the average of daily mean discharges, in cubic feet per second, for a water year (October 1 through September 30) or for several years. The USGS annual data reports show annual mean discharge for the current water year and for the period of record of the gage. For this report, unless otherwise noted the annual mean discharge for a gage refers to the long-term (period of record) annual mean discharge. Estimates of long-term annual mean discharge, sometimes referred to as “mean annual” or “average” discharge, have been made for some nongaged springs (for example, Aley, 1976; Aley and Aley, 1987; Keller, 2000; Vandike, 1997; Vineyard and Feder, 1982). The term “annual mean discharge” is used herein for gaged spring and stream sites and nongaged springs, and is identified as an estimate where applicable.

A seepage run is a series of discharge measurements of streams and springs during low base-flow conditions that is conducted to determine the groundwater component of stream discharge, and to determine where stream discharge is lost to the subsurface in losing streams or where discharge increases from groundwater discharge to streams. A 1941 seepage run consisted of 27 discharge measurements made on the Current River from 0.5 mi upstream from the mouth of Jacks Fork to 3.1 mi downstream from the USGS gage at Van Buren from August 21 to 23, 1941, and September 14 to 16, 1941, and 11 discharge measurements made on Jacks Fork from September 14 to 18, 1941 (data on file at the U.S. Geological Survey office, Rolla, Missouri). A 1966 seepage run consisted of 111 low base-flow discharge measurements made on the Current River from October 18 to 20, 1966 and on November 8, 1966, and Jacks Fork from October 31 to November 3, 1966 (Skelton, 1976). A 1967 seepage run consisted of 12 low base-flow discharge measurements on Sinking Creek on October 3, 1967 (Skelton, 1976). More recent seepage runs identified losing and gaining reaches of the Eleven Point River and its tributaries (Spring Creek and Hurricane Creek; Kleeschulte, 2000). A seepage run on Logan Creek in August 2006 also identified losing and gaining stream reaches (Kleeschulte, 2008; Schumacher, 2008).

Dye tracer tests have been conducted in the study area and adjacent lands since the late 1960s to determine groundwater flow directions and delineate spring recharge areas. The DGLS maintains a database of successful dye traces (Missouri Department of Natural Resources, 2007). The location of most of these is shown in figure 4. Many of these studies were conducted by Ozark Underground Laboratory for the USFS or NPS, and are reported in Aley (1975, 1976, 1978, 1982), Aley and Aley (1987, 1989), and Aley and Moss (2006a, 2006b). These reports describe dye tracer-test methods, analytical techniques, spring discharge, and delineate spring recharge areas for the larger springs and some smaller springs in the Current River Basin.

Other dye tracer tests have been conducted in the study area and adjacent lands by the DGLS, USFS, and USGS, and are cataloged in the DGLS dye trace database. One of the earliest dye traces was reported by Feder and Barks (1972), who injected dye in a losing reach of Logan Creek, which is in the Black River Basin east of the Current River Basin. Dye was recovered at Blue Spring along the Current River. Maxwell (1974) injected dye in Logan Creek near the injection point of Feder and Barks (1972), and also in Logan Creek several miles downstream; dye from both traces was recovered at Blue Spring. Dye from other dye traces conducted by Ozark Underground Laboratory in and near Logan Creek also was recovered at Blue Spring and nearby Cove Spring and Gravel Spring (fig. 4; Aley and Aley, 1987). Logan Creek is of particular interest because a lead and zinc mine, mill, and tailings lake are located in the Logan Creek drainage basin upstream from the dye injection points. Keller (2000) conducted dye traces to Welch Spring and revised previous estimates of the spring recharge area. Imes and Fredrick (2002) conducted a dye trace from Jam Up Creek (figs. 1 and 4), a tributary of Jacks Fork, to Big Spring, confirming a previous trace reported by Aley (1975). Imes and others (2007) reported on investigations of Big Spring, including previous dye traces, as part of a study to delineate the Big Spring recharge area, and also used spring discharge and specific conductance-measurements to determine base-flow and quick-flow discharge rates and ages of water for Big Spring. Other dye traces conducted by the USGS as part of lead mining related issues studies in southern Missouri are on file at the DGLS.

The USGS has mapped the bedrock geology of several 1:24,000 quadrangles in the southern part of the study area as part of the National Cooperative Geologic Mapping Program. One conclusion from this program is that cave systems have developed along bedding planes with no correlation between joint orientations and cave passages (Orndorff and others,

2001). Also, cave passages occur immediately below sandstone horizons in most cases.

Water samples have been collected from springs and from the Current River and Jacks Fork by the USGS at gages or other locations. Barks (1978) collected water samples from 26 surface-water sites and from 7 springs from 1973 to 1975. Davis and Richards (2001a, 2001b) and Davis and Barr (2006) collected water and bed-sediment samples of Jacks Fork to determine the source of microbiological contamination of a reach of Jacks Fork. Schumacher (2008) collected water samples from Logan Creek and Blue Spring, studied historic water-quality data for those locations, and concluded that water chemistry in Blue Spring has been affected by mining in the Logan Creek Basin. The NPS has also maintained its own program of stream and spring water-quality sampling.

Methods

Potentiometric-Surface Map

Water-level measurements were made in 114 wells in November and December 2006, and in 5 wells in January 2007 to map the potentiometric surface of the Ozark aquifer north of Jacks Fork and east of the Current River. In addition, two springs were visited during the well inventory, and the altitudes of their orifices were determined and used as additional data points representing minimum groundwater altitudes. The site number, location, land-surface altitude, well depth and casing depth (where known), measured depth to water, and water-level altitude are given in table 1, as well as the altitude of the orifice of springs that were visited during the well inventory. The locations are shown by latitude and longitude degree-minute-second coordinates, which were determined using a hand-held Global Positioning System (GPS) unit, and by the General Land Office coordinate system (fig. 6). The land-surface altitude was determined by plotting the well or spring location on a 7 ½-minute topographic map and interpreting the land-surface altitude of that location. The land-surface altitudes are considered accurate to one-half the topographic contour interval, which is plus or minus 10 ft for most of the area. Well depth and casing depth are given for those wells where that information is available in the DGLS database of permitted wells (Missouri Department of Natural Resources, 2007), and for other wells where this information was known by the well owner. Well depth is known for 71 wells and casing depth is known for 35 wells.

Water-level measurements were made by extending an electric tape down the well until the water-surface was contacted, or by an acoustic meter that emits a sound wave and measures the time for the sound wave to reflect off the water surface and return to the meter. Efforts were made to ensure that the measurements represented as close to static conditions as possible by making measurements in wells that had not been pumped recently or by waiting a period of time (usually 10–15 minutes) for the water level to recover from recent pumping, and monitoring the recovery until the measurement was made. Water levels were measured to the nearest 0.01 ft with an electric tape or to the nearest 0.5 ft with an acoustic meter. Water-level measurements ranged from 3.62 ft to 470.9 ft below land surface. The water level was below the reach of the electric tape in two wells; the water-level altitude for these wells is shown as a less-than value in table 1. Water was flowing from two wells; the water level for these wells is shown in table 1 as the land-surface altitude for each well plus 1 foot for the length of well casing above the land surface, which is a minimum value for the hydraulic head in each well.

In addition to measured water-level altitudes of wells, spring-altitude data were used, including the two springs that were checked during the well inventory. The DGLS maintains a database of springs (Missouri Department of Natural Resources, 2007), including their altitude, and some of the 270 springs that are located in the study area were used as additional data points. The altitudes of streams also were used as additional data points. Potentiometric contours (fig. 7) were drawn to intersect streams at locations of common altitude, except for losing streams where contours were drawn to be below the stream surface. The DGLS database of losing streams (Missouri Department of Natural Resources, 2007) was used with modifications to four streams based on recent seepage runs performed by the USGS (Kleeschulte, 2000; Kleeschulte, 2008; Schumacher, 2008). The losing stream segments in the DGLS database probably do not represent all the losing streams in the study area – only those which have been studied by the DGLS and found to be losing.

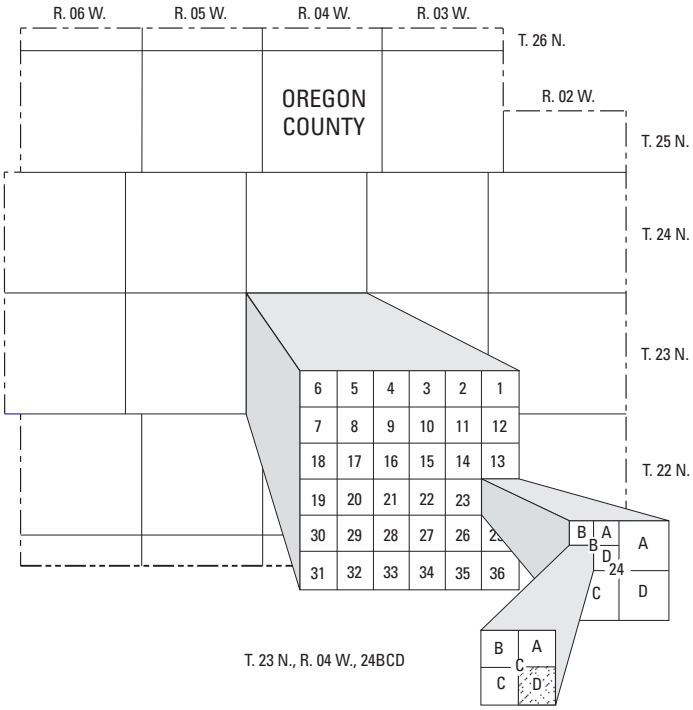

Figure 6. General Land Office coordinate system.

Table 1. Ground-water levels measured in domestic wells, observation wells, and springs during November and December 2006 and January 2007 in areas surrounding the Ozark National Scenic Riverways, Missouri.

[fig., figure; ddmmss, degree, minute, second; ft, foot; mm/dd/yyyy, month/day/year; DGLS, Missouri Division of Geology and Land Survey; --, no data; >, greater than; < less than]

Site number (fig. 7)	Field identifier	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land-surface altitude (ft)	Well depth (ft)	Casing depth (ft)	Water-level measurement			Comment
								Date (mm/dd/yyyy)	Depth to water (ft)	Water-level altitude (ft)	
1	DM-1	372957	914610	T32N R08W 01CCC	1,222	--	--	11/03/2006	129.0	1,093	
2	DM-2	372734	914739	T32N R08W 22DBA	1,302	290	--	11/03/2006	197.6	1,104	
3	DM-3	372708	914104	T32N R07W 22DDD	1,020	500	--	11/03/2006	94.4	926	
4	DM-4	372626	914331	T32N 0707W 29DCA	1,220	240	84	11/03/2006	165.9	1,054	
5	DM-5	372844	915156	T32N R09W 13ADB	1,280	550	316	11/03/2006	185.6	1,094	
6	DM-6	372443	915018	T31N R08W 05CDD	1,305	210	118	11/07/2006	159.7	1,145	
7	DM-7	372409	914502	T31N R07W 07BCB	1,305	--	--	11/07/2006	156.6	1,148	
8	DM-8	372012	914759	T30N R08W 03ABB	1,342	352	--	11/07/2006	308.0	1,034	
9	DM-9	372013	914636	T30N R08W 02AAB	1,305	375	--	11/07/2006	267.1	1,038	
10	DM-10	372158	914332	T31N R07W 20DCD	1,282	410	133	11/07/2006	264.2	1,018	
11	DM-11	372339	914122	T31N R07W 10DCD	1,100	360	105	11/07/2006	154.7	945	
12	DM-12	371838	914059	T30N R07W 11CBC	1,220	225	--	11/09/2006	195.5	1,024	
13	DM-13	371541	914007	T30N R07W 35AAA	1,320	--	--	11/09/2006	196.0	1,124	
14	DM-14	372047	913724	T31N R06W 30BAC	1,220	615	--	11/09/2006	404.0	816	
15	DM-16	371238	913434	T29N R06W 02CCD	1,160	--	--	11/09/2006	239.7	920	
16	DM-17	371313	915335	T29N R09W 02D	1,440	257	--	11/14/2006	114.0	1,326	
17	DM-18	370837	915353	T29N R09W 35CCB	1,405	375	208	11/14/2006	179.6	1,225	
18	DM-19	370631	914948	T28N R08W 09CDC	1,255	250	--	11/14/2006	164.4	1,091	
19	DM-20	370522	914625	T28N R08W 24BAC	1,142	--	--	11/14/2006	132.7	1,009	
20	DM-21	371836	915040	T30N R08W 08CDC	1,395	380	--	11/20/2006	240.7	1,154	
21	DM-22	370940	915028	T29N R08W 29ACD	1,270	--	--	11/20/2006	122.0	1,148	
22	DM-23	371502	914646	T30N R08W 35DDC	1,315	--	--	11/20/2006	127.7	1,187	
23	DM-24	371240	914345	T29N R07W 05DDC	1,368	--	--	11/20/2006	185.4	1,183	
24	DM-25	371455	914949	T30N R08W 04BBA	1,305	--	--	11/20/2006	136.5	1,168	
25	DM-26	370803	914336	T28N R07W 05ADD	1,295	--	--	11/21/2006	177.9	1,117	

Table 1. Ground-water levels measured in domestic wells, observation wells, and springs during November and December 2006 and January 2007 in areas surrounding the Ozark National Scenic Riverways, Missouri.—Continued

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Site number (fig. 7)	Field identifier	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land-surface altitude (ft)	Well depth (ft)	Casing depth (ft)	Water-level measurement			Comment
								Date (mm/dd/yyyy)	Depth to water (ft)	Water-level altitude (ft)	
26	DM-27	370456	914210	T28N R07W 22CAC	1,178	--	--	11/21/2006	204.6	973	
27	DM-28	370441	913745	T28N R06W 20CDD	1,145	400	245	11/21/2006	105.3	1,040	
28	DM-29	370739	913614	T28N R06W 04DAB	1,162	540	191	11/21/2006	309.3	853	
29	DM-30	370723	913941	T28N R07W 01DC	1,250	--	--	11/27/2006	392.8	857	
30	DM-32	371448	913655	T29N R06W 04BBB	1,210	700	--	12/06/2006	353.5	857	
31	DM-33	371637	915233	T30N R09W 25BAD	1,345	300	84	11/28/2006	69.5	1,275	
32	DM-34	371151	915033	T29N R08W 08DCC	1,385	330	84	11/28/2006	95.5	1,289	
33	DM-35	371554	914423	T30N R08W 30DDD	1,300	290	--	11/28/2006	165.3	1,135	
34	DM-36	371232	914018	T29N R07W 11AAA	1,260	395	301	11/28/2006	276.1	984	
35	DM-37	371851	913745	T30N R06W 08BCC	1,230	465	--	12/06/2006	320.6	909	
36	DM-38	371508	913803	T30N R06W 31DBD	1,210	500	210	12/06/2006	246.1	964	
37	DM-39	371547	913604	T30N R06W 28DCC	1,080	--	--	12/06/2006	123.3	957	
38	MK-1	373343	911837	T33N R03W 18BBA	1,430	--	--	11/07/2006	158.7	1,271	
39	MK-2	372836	910017	T32N R01W 13BBD	860	--	--	11/07/2006	76.1	784	
40	MK-3	372836	911145	T32N R02W 07DDB	1,220	305	210	11/07/2006	61.2	1,159	
41	MK-4	371332	910019	T29N R02W 01DCA	750	315	215	11/08/2006	52.9	697	
42	MK-5	372215	910655	T31N R02W 13CDC	1,010	1,600	--	11/08/2006	-1.0	1,011	Flowing artesian well
43	MK-6	371727	910223	T30N R02W 15ACC	1,082	325	--	11/08/2006	208.1	874	
44	MK-7	371523	910604	T30N R01W 30CCA	835	160	--	11/08/2006	65.8	769	
45	MK-8	371424	910534	T30N R01W 31DCD	800	--	--	11/08/2006	204.8	595	
46	MK-9	372329	911608	T31N R03W 09DAD	1,245	--	--	11/09/2006	206.6	1,038	
47	MK-10	373056	911159	T33N R02W 31ABB	1,040	300	--	11/09/2006	18.1	1,022	
48	MK-11	372103	910939	T31N R02W 28ADB	1,015	130	--	11/09/2006	-1.0	1,016	Flowing artesian well
49	MK-12	371733	910748	T30N R02W 14ACC	880	180	--	11/09/2006	33.0	847	
50	MK-13	371659	910814	T30N R02W 23BBA	940	--	--	11/09/2006	157.5	782	

Table 1. Ground-water levels measured in domestic wells, observation wells, and springs during November and December 2006 and January 2007 in areas surrounding the Ozark National Scenic Riverways, Missouri.—Continued

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Site number (fig. 7)	Field identifier	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land-surface altitude (ft)	Well depth (ft)	Casing depth (ft)	Water-level measurement			Comment
								Date (mm/dd/yyyy)	Depth to water (ft)	Water-level altitude (ft)	
51	MK-14	371804	910450	T30N R02W 08CCA	920	--	--	11/09/2006	72.4	848	
52	MK-15	371432	910002	T30N R01W 36DDB	690	--	--	11/09/2006	12.0	678	
53	MK-16	372518	911153	T32N R02W 31DAB	1,265	292	211	11/07/2006	104.3	1,161	
54	MK-17	372351	910422	T31N R01W 08ABC	1,250	--	--	11/07/2006	212.5	1,037	
55	MK-18	372121	910248	T31N R01W 27BBB	1,035	274	--	11/08/2006	68.3	967	
56	MK-19	372853	910618	T32N R02W 12ADB	1,150	250	210	11/03/2006	133.3	1,017	
57	MK-20	372608	910633	T32N R02W 25ACD	1,165	275	250	11/03/2006	142.4	1,023	
58	MK-21	371910	910811	T30N R02W 02CBA	990	110	80	11/03/2006	60.5	930	
59	PB-1	371349	910234	T29N R01W 03	727	--	--	11/07/2006	110.5	616	
60	PB-2	371139	910615	T29N R01W 07CBD	759	330	152	11/07/2006	126.5	632	
61	PB-3	370908	910652	T29N R02W 25ABD	613	--	--	11/07/2006	10.2	603	
62	PB-4	371136	905830	T29N R01E 17CBD	818	--	--	11/07/2006	157.6	660	
63	PB-5	370853	905615	T29N R01E 34CAC	720	330	84	11/08/2006	134.4	586	
64	PB-6	370837	910047	T28N R01E 01BBA	917	--	--	11/08/2006	169.6	747	
65	PB-7	370430	910032	T28N R01W 25DBB	593	--	--	11/08/2006	15.6	577	
66	PB-8	365114	904945	T25N R02E 03AAC	724	180	170	11/08/2006	109.3	615	
67	PB-9	370013	905408	T27N R01E 12DCC	883	--	--	11/08/2006	176.8	706	
68	PB-10	365533	904736	T26N R02E 12ABD	886	206	--	11/09/2006	91.3	795	
69	PB-11	365753	905115	T27N R02E 28CBA	862	--	--	11/09/2006	152.0	710	
70	PB-12	370407	905243	T28N R02E 30DCA	905	--	--	11/09/2006	212.6	692	
71	PB-13	371107	911029	T29N R02W 16BAB	590	--	--	11/09/2006	21.0	569	
72	PB-14	373807	913326	T34N R06W 23ADB	1,180	175	147	11/20/2006	32.3	1,148	
73	PB-15	371308	912624	T29N R05W 01D	1,100	575	274	11/20/2006	337.0	763	
74	PB-16	371417	913008	T29N R05W 04BBD	1,000	--	--	11/20/2006	266.6	733	
75	PB-17	371414	913010	T29N R05W 04BCA	995	--	--	11/20/2006	269.2	726	

Table 1. Ground-water levels measured in domestic wells, observation wells, and springs during November and December 2006 and January 2007 in areas surrounding the Ozark National Scenic Riverways, Missouri.—Continued

[fig., figure; ddmmss, degree, minute, second; ft, foot; mm/dd/yyyy, month/day/year; DGLS, Missouri Division of Geology and Land Survey; --, no data; >, greater than; < less than]

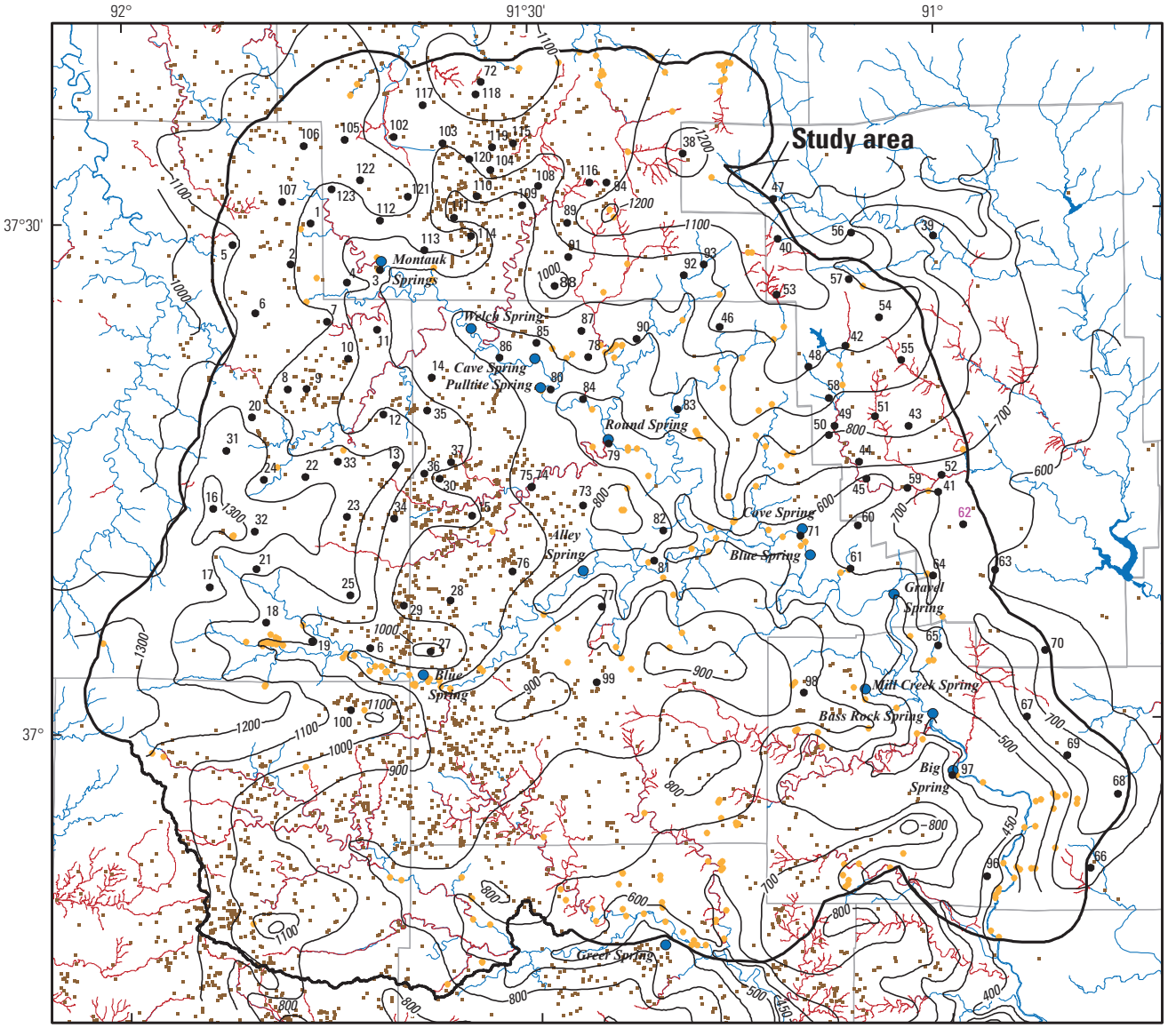
Site number (fig. 7)	Field identifier	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land-surface altitude (ft)	Well depth (ft)	Casing depth (ft)	Water-level measurement			Comment
								Date (mm/dd/yyyy)	Depth to water (ft)	Water-level altitude (ft)	
76	PB-18	370918	913139	T29N R05W 30DAA	1,145	--	--	11/20/2006	274.9	870	
77	PB-19	370709	912509	T28N R04W 06DDD	1,022	350	--	11/20/2006	173.8	848	
78	PB-20	372151	912550	T31N R05W 24DDB	1,115	--	--	11/21/2006	247.7	867	
79	PB-21	371645	912427	T30N R04W 20CBA	740	--	--	11/21/2006	77.6	662	
80	PB-22	371958	912839	T31N R05W 34CDC	740	--	--	11/21/2006	21.6	718	
81	PB-23	370947	912114	T29N R04W 23CDD	840	--	--	11/21/2006	175.0	665	
82	PB-24	371135	912032	T29N R04W 12CCA	760	--	--	11/21/2006	47.3	713	
83	PB-25	371841	911921	T30N R04W 12AAC	780	--	--	11/21/2006	0.0	780	Spring
84	PB-26	371922	912616	T30N R05W 01DBB	742	--	--	11/21/2006	50.8	691	
85	PB-27	372243	912938	T31N R05W 16CDB	920	--	--	11/27/2006	146.4	774	
86	PB-28	372153	913223	T31N R06W 24DDD	840	425	--	11/27/2006	66.4	774	DGLS observation well
87	PB-29	372323	912619	T31N R05W 12CDD	1,148	--	--	11/27/2006	297.3	851	
88	PB-30	372603	912813	T32N R05W 27DCC	1,255	--	--	11/27/2006	164.3	1,091	
89	PB-31	372945	912714	T32N R05W 02DBC	1,289	--	--	11/28/2006	200.5	1,088	
90	PB-32	372252	912214	T31N R04W 15CBB	1,080	--	--	11/28/2006	253.8	826	
91	PB-33	372744	912711	T32N R05W 14DCC	1,318	500	200	11/28/2006	370.4	948	
92	PB-34	372632	911843	T32N R03W 30BAC	944	--	--	11/28/2006	3.62	940	
93	PB-35	372711	911714	T32N R03W 20DAA	976	--	--	11/28/2006	0.0	976	Tree Grove Spring
94	PB-36	373206	912418	T33N R04W 20CCC	1,338	597	--	11/28/2006	330.3	1,008	
[1]96	PB-38	365053	905719	T25N R01E 04DDC	470	--	--	12/08/2006	27.6	442	
97	PB-39	365652	905942	T26N R01E 06CCC	470	56	--	12/08/2006	5.42	465	DGLS observation well
98	PB-40	370153	911026	T27N R02W 04CDA	735	220	--	12/08/2006	69.0	666	
99	PB-41	370243	912537	T27N R04W 06ABB	1,065	405	--	12/11/2006	227.8	837	
100	PB-42	370117	914338	T27N R07W 09CCC	1,205	450	260	12/11/2006	133.5	1,072	

Table 1. Ground-water levels measured in domestic wells, observation wells, and springs during November and December 2006 and January 2007 in areas surrounding the Ozark National Scenic Riverways, Missouri.—Continued

[fig., figure; ddmmss, degree, minute, second; ft, foot; mm/dd/yyyy, month/day/year; DGLS, Missouri Division of Geology and Land Survey; --, no data; >, greater than; < less than]

Site number (fig. 7)	Field identifier	Latitude (ddmmss)	Longitude (ddmmss)	General land office coordinate	Land-surface altitude (ft)	Well depth (ft)	Casing depth (ft)	Water-level measurement			Comment
								Date (mm/dd/yyyy)	Depth to water (ft)	Water-level altitude (ft)	
[1]102	JGD-2	373458	913955	T33N R07W 11AAA	1,220	290	150	11/09/2006	159.3	1,061	
103	JGD-3	373433	913619	T33N R06W 09BCD	1,300	465	294	11/09/2006	297.2	1,003	
104	JGD-4	373256	913249	T33N R06W 24BAD	1,268	--	--	11/09/2006	231.8	1,036	
105	JGD-5	373449	914334	T33N R07W 08ABC	1,322	310	173	11/14/2006	197.3	1,125	
106	JGD-6	373430	914634	T33N R08W 11DAB	1,361	300	--	11/14/2006	239.7	1,121	
107	JGD-7	373113	914814	T33N R08W 34BDC	1,295	315	--	11/14/2006	130.7	1,164	
108	JGD-10	373157	912919	T33N R05W 28ABC	1,260	515	448	11/28/2006	294.0	966	
109	JGD-11	373049	913032	T33N R05W 32CAA	1,283	565	--	11/28/2006	405.6	877	Spring
110	JGD-12	373125	913352	T33N R06W 26CDD	1,292	--	--	11/28/2006	373.6	918	
111	JGD-13	373010	913534	T32N R06W 04ADD	1,328	560	169	11/28/2006	470.9	857	
112	JGD-30	373002	914101	T32N R07W 03DAD	1,260	400	--	01/10/2007	166.7	1,093	DGLS observation well
113	JGD-31	372816	913748	T32N R06W 18DAD	1,180	300	--	01/10/2007	169.8	1,010	
114	JGD-32	372905	913421	T32N R06W 11CBC	1,310	550	--	01/10/2007	266.2	1,044	
115	JGD-40	373429	913107	T33N R05W 07ADD	1,300	550	--	01/12/2007	269.7	1,030	
116	JGD-41	373207	912533	T33N R04W 19CCC	1,310	500	--	01/12/2007	243.0	1,067	
117	JR-1	373649	913745	T34N R06W 30DDD	1,211	468	--	11/03/2006	146.9	1,064	
118	JR-2	373722	913350	T34N R06W 26BAD	1,262	150	--	11/03/2006	91.5	1,170	
119	JR-3	373417	913242	T33N R06W 12DBC	1,325	650	290	11/03/2006	>297.8	<1027.2	Tree Grove Spring
120	JR-4	373335	913422	T33N R06W 14CBB	1,335	600	294	11/03/2006	>298.5	<1036.5	
121	JR-5	373126	913857	T33N R07W 36AAB	1,320	190	160	11/03/2006	131.1	1,189	
122	JR-06	373227	914226	T33N R07W 21DCC	1,332	450	189	11/03/2006	189.7	1,142	DGLS observation well
123	JR-07	373157	914434	T33N R07W 30DBA	1,240	260	147	11/03/2006	157.7	1,082	

[1]site number is non-sequential



Base from U.S. Geological Survey digital data, 1995, 1:24,000, 1:100,000
Universal Transverse Mercator projection, Zone 15

Sinkhole and spring locations and losing streams modified from Missouri Department of Natural Resources, 2007. Potentiometic contours in approximately southern half of study area are modified from Imes and others, 2007

0 5 10 15 20 25 MILES

0 5 10 15 20 25 KILOMETERS

EXPLANATION

800 — **Potentiometric contour and altitude, in feet, of potentiometric surface, 2000–07. Shows altitude at which water level would have stood in tightly cased well. Contour interval 100 feet. Datum is National Geodetic Vertical Datum of 1929**

31 **Location of water-level measurement and site number for wells measured in 2006–07**

Losing stream

Sinkhole

Spring

Figure 7. Potentiometric surface of the study area, 2000–07, and locations of measured wells and springs, sinkholes, losing streams, and springs.

Low Base-Flow Discharge Measurements

A seepage run, consisting of 255 measurements and estimates of discharge and observations of no discharge, was conducted on the Current River, Jacks Fork, and Sinking Creek from August 14 to 18, 2006 (figs 8–10; table 2). Seepage run locations were not restricted to the ONSR and extended downstream as far as Doniphan, which is about 20 mi downstream from the boundary of the ONSR. Some of the stream-discharge measurements were made at or close to the locations of measurements made in similar low base-flow seepage runs in fall 1941, fall 1966, and fall 1967, and others were made at locations based on conditions encountered at the time of measurement. Inflow from springs and tributaries was measured, or estimated where the discharge was too small to be measured, and observations of no flow were made where tributaries or spring branches were not flowing. Measurements were conducted by four teams of usually two people each working independently on different sections of the rivers. The procedure for each team was to make a series of measurements in a downstream direction, then on the next day repeat the last measurement of the day before, and continue with another set of downstream measurements. Also, when a team reached the section of the river that another team had measured, a discharge measurement was made, repeating the other team's measurement. The repeated measurements allow for continuity by correlating measurements of one section of the river with measurements of another section of the river, and for correlating discharge that changed slightly from one day to the next as recorded at USGS stream gages. Measurements were made by wading and from boats, using standard USGS discharge measurement practices, or discharge was estimated (Rantz and others, 1982; Oberg and others, 2005). Measurement conditions varied throughout the seepage run from good where the measured discharge is considered to be within 5 percent of the actual discharge, to poor where the difference between the measured and actual discharge is considered to be greater than 8 percent of the actual discharge. An example of a condition limiting the accuracy of a measurement is where there is considerable flow through the gravel streambed, which cannot be measured.

Current River Temperature Profile

During August 2006, a temperature profile was conducted along an 85-mi reach of the Current River from Akers Ferry to Cataract Landing to determine if previously unknown springs exist in the streambed (fig. 11). Temperature profiling was done in a Lagrangian framework (moving downstream at the same velocity as the river) similar to methods used on the Yakima River in Washington by Vaccaro and Maloy (2006). A multiparameter water-quality probe (In-Situ TROLL 9000™) was used to measure temperature and specific conductance near the streambed. The probe was suspended by hand to the river bottom from the front of a canoe with a 25 ft long cable. The water-quality probe was connected to a hand-held Trimble Recon ™ field computer equipped with a GPS receiver card. The GPS and water-quality probe were interfaced using Hydroplus CE ™ software (Field Data Solutions Inc., 2005). The software recorded readings from the water-quality probe and GPS every 3 seconds. Two Solinst Levelogger ™ temperature and pressure transducers were used to record water-surface temperature and river depth. One transducer was suspended 0.5 ft below the water surface from the rear of the canoe. The second pressure transducer was attached to the bottom of the water-quality probe and was used to record depth (the water-quality probe was not equipped with an internal pressure transducer). Because the pressure transducers used were sealed, a third pressure transducer was carried in a shaded area within the canoe and used to record barometric pressure and adjust depth readings for barometric pressure and altitude changes. A laptop computer was used to program the pressure transducers at the beginning of each day to collect readings every 3 seconds. The pressure transducers were downloaded every evening. The laptop computer time was synchronized to the GPS receiver on the hand-held computer, and time (to the nearest second) was used to link the pressure transducer data to the water-quality and GPS data in a spreadsheet program.

Accuracy of the hand-held GPS receiver was stated at plus or minus 30 ft. Errors outside of this limit were encountered where the GPS signal was lost along bluffs and under heavy tree canopy. In addition, a poor contact between the GPS receiver card and the hand-held computer resulted in blocks of lost or erroneous GPS readings along nearly 13 miles of the profiled reach. This error was not discovered until the data were processed and imported into a Geographic Information System (GIS) database after the field effort. Accuracy of the pressure transducers was stated by the manufacturer at 0.05 degrees Celsius (ºC) for temperature and 0.016 ft for depth. The manufacturer's specifications for the water-quality probe reported accuracy of 0.1 ºC for temperature and 0.5 percent for specific conductance. The accuracy of the temperature readings from the thermistors in the water-quality probe and the pressure transducers was not checked against a National Bureau of Standards (NBS)-traceable thermometer before the temperature profile was done. However, as a field-quality check, at the beginning and end of the temperature profile field effort, the water-quality probe and pressure transducers were suspended in the stream at the same location and allowed to equilibrate for 15 minutes. A comparison of readings from these field checks indicated that temperatures recorded by the pressure transducers were within 0.1 ºC of each other, but that the temperatures recorded by the water-quality probe were consistently about 0.3 ºC lower. The apparent bias between the pressure transducer and water-quality probe temperature readings was consistent throughout the profiling effort.

Specific conductance values measured by the water-quality probe were temperature compensated to express readings in microsiemens per centimeter at 25 ºC (µS/cm). The probe was calibrated daily to within 2 percent using 250-µS/cm and 500-µS/cm NBS-traceable specific conductance standards. A check

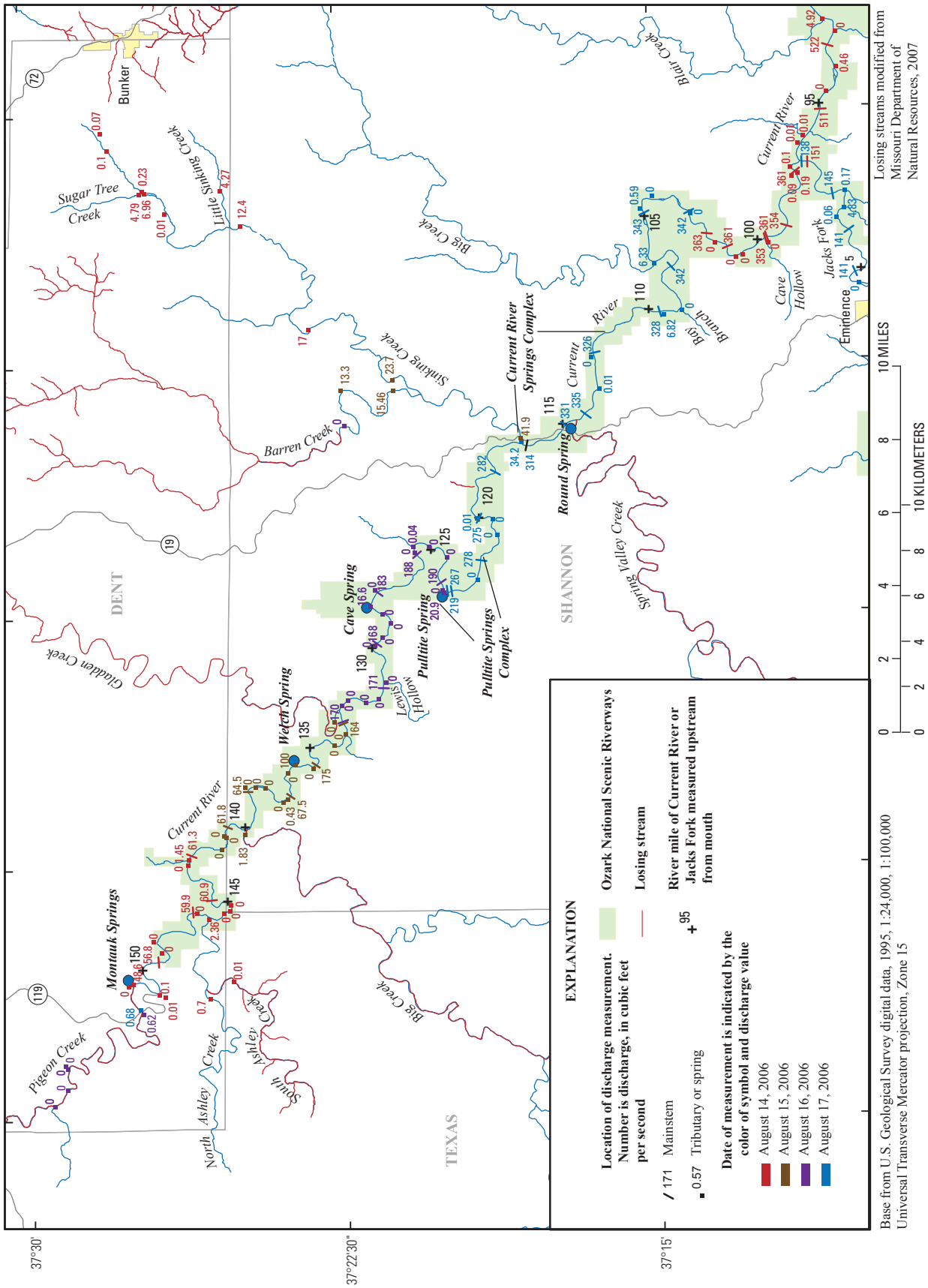


Figure 8. Locations of discharge measurements made on the upper Current River and Sinking Creek for the August 2006 seepage run.

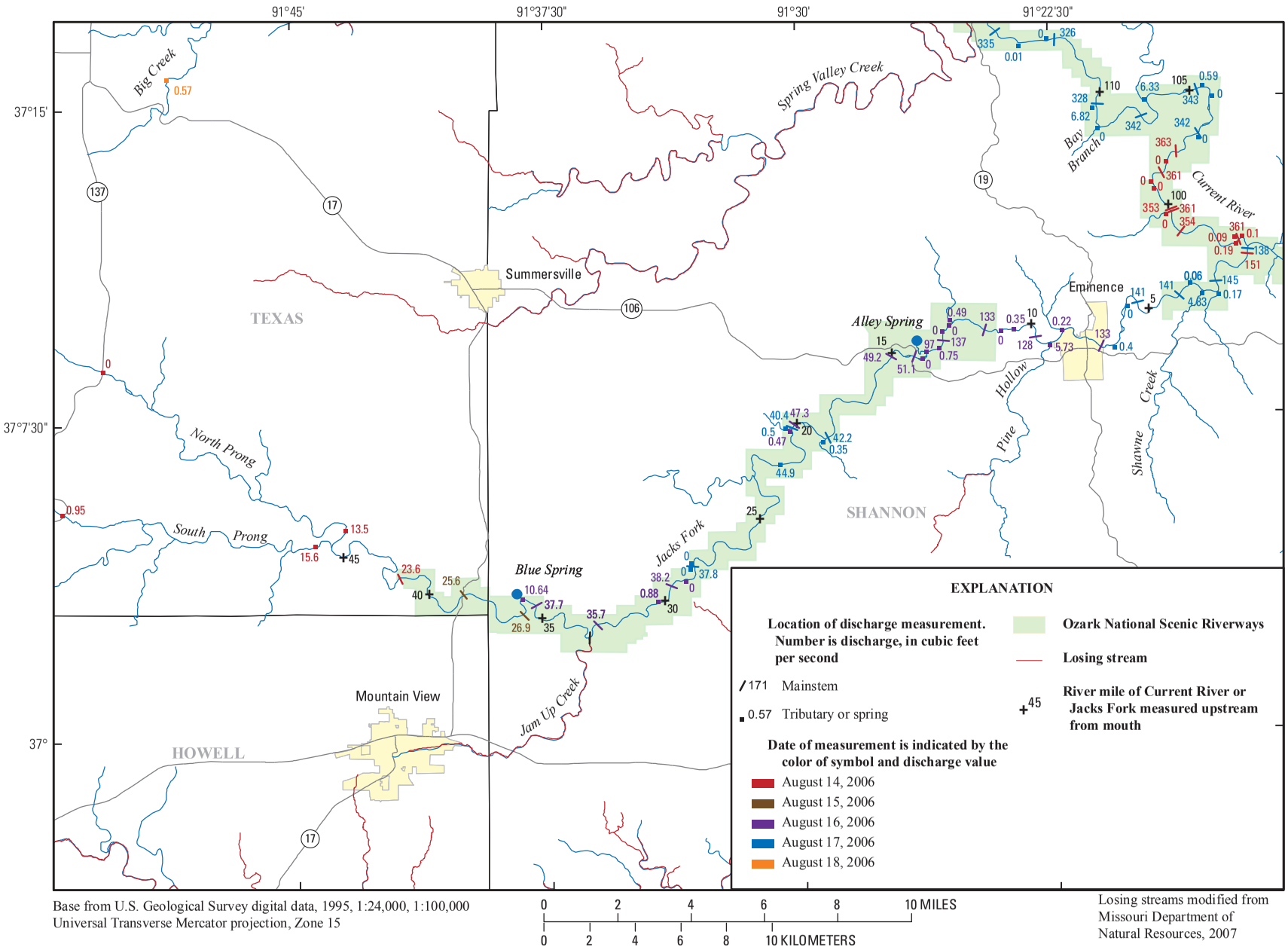


Figure 9. Locations of discharge measurements made on Jacks Fork for the August 2006 seepage run.

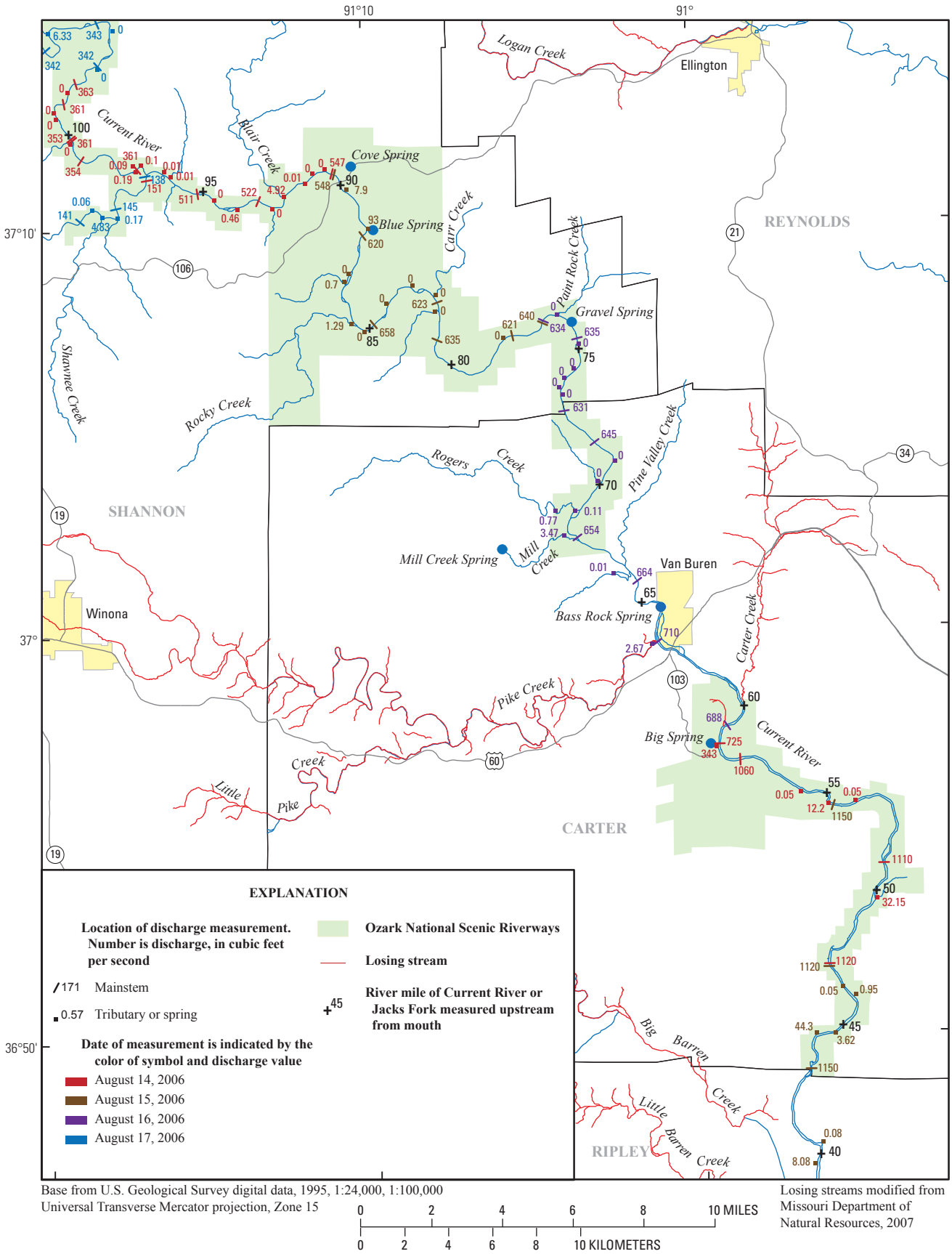


Figure 10. Locations of discharge measurements made on the lower Current River for the August 2006 seepage run.

standard (250 µS/cm) was run at the end of each day. All check standards were within 2 percent of the expected values.

Dye Tracing

Two dye tracer tests were conducted for this investigation to better define discrete groundwater flow in an area between Logan Creek and the Current River. On July 11, 2006, 3.5 pounds (lbs) of fluorescein dye were injected into storm runoff in a tributary of Carr Creek along Highway 106 in Reynolds County, approximately 1,400 ft northeast of the Shannon County – Reynolds County line. Flow was observed to be lost to the subsurface within about 150 ft of the injection point. Dye packets of activated charcoal were placed in Blue Spring, Powder Mill Spring, Cove Spring, Gravel Spring, Carr Creek and three springs along Carr Creek, the Current River at the Highway 106 bridge, and several other small springs and tributaries (dye injection, monitoring locations, and other details for each dye trace are kept on file in the offices of the USGS and DGLS). The charcoal packets were collected approximately weekly at first, then approximately every 2 weeks, through September 12, 2006. A solution was used to elute any adsorbed dye from the charcoal and was analyzed using a scanning spectrofluorophotometer. A second dye tracer test was initiated on December 1, 2006, by injecting 2 gallons of Rhodamine-WT dye into storm runoff in the same tributary to Carr Creek approximately 3,200 ft downstream from the first dye injection location. Flow in the tributary was lost within approximately 2,000 ft of the injection point. Charcoal packets were placed at the same monitoring locations and were collected through March 9, 2006, and analyzed using a scanning spectrofluorophotometer. For quality assurance purposes, a charcoal blank (a charcoal packet that had not been placed in water) also was analyzed for each set of samples for each dye tracer test.

Landscape Characteristics

A series of maps was created to display the variability of landscape characteristics throughout the study area. These landscape characteristics were quantified by dividing the study area into 800-m (meter) cells and, for most characteristics, creating a raster representation of the density of each characteristic in each cell. This allows a comparison of the density of a characteristic in one area with the density elsewhere in the study area, and thereby enhances an understanding of how the potential for any given characteristic to affect water movement varies throughout the study area. The cell size of 800 m (which represents about 160 acres on the ground) was chosen because the area is large enough that density of sparse data (for example, sinkhole locations) would be effectively concentrated, while at the same time small enough to provide sufficient resolution to accurately portray density in a relatively small area.

Raster and vector types of source data, which were originally produced at various scales by various State and Federal agencies, were used to create the landscape characteristic maps. Raster data represent a landscape characteristic (for example, topography) using a regularly spaced grid with each cell in the grid containing a single value, altitude in the case of topography. The raster data cell size can vary substantially depending on the intended use of the data. Vector data represent a landscape characteristic using geometric point, line, or area features where the geometric feature corresponds to the spatial extent of the mapped characteristic on the landscape. For example, losing streams are represented as lines. All data were rasterized to a base mapping unit using a grid cell size of 10 m. The international system of units (SI) was chosen as the mapping unit of measure to be consistent with the native mapping units of the available spatial data. Additionally, converting from SI units to English units could have caused spatial registration problems because of the rounding error of the computation. The 10-m cell size was chosen because it corresponded to the highest resolution raster data set (topography) that was available and it represented a small enough cell size to represent linear and point vector data accurately.

Data originally in raster format where the cell size was larger than 10 m were resampled to a 10-m grid cell size. Vector data were rasterized by overlaying a 10-m grid on the vector data and then assigning the value of 1 anywhere the vector data intersected a grid cell. Cells with no vector data were assigned the “no data” value.

Aggregation of the 10-m grid to the 800-m grid was done using one of three functions: sum, maximum, or mean. When 10-m data were aggregated up to the 800-m analysis cell size by summing, such as with sinkhole location (point features), losing streams (line features), and losing stream drainage areas (area features), the resultant grid represents a density (number of base mapping 10-m cells that represent a mapped characteristic contained within an 800-m analysis cell). The 800-m analysis cell is eighty 10-m cells in width and length for a total possible number of 6,400 base mapping 10-m cells in the 800-m analysis cell. For example, a losing stream passes through one of the 800-m cells and is represented by 150 10-m cells. The value of the 800-m cell at this location would be 150, about 2 percent (150/6400) of the area of the 800-m cell. Landscape characteristics that are area features, such as losing stream drainage areas, have a density of 100 percent where the 800-m analysis cell is completely within the landscape characteristic area and 0 when the cell is completely outside the area. The 800-m analysis cells that intersect the boundary of the landscape characteristic feature area vary in density because only a portion of the cell is covered by the area feature. When aggregated using the maximum function, such as with Strahler stream order, the resultant grid represents the maximum value of the 6,400 10-m cells of the mapped characteristic within the 800-m analysis cell. When aggregated using mean, such as with land slope, the resultant grid represents the computed mean value of the 6,400 10-m cells of the mapped characteristic within the 800-m analysis cell.

The range of density, maximum, and mean values for 800-m analysis cells was divided into 10 equal intervals or classes (cells were assigned the value “no data” when the mapped characteristic was not present). Each class is represented by a color on the landscape characteristic map, but depending on the distribution of values, all classes may not be represented for each landscape characteristic. The same number of classes was used for each map so the range in colors would be consistent from map to map. Any specific method employed for a given landscape characteristic is described in the section “Landscape Characteristics.”

Geohydrologic Investigations

This section describes the geohydrologic system in the study area and the geohydrologic data that were compiled or collected for this study. The water resources of the ONSR are surface water and groundwater. Most of the experience a recreational user of the park has is with surface water: canoeing, fishing, and swimming. However, most of the surface water in the Current River and Jacks Forks has its origin as groundwater that discharges at springs. Precipitation that falls in upland areas moves as runoff to the Current River and Jacks Fork by way of a network of tributary streams or enters the groundwater system by slow infiltration or rapidly through sinkholes, losing streams, or solution-enlarged fractures. The many sinkholes in the upland areas are surficial expressions of a subsurface network of caves or smaller karst conduits that are capable of transmitting groundwater rapidly. Losing streams also are indicative of high permeability in the subsurface and result from the piracy of surface-water flow by subsurface karst conduits. Groundwater captured by these karst features moves relatively rapidly as turbulent flow through a network of interconnected openings (conduits) and discharges as large and small springs located along streams or in the streambed. Groundwater may move over short or long distances: three dye traces from the vicinity of Mountain View to Big Spring had a straight-line distance of over 36 mi (fig. 4).

Groundwater also moves through the subsurface in a more diffuse manner, along small fractures and bedding planes. This type of groundwater flow is much slower than conduit flow, and absent karst features is the dominant manner in which groundwater flows. In the study area, however, which has many karst features, more groundwater discharges to the Current River and Jacks Fork by conduit flow than by diffuse flow.

Other conditions such as the amount and intensity of precipitation can affect the way water moves from the uplands through the geohydrologic system. Small amounts of precipitation are more likely to infiltrate through soils as diffuse recharge to the groundwater system and not run off to streams as surface-water flow. More intense or longer duration precipitation will cause runoff that recharges the groundwater system as discrete, or concentrated, recharge through sinkholes, solution-enlarged fractures, or losing streams. If the flow in a losing stream is large enough, some of the flow will bypass areas of entry to the subsurface and continue downstream as surface-water flow.

Potentiometric-Surface Map

Potentiometric-surface contours were drawn north of Jacks Fork and east of the Current River for this report. The potentiometric surface had previously been mapped east of the well inventory area using water-level measurements collected in 1998 (Mugel and Imes, 2003) and west of this well inventory area using water-level measurements collected in 1999 (Kleeschulte, 2001). Three of the wells that were measured to the east in 1999 also were measured in the well inventory in 2006–07. The water-level differences from 1999 to 2006 in these wells were +2 ft [well (site number) 47; table 1], -5 ft (well 53), and -10 ft (well 54). Five of the wells that were measured to the west in 1998 also were measured in 2006. The water-level differences from 1998 to 2006 were -10 ft (well 6), -14 ft (well 2), -22 ft (well 20), -32 ft (well 5), and -58 ft (well 8). Because the 2006–07 map area slightly overlaps each of the map areas to the east and west, the existing potentiometric contour lines were used to guide the trends of the new contour lines at the east and west edges of the 2006–07 study area where new data are more sparse, but only 2006–07 data values were used.

Two potentiometric surfaces, a deep surface and a shallow surface, previously were mapped south of Jacks Fork (Imes and others, 2007), an area that includes the approximately southern half of this study area. Water-level measurements were made in the summer and the fall of 2000; however, only the summer measurements were used for the potentiometric-surface maps in that report. Five wells measured for that study also were measured in 2006. The water level differences for these wells from summer 2000–06 and fall 2000–06 were +2.5 ft and +0.2 ft (well 95), +12.5 ft and +33 ft (well 99), +13.7 ft and +17.2 ft (well 96), +17.0 ft and +18.0 ft, (well 98) and +112.1 ft and + 82.2 ft (well 97).

The shallow potentiometric surface represents near water-table conditions, and the deep potentiometric surface represents groundwater hydraulic heads within the more mature karst areas (Imes and others, 2007). Only one potentiometric surface was mapped for the 2006–07 measurements to the north and east. The conditions prompting the interpretation of two potentiometric surfaces (Imes and others, 2007), that is, large vertical head differences in close proximity to each other, were not apparent in the newly mapped area to the north and east because they were not present or because the density of measurements was not sufficient to reveal them. The potentiometric surface in the newly mapped area is meant to represent near water-table conditions, and is joined to the shallow potentiometric surface of Imes and others (2007) to complete the potentiometric surface of the study area for 2000–07 (fig. 7). It is reasonable to join the contours despite the difference

Table 2. Results of a seepage run on the Current River, Jacks Fork, and Sinking Creek, August 14–18, 2006.

[mm/dd/yyy, month/day/year; hhmm, hour minute; mi, mile; ft³/s, cubic foot per second, --, no data; N/A, not applicable]

Site number[1]	U.S. Geological Survey station number	Date (mm/dd/yyyy)	Time (hhmm)	River mile[2] (mi)	Location description	Discharge (ft³/s)	Type	Rating
					Current River			
129	07068000	08/15/2006	1914	23.0	Current River at Doniphan	1,230	Measurement	Fair
121	--	08/15/2006	1846	25.2	Tributary near Pine Bluff	.60	Estimated	Poor
120	--	08/15/2006	1816	26.3	Tributary near Cedar Bluff	.01	Estimated	Poor
128	--	08/15/2006	1748	28.1	Current River	1,200	Measurement	Fair
119	--	08/15/2006	1737	28.3	Tributary near Deer Leap Recreation Area	.01	Estimated	Poor
118	--	08/15/2006	1717	28.8	Hargus Eddy	1.53	Measurement	Fair
117	--	08/15/2006	1627	34.1	Compton Creek	0	Observation	N/A
127	--	08/15/2006	1606	34.5	Current River	1,190	Measurement	Fair
116	--	08/15/2006	1543	34.6	Buffalo Creek	10.1	Measurement	Fair
115	--	08/15/2006	1506	35.5	Tributary below Round Bay	.01	Estimated	Poor
113	--	08/15/2006	1435	36.9	Tributary below Cedar Creek Recreation Area	1	Estimated	Poor
114	--	08/15/2006	1443	36.9	Tributary above Round Bay	0	Observation	N/A
126	--	08/15/2006	1359	38.4	Current River	1,180	Measurement	Fair
112	--	08/15/2006	1335	39.0	Spring below Conway Hollow	37.2	Measurement	Fair
111	--	08/15/2006	1305	39.8	Twin Springs	8.08	Measurement	Fair
110	--	08/15/2006	1452	40.2	Current River inflow near Jakes Valley	.08	Estimated	Poor
125	--	08/15/2006	1139	43.1	Hawes Recreation Area	1,150	Measurement	Fair
109	--	08/15/2006	1108	44.2	Hall Hollow	44.3	Measurement	Fair
108	--	08/15/2006	1043	44.7	Stillhouse Hollow	3.62	Measurement	Fair
107	--	08/15/2006	1011	45.9	Creek below Bedell Hollow	.95	Measurement	Poor
106	--	08/15/2006	1001	46.4	Creek below Panther Spring	.05	Estimated	Poor
124	--	08/14/2006	1757	47.2	Current River	1,120	Measurement	Fair
131	--	08/15/2006	0913	47.2	Current River	1,120	Measurement	Fair
105	--	08/14/2006	1710	49.7	Spring inlet below Cataract Landing	32.2	Measurement	Good
123	--	08/14/2006	1552	50.9	Current River	1,110	Measurement	Fair
104	--	08/14/2006	1452	53.9	Creek near Chilton	.05	Estimated	Poor
130	--	08/15/2006	1435	54.5	Current River	1,150	Measurement	Fair
103	--	08/14/2006	1408	54.6	Spring near Current River	12.2	Measurement	Fair
102	--	08/14/2006	1345	55.6	Long Bay Hollow	.05	Estimated	Poor
122	--	08/14/2006	1311	57.8	Current River	1,060	Measurement	Fair
100	07067500	08/14/2006	1128	58.3	Big Spring near Van Buren	343	Measurement	Poor
101	--	08/14/2006	1220	58.6	Current River	725	Measurement	Fair
169	--	08/16/2006	1655	59.2	Current River above Big Spring	688	Measurement	Fair
168	07067000	08/16/2006	1600	63.2	Current River at Van Buren	710	Measurement	Fair
167	--	08/16/2006	1520	63.3	Pike Creek	2.67	Measurement	Poor
235	--	08/16/2006	1435	65.7	Current River	664	Measurement	Good
194	--	08/16/2006	--	66.1	House Creek at M Highway	0.01	Estimated	Poor
233	--	08/16/2006	1804	67.9	Mill Creek at M Highway	3.47	Measurement	Fair
234	--	08/16/2006	1340	68.0	Current River	654	Measurement	Good

Table 2. Results of a seepage run on the Current River, Jacks Fork, and Sinking Creek, August 14–18, 2006.—Continued

[mm/dd/yyy, month/day/year; hhmm, hour minute; mi, mile; ft³/s, cubic foot per second, --, no data; N/A, not applicable]

Site number[1]	U.S. Geological Survey station number	Date (mm/dd/yyyy)	Time (hhmm)	River mile[2] (mi)	Location description	Discharge (ft³/s)	Type	Rating
232	--	08/16/2006	1814	68.7	Rogers Creek at M Highway	0.77	Measurement	Poor
231	--	08/16/2006	1253	69.1	Near Rogers Creek	0.11	Measurement	Poor
179	--	08/16/2006	--	70.1	S128 Shilton Creek	0	Observation	N/A
230	--	08/16/2006	--	70.5	Hollow downstream from Spring Hollow	0	Observation	N/A
229	--	08/16/2006	1150	71.6	Current River upstream from original site	645	Measurement	Good
223	--	08/16/2006	1110	72.8	Current River downstream from original site	631	Measurement	Good
226	--	08/16/2006	--	73.2	No flow	0	Observation	N/A
228	--	08/16/2006	--	73.5	No flow	0	Observation	N/A
227	--	08/16/2006	--	73.8	No flow	0	Observation	N/A
225	--	08/16/2006	--	74.2	No flow	0	Observation	N/A
224	--	08/16/2006	--	75.2	No flow	0	Observation	N/A
222	--	08/16/2006	1000	75.3	Current River downstream from original site	635	Measurement	Good
181	--	08/16/2006	--	76.1	S50 Paint Rock Creek	0	Observation	N/A
220	--	08/15/2006	--	76.6	Current River	640	Measurement	Good
221	--	08/16/2006	0920	76.6	Current River next day reference measurement	634	Measurement	Good
219	--	08/15/2006	1725	77.7	Current River	621	Measurement	Fair
180	--	08/15/2006	--	77.9	S125 near Sugarcamp Hollow	0	Observation	N/A
216	--	08/15/2006	1545	81.0	Current River measurement made below original site	635	Measurement	Good
182	--	08/15/2006	--	81.9	Thorny Creek	0	Observation	N/A
218	--	08/15/2006	1425	82.1	Current River	623	Measurement	Good
215	--	08/15/2006	--	82.3	Carr Creek	0	Observation	N/A
214	--	08/15/2006	--	82.6	Pole Cat Hollow	0	Observation	N/A
183	--	08/15/2006	--	84.0	Round Hollow	0	Observation	N/A
217	--	08/15/2006	1330	84.8	Current River	658	Measurement	Good
193	--	08/15/2006	--	85.1	Brand Wiede Hollow	0	Observation	N/A
213	--	08/15/2006	1203	85.4	Rocky Creek	1.29	Measurement	Poor
212	--	08/15/2006	1140	86.7	Indian Creek	.70	Measurement	Poor
211	--	08/15/2006	--	87.0	S123 Little Indian Creek	0	Observation	N/A
210	--	08/15/2006	1115	88.3	Current River below Blue Springs	620	Measurement	Good
209	[3]07066550	08/15/2006	1030	88.5	Blue Spring on Current River	93.0	Measurement	Poor
208	--	08/15/2006	0950	89.7	Powder Mill Spring and Cove Spring	7.90	Measurement	Fair
166	--	08/14/2006	2025	90.4	Current River above Highway 106 bridge	547	Measurement	Fair
206	--	08/15/2006	--	90.4	Current River above Highway 106 bridge	548	Measurement	Good
185	--	08/14/2006	--	90.6	S120 Little Bloom Creek	0	Observation	N/A
205	--	08/14/2006	--	91.0	Bloom Creek	0	Observation	N/A
204	--	08/14/2006	--	91.4	S122 Clint Williams Spring	.01	Estimated	Poor
207	--	08/14/2006	1940	92.1	Blair Creek	4.92	Measurement	Poor

Table 2. Results of a seepage run on the Current River, Jacks Fork, and Sinking Creek, August 14–18, 2006.—Continued

[mm/dd/yyy, month/day/year; hhmm, hour minute; mi, mile; ft³/s, cubic foot per second, --, no data; N/A, not applicable]

Site number[1]	U.S. Geological Survey station number	Date (mm/dd/yyyy)	Time (hhmm)	River mile[2] (mi)	Location description	Discharge (ft³/s)	Type	Rating
184	--	08/14/2006	--	92.6	S115	0	Observation	N/A
203	--	08/14/2006	1900	93.1	Current River	522	Measurement	Good
201	--	08/14/2006	1727	93.7	Thorny Hollow	.46	Measurement	Poor
202	--	08/14/2006	--	94.6	S116 near Coot Hollow	0	Observation	N/A
165	--	08/14/2006	1807	95.1	Big long pool 1/2 mile below old gage pool	511	Measurement	Fair
195	--	08/14/2006	--	96.0	Mathews Branch	.01	Estimated	Poor
196	--	08/14/2006	--	96.2	Near Barn Hollow	.01	Estimated	Poor
160	--	08/14/2006	1454	97.0	Ebb and Flow Spring	.09	Measurement	Poor
186	--	08/14/2006	--	97.0	Thompson Creek S118	.10	Estimated	Poor
161	--	08/14/2006	1437	97.2	Slough near Thompson Creek	.19	Measurement	Poor
164	--	08/14/2006	1620	97.2	Current River	361	Measurement	Good
200	--	08/14/2006	1500	99.2	Current River	354	Measurement	Fair
162	--	08/14/2006	--	99.9	Current River	353	Measurement	Good
199	--	08/14/2006	1413	99.9	Current River	361	Measurement	Good
187	--	08/14/2006	--	99.9	Sutton Creek	0	Observation	N/A
159	--	08/14/2006	--	100.4	No flow	0	Observation	N/A
158	--	08/14/2006	--	100.9	Creek near Twin Rocks	0	Observation	N/A
157	--	08/14/2006	--	101.3	150 feet below bluff left bank	361	Measurement	Good
197	--	08/14/2006	--	101.7	Barn Hollow	0	Observation	N/A
198	--	08/14/2006	1040	102.1	Current River/Jerktail Landing	363	Measurement	Good
178	--	08/17/2006	1425	103.0	Current River	342	Measurement	Fair
188	--	08/17/2006	--	103.0	Creek near Asher Branch	0	Observation	N/A
190	--	08/17/2006	--	104.2	Mill Hollow	0	Observation	N/A
176	--	08/17/2006	1342	104.8	Tributary measured 200 feet above Current River	.59	Measurement	Poor
175	--	08/17/2006	1345	104.9	Current River	343	Measurement	Good
177	--	08/17/2006	1252	106.4	Big Creek at Current River	6.33	Measurement	Fair
174	--	08/17/2006	1150	107.6	Current River	342	Measurement	Good
189	--	08/17/2006	--	109.1	S114 near Bay Branch	0	Observation	N/A
171	--	08/17/2006	1055	109.7	Current River	328	Measurement	Good
172	--	08/17/2006	1039	109.7	Spring flow not named	6.82	Measurement	Fair
173	--	08/17/2006	0955	112.4	Current River	326	Measurement	Fair
192	--	08/17/2006	--	112.4	Barn Hollow ponded	0	Observation	N/A
191	--	08/17/2006	--	113.1	Turkey Pen Hollow	.01	Estimated	Poor
170	--	08/17/2006	0855	114.2	Current River below Round Springs	335	Measurement	Good
76	--	08/17/2006	1525	114.9	Current River above Round Spring	331	Measurement	Fair
75	--	08/17/2006	1436	116.3	Current River below Sinking Creek	314	Measurement	Fair
74	--	08/17/2006	1400	116.4	Sinking Creek	34.2	Measurement	Fair
236	--	08/15/2006	1320	116.4	Sinking Creek at Current River	41.9	Measurement	Good
73	--	08/17/2006	1300	118.0	Current River below James Hollow	282	Measurement	Poor
71	--	08/17/2006	1145	119.8	Sugar Camp Hollow	.01	Estimated	Poor
72	--	08/17/2006	1154	119.9	Current River below Sugar Camp Hollow	275	Measurement	Fair

Table 2. Results of a seepage run on the Current River, Jacks Fork, and Sinking Creek, August 14–18, 2006.—Continued

[mm/dd/yyy, month/day/year; hhmm, hour minute; mi, mile; ft³/s, cubic foot per second, --, no data; N/A, not applicable]

Site number[1]	U.S. Geological Survey station number	Date (mm/dd/yyyy)	Time (hhmm)	River mile[2] (mi)	Location description	Discharge (ft³/s)	Type	Rating
70	--	08/17/2006	1130	120.3	Mill Hollow	0	Observation	N/A
69	--	08/17/2006	1110	120.8	Gyllard Hollow	0	Observation	N/A
68	--	08/17/2006	1051	121.7	Current River below Pulltite Complex	278	Measurement	Fair
67	--	08/17/2006	1030	122.3	Boyds Creek	0	Observation	N/A
66	--	08/17/2006	1006	123.2	Current River below Gravel and Shoal Spring	267	Measurement	Fair
64	--	08/17/2006	0845	123.2	Current River below Hydrant Spring	219	Measurement	Poor
61	--	08/16/2006	1622	123.4	Pulltite Spring	20.9	Measurement	Fair
62	--	08/16/2006	1645	123.4	Pulltite Hollow	0	Observation	N/A
60	--	08/16/2006	1625	123.6	Current River above Pulltite	190	Measurement	Fair
59	--	08/16/2006	1530	124.4	Big Hollow	0	Observation	N/A
58	--	08/16/2006	1510	125.2	Harrison Creek	0	Observation	N/A
57	--	08/16/2006	1450	125.7	Troublesome Creek	.04	Measurement	Poor
56	--	08/16/2006	1430	125.8	Footlog Hollow	0	Observation	N/A
55	--	08/16/2006	1425	125.9	Current River at Footlog Hollow	188	Measurement	Fair
53	--	08/16/2006	1310	127.9	Parker Hollow	0	Observation	N/A
54	--	08/16/2006	1330	127.9	Current River below Cave Spring	183	Measurement	Fair
52	--	08/16/2006	1245	128.3	Cave Spring Cave	16.6	Measurement	Poor
51	--	08/16/2006	1230	128.7	Unnamed tributary	0	Observation	N/A
50	--	08/16/2006	1215	129.1	FishTrap Hollow	0	Observation	N/A
49	--	08/16/2006	1200	129.6	Unnamed tributary	0	Observation	N/A
47	--	08/16/2006	1130	129.8	Unnamed tributary	0	Observation	N/A
48	--	08/16/2006	1130	129.8	Current River above Cave Spring	168	Measurement	Fair
46	--	08/16/2006	1115	131.2	Lewis Hollow	0	Observation	N/A
45	--	08/16/2006	1038	131.3	Current River below Akers	171	Measurement	Good
44	--	08/16/2006	1030	131.7	Unnamed tributary	0	Observation	N/A
43	--	08/16/2006	1010	132.1	Unnamed tributary	0	Observation	N/A
42	--	08/16/2006	0945	132.6	Unnamed tributary	0	Observation	N/A
41	--	08/16/2006	0930	132.8	Unnamed tributary	0	Observation	N/A
39	--	08/15/2006	1830	132.9	Gladen Creek	.01	Measurement	Poor
38	07064533	08/15/2006	1730	133.3	Current River above Akers	164	Measurement	Fair
40	07064533	08/16/2006	0903	133.3	Current River above Akers	170	Measurement	Fair
37	--	08/15/2006	1715	133.7	Dooly Hollow	0	Observation	N/A
36	--	08/15/2006	1645	134.2	Unnamed tributary	0	Observation	N/A
34	--	08/15/2006	1610	135.7	Tributary near Howell Hollow	0	Observation	N/A
35	--	08/15/2006	1619	135.7	Current River below Welch Spring	175	Measurement	Fair
33	--	08/15/2006	1515	136.2	Welch Spring	100	Measurement	Poor
32	--	08/15/2006	1500	136.6	Unnamed tributary	0	Observation	N/A
31	--	08/15/2006	1429	137.3	Spring at Medlock Cave	.43	Measurement	Poor
30	--	08/15/2006	1356	137.4	Current River above Medlock Cave	67.5	Measurement	Fair
29	--	08/15/2006	1345	137.6	Unnamed tributary	0	Observation	N/A
28	--	08/15/2006	1330	138.3	Job Hollow	0	Observation	N/A
27	--	08/15/2006	1315	138.6	Bay Hollow	0	Observation	N/A

Table 2. Results of a seepage run on the Current River, Jacks Fork, and Sinking Creek, August 14–18, 2006.—Continued

[mm/dd/yyy, month/day/year; hhmm, hour minute; mi, mile; ft³/s, cubic foot per second, --, no data; N/A, not applicable]

Site number[1]	U.S. Geological Survey station number	Date (mm/dd/yyyy)	Time (hhmm)	River mile[2] (mi)	Location description	Discharge (ft³/s)	Type	Rating
25	--	08/15/2006	1240	138.8	Current River at Lewis Hollow	64.5	Measurement	Fair
26	--	08/15/2006	1330	138.8	Lewis Hollow	0	Observation	N/A
24	--	08/15/2006	1133	140.0	Big Creek	1.83	Measurement	Poor
99	--	08/18/2006	0925	140.0	Big Creek near Yukon	.57	Measurement	Poor
23	--	08/15/2006	1030	140.6	Current River below Cedar Grove	61.8	Measurement	Poor
22	--	08/15/2006	1000	140.9	White Oak Hollow	0	Observation	N/A
21	--	08/15/2006	0900	141.0	Tributary on right bank	0	Observation	N/A
20	--	08/15/2006	0800	141.4	Tributary on right bank	0	Observation	N/A
19	--	08/14/2006	1820	142.4	Current River below Parker Hollow	61.3	Measurement	Fair
18	--	08/14/2006	1805	142.5	Parker Hollow branch mouth	1.45	Measurement	Poor
17	--	08/14/2006	1730	142.7	Brushy Hollow tributary	0	Observation	N/A
16	--	08/14/2006	1700	144.2	Current River below Ashley Creek	60.9	Measurement	Poor
15	--	08/14/2006	1645	145.0	Unnamed tributary	0	Observation	N/A
14	--	08/14/2006	1630	145.1	Unnamed tributary Bell Hollow	0	Observation	N/A
13	--	08/14/2006	1615	145.3	Unnamed tributary Alfred Hollow	0	Observation	N/A
12	--	08/14/2006	1600	145.8	Ashley Creek	2.36	Measurement	Fair
6	--	08/14/2006	1330	145.8	South Ashley Fork	.01	Estimated	Poor
7	--	08/14/2006	1400	145.8	North Ashley Fork	.70	Estimated	Poor
11	--	08/14/2006	1545	146.2	Unnamed tributary	0	Observation	N/A
10	--	08/14/2006	1527	146.4	Current River above Ashley Creek	59.9	Measurement	Fair
5	--	08/14/2006	1330	148.3	Inman Branch	0	Observation	N/A
4	--	08/14/2006	1300	148.7	Unnamed tributary	0	Observation	N/A
3	[3]07064440	08/14/2006	1220	149.3	Current River at Montark State Park	56.8	Measurement	Fair
8	--	08/14/2006	1430	150.7	Unnamed tributary	.01	Estimated	Poor
9	--	08/14/2006	1500	150.7	Unnamed spring at Montark State Park	.10	Estimated	Poor
1	[3]07064400	08/14/2006	1115	151.5	Montark Springs	48.6	Measurement	Poor
2	--	08/14/2006	1145	--	Unnamed tributary	0	Observation	N/A
77	--	08/14/2006	1015	--	Pigeon Creek at Highway 119	.68	Measurement	Poor
251	--	08/16/2006	1255	--	Pigeon Creek at Highway 119 bridge	.62	Measurement	Poor
245	--	08/16/2006	--	--	Pigeon Creek	0	Observation	N/A
246	--	08/16/2006	--	--	Pigeon Creek	0	Observation	N/A
247	--	08/16/2006	--	--	Pigeon Creek	0	Observation	N/A
248	--	08/16/2006	--	--	Pigeon Creek	0	Observation	N/A
					Jacks Fork			
156	--	08/17/2006	1516	0	Jacks Fork near Current River	138	Measurement	Fair
163	--	08/14/2006	1705	0.2	1/4 mile up Jacks Fork above Two Rivers	151	Measurement	Good
155	--	08/17/2006	1404	1.8	Jacks Fork	145	Measurement	Fair
154	--	08/17/2006	1342	2.1	Little Shawnee Creek	.17	Measurement	Poor
153	--	08/17/2006	1253	2.6	Shawnee Creek	4.83	Measurement	Fair
152	--	08/17/2006	1241	2.9	Spring downstream from Bald Knob Hollow	.06	Estimated	Poor
151	--	08/17/2006	1138	3.4	Jacks Fork	141	Measurement	Fair

Table 2. Results of a seepage run on the Current River, Jacks Fork, and Sinking Creek, August 14–18, 2006.—Continued

[mm/dd/yyy, month/day/year; hhmm, hour minute; mi, mile; ft^3/s, cubic foot per second, --, no data; N/A, not applicable]

Site number[1]	U.S. Geological Survey station number	Date (mm/dd/yyyy)	Time (hhmm)	River mile[2] (mi)	Location description	Discharge (ft^3/s)	Type	Rating
150	--	08/17/2006	1036	5.1	Jacks Fork	141	Measurement	Fair
149	--	08/17/2006	1022	5.6	Creek near Coppermine Hollow	0	Observation	N/A
148	--	08/17/2006	0859	6.8	Creek near Eminence	.40	Measurement	Poor
146	07066000	08/16/2006	1600	7.3	Jacks Fork at Eminence	133	Measurement	Fair
145	--	08/16/2006	1445	8.6	Story's Creek	.22	Measurement	Poor
144	--	08/16/2006	1416	9.1	Mahan's Creek	5.73	Measurement	Fair
143	--	08/16/2006	1351	9.6	Jacks Fork	128	Measurement	Fair
142	--	08/16/2006	1319	10.5	Possum Trot Hollow	.35	Measurement	Poor
141	--	08/16/2006	1302	11.0	Tributary of Jacks Fork	0	Observation	N/A
140	--	08/16/2006	1407	11.4	Jacks Fork	133	Measurement	Fair
139	--	08/16/2006	1129	12.4	Creek downstream from Low Gap Hollow	.49	Estimated	Poor
138	--	08/16/2006	1115	12.6	Low Gap Hollow	0	Observation	N/A
137	--	08/16/2006	1103	12.8	Creek along bluff inflow of Jacks Fork	0	Observation	N/A
136	--	08/16/2006	1039	13.0	Jacks Fork	137	Measurement	Fair
135	--	08/16/2006	1018	13.3	Creek near Alley Spring	.75	Measurement	Poor
134	[3]07065500	08/16/2006	0946	13.6	Alley Spring on Jacks Fork	97.0	Measurement	Fair
133	--	08/16/2006	0935	13.8	Creek at Alley Spring	0	Observation	N/A
132	07065495	08/16/2006	0845	14.1	Jacks Fork at Alley Spring	51.1	Measurement	Fair
147	--	08/16/2006	1642	15.0	Jacks Fork	49.2	Measurement	Fair
86	--	08/17/2006	1605	18.6	Jacks Fork near Allen Branch	42.2	Measurement	Fair
87	--	08/17/2006	1638	18.7	Allen Branch	.35	Measurement	Poor
84	--	08/17/2006	1422	19.9	Bay Creek	.50	Measurement	Poor
85	--	08/17/2006	1453	19.9	Jacks Fork near Bay Creek	40.4	Measurement	Fair
249	--	08/16/2006	1730	19.9	Bay Creek	.47	Measurement	Poor
250	--	08/16/2006	1650	19.9	Jacks Forks below Bay Creek	47.3	Measurement	Good
83	--	08/17/2006	1340	21.7	Jacks Fork upstream from Bay Creek	44.9	Measurement	Fair
81	--	08/17/2006	1000	28.4	Stillhouse Hollow	0	Observation	N/A
82	--	08/17/2006	1000	28.4	Spring near Stillhouse Hollow	0	Observation	N/A
80	--	08/17/2006	0951	28.5	Jacks Fork near Stillhouse Hollow	37.8	Measurement	Fair
98	--	08/16/2006	1400	28.9	Johny Hollow	0	Observation	N/A
97	--	08/16/2006	1314	29.5	Jacks Fork near Rymer Spring	38.2	Measurement	Fair
96	--	08/16/2006	1211	30.1	Flat Rock Hollow	.88	Measurement	Poor
95	--	08/16/2006	1034	32.3	Jacks Fork near Red Bluff	35.7	Measurement	Fair
94	--	08/16/2006	0945	32.8	Jacks Fork near Jam Up Cave	37.7	Measurement	Fair
253	--	08/16/2006	0940	35.5	Jacks Fork below Blue Spring	37.7	Measurement	Good
252	--	08/16/2006	0855	35.9	Blue Spring	10.6	Measurement	Fair
93	--	08/15/2006	1155	36.4	Jacks Fork upstream from Blue Spring	26.9	Measurement	Fair
92	07065200	08/15/2006	1000	38.5	Jacks Fork near Mountain View	25.6	Measurement	Fair
91	--	08/14/2006	1755	41.4	Jacks Fork near VFW Campground	23.6	Measurement	Fair
90	--	08/14/2006	1448	--	North Prong Jacks Fork	13.5	Measurement	Fair
88	--	08/14/2006	--	--	North Prong Jacks Fork	0	Observation	N/A
89	--	08/14/2006	1550	--	South Prong Jacks Fork	15.6	Measurement	Fair
79	--	08/14/2006	1702	--	South Prong Jacks Fork	0.95	Measurement	Poor

Table 2. Results of a seepage run on the Current River, Jacks Fork, and Sinking Creek, August 14–18, 2006.—Continued

[mm/dd/yyy, month/day/year; hhmm, hour minute; mi, mile; ft³/s, cubic foot per second, --, no data; N/A, not applicable]

Site number[1]	U.S. Geological Survey station number	Date (mm/dd/yyyy)	Time (hhmm)	River mile[2] (mi)	Location description	Discharge (ft³/s)	Type	Rating
					Sinking Creek			
243	--	08/15/2006	1105	--	Barren Fork	15.5	Measurement	Good
241	--	08/15/2006	0955	--	Twin Spring Sinking Hollow	13.3	Measurement	Fair
242	--	08/16/2006	1535	--	Barren Fork	0	Observation	N/A
244	--	08/15/2006	1155	--	Sinking Creek Campground ford	23.7	Measurement	Good
238	--	08/14/2006	1650	--	Sinking Creek at Cave Spring	17.0	Measurement	Good
240	--	08/14/2006	1530	--	Sinking Creek	12.4	Measurement	Good
239	--	08/14/2006	1450	--	Little Sinking Creek	4.27	Measurement	Fair
237	--	08/14/2006	1415	--	Hellums Hollow	.01	Measurement	Poor
258	--	08/14/2006	1210	--	Sugar Tree Grove, lower	6.96	Measurement	Fair
256	--	08/14/2006	1055	--	Sugar Tree Grove Spring	4.79	Measurement	Fair
257	--	08/14/2006	1315	--	Sugar Tree Little Spring	.23	Measurement	Poor
255	--	08/14/2006	1000	--	Sinking Creek at Black Henry Hollow	.10	Measurement	Poor
254	--	08/14/2006	0908	--	Chatman Hollow	.07	Measurement	Poor

[1]Site number is not sequential. Sites are listed by increasing river mile.

[2]River mile is distance, in miles, upstream from mouth of the Current River at the Black River, or distance, in miles, upstream from the mouth of Jacks Fork at the Current River; river miles not shown for Sinking Creek.

[3]U.S. Geological Survey gage was not in operation at the time of the seepage run.

in time of measurement (summer 2000 compared to late 2006/early 2007) because the map is generalized with a 100-ft contour interval, and the contours are joined at or near the Current River and Jacks Fork. These are areas of groundwater discharge where groundwater levels do not fluctuate a great deal relative to the 100-ft contour interval, even in floods. The water-level differences between summer 2000–06 for the four of five wells that were used by Imes and others (2007) to construct their shallow potentiometric-surface map range from +2.5 ft to +17.0 ft, which is not large relative to the 100-ft contour interval of the map. The fifth well (+112.1 ft) was used by Imes and others (2007) to map the deep potentiometric surface and was not used for the study area potentiometric map (fig. 7). The shallow potentiometric surface of Imes and others (2007) is not reinterpreted here, but is presented only with a few modifications to areas where the potentiometric surface appeared to be above the land surface. This situation is largely the result of the superposition of a detailed land surface over a generalized potentiometric surface and is to a certain extent unavoidable. The potentiometric surface of Imes and others (2007) was slightly modified in a few areas along streams where this difference was the largest, and the potentiometric contours in the newly mapped area were drawn to avoid this situation as much as possible.

The potentiometric-surface map of the study area (fig. 7) shows the general pattern of high hydraulic head in upland areas and progressively lower head closer to streams and generally mimics the land-surface topography. This indicates groundwater flow to the rivers because water flows from areas of high head to areas of low head. A groundwater divide (not shown on figure 7) can be interpreted from the potentiometric-surface map to show the separation of groundwater flowing to the Current River from groundwater flowing away from the Current River. In some places, notably along Logan Creek (fig. 1) and the northeastern part of the study area, the groundwater divide extends beyond the surface-water divide, indicating interbasin transfer of groundwater between surface-water basins.

Contours that inflect upstream around a stream indicate that groundwater discharges to the stream as diffuse discharge in the streambed or from springs at the stream or in the streambed. Contours wrap particularly tightly around the Current River and Jacks Fork. However, contours also wrap around a few losing streams at a lower altitude than the streambed. This may indicate the presence of subsurface karst conduits beneath the losing stream that depress the water table, thereby causing the stream to lose flow. In other places, contours pass through losing streams at a lower altitude than the losing stream without deflecting. A low hydraulic gradient, as indicated by widely spaced potentiometric contours, occurs in much of the upland area west of the Current River, associated with areas of high sinkhole density (fig. 7). The density of sinkholes indicates the presence of a network of subsurface karst conduits, which depresses the water table and causes the hydraulic gradient to be low.

Table 3. Daily mean discharge and daily precipitation at U.S. Geological Survey gages in the Current River Basin during the 2006 seepage run.

[ft^3/s, cubic foot per second; in., inch]

Date	Daily mean discharge							Precipitation	
	Current River above Akers [1]07064533 (ft^3/s)	Jacks Fork near Mountain View [1]07065200 (ft^3/s)	Jacks Fork at Alley Spring [1]07065495 (ft^3/s)	Jacks Fork at Eminence [1]07066000 (ft^3/s)	Current River at Van Buren [1]07067000 (ft^3/s)	Big Spring near Van Buren [1]07067500 (ft^3/s)	Current River at Doniphan [1]07068000 (ft^3/s)	Jacks Fork at Alley Spring [1]07065495 (in.)	Jacks Fork at Eminence [1]07066000 (in.)
August 10, 2006[2]	160	29	56	151	715	325	1,290	0	0
August 11, 2006[2]	159	29	58	155	727	323	1,310	0	.67
August 12, 2006[2]	162	29	61	155	786	322	1,320	0	0
August 13, 2006[2]	164	28	58	151	755	321	1,330	0	0
August 14, 2006	165	27	55	147	741	320	1,300	.03	.44
August 15, 2006	166	26	52	140	765	319	1,290	0	0
August 16, 2006	163	24	49	135	726	318	1,270	0	0
August 17, 2006	161	23	47	133	702	319	1,250	0	0
August 18, 2006	160	23	45	130	697	318	1,240	0	0

[1]U.S. Geological station number.

[2]August 10, 11, 12 and 13 were the 4 days before the seepage run began.

Although most groundwater reaches the Current River and Jacks Forks through springs, the details of flow through subsurface conduits is not apparent in figure 7. However, groundwater flow to springs is shown in a general way by spring recharge areas (delineated in large part by dye traces; fig. 4), which show the propensity for precipitation to be captured by subsurface conduits and eventually discharge at springs. The shapes of spring recharge areas mimic the potentiometric-surface contours to varying degrees, and generally coincide with the trends of major groundwater divides and groundwater troughs to a lesser extent. Groundwater troughs can reflect the presence of subsurface karst conduits, and show the convergence of flow to springs. This is probably best demonstrated by the Welch Spring and Blue Spring (Current River) recharge areas (figs. 4 and 7).

Low Base-Flow Discharge Measurements

The 2006 seepage run was conducted during low base-flow conditions when stream discharge represented the maximum groundwater component, or base flow of the stream discharge, with little additional inflow from surface-water runoff. However, there was some local precipitation in the area prior to and on the first day of the seepage run. Precipitation was recorded at the Jacks Fork at Eminence precipitation gage 3 days before the seepage run began [0.67 inch (in.) on August 11, 2006] and during the first day of the seepage run (0.44 in. on August 14, 2006) (table 3). The USGS precipitation gage at Jacks Fork at Alley Spring recorded only 0.03 in. of precipitation on August 14. Small increases in discharge followed by decreases in discharge were recorded at several gages, including the Current River at Van Buren gage, which is the most downstream gage on the Current River in the ONSR (table 3). The team making measurements downstream from Van Buren on August 14, 2006, reported turbid discharge from a few tributaries, indicating that at least some of the discharge was runoff. Although discharge measurements made at the same location on two different days can have different values because of measurement error, it is possible that the difference in river discharge is caused by precipitation. For example, the discharge of Jacks Fork near its mouth was measured at 151 ft^3/s on August 14, 2006 (the day the Jacks Fork at Eminence precipitation gage recorded 0.44 in. of precipitation), and at 138 ft^3/s on August 17, a difference of 13 ft^3/s (table 2). The USGS gage at Jacks Fork at Eminence recorded a discharge of 147 ft^3/s on August 14, and 133 ft^3/s on August 17, also a difference of 13 ft^3/s (table 3).

The streamflow conditions for the 2006 seepage run were low but not at historic low-flow conditions as compared with historic low-flow instantaneous discharges recorded at USGS gages (table 4). Comparison of 2006 low base-flow discharge measurements with low base-flow discharge measurements made in the 1941 and 1966 seepage runs also are shown on table 4. The discharge measured in 2006 generally was similar to or smaller than the 1966 measured discharge along the Current River. In contrast, the 2006 measured discharge was larger

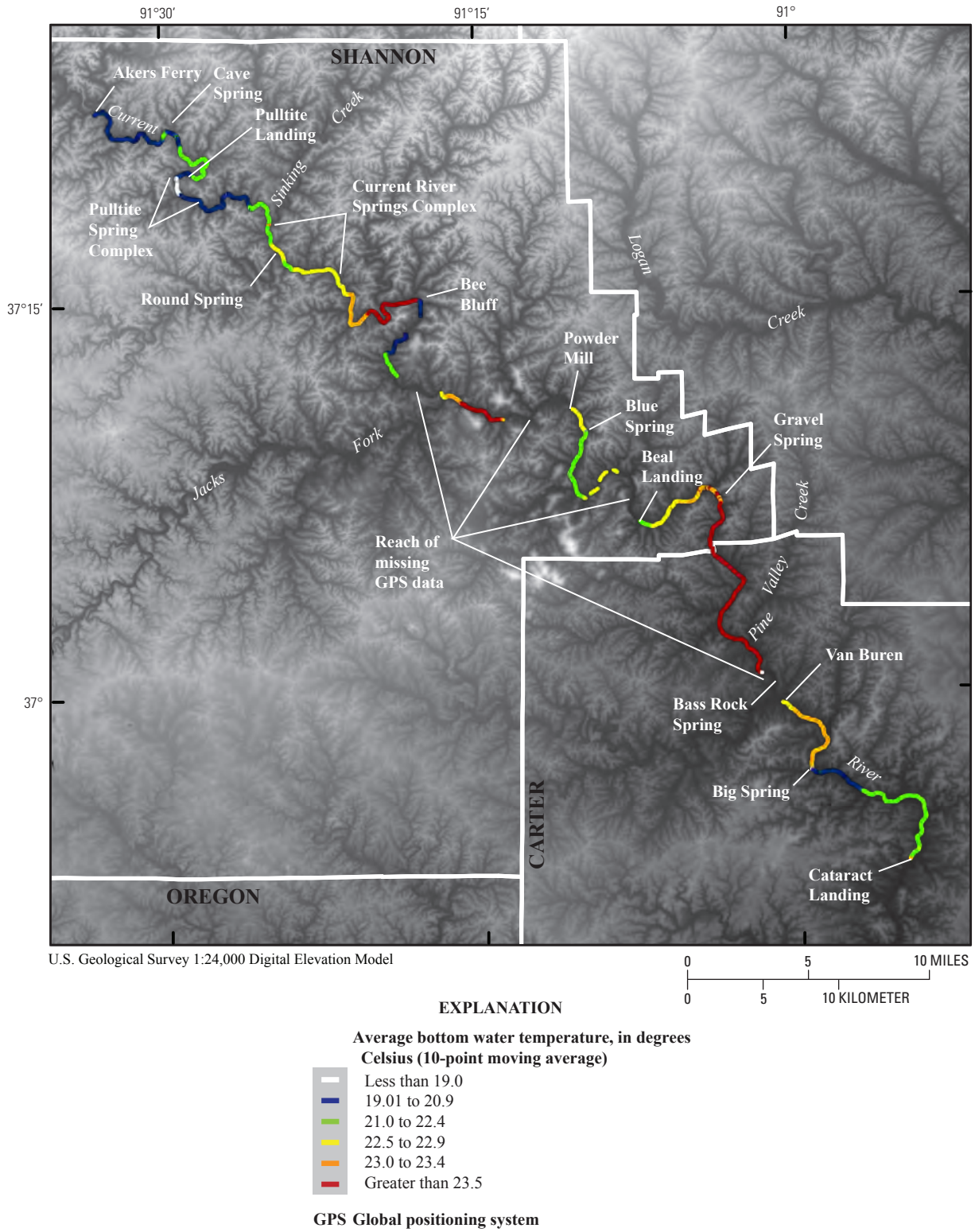


Figure 11. Average water temperature at river bottom during the temperature profile of the Current River from Akers Ferry to Cataract Landing, August 14 through August 24, 2006.

Table 4. Comparison of 1941, 1966, and 2006 seepage run discharge measurements at selected locations, and annual mean and instantaneous low-flow discharge for U.S. Geological Survey gages.

[ft³/s, cubic feet per second; mm/yyyy, month/year; --, no data]

Location[1]	1941 Seepage run discharge[2] (ft³/s)	1966 Seepage run discharge[3] (ft³/s)	2006 Seepage run discharge (ft³/s)	2006 Seepage run discharge as percentage of annual mean discharge (percent)	U.S. Geological Survey gage				
					Station number	Annual mean discharge[4] (ft³/s)	Instantaneous low-flow discharge[4] (ft³/s)	Instantaneous low-flow discharge[4] (mm/yyyy)	Period of record (mm/yyyy)
Montauk Springs	--	62	48.6	--	07064400	[5]--	[6]38.2	08/1934; [6]01/1956	1965, 1967–68
Current River at Montauk State Park	--	[7]63.8	[8]56.8	--	07064440	137	44	01/2008	02/2007 to present[9]
Welch Spring on Current River	--	108	100	--		--	--	--	--
Current River approximately 0.6 mile downstream from Welch Spring	--	194	175	--		--	--	--	--
Current River above Akers	--	203	164	45	07064533	361	119	10/2005	07/2001 to present[9]
Cave Spring on Current River	--	16.6	16.6	--		--	--	--	--
Current River approximately 0.2 mile upstream from Pulltite Spring	--	210	190	--		--	--	--	--
Current River approximately 1.7 mile downstream from Pulltite Spring	--	304	278	--		--	--	--	--
Round Spring on Current River	--	18.4	--	--	07065000	46.9	10	12/1937	10/1928 to 09/1939 and 08/1965 to 12/1979
Jacks Fork near Mountain View	--	27	25.6	13	07065200	200	15	10/2001	10/2001 to present[9]
Jacks Fork approximately 0.7 mile upstream from Blue Spring	--	26	26.9	--		--	--	--	--
Blue Spring on Jacks Fork	--	9.8	10.6	--		--	--	--	--
Jacks Fork at Alley Spring	32.8	41	51	19	07065495	274	22	09/2000	03/1993 to present[9]
Alley Spring on Jacks Fork	70	65	97	72	07065500	135	54	10/1934	10/1928 to 09/1939 and 08/1965 to 12/1979
Jacks Fork at Eminence	103	115	133	29	07066000	464	64	08/1936	10/1921 to present[9]

Table 4. Comparison of 1941, 1966, and 2006 seepage run discharge measurements at selected locations, and annual mean and instantaneous low-flow discharge for U.S. Geological Survey gages.-Continued

[ft^3/s, cubic feet per second; mm/yyyy, month/year; --, no data]

Location[1]	1941 Seepage run discharge[2] (ft^3/s)	1966 Seepage run discharge[3] (ft^3/s)	2006 Seepage run discharge (ft^3/s)	2006 Seepage run discharge as percentage of annual mean discharge (percent)	U.S. Geological Survey gage				
					Station number	Annual mean discharge[4] (ft^3/s)	Instantaneous low-flow discharge[4] (ft^3/s)	(mm/yyyy)	Period of record (mm/yyyy)
Jacks Fork at mouth	118	140	138, 151	--		--	--	--	--
Current River near Eminence (downstream from mouth of Jacks Fork)	433	527	511	35	07066500	1,456	324	10/1956	08/1921 to 09/1975
Blue Spring on Current River	90.4	88.4	93	--	07066550	--[10]	[11,12]62	09/1971	08/1970 to 09/1971
Current River approximately 0.7 mile downstream from Thorny Creek	--	646	635	--		--	--	--	--
Current River downstream from Gravel Spring	--	686	635	--		--	--	--	--
Current River at Van Buren	634	718	710	36	07067000	1,986	473	10/1956	10/1912 to present[9]
Big Spring near Van Buren	277	[13]305	343	77	07067500	446	[11]236	10/1956	10/1921 to 09/1996 and 02/2000 to present[9]

[1]Seepage run measurements generally were made close to each other in different years but were as much as 0.5 mile from each other.

[2]Data on file at the U.S. Geological Survey office, Rolla, Missouri.

[3]Source of data is Skelton (1976).

[4]Annual mean discharge and instantaneous low-flow discharge values are for the period of record; except as noted, sources of data are U.S. Geological Survey annual data reports for 1975, 1979, and 2008 (U.S. Geological Survey, 1976, 1980, 2008a).

[5]Annual mean discharge was 58 ft^3/s for 1965, 73 ft^3/s for 1967, and 86 ft^3/s for 1968 (U.S. Geological Survey, 1968), but no long-term annual mean discharge is available for the period of record.

[6]Source of data is U.S. Geological Survey (1968). A few discharge measurements were made before the gage was installed.

[7]1.78 ft^3/s discharge in Pigeon Creek upstream from Montauk Springs was added to discharge measurement of Montauk Springs.

[8]Discharge measurement for 2006 seepage run was made near location of gage installed in 2007.

[9]Present is 2008.

[10]The annual mean discharge was 107.8 ft^3/s for 1971 when a gage was in place (U.S. Geological Survey, 2008b), but a longer term annual mean discharge has not been calculated.

[11]Discharge is minimum daily mean value for gage.

[12]Source of data is U.S. Geological Survey (2008b).

[13]Discharge was not measured for the 1966 seepage run; discharge given is the daily mean discharge for October 19, 1966, from the U.S. Geological Survey gage at Big Spring (U.S. Geologcial Survey, 2008a).

than the 1966 measured discharge at several locations on Jacks Fork, including Alley Spring. The 1941 seepage run was conducted only on Jacks Fork and the Current River downstream from the mouth of Jacks Fork. Discharge measured in 1941 was lower than in either 1966 or 2006 but also was not at historic low-flow conditions.

The results of the seepage run are given on figures 8, 9, and 10, and table 2, and are referenced in the section "Spring Discharge, Spring Recharge Areas, and Sources of Water to the Current River and Jacks Fork" (most of the seepage run locations downstream from the boundary of the ONSR are not shown on figure 10). In general, the seepage run showed gaining conditions, that is, the Current River, Jacks Fork, and Sinking Creek gained flow with increasing distance downstream. Most of the gain was from discharge from identified springs (fig. 4), and a smaller amount of gain was from tributaries whose discharge probably originated as spring discharge or from springs or diffuse groundwater discharge in the streambed. Any two adjacent measurements may appear to indicate a loss of flow or a gain of flow that cannot be attributed to inflow from known springs or tributaries, but each measurement has an associated error, and trends in discharge need to account for the range of possible discharge that could exist at each measurement location given the measurement error. This is particularly illustrated by a 23.4-mi reach of Jacks Fork (river mi 28.5 to 5.1; fig. 9) from about 19 mi upstream from Eminence to about 2 mi downstream from Eminence, which appears to indicate a gain in flow followed by a loss, and then a gain. However, while there may have been a small gain in flow that cannot be attributed to known springs or tributaries, it cannot be shown that there was a loss of flow after accounting for measurement error. The potentiometric-surface map (fig. 7) does not indicate any losing conditions along Jacks Fork.

Current River Temperature Profile

A temperature profile along an 85-mi reach of the Current River between Akers Ferry and Cataract Landing was conducted August 14 through August 24, 2006. The primary purpose of the temperature profile was to identify previously unknown springs discharging directly into the streambed of the Current River. The temperature profile was conducted during low-flow conditions in August to maximize the temperature contrast between the river and spring inflows. The 54-mi reach from Akers Ferry to Beal Landing was done on August 14 through August 17 and the remaining lower 31-mi reach was completed on August 23 and 24, 2006 (table 5). Because of the large number of park visitors during the weekend, the temperature profile was suspended on August 17 and resumed the following week. On August 22, the reach from Pulltite to Round Spring was redone to verify results from the previous week. The reach from Beal Landing to Van Buren was done on August 23, and the final reach from Van Buren to Cataract Landing was done on August 24. A poor connection between the GPS receiver card and the field hand-held computer resulted in GPS readings not being recorded for about 13 mi of the 85-mi profiled reach of the Current River (fig. 11). Profile data along these reaches were evaluated using time and field notes.

Results of the temperature profile indicate a general increase in river bottom temperature with increasing distance downstream (fig. 11). Excluding inflows from springs or tributaries, the average bottom temperature (10-point moving average) along the main stem of the Current River ranged from 19.4 ºC at the upstream site at Akers Ferry to 26.4 ºC upstream from Bass Rock Spring near Van Buren, Missouri (a previously undocumented spring; table 5). Average bottom temperatures were lower within or immediatley downstream from inflows of springs such as Cave Spring (15.6 ºC), Fire Hydrant Spring which is part of the Pulltite Springs Complex (fig. 11; 14.0 ºC), Blue Spring (16.8 ºC), Bass Rock Spring (14.0 ºC), and Big Spring (14.4 ºC). Direct temperature measurements were made only at the orifices of Gravel Spring, Fire Hydrant Spring, and Bass Rock Spring, which discharged directly into the river. As expected, because of incomplete mixing, instantaneous bottom temperatures at Cave Spring (13.7 ºC) and Blue Spring (14.4 ºC) were lower than the 10-point moving river bottom average temperatures. The warmest bottom temperatures were measured near the mouth of Sinking Creek (average bottom temperature of 24.7 to 26.6 ºC) and an average bottom temperature of 27.4 ºC measured in a slough at the mouth of Pine Valley Creek (table 5; fig. 11). The warm inflow from Sinking Creek (more than 28.0 ºC measured at the mouth of the creek on August 22, 2006) was in sharp contrast to the 21.6 ºC average bottom temperature measured in the Current River immediately upstream from Sinking Creek.

Average surface temperatures of the Current River generally were slightly higher than the average bottom temperatures and ranged from about 20.0 ºC at the upstream site at Akers Ferry to 26.8 ºC in the pool containing Bass Rock Spring near Van Buren, Missouri (table 5). The general increase in bottom and surface temperature with distance downstream is caused by the longer residence time of water in the stream that allows for warming by contact with the warmer summer air temperatures and exposure to sunlight during the daytime hours in which the temperature profile was done. For example, during the 3-hour period from about 15:45 to 18:45 on the afternoon of August 15, 2006, that it took to traverse the nearly 10-mi reach from Round Spring to Bee Bluff, the average bottom temperature steadily increased from about 22.5 ºC downstream from Round Spring to more than 24.0 ºC at Bee Bluff (fig. 12). Except for the reach from Beal Landing to Van Buren, where the largest temperature was measured at the upper end of the pool containing Bass Rock Spring, generally the warmest water temperatures were recorded in the afternoon hours at the end of each profiled reach.

As expected, abrupt drops in bottom temperature were detected as inflows of major springs were passed. For example, average bottom temperature decreased from 22.8 ºC upstream from Round Spring to 22.0 ºC at about 15:35 as

Table 5. Temperature profiled reaches along the Current River, August 2006.

[mm/dd/yyyy, month/day/year; hh:mm, hour:minute; ºC , degrees Celsius; ft, feet;--, no data; mi, mile]

Reach	Date and time (mm/dd/yyyy) (hh:mm)	Distance (river miles)	Beginning and ending main stem bottom temperatures		Bottom temperature extremes		Water-surface temperature extremes[1]		Maximum recorded depth[3] (ft)
			Beginning average[2] bottom temperature (ºC)	Ending average[2] bottom temperature (ºC)	Main stem or inflow average[2] minimum (ºC)	Main stem or inflow average[2] maximum (ºC)	Average[2] minimum (ºC)	Average[2] maximum (ºC)	
Akers Ferry to Pulltite Spring	08/14/2006 13:00–17:00	9.5	19.4	22.5 (Pulltite Landing)	15.6 (at Cave Spring)	22.5	20.0	22.7	9.6
Pulltite Spring to Bee Bluff	08/15/2006 11:55–18:30	19.5	20.2	24.1 (Bee Bluff gravel bar)	15.2 (Downstream from Pulltite Spring) 14.0 (Fire Hydrant Spring)	24.1 (Bee Bluff) 24.7 (Mouth of Sinking Creek)	18.0 (at Fire Hydrant Spring)	24.5 (Mouth of Sinking Creek)	8.4
Bee Bluff to Powder Mill	08/16/2006 07:30–15:50	15	20.5	25.7 (Powder Mill Landing)	20.5	25.7	20.9	25.9	15.3
Powder Mill to Beal Landing	08/17/2006 09:20–12:45	10	22.6	23.8	16.8 (Downstream from Blue Spring)	23.8 (Beal Landing)	20.9 (Downstream from Blue Spring)	24.3	20.8
Pulltite Spring to Round Spring	08/22/2006 12:25–15:50	9.5	19.7	23.0 (Landing upstream from State Highway 19)	14.0 (Fire Hydrant Spring)	26.6 (Mouth of Sinking Creek)	20.2	23.0	7.1
Beal Landing to Van Buren	08/23/2006 10:20–17:20	17	23.9	26.2 (U.S. Highway 60 bridge)	14.0 (Bass Rock Spring)	26.4 (Upstream from Bass Rock Spring) 27.4 (Pine Valley Creek slough)	23.8	26.8 (Pool containing Bass Rock Spring)	14.4
Van Buren to Cataract Landing[4]	08/24/2006 07:50–12.45	14	23.0	22.3	[4]14.4 (Big Spring inflow)	[5]23.2 (Upstream from Big Spring)	17.0 (Downstream from Big Spring)	22.8	[6]8.8

[1]Pressure transducer used to record water-surface temperature was biased 0.3 0 C higher than water-quality probe used to measure bottom temperature.

[2]10-point moving average.

[3]Depth is maximum depth recorded by hand-suspended pressure transducer deployed beneath the boat and may not reflect the maximum stream depth.

[4]A cross section 0.2 mi downstream from Big Spring had a minimum temperature of 19.9 ºC on the west side of the river and maximum temperature of 23.8 degrees ºC on the east side of the river.

[5]Profile done during early morning with overcast resulting in lower water temperatures compared to upstream reach.

[6]No depth data from approximately 4.5 mi upstream from Cataract Landing because of pressure transducer malfunction.

the inflow from Round Spring was encountered (fig. 12). The average bottom temperature decreased relatively rapidly as the spring water and river mixed within a pool downstream from the spring inflow, then began a gradual rise from about 22.5 ºC beginning at about 15:45. No temperature anomalies were noted along the reach identified as the Current River Springs Complex (figs. 11 and 12). However, a small temperature decrease that may be a small spring in the streambed was noted at about river mile 109.7 just upstream from the mouth of Grassy Creek (fig. 12), which is downstream from the Current River Springs Complex. Except for the anomaly at river mile 109.7, no temperature anomalies that were not attributable to known spring inflows or tributaries were detected along the reach between Akers Ferry (river mile 133.3) and Blue Spring (river mile 88.5; fig. 11).

Average bottom temperature decreased substantially as inflow from Blue Spring was passed during the morning of August 17, 2006 (fig. 13). The magnitude of the inflow from Blue Spring was such that it resulted in an overall cooling of the Current River. The average bottom temperature decreased from 22.7 ºC upstream from the spring inflow to 16.8 ºC as the mouth of the spring branch was passed (the spring orifice is about 0.25 mi upstream from the mouth of the spring branch). After a short reach of variable temperature because of incomplete mixing, the average river bottom temperature stabilized at about 21.5 ºC along a riffle about 0.3-mi downstream before beginning the typical steady rise as daytime temperatures increased (fig. 13).

The difference in average river bottom temperature upstream and downstream from a spring can be used to estimate the groundwater heat flux (temperature multiplied by discharge) of the spring. A mass-balance on heat calculation, assuming equilibrium mixing, can be used to estimate the discharge of groundwater from a spring using the following relations:

$$Qu \times Tu + Qg \times Tg = Qd \times Td \quad (1)$$

$$Qu + Qg = Qd \quad (2)$$

where

- *Qu* is the discharge upstream in cubic foot per second;
- *Tu* is the average upstream temperature in degrees Celsius;
- *Qg* is the groundwater inflow in cubic foot per second;
- *Tg* is the average groundwater temperature in degrees Celsius;
- *Qd* is the downstream river discharge in cubic foot per second; and
- *Td* is the average downstream river temperature in degrees Celsius.

This approach is a modification of the approach that was used by Vaccaro and Maloy (2006) to examine groundwater inflows along reaches of the Yakima River. For Blue Spring (Current River), discharge measurements made for the seepage run during the week of August 14, 2006, indicate that the discharge of the Current River upstream from Blue Spring was 556 ft^3/s after accounting for inflow from Cove Spring and Powder Mill Spring (table 2). To avoid the additive effect associated with the upstream and downstream discharge measurement errors on the main stem, the magnitude of which could be large compared to most spring flows, only one of the upstream *(Qu)* or downstream *(Qd)* discharge measurements was used in the mass balance on heat calculation (equation 1). Equation 2 was used to substitute for the remaining main stem discharge. Substituting the measured average bottom temperature of the Current River upstream (22.7 ºC) and downstream (21.5 ºC) from Blue Spring, minimum instantaneous temperature of the spring branch inflow of 14.4 º C, discharge of 556 ft^3/s upstream from Blue Spring, and substituting equation 2 for the downstream discharge yields an estimated discharge of Blue Spring of 94 ft^3/s. This value is within 1 percent of the 93 ft^3/s measured at the spring on August 15, 2006. Solving the above equations using the downstream discharge of 620 ft^3/s results in an estimated discharge of 90 ft^3/s for Blue Spring (within about 4 percent of the actual measured value). The substitution approach was used because the sum of the actual measured upstream discharge (556 ft^3/s) plus Blue Spring discharge (93 ft^3/s) was 29 ft^3/s larger than the 620 ft^3/s measured downstream from Blue Spring. The difference, however, was within the 5 percent error based on the measurement ratings. While within 5 percent, the difference in the upstream and downstream measurements would yield a discharge of 64 ft^3/s for Blue Spring (only 69 percent of the actual measured value). If both the upstream and downstream discharge measurements were used in equation 1, the discharge estimated for Blue Spring would be only 49 ft^3/s.

The sensitivity of the above relations to estimate groundwater inflow is dependant on the accuracy and precision of the temperature and discharge measurements, and the differences in temperature and discharge between the river and groundwater at the location of groundwater inflow. For example, given a minimum detectable temperature differential of 0.2 ºC (two times the 0.1 ºC precision of the water-quality probe thermistor), and using the same values above (*Qu* of 556 ft^3/s, *Tu* of 22.7 ºC, *Tg* of 14.4 ºC), but substituting 22.5 ºC for *Td* (*Tu* minus the minimum detectable temperature difference of 0.2 ºC), the minimum groundwater inflow into the Current River that could be detected at this location would be about 13.7 ft^3/s or about 2.5 percent of the upstream discharge. As the temperature difference between the river and groundwater inflow decreases the minimum detectable *Qg* increases.

A small temperature anomaly was identified along the reach from Powder Mill to Beal Landing profiled on August 17, 2006. The anomaly was downstream from Blue Spring at about river mile 85.1 near Rocky Creek (fig. 13). This second temperature anomaly was associated with a sudden increase

in specific conductance from about 325 µS/cm to 350 µS/cm. The exact location and length of the anomaly within the river could not be detected because the GPS signal was intermittently lost along this reach, but its duration was short (less than 0.5 minute float time). An examination of the pressure transducer data along this reach indicates that the water depth where the anomaly occurred was between about 0.7 and 1.5 ft deep. The intermittent GPS readings along this reach indicate that the anomaly was along the right bank of the river (looking downstream) at the downstream end of a steep bluff near the mouth of Brandwiede Hollow. This anomaly is probably inflow from Brandwiede Hollow as field notes indicate a small cool tributary inflow in this area (fig. 13). Several sharp drops in specific conductance values along the reach between Powder Mill and Beal Landing on figure 13 are the result of the water-quality probe being temporarily exposed above the water surface as shallow rapids were encountered. The deepest river depth recorded along the 85-mi profiled reach was 20.8 ft in a pool just upstream from Rocky Creek (fig. 13).

The discharge from Gravel Spring was not directly measured during the August 2006, seepage run, and the mass-balance on heat calculation was used to estimate its discharge. A river discharge of 640 ft^3/s was measured on August 15, 2006, 1.0-mi upstream from Gravel Spring (fig. 10). The average river bottom temperature upstream from the spring was 23.9 ºC and the spring temperature and specific conductance were 13.8 ºC and 340 µS/cm (fig. 14). Following a small and short decrease in average river bottom temperature (minimum of 22.6 ºC) caused by incomplete mixing of the inflow from Gravel Spring, the average river bottom temperature stabilized at 23.7 ºC within a riffle about 0.4-mi downstream from the spring (fig. 14). The subtle difference in average river bottom temperatures (0.2 ºC) is at the limit of the method and yielded an estimated discharge of 12.9 ft^3/s for Gravel Spring.

The lower part of the reach from Beal Landing to Van Buren (downstream from Rogers Creek) contained two temperature anomalies. The first was a small seep emerging from a rock bluff at about river mile 65.1 that contained an unusually large specific conductance value (more than 600 µS/cm, fig. 15). This seep is located outside the ONSR boundary and could be related to septic effluent from several nearby homes at the top of the bluff. A second anomaly was a large temperature decrease detected within a pool near river mile 64.1. The average river bottom temperature decreased from 26.2 ºC at the upstream end of the pool to 14.0 ºC within the pool, then stabilized to 25.6 ºC within a riffle 0.15-mi downstream (fig. 15). Unfortunately, a poor connection between the hand-held computer and GPS card resulted in erroneous GPS readings throughout this entire reach, and the exact location of the anomaly within the pool was estimated from field notes and times from the water-quality probe and pressure transducer data log files. The ONSR staff had indicated that a spring was suspected in this reach because of gas bubbles observed floating to the water surface. The pressure transducer data indicates that the pool was about 12.5 ft deep with a sharp thermocline developed about 8 to 9 ft deep. Above this thermocline, the water temperature was more than 26 ºC compared to the less than 15 ºC below the thermocline. The pool is locally referred to as “Bass Rock” and the temperature anomaly is referred to herein as “Bass Rock Spring.” A river discharge of 664 ft^3/s was measured on August 16, 2006, about 1.4-mi upstream from Bass Rock Spring. Using the mass-balance on heat calculation, the upstream Current River discharge of 664 ft^3/s, and minimum instantaneous bottom temperature of 13.9 ºC for the groundwater inflow temperature, the discharge of Bass Rock Spring was estimated at 34.1 ft^3/s (34.4 ft^3/s using the downstream Current River discharge) . This estimated spring flow is at the 5 percent error limit for the upstream and downstream Current River discharge measurements. A discharge of 707 ft^3/s (710 ft^3/s less 2.67 ft^3/s inflow from Pike Creek) was measured about 1.0-mi downstream from Bass Rock Spring indicating a possible gain of 43 ft^3/s along the 2.4-mi reach between the upstream and downstream discharge measurement sites, which compares favorably with the 34.1 ft^3/s estimate for Bass Rock Spring derived from the temperature profile. Bass Rock Spring is similar to Pulltite Spring and Blue Spring in that its specific conductance value (295 µS/cm) was smaller than the specific conductance of the Current River upstream from the spring (330 µS/cm, table 6). In contrast, the specific conductance values of Cave Spring, Gravel Spring, and Big Spring were larger than the Current River upstream from these springs.

Dye Tracing

The first of the two dye tracer tests conducted by the USGS in 2006 (dye injection date of July 11, 2006) was unsuccessful because dye was not recovered at any of the dye packet locations. The second dye tracer test (dye injection date of December 1, 2006) was successful. Dye was detected only from charcoal packets placed in Blue Spring (Current River), beginning with a packet collected on December 6, 2006, and ending with a packet collected on January 12, 2007. The straight-line dye flow path for this tracer test is one of several traces shown going to Blue Spring in figure 4. It is not known why dye was not recovered from the first dye tracer test, as its injection location was only about 3,200 ft from the second dye injection. However, during the course of recovering dye packets soon after the first injection, a few more dye packets were deployed, including at three small springs along Carr Creek and one small tributary near Blue Spring. It is possible that dye emerged at one of these locations before the packets were deployed, although it would be expected that some residual dye would have emerged after the dye packets were deployed.

Spring Discharge, Spring Recharge Areas, and Sources of Water to the Current River and Jacks Fork

There are three ways by which water can move to the Current River or Jacks Fork: (1) surface-water runoff, (2) discharge of groundwater from springs, and (3) discharge of diffuse groundwater flow. Although there was very little surface-water runoff during the low base-flow conditions of the 2006 seepage run, there can be considerable runoff during intense or extended precipitation events. The 2006 seepage run showed discharge of water from some tributaries, but most of this probably has its source also as springs that feed the tributaries. (However, as noted above, a few tributaries downstream from Van Buren were observed to be flowing turbid following a local precipitation event on August 14, 2006.) Most groundwater moves relatively quickly as discrete flow in conduits to springs, but groundwater also can move more slowly as diffuse flow along small fractures and bedding planes and through small vugs. Diffuse groundwater flow can discharge from the riverbank or streambed, or can move to conduits in the subsurface and become discrete groundwater flow. Whereas diffuse groundwater flow maintains base flow in many streams elsewhere, discrete flow is much more important in maintaining base flow in karst settings such as the ONSR.

Over 270 springs have been identified in the study area (Missouri Department of Natural Resources, 2007; fig. 4). This section describes, in downstream order, 13 springs in the study area for which recharge areas have been estimated (fig. 4). These 13 springs include the larger springs that contribute flow to the Current River and Jacks Fork in the ONSR. These springs have not been investigated in any detail in this study (only two dye tracer tests were conducted), and this section represents mostly a compilation from other studies. For all but one spring (Bass Rock Spring), the estimated recharge areas in figure 4 are reproduced unchanged or slightly modified from previous investigations (Aley and Aley, 1987; Imes and others, 2007; Keller, 2000; Vandike, 1997) mostly on the basis of the potentiometric-surface map developed for this study. All or part of two other estimated spring recharge areas, which are not discussed in this report because they do not discharge to the ONSR, are reproduced from Imes and others (2007): Greer Spring discharges to the Eleven Point River immediately south of the study area, but most of its recharge area is in the study area; Mammoth Spring is in Arkansas, but a portion of its recharge area is in the southwestern part of the study area.

Spring recharge area boundaries are approximate because they are only estimates of where precipitation falling on the land surface has the potential to enter the groundwater system and discharge at a particular spring. If water-level data were sufficiently dense to delineate subsurface conduits, a more detailed potentiometric surface could be used to construct more detailed spring recharge areas. Instead, both potentiometric contours and spring recharge areas are generalized, and spring recharge area boundaries, as previously stated, only generally correspond with the configuration of the potentiometric surface. Dye traces help to define spring recharge areas, but generally only a few dye traces exist for each spring, and the need for more dye tracing exists for all springs. Most of the dye traces shown in figure 4 are compiled from Aley and Aley (1987) and from other dye traces contained in the dye trace database maintained by the DGLS (Missouri Department of Natural Resources, 2007). Dye traces from different injection points converge to a spring, and less commonly traces diverge from a single injection point in the case where dye was recovered at more than one spring (fig. 4). Not all the precipitation that falls in a spring recharge area discharges from that spring because surface water runoff also moves to rivers, especially during storm runoff events, and there is also a smaller amount of groundwater flow that discharges at smaller springs and as diffuse groundwater discharge in streambeds. Aley (1976) estimated that there is approximately 1 square mile (mi^2) of spring recharge area for each cubic foot per second of annual mean spring discharge. Vandike (1997) suggests that because some precipitation flows to rivers as surface-water flow after heavy rains instead of infiltrating to the groundwater system, the actual recharge area may be larger. Some spring recharge areas overlap or are contained in recharge areas of other springs, and were drawn this way (Aley and Aley, 1987) in response to dye traces that showed a divergence from the injection point to more than one spring.

A long-term (period of record) annual mean discharge value is available for three springs that are or previously were monitored by a USGS gage (Big Spring, Round Spring, and Alley Spring). The USGS operated a gage at Blue Spring (Current River) for about 1 year and at Montauk Springs for 3 years, but a long-term annual mean discharge is not available for either spring. Discharge measurements are available for most of the springs discussed in this section, and an average of discharge measurements, which is not the same as an annual mean discharge, has been reported for some of the springs (for example, Vineyard and Feder, 1982). Because an average of discharge measurements may not include measurements of large quantities of discharge, which are difficult to measure during periods of high water, and because of the small number of measurements for most of the nongaged springs, an average of discharge measurements may be lower than the estimated or actual annual mean discharge for the spring. Estimates of long-term annual mean discharge have been made for some springs (for example, Aley, 1976; Aley and Aley, 1987; Keller, 2000; Vandike, 1997; Vineyard and Feder, 1982).

Discharge and recharge area data for the 13 springs in the study area for which recharge areas have been estimated are shown in table 7. These 13 springs accounted for 82 percent (867 ft^3/s, using an estimate of 12 ft^3/s for Round Spring) of the 1,060 ft^3/s discharge of the Current River at Big Spring during the 2006 seepage run. The percentage of the total discharge from springs was larger than this because of additional discharge from other small, unmeasured springs along the Current River and Jacks Fork and their tributaries

that was not included in this figure. To correct this, a running downstream total was made of spring and tributary discharges from the 2006 USGS seepage run, including these 13 springs, and is shown in table 7 as cumulative spring discharge at the locations of these 13 springs. This assumes that measured discharges from tributaries, such as Sinking Creek and the two prongs of Jacks Fork above Blue Spring, have their origin as spring discharge. While it is possible that some of this discharge is diffuse flow through the streambeds, the DGLS spring database (Missouri Department of Natural Resources, 2007) shows several springs along Sinking Creek and the two prongs of Jacks Fork, with more along the south prong than the north prong. In addition, the USGS 1:24,000 topographic maps identify some springs; in some places it is observed that the discharge increased downstream from an identified spring. Accounting for all possible spring inflows, the cumulative discharge from springs was over 90 percent of the river discharge at most of the spring locations in table 7, and was 92 percent at Big Spring (table 7). Except for some storm related runoff downstream from near Big Spring, the cumulative discharge from springs was also about 92 percent at the downstream end of the ONSR (not shown on table 7). The remainder, which was less than 10 percent of the discharge at most locations, is the net increase in measured discharge from upstream to downstream measurement stations, which cannot necessarily be attributed to springs, and is groundwater that has discharged to the streambed as diffuse flow or from unidentified springs in the streambed. Because some of this discharge could still be from springs, this remaining discharge represents the maximum discharge that could be attributed to discharge of diffuse groundwater flow.

The surface-water basin, groundwater basin, and estimated spring recharge areas at selected springs and other locations along the Current River and Jacks Fork are shown in figures 16 through 23. The surface-water basin is the area that contributes water to the rivers by surface-water runoff and is defined by land-surface topography. This area is important during periods of surface-water runoff following intense or extended precipitation. The groundwater basin is defined by the potentiometric-surface upgradient from each location, and is approximate because the potentiometric surface is generalized. Because the groundwater basin is approximate and the spring recharge area is estimated, some spring recharge areas (for example, Welch Spring) extend beyond the groundwater divide. A more detailed potentiometric surface defined by more water-level measurements, and better defined spring recharge areas based on additional dye traces would result in a better correspondence. Table 8 shows various areal statistics for these contributing areas at several locations, including the locations depicted in figures 16 through 23. These contributing areas are estimated spring recharge area, total spring recharge area (the union of all spring recharge areas at and upstream from the specified location), surface-water basin, groundwater basin, and total contributing area (the union of the surface-water basin, groundwater basin, and total spring recharge area). The total spring recharge area includes only the 13 springs for which recharge areas have been estimated (fig. 4). This results in an underestimate of what the total spring recharge area really is, and, therefore, an overestimate of what percent a given spring's recharge area is of the total spring recharge area. This does not affect the statistics a great deal along the Current River because of the large quantity of water involved, but is notable along Jacks Fork because the discharge from unidentified springs in the two prongs of the upper Jacks Fork is substantial relative to stream discharge (fig. 9).

Selected Springs and Other Locations Along the Current River and Jacks Fork

Montauk Springs

Montauk Springs (figs. 4 and 16) is actually a single spring with a bedrock opening that became filled with gravel following a flood in the early twentieth century, causing the spring discharge to rise in several pools, gravel bars, and creek beds in the flood-plain alluvium (Vandike, 1997). It is referred to herein as a single spring. Although it is located upstream from the ONSR, it is a major source of stream discharge in the upper Current River at the upstream boundary of the ONSR. Montauk Springs is the eleventh largest spring in Missouri, and the fifth largest spring in the Current River Basin (Vineyard and Feder, 1982). The annual mean discharge for the 3 years the USGS maintained a gage at Montauk Springs was 58 ft^3/s in 1965, 73 ft^3/s in 1967, and 86 ft^3/s in 1968, but no longer term annual mean discharge value is available. The average of 28 discharge measurements made from 1980 through 1994 was 87.6 ft^3/s (Vandike, 1997). Aley (1976) estimated the annual mean discharge from Montauk Springs at 100 ft^3/s (table 7). The discharge measured during the 1966 seepage run was 62 ft^3/s (table 4). The discharge measured during the 2006 seepage run was 48.6 ft^3/s, which represented 99 percent of the flow in the Current River at that point (table 7). The estimated recharge area for Montauk Springs shown in figures 4 and 16 is 99 mi^2, and is modified from Aley and Aley (1987) and from Vandike (1997) to better reflect the general trends in the potentiometric surface (fig. 7). A small portion of this recharge area is outside the Current River surface-water basin (fig.16). The annual mean discharge for 2008 for a USGS gage on the Current River downstream from Montauk Springs (Current River at Montauk State Park; USGS station number 07064440) installed in 2007 is 137 ft^3/s (table 4).

Welch Spring

Welch Spring (fig. 4 and 16) is the next large spring downstream from Montauk Springs. Because no gage has been operated there, an annual mean discharge is not known and only estimates of annual mean discharge have been made. Vineyard and Feder (1982) estimated that its annual mean discharge was 116 ft^3/s. Aley (1976) estimated an annual mean discharge of 140 ft^3/s. More recently, Keller (2000) estimated

an annual mean discharge of 229 ft^3/s and suggested that a flood in 1985 changed the character of the spring channel such that some of the flow that had gone through the alluvial gravel before 1985 could now be measured, resulting in larger discharge measurements. An estimated annual mean discharge of 229 ft^3/s is used in this report (table 7), ranking Welch Spring as the third largest spring in Missouri and the second largest spring in the Current River Basin, instead of the eighth largest spring in Missouri and the fourth largest spring in the Current River Basin (Vineyard and Feder, 1982). The discharge measured during the 1966 seepage run was 108 ft^3/s (table 4), and the discharge measured in the 2006 seepage run was 100 ft^3/s, which represented 57 percent of the discharge in the Current River at that location (table 7).

The estimated recharge area for Welch Spring shown on figures 4 and 16 is 214 mi^2 and is reproduced from Keller (2000) who, based on additional dye tracing and in an effort to account for an estimate of a larger annual mean discharge, modified the recharge area shown by Aley and Aley (1987). The spring recharge area for Welch Spring is almost entirely outside the surface-water basin for the Current River at Welch Spring, and the groundwater basin at that location is much larger than the surface-water basin (fig. 16). The recharge area for Welch Spring is 68 percent of the total spring recharge area at that location (Welch Spring and Montauk Springs; table 8). It would, therefore, be expected that Welch Spring would supply approximately 68 percent of the discharge of the Current River that is attributable to spring discharge; table 7 shows that Welch Spring contributed 65 percent of the cumulative spring discharge at that location as measured in the 2006 seepage run.

Cave Spring

The next substantial spring downstream along the Current River is Cave Spring (figs 4 and 17). Aley (1976) estimated that the annual mean discharge from Cave Spring is 41.5 ft^3/s. The discharge measured in the 1966 seepage run was 16.6 ft^3/s, and the discharge measured in the 2006 seepage run also was 16.6 ft^3/s, which represented 9 percent of the flow in the Current River at that point (table 7). The recharge area for Cave Spring shown on figures 4 and 17 is 40 mi^2 and is reproduced from Aley and Aley (1987). A small portion of this recharge area overlaps the recharge area for Welch Spring.

Pulltite Springs Complex

The Pulltite Springs Complex, as described by Aley and Aley (1987), includes Pulltite Spring, Fire Hydrant (Kampers) Spring, Boiling Sand Spring, Gravel Spring [a small spring, not to be confused with Gravel Spring downstream from Blue Spring (Current River)], and unnamed springs in the channel of the Current River between Pulltite Spring and the mouth of Little Field Hollow, 1.9 mi downstream from Pulltite Spring (figs. 1, 8, and 17). The USGS measured 18.2 ft^3/s from Pulltite Spring in the 1966 seepage run (Skelton, 1976) and 20.9 ft^3/s in the 2006 seepage run. The USGS measured 3 ft^3/s from Fire Hydrant Spring during the 1966 seepage run (Skelton, 1976), but discharge was not measured in the 2006 USGS seepage run. The USGS measured 17.5 ft^3/s from what was called Sand and Gravel Springs [probably what Aley and Aley (1987) referred to separately as Boiling Sand Spring and Gravel Spring] during the 1966 seepage run (Skelton, 1976), but discharge was not measured during the 2006 USGS seepage run.

Aley (1978) estimated that the annual mean discharge from the Pullite Springs Complex is 142 ft^3/s, and that figure is used in table 7. The 2006 USGS seepage run indicated a total discharge of 77 ft^3/s from Pulltite Spring, Fire Hydrant Spring, Sand and Shoal Springs (Boiling Sand Spring and Gravel Spring), and unnamed springs in the channel of the Current River between Pulltite Spring and a location on the Current River 0.25 mi downstream from Pulltite Spring, by subtracting the Current River discharge upstream from these springs (190 ft^3/s; site 60, table 2) from the Current River discharge downstream from these springs (267 ft^3/s; site 66, table 2; fig. 8). The gain in discharge from 0.25 mi downstream from Pulltite Spring to a location 0.25 mi above Little Field Hollow, a distance of 1.4 mi, was 11 ft^3/s for a total discharge of 88 ft^3/s for the Pulltite Springs Complex (table 7). This represented 32 percent of the discharge in the Current River at the lower end of the Pulltite Springs Complex (table 7). The 1966 seepage run indicated a total discharge of 94 ft^3/s for the Pulltite Springs Complex, and a gain in flow of 14 ft^3/s over the same reach of the Current River as the 11 ft^3/s gain in the 2006 seepage run. These small discharges in the lower reach of the Pulltite Springs Complex measured in the 1966 and 2006 seepage runs indicates that most of the discharge from unnamed springs of the Pulltite Springs Complex occurs in the first 0.25 mi below Pulltite Spring, at least during low base-flow conditions. Despite the small inflow downstream from this location, the downstream extent of the Pulltite Springs Complex is not redefined here, because a dye trace was successful from within the Pulltite Spring recharge area to several springs of the complex, including one in the Current River channel upstream from Little Field Hollow (Aley and Aley, 1987), and because spring discharge into the streambed is probably greater during periods of large river discharge.

Aley and Aley (1987) proposed a recharge area of 162 mi^2 for the Pulltite Springs Complex. That recharge area is reproduced in figures 4 and 17 with only the northeastern boundary modified to not be coincident with the Current River upstream from Pulltite Spring. The recharge area shown in figures 4 and 17 is 145 mi^2, and overlaps a small portion of the recharge area of Round Spring and the Current River Springs Complex.

Round Spring and the Current River Springs Complex

Round Spring and the Current River Springs Complex are considered together, as Aley and Aley (1987) show a common recharge area (figs. 4 and 17). Round Spring has an annual mean discharge of 46.9 ft^3/s based on 25 years of record at a USGS gage (1928–1939 and 1965–1979; U.S. Geological

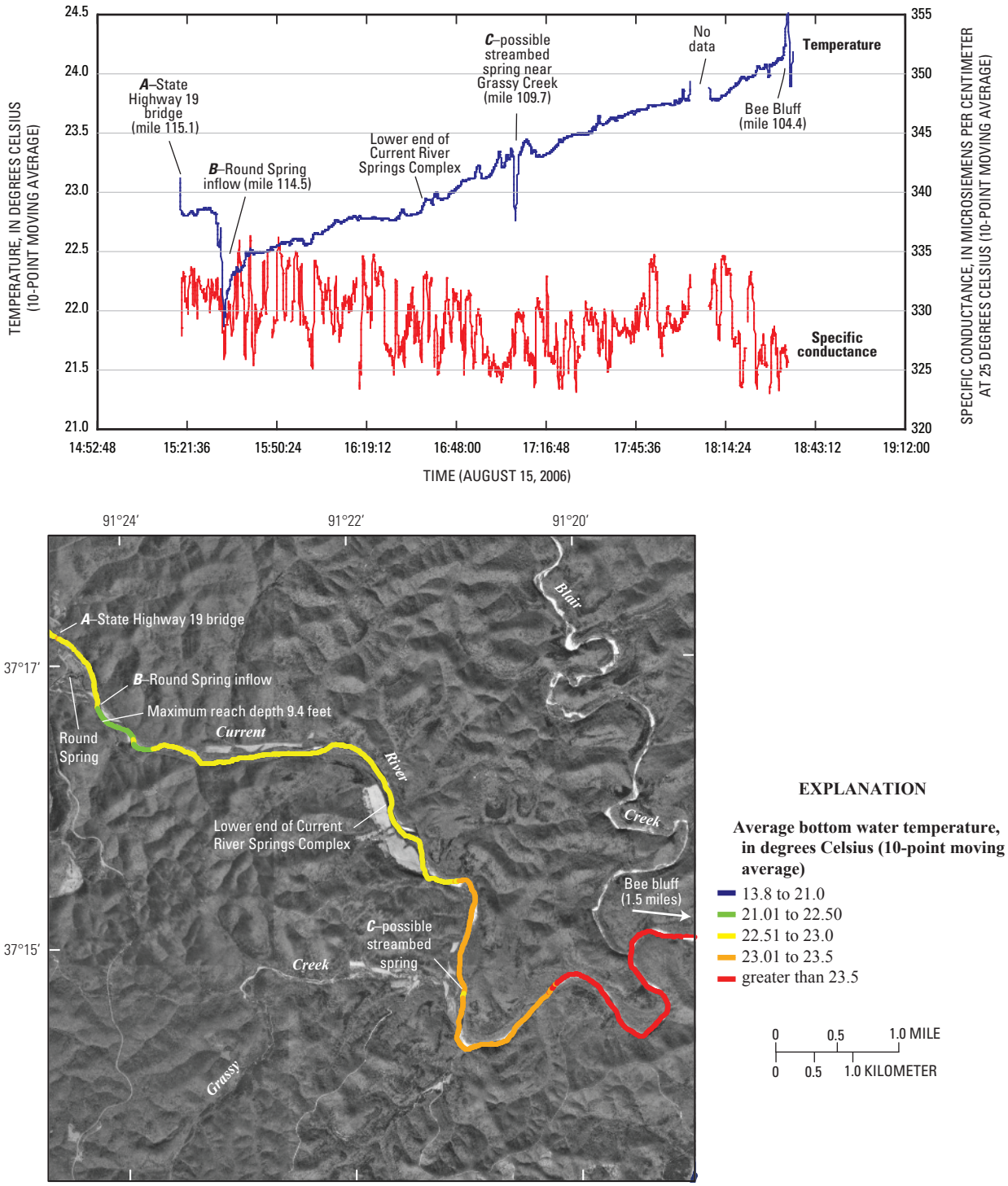


Figure 12. Average water temperature and specific conductance at river bottom along a 10-mile reach of the Current River downstream from State Highway 19 bridge near Round Spring on August 15, 2006.

Survey, 1980; tables 4 and 7). Because of excessive watercress, a discharge measurement of Round Spring was not obtained for the 2006 seepage run. The discharge measured in the USGS 1966 seepage run was 18.4 ft^3/s (table 4). Aley and Aley (1987) defined the Current River Springs Complex as springs that discharge in or near the channel of the Current River from the mouth of Sinking Creek, 1.7 mi upstream from Round Spring, to the mouth of Root Hollow, 2.7 miles downstream from Round Spring, not including Round Spring, for a total distance of 4.4 mi (figs. 1, 8 and 17). Aley (1976, 1978) estimated that the annual mean discharge from the Current River Springs Complex was 125 ft^3/s by applying a factor

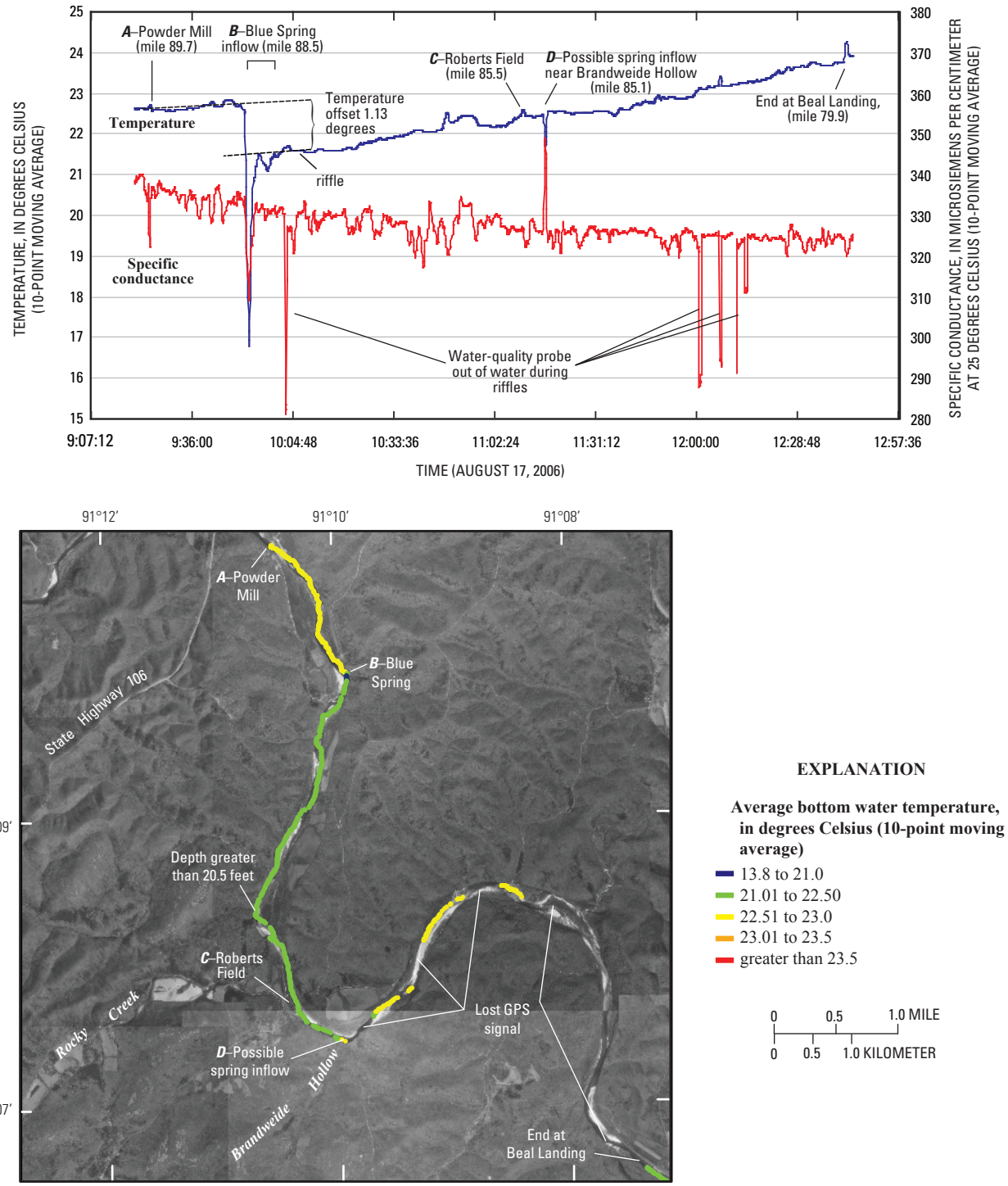


Figure 13. Average water temperature and specific conductance at river bottom along a 10-mile reach of the Current River downstream from Powder Mill to Beal Landing on August 17, 2006.

of 2.5 to the 1966 USGS seepage run data that indicated an apparent increase of discharge of about 50 ft^3/s over that reach of the river, not including Round Spring. The 2.5 factor was based on the ratio of the annual mean discharge from Round Spring (46.9 ft^3/s) to the 1966 low-flow seepage-run discharge measurement from Round Spring (18.4 ft^3/s) (table 4). The apparent discharge increase of about 50 ft^3/s was calculated by subtracting 311 ft^3/s (discharge measured 0.4 mi upstream from Round Spring) and 18.4 ft^3/s (Round Spring discharge) from 379 ft^3/s (the measured discharge 0.6 mi upstream from Root Hollow). However, the Current River Springs Complex discharges substantially less water than this. The discharge

measurement of 311 ft^3/s was made on November 8, 1966, whereas the other measurements through the reach of the Current River Springs Complex were made on October 19, 1966, when discharge in the Current River was greater because of precipitation that had fallen in parts of the Current River Basin on October 18 and 19 (National Oceanic and Atmospheric Administration, 1966). Several discharge measurements made at common locations on the Current River on October 18 or 19, 1966, and November 8, 1966, indicated that the discharge measured in November was 17 ft^3/s to 34 ft^3/s less than in October. Based on these findings, the sum (348 ft^3/s) of the October discharge measurement of the Current River at the lower end of the Pulltite Springs Complex (304 ft^3/s) and the discharge from Sinking Creek (44 ft^3/s) should be used instead of 311 ft^3/s to calculate the discharge from the Current River Springs Complex. This yields a gain in flow of only 12.6 ft^3/s from the Current River Springs Complex (379 ft^3/s minus 348 ft^3/s minus 18.4 ft^3/s from Round Spring) for the 1966 seepage run. Also, the 2006 seepage run shows a gain of only 12 ft^3/s for the combined Round Spring and Current River Springs Complex from the mouth of Sinking Creek to 0.7 mi upstream from Root Hollow. Because no discharge measurement is available for Round Spring for the 2006 seepage run, the amount of this 12 ft^3/s that can be attributed to the Current River Springs Complex cannot be determined, but it is smaller than 12 ft^3/s. There may still be discharge from springs of the Current River Springs Complex, but the discharge would be too small to be detected by subtracting upstream from downstream measurements, given the associated measurement errors. Also, the 2006 temperature profile measurements did not indicate any influx of spring discharge throughout the length of the Current River Springs Complex. Small springs exist along the Current River throughout the reach of the Current River Springs Complex, and dye traces have been successful to these springs (Aley and Aley, 1987). Dye traces with recovery of dye from dye packets placed in the Current River also have been reported (Aley and Aley, 1987), but because some of these could have been the result of dye discharging from an upstream spring (for example, Round Spring) before moving downstream to the dye packets, a few dye paths that showed recovery of dye at locations in the streambed of the Current River (Aley and Aley, 1987; Missouri Department of Natural Resources, 2007) are not shown on figure 4.

Disregarding the apparent small discharge from the Current River Springs Complex in the 2006 seepage run and instead using the 1966 seepage run discharge of 12.6 ft^3/s and applying a 2.5 factor, the annual mean discharge from the Current River Springs Complex is estimated to be 32 ft^3/s. Combined with an annual mean discharge from Round Spring of 46.9 ft^3/s, the annual mean discharge from the combined Round Spring and Current River Springs Complex would be about 79 ft^3/s. The recharge area shown in figures 4 and 17 is 119 mi^2, and is reproduced from Aley and Aley (1987) with only slight modification. A small portion of the estimated recharge area is on the east side of the Current River as demonstrated by dye tracing, and a small portion of the recharge area overlaps the recharge area for the Pulltite Springs Complex (Aley and Aley, 1987).

Current River at the Mouth of Jacks Fork

The surface-water basin and groundwater basin for the Current River at the mouth of Jacks Fork, and spring recharge areas upstream from that location are shown in figure 17. The groundwater basin and surface-water basin are more similar in size than at Welch Spring (fig. 16). Because the recharge areas for Cave Spring, Pulltite Springs Complex, and Round Spring and the Current River Springs Complex are mostly or entirely within the surface-water basin, the percentage of the total spring recharge area that is outside the surface-water basin is lower (29 percent) than at Welch Spring (73 percent).

Blue Spring (Jacks Fork)

Blue Spring on the upper Jacks Fork (fig. 4) is the second largest spring on Jacks Fork, behind Alley Spring. Aley (1976) estimated that the annual mean discharge from Blue Spring was 24.5 ft^3/s by applying a factor of 2.5 to the low-flow discharge of 9.8 ft^3/s measured during the 1966 USGS seepage run (Skelton, 1976). The 2.5 factor is based on the ratio of the annual mean discharge of Round Spring to the 1966 low-flow seepage run measurement of the discharge from Round Spring. The discharge from Blue Spring measured during the 2006 seepage run was 10.6 ft^3/s, which represented 27 percent of the discharge of Jacks Fork at that location (table 7). The recharge area shown on figures 4 and 18 is reproduced from the estimated recharge area in Aley and Aley (1987), which is based on only one successful dye trace to Blue Spring and a concentration of sinkholes north-northeast of Blue Spring that are thought to contribute water to the spring. The recharge area is 56 mi^2, which is substantially more than 24.5 mi^2 if the estimate of 1 mi^2 of recharge area for 1 ft^3/s of annual mean discharge (Aley, 1976) is applied. The recharge area is larger than this because most of the Blue Spring recharge area is shared with the Alley Spring recharge area (Aley and Aley, 1987).

Alley Spring

Alley Spring is the seventh largest spring in Missouri and the third largest spring in the Current River Basin (behind Big Spring and Welch Spring), using Keller's (2000) revised estimate of the annual mean discharge from Welch Spring, and 127 ft^3/s for the annual mean discharge from Blue Spring (Current River; Schumacher, 2008). The annual mean discharge from Alley Spring is 135 ft^3/s, based on a USGS gage that was operated at Alley Spring from 1928 to 1939 and from 1965 to 1979 (U.S. Geological Survey, 1980; tables 4 and 7). The measured discharge from Alley Spring was 70 ft^3/s in the 1941 seepage run and 65 ft^3/s in the 1966 seepage run (table 4). The discharge measured during the 2006 seepage run was 97 ft^3/s, which represented 71 percent of the discharge of Jacks Fork at that location (table 7). The estimated recharge area for Alley Spring shown in figures 4 and 18 is 147 mi^2, and was

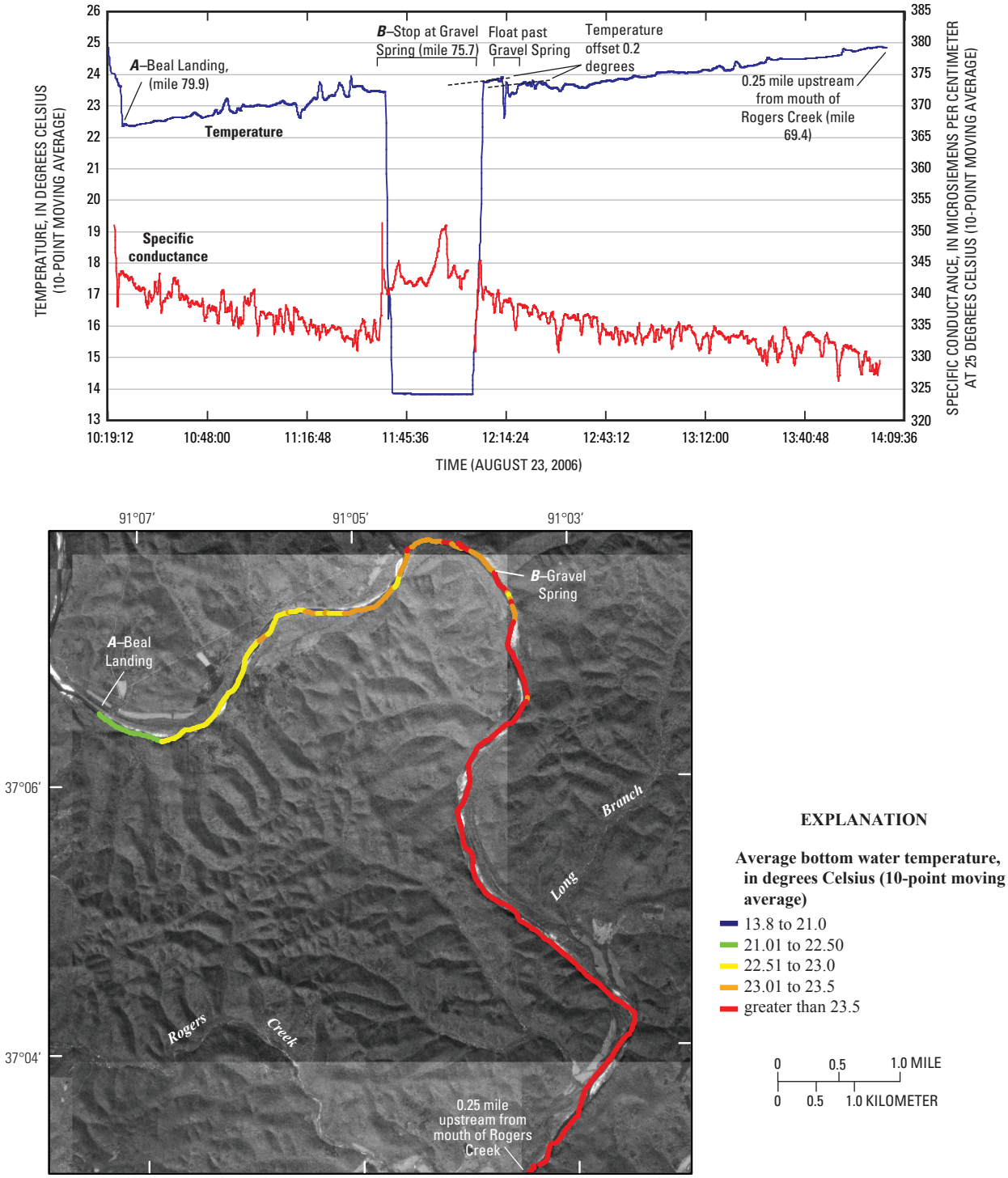


Figure 14. Average water temperature and specific conductance at river bottom along a 10-mile reach of the Current River upstream from Rogers Creek on August 23, 2006.

modified from Aley and Aley (1987) by extending its western boundary to include the injection point of a recent successful dye trace to Alley Spring (Aley and Moss, 2006b) that had been outside the previously estimated recharge area.

The surface-water basin and groundwater basin for Jacks Fork at Alley Spring, the Alley Spring recharge area, and the Blue Spring (Jacks Fork) recharge area, which is upstream from Alley Spring, are shown in figure 18. The surface-water and groundwater basins are of similar size, and a large portion of the total of the Blue Spring and Alley Spring recharge areas (51 percent) lies outside the surface-water basin (table 8). The Alley Spring recharge area is 92 percent of the total

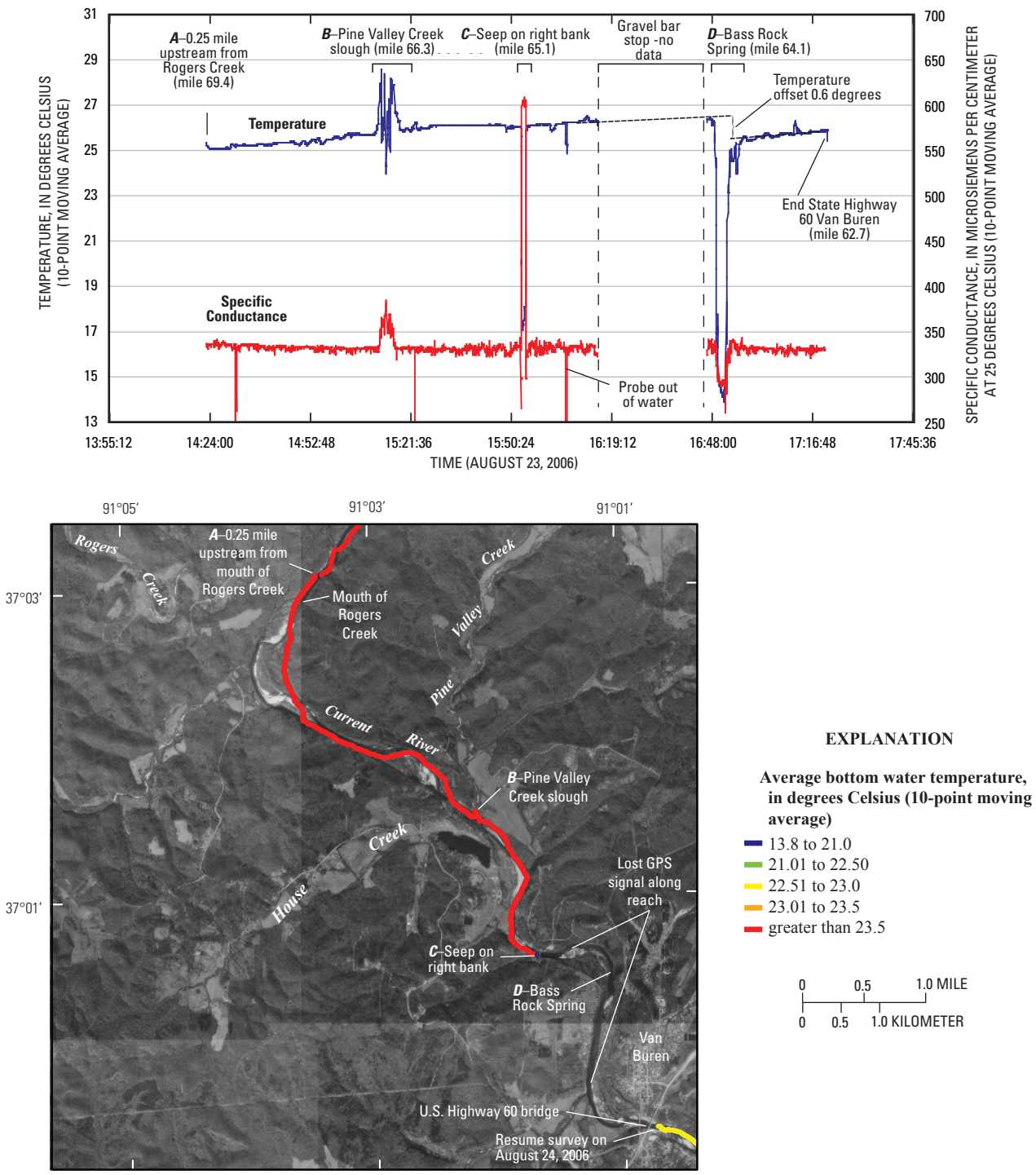


Figure 15. Average water temperature and specific conductance at river bottom along a 7-mile reach of the Current River upstream from Van Buren on August 23, 2006.

spring recharge area (Blue Spring and Alley Spring) at that location along Jacks Fork (table 8), but this would be a lower percentage if recharge areas (which have not been estimated) for spring discharge to the two prongs of Jacks Fork were included. The discharge from Alley Spring measured in the 2006 seepage run represented 70 percent of the cumulative spring discharge at that location, which includes the discharge in the two prongs of Jacks Fork as spring discharge (table 7). Approximately 100 percent of the 2006 seepage run measured discharge in Jacks Fork at Alley Spring was from spring discharge (table 7).

Table 6. Estimated average temperature and specific conductance values of selected major springs and the Current River during the August 2006 temperature profile.

[mm/dd/yyyy, month/day/year; µS/cm, microsiemens per centimeter at 25 degrees Celsius; ºC, degrees Celsius; --, no data]

Spring	Date (mm/dd/yyyy)	Spring measurements		Current River upstream from spring	
		Specific conductance (µS/cm)	Temperature (ºC)	Specific conductance (µS/cm)	Temperature (ºC)
Cave Spring	08/14/2006	318	13.7	310	21.0
Pulltite Springs Complex	08/15/2006	290	14.0	330	[1]20.2
Round Spring	--	--	--	330	22.8
Blue Spring	08/17/2006	300	14.4	333	22.7
Gravel Spring	08/23/2006	340	13.8	334	23.9
Bass Rock Spring	08/23/2006	295	13.9	333	26.2
Big Spring	08/24/2006	350	14.4	333	[1]23.1

[1]Profile done during early morning with overcast resulting in lower water temperatures compared to upstream reach.

Jacks Fork at its Mouth at the Current River

The surface-water basin and groundwater basin for Jacks Fork at its mouth at the Current River, and spring recharge areas (Blue Spring and Alley Spring) upstream from that location are shown in figure 19. The surface-water and groundwater basins are of similar size (table 8). About 48 percent of the total spring (Blue Spring and Alley Spring) recharge area for Jacks Fork at its mouth at the Current River is outside the surface-water basin (table 8), but this probably would be a lower percentage if recharge areas (which have not been estimated) for spring discharge to the two prongs of Jacks Fork were included. The combined measured discharge from Blue Spring and Alley Spring during the 2006 seepage run was 108 ft^3/s, which is 78 percent of the 138 ft^3/s discharge that was measured the next day at the mouth of Jacks Fork. About 37 percent (48 percent of 78 percent) of the discharge of Jacks Fork at its mouth probably originates as precipitation outside the surface-water basin during low base-flow conditions.

Current River near Eminence

Statistics for contributing areas to the Current River near Eminence are given in table 8. This location is just downstream from the mouth of Jacks Fork, and, therefore, includes the contributing areas to Jacks Fork. The groundwater basin is slightly larger than the surface-water basin, and only 22 percent of the combined spring recharge area is outside the surface-water basin.

Cove Spring

Cove Spring is a small spring on the Current River but it is described in this report because a recharge area for the spring has been estimated based on three successful dye traces to it (Aley and Aley, 1987). Water from Cove Spring flows about 3,700 ft down Powder Mill Creek to the Current River. Discharge from Powder Mill Spring flows into Powder Mill Creek about 900 ft upstream from the Current River. Powder Mill Spring was observed during dye tracing in 2006 and 2007 to have less discharge than Cove Spring. The combined discharge of Cove Spring and Powder Mill Spring was 7.9 ft^3/s in the 2006 seepage run (fig. 10). Aley and Aley (1987) did not estimate an annual mean discharge for Cove Spring, but their estimated recharge area is 29 mi^2 (figs. 4 and 20; table 7). Although discharge data for Cove Spring are limited, this recharge area appears large for such a small spring. However, the recharge area for Cove Spring is contained in the recharge area for Blue Spring (Current River) and overlaps the recharge area for Gravel Spring. Aley and Aley (1987) state that most of the water entering the groundwater system in the Cove Spring recharge area probably discharges to Blue Spring. Also, the recharge area for Cove Spring probably supplies water to Powder Mill Spring. A portion of the Cove Spring recharge area is along Logan Creek, outside the Current River Basin.

Blue Spring (Current River)

The next large spring downstream on the Current River is Blue Spring. The annual mean discharge from Blue Spring was 107.8 ft^3/s in 1971 when the USGS operated a gage at Blue Spring for about a year (U.S. Geological Survey, 2008b), but a longer term annual mean discharge is not available. Vineyard and Feder (1982) reported that the average of 19 discharge measurements made between 1923 and 1965 was 107 ft^3/s, and estimated that the annual mean discharge from Blue Spring was 139 ft^3/s. Vandike (1997) combined these 19 discharge measurements with 28 discharge measurements by the USGS between 1980 and 1994 and calculated an average of 131 ft^3/s for these 47 discharge measurements. Schumacher (2008) summarized data for 115 discharge measurements made by the USGS from 1923 through 2006, including some measurements that had not previously been compiled. The discharge measurements ranged from 59.3 to 290 ft^3/s with a median of 108 ft^3/s and a mean of 127 ft^3/s. This compilation is more complete than others, and 127 ft^3/s is used as an estimate of the annual mean discharge from Blue Spring (table 7), although this could be an underestimate if large discharges

Table 7. Spring discharge, river discharge, cumulative spring discharge, spring recharge area, and spring recharge area per unit spring discharge at selected springs along the Current River and Jacks Fork measured during the 2006 low base-flow seepage run.

[ft^3/s, cubic foot per second; mi^2, square mile; $mi^2/ft^3/s$, square mile per cubic foot per second; --, no data]

Spring	Spring discharge (ft^3/s)	River discharge at spring[1] (ft^3/s)	Spring discharge as percentage of river discharge (percent)	Cumulative spring discharge[2] (ft^3/s)	Spring discharge as percentage of cumulative spring discharge (percent)	Cumulative spring discharge as percentage of river discharge (percent)	Estimated spring recharge area[3] (mi^2)	Anual mean spring discharge[4] (ft^3/s)	Spring recharge area per unit annual mean spring discharge ($mi^2/ft^3/s$)	Spring recharge area per unit 2006 low base-flow spring discharge ($mi^2/ft^3/s$)	2006 low base-flow spring discharge as percentage of annual mean spring discharge (percent)
Montauk Springs	48.6	[5]49.3	99	49.3	99	100	99	100	0.99	2.04	49
Welch Spring	100	175	57	155	65	89	214	229	.93	2.14	44
Cave Spring	16.6	183	9	171	10	93	40	41.5	.96	2.41	40
Pulltite Springs Complex	88	278	32	259	34	93	145	142	1.02	1.65	62
Round Spring	--	335	--	[6]306	--	91	[7]--	[8]46.9	--	--	--
Blue Spring (Jacks Fork)	10.6	39.7	27	39.7	27	100	56	24.5	2.29	5.28	43
Alley Spring	97	137	71	138	70	[9]100	147	[8]135	1.09	1.52	72
Cove Spring	[10]7.9	[11]527	1	485	2	92	29	[7]--	--	3.67	--
Blue Spring (Current River)	93	620	15	578	16	93	137	127	1.08	1.47	73
Gravel Spring	[12]12.9	635	2	592	2	93	29	35	.83	1.93	43
Mill Creek Spring	3.47	[13]657	1	597	1	91	48	[7]--	--	13.8	--
Bass Rock Spring	[12]34.1	[14]707	5	631	5	89	70	[7]--	--	2.00	--
Big Spring	343	1060	32	977	35	92	430	[8]446	.97	1.25	77

[1]Based on closest measurement downstream from spring, except as noted.

[2]Cumulative spring discharge is the sum of discharges from the spring at that location and all upstream springs. It includes measured discharge from identified springs and tributaries whose discharge is assumed to have originated as springs.

[3]Various sources for estimates of recharge area: Aley and Aley (1987); Imes and others (2007); Keller (2000); Vandike (1997). Spring recharge areas include areas of overlap with other spring recharge areas.

[4]The annual mean discharge is for the period of record of the U.S. Geological Survey gage, as noted, or is estimated for nongaged springs. Various sources for estimates of annual mean discharge: Aley and Aley (1987); Keller (2000); Schumacher (2008).

[5]River discharge calculated by adding 0.68 ft^3/s discharge of Pigeon Creek above Montauk Spring to measurement of Montauk Spring.

[6]For calculation of cumulative spring discharge only, the discharge from Round Spring is assumed to be 12 ft^3/s, which is the combined discharge from Round Spring and the Current River Springs Complex.

[7]No estimate of annual mean discharge is available.

[8]Value is annual mean discharge for gage that is or was at spring. See table 4 for gage period of record.

[9]The calculated percentage is actually 101 percent, because of discharge measurement roundoff.

[10]The discharge shown for Cove Spring includes a small amount of dishcarge from Powder Mill Spring.

[11]Calculated by subtracting the discharge of Blue Spring from the downstream discharge measurement.

[12]Discharge estimated from temperature profile measurements.

[13]Discharge is sum of discharge from Mill Creek Spring and Current River discharge just upstream from Mill Creek Spring.

[14]Downstream discharge adjusted for inflow of 2.67 ft^3/s.

Table 8. Areal statistics for areas contributing water to the Current River and Jacks Fork at selected locations along the Current River and Jacks Fork.

[mi^2, square mile; --, no data]

Location along Current River or Jacks Fork	Estimated spring recharge area[1] (mi^2)	Total spring recharge area[2] (mi^2)	Surface-water basin (mi^2)	Ground-water basin[3] (mi^2)	Total contributing area[4] (mi^2)	Spring recharge area as percentage of total spring recharge area (percent)	Spring recharge area outside surface-water basin (mi^2)	Percentage of spring recharge area outside surface-water basin (percent)	Total spring recharge area outside surface-water basin (mi^2)	Percentage of total spring recharge area outside surface-water basin (percent)
Welch Spring	214	313	282	507	571	68	209	98	230	73
Current River at the mouth of Jacks Fork	--	597	826	980	1,059	--	--	--	173	29
Alley Spring	147	159	323	349	423	92	81	55	81	51
Jacks Fork at the mouth of the Current River	--	159	444	449	540	--	--	--	77	48
Current River near Eminence (downstream from the mouth of Jacks Fork)	--	756	1,273	1,434	1,500	--	--	--	163	22
Blue Spring (Current River)	137	893	1,345	1,616	1,686	15	105	77	268	30
Current River at Van Buren	--	1,034	1,670	1,967	2,058	--	--	--	293	28
Big Spring	430	1,387	1,710	1,995	2,287	31	239	56	506	36
Current River at downstream end of Ozark National Scenic Riverways	--	1,387	1,814	2,104	2,397	--	--	--	499	36

[1]Various sources for estimated spring recharge area: Aley and Aley (1987); Imes and others (2007); Keller (2000). Spring recharge areas include areas of overlap with other spring recharge areas.

[2]Total spring recharge area is the union of all spring recharge areas at and upstream from the specified location. It includes only springs for which recharge areas have been estimated.

[3]The groundwater basin is defined by the generalized potentiometric surface.

[4]Total contributing area is the union of the surface-water basin, groundwater basin, and total spring recharge area.

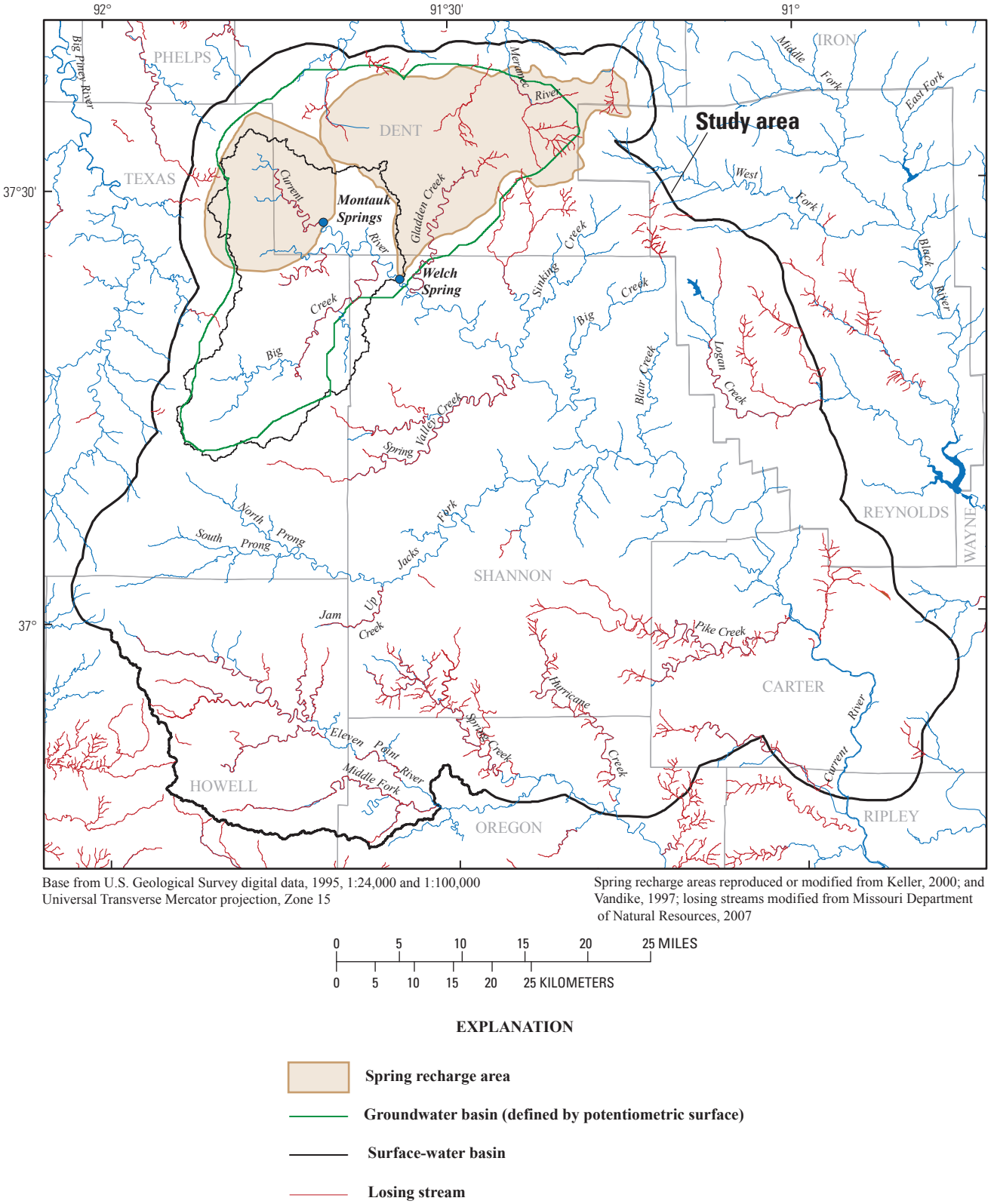


Figure 16. Surface-water basin and groundwater basin of the Current River at Welch Spring and the Welch Spring and Montauk Springs recharge areas.

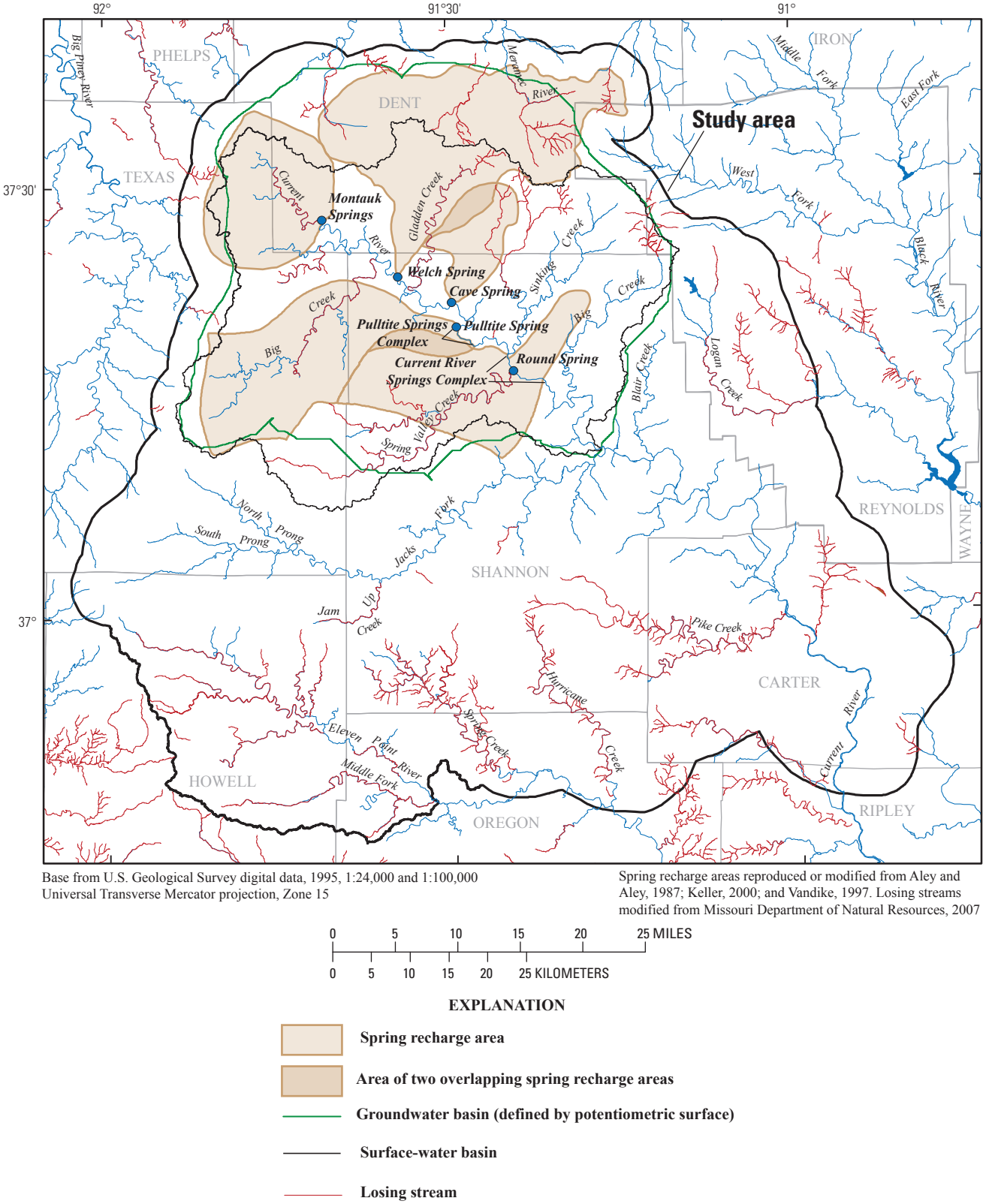


Figure 17. Surface-water basin and groundwater basin of the Current River at the mouth of Jacks Fork and upstream spring recharge basins.

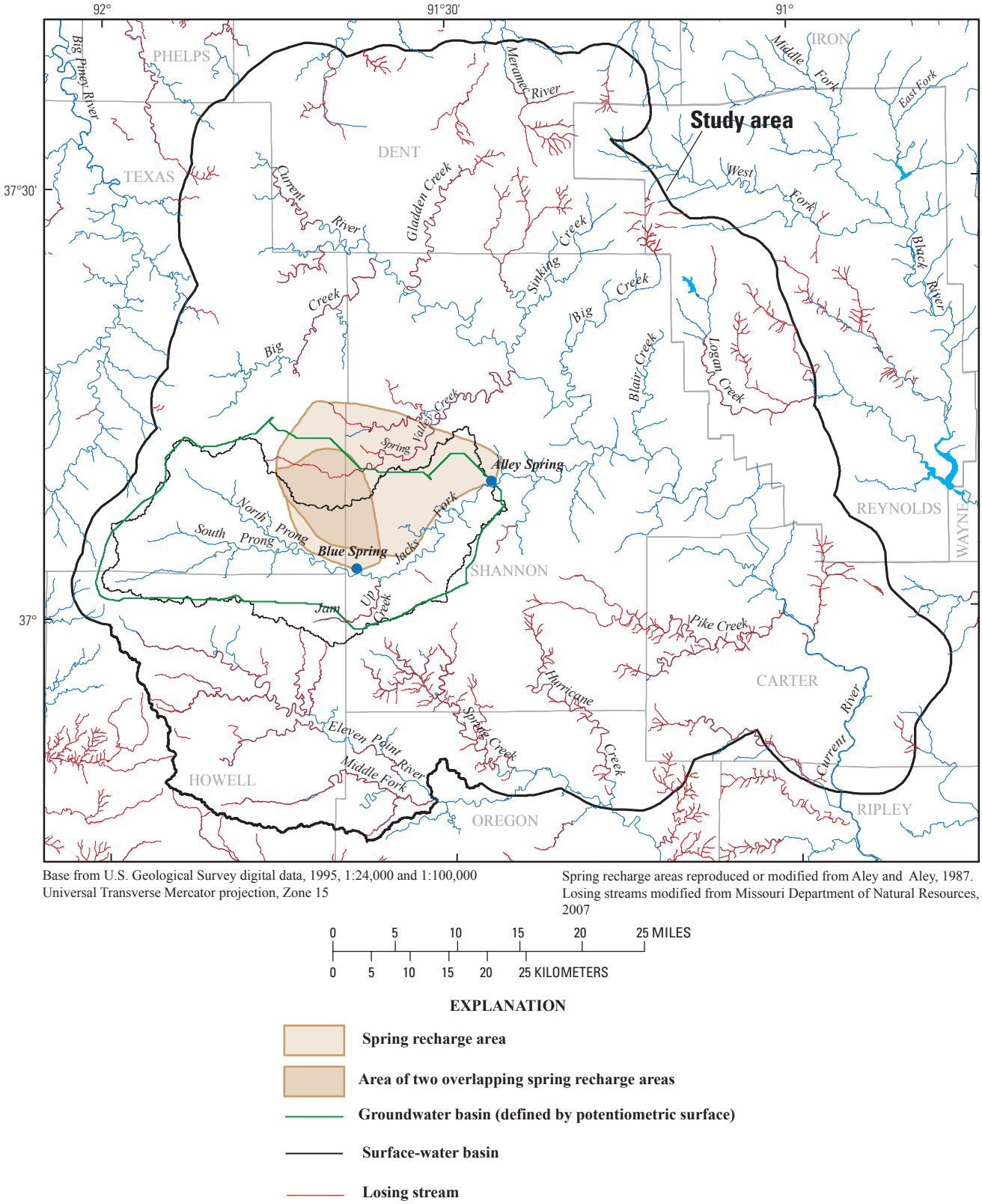


Figure 18. Surface-water basin and groundwater basin of Jacks Fork at Alley Spring and the Alley Spring and Blue Spring recharge areas.

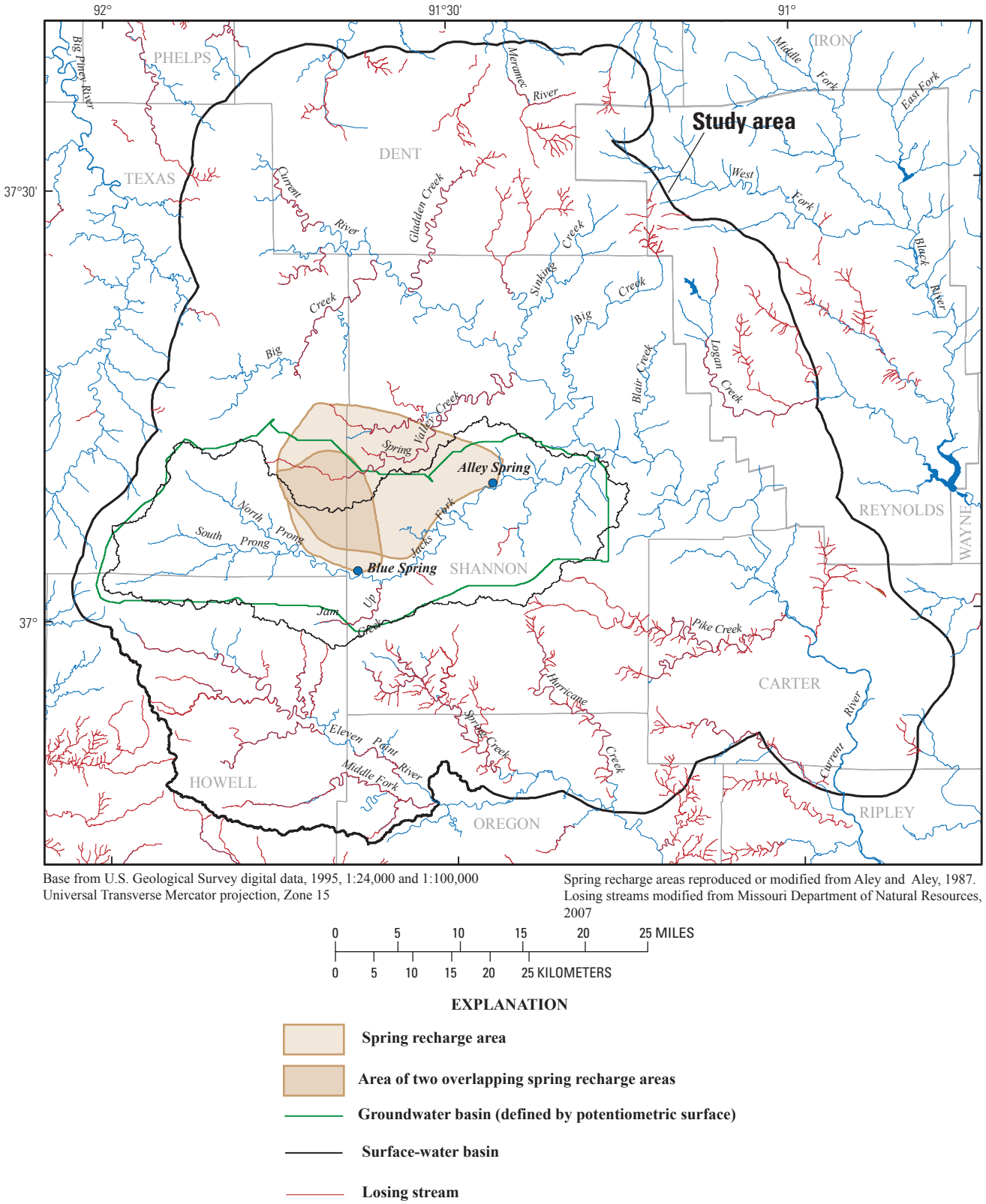


Figure 19. Surface-water basin and groundwater basin of Jacks Fork at the mouth of Jacks Fork and the Alley Spring and Blue Spring recharge areas.

are underrepresented. At 127 ft^3/s, Blue Spring would be the eighth largest spring in Missouri and the fourth largest spring in the Current River Basin (behind Big Spring, Welch Spring, and Alley Spring), using Keller's (2000) estimate of the annual mean discharge from Welch Spring. Vineyard and Feder (1982) ranked Blue Spring as the seventh largest spring in Missouri and the second largest spring in the Current River Basin. The USGS measured 90.4 ft^3/s during the 1941 seepage run, 88.4 ft^3/s during the 1966 seepage run (Skelton, 1976), and 93 ft^3/s during the 2006 seepage run (table 4). The recharge area shown in figures 4 and 20 is 137 mi^2 and is reproduced from Aley and Aley (1987). Most of the recharge area is along Logan Creek in the Black River Basin, outside the Current River Basin, and Blue Spring is an excellent example of interbasin transfer of groundwater. The Blue Spring recharge area contains the recharge area of Cove Spring and overlaps a portion of the recharge area of Gravel Spring.

The surface-water basin and groundwater basin for the Current River at Blue Spring, the estimated Blue Spring recharge area, and the spring recharge areas upstream from Blue Spring are shown in figure 20. The groundwater basin is slightly larger than the surface-water basin, and 77 percent of the Blue Spring recharge area is outside the surface-water basin (table 8). The Blue Spring recharge area represents 15 percent of the total spring recharge area (Blue Spring recharge area and all recharge areas upstream from Blue Spring; table 8). It would, therefore, be expected that Blue Spring would supply approximately 15 percent of the discharge in the Current River that is attributable to spring discharge; table 7 shows that Blue Spring contributed 15 percent of the discharge in the Current River and 16 percent of cumulative spring discharge at that location during the 2006 seepage run.

Gravel Spring

Gravel Spring discharges along the left bank of the Current River from the streambed and a small gravel bar. Vineyard and Feder (1982) reported five measurements made between 1934 and 1964 which ranged from 12 to 30 ft^3/s. Aley and Aley (1987) estimated that the annual mean discharge from Gravel Spring was 35 ft^3/s (table 7), although this is based on little data. The spring was not measured during the 2006 seepage run, but data from the temperature profile were used to estimate a discharge of 12.9 ft^3/s (table 7; see section titled "Current River Temperature Profile"). This discharge is about 2 percent of the discharge in the Current River at that location (table 7). The 2006 seepage run discharge data could theoretically be used to calculate the discharge of Gravel Spring by subtracting the discharge measurement upstream from the spring from the discharge measurement downstream from the spring, but the discharge from Gravel Spring was within the measurement error of the Current River discharge measurements. The discharge from Gravel Spring was measured at 14 ft^3/s during the 1966 seepage run (Skelton, 1976).

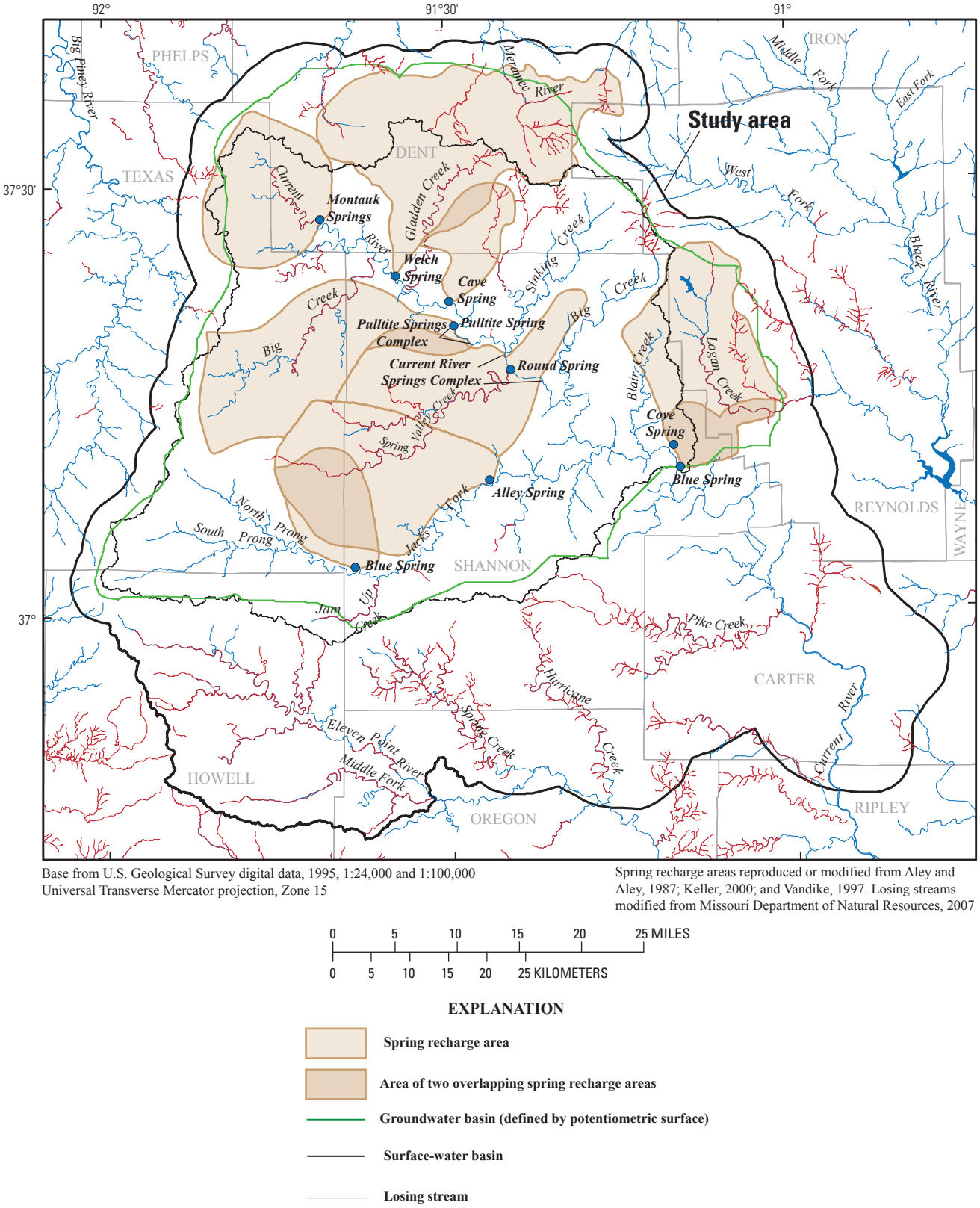
The recharge area for Gravel Spring shown in figures 4 and 21 is modified from Aley and Aley (1987) by moving its eastern boundary to the west to coincide with the groundwater divide that is indicated by the potentiometric-surface map (fig. 7). This modification results in a decrease in area from 44 to 29 mi^2. Approximately 7 mi^2 of the recharge area is shared with the recharge areas of Blue Spring and Cove Spring. A portion of the Gravel Spring recharge area is along Logan Creek, outside the Current River Basin.

Mill Creek Spring

Mill Creek Spring is located on Mill Creek approximately 3 mi upstream from the Current River and is not in the ONSR, but is discussed in this report because it is in the study area, its discharge flows into the Current River, and a recharge area for it has been estimated (Aley and Aley, 1987). Vineyard and Feder (1982) reported three no-flow discharge measurements and one measurement of 40.4 ft^3/s between 1942 and 1964. The USGS measured 1.24 ft^3/s from Mill Creek Spring during the 1966 seepage run (Skelton, 1976) and measured 3.47 ft^3/s in Mill Creek downstream from the spring during the 2006 seepage run (fig. 10; table 7). Aley and Aley (1987) estimated that the annual mean discharge is 30 ft^3/s, but state that this estimate was based on few data and could be in error; that value is not given in table 7. Their recharge area of 48 mi^2 (figs. 4 and 21) is large for a small spring, but was estimated to accommodate a straight line distance of over 12 mi for a dye trace to the spring, and because most of the Mill Creek Spring recharge area is contained in the Big Spring recharge area (Aley and Aley, 1987).

Bass Rock Spring

The discharge from Bass Rock Spring, which is a spring that has not previously been described, rises in a pool from the streambed of the Current River immediately upstream from Van Buren, in a part of the river that is outside the ONSR. Its location was described by Mike Gossett of the NPS (Mike Gossett, oral commun, 2006). Evidence of its presence during the temperature profiling of the Current River was gas bubbles emerging from the streambed and a substantial drop in the average river bottom water temperature. The temperature profile data indicate a discharge of about 34.1 ft^3/s, which represents approximately 5 percent of the flow in the Current River at that location, and ranks Bass Rock Spring as the sixth largest spring in the Current River Basin (table 7; see section titled "Current River Temperature Profile"). No dye tracer testing has been conducted to this spring, and a recharge area for it has not previously been estimated. It is not known if the source of the spring water is east or west of the Current River, so a recharge area was drawn that covers an area along losing streams on each side of the river (figs. 4 and 21), with a total area of about 70 mi^2.



Base from U.S. Geological Survey digital data, 1995, 1:24,000 and 1:100,000
Universal Transverse Mercator projection, Zone 15

Spring recharge areas reproduced or modified from Aley and Aley, 1987; Keller, 2000; and Vandike, 1997. Losing streams modified from Missouri Department of Natural Resources, 2007

Figure 20. Surface-water basin and groundwater basin of the Current River at Blue Spring and the Blue Spring and upstream spring recharge areas.

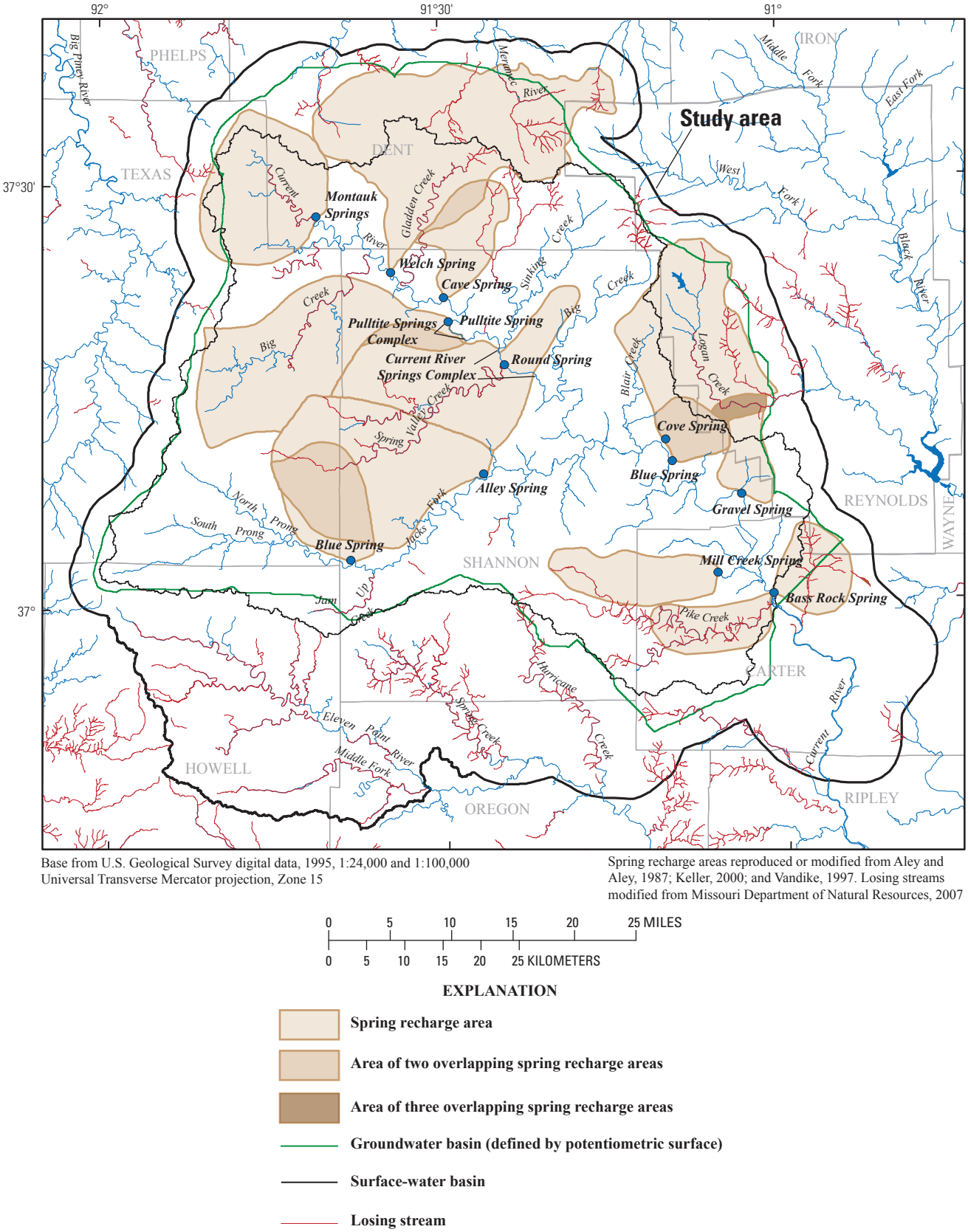


Figure 21. Surface-water basin and groundwater basin of the Current River at Van Buren and upstream spring recharge areas.

Current River at Van Buren

The surface-water basin and groundwater basin for the Current River at Van Buren and spring recharge areas upstream from Van Buren are shown in figure 21. The groundwater basin is slightly larger than the surface-water basin, and about 28 percent of the total spring recharge area is outside the surface-water basin (table 8). The discharge that can be attributed to springs was 89 percent of the measured discharge of the Current River at Van Buren during the low base-flow conditions of the 2006 seepage run.

Big Spring

Big Spring is the largest spring in Missouri with an annual mean discharge of 446 ft^3/s (U.S. Geological Survey, 2008a), based on data recorded at a gage from 1921 to 1996 and 2000 to present (2008) (table 4). The discharge measured in the 1941 seepage run was 277 ft^3/s, and the discharge measured in the 2006 seepage run was 343 ft^3/s (table 4). The discharge from Big Spring was not measured in the 1966 seepage run, but the data from the gage at Big Spring indicate a discharge of 305 ft^3/s on October 19, 1966, while the seepage run was being conducted (table 4). The Big Spring recharge area (figs. 4 and 22) is reproduced from Imes and others (2007) and is 430 mi^2. Their recharge area does not extend as far west as the recharge area shown in Aley (1975) because they did not consider two dye traces from that area to be conclusive. However, these dye traces are shown on figure 4, as Imes and others (2007) also showed them.

The surface-water basin and groundwater basin for the Current River at Big Spring, the Big Spring recharge area, and spring recharge areas upstream from Big Spring are shown in figure 22. The groundwater basin is slightly larger than the surface-water basin, and 56 percent of the Big Spring recharge area is outside the surface-water basin (table 8). The Big Spring recharge area represents 31 percent of the total spring recharge area at that location on the Current River (table 8). It would, therefore, be expected that Big Spring would supply approximately 31 percent of the discharge in the Current River that is attributable to spring discharge; Big Spring contributed 35 percent of cumulative spring discharge to the Current River at Big Spring during the 2006 seepage run (table 7). Big Spring contributed 32 percent of the discharge in the Current River at Big Spring during the 2006 seepage run, which is a smaller percentage than for other large springs upstream (for example, Montauk Springs, 99 percent; Welch Spring, 57 percent; Alley Spring, 71 percent; table 7), because of the large discharge of the Current River at that location (1,060 ft^3/s; table 7). About one-half of the Big Spring recharge area is outside the groundwater basin (fig. 22). The groundwater basin was defined by the potentiometric surface (fig. 7) that reproduces the shallow potentiometric surface in Imes and other (2007). There is a better correspondence between the Big Spring recharge area and the deep potentiometric surface in Imes and others (2007) that represents groundwater hydraulic heads within the more mature karst areas.

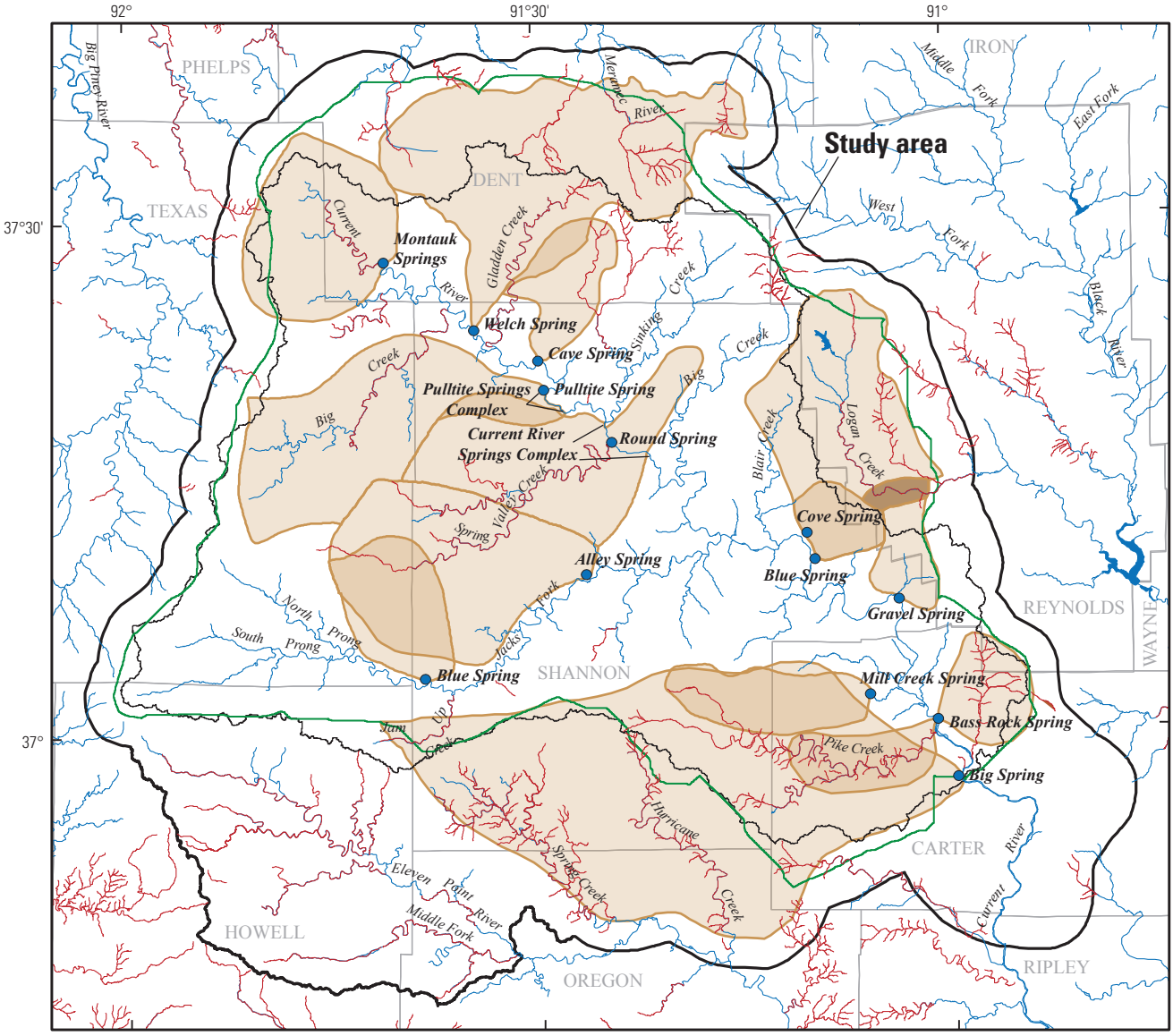
Current River at the Downstream End of the Ozark National Scenic Riverways

The surface-water basin and groundwater basin for the Current River at the downstream end of the ONSR and spring recharge areas upstream from that location are shown in figure 23. The surface-water basin and groundwater basin are only slightly larger than at Big Spring (fig. 22), and the total spring recharge area is the same as at Big Spring (table 8). About 36 percent of the total spring recharge area is outside the surface-water basin (table 8).

Spring Recharge Area Per Unit Annual Mean Spring Discharge

The annual mean spring discharges presented in this report are estimates except for Big Spring, Round Spring, and Alley Spring for which long periods of record from USGS stream gages have enabled calculations of long-term annual mean discharge (table 4). The spring recharge area per unit annual mean spring discharge is 0.97 $mi^2/ft^3/s$ (square mile per cubic foot per second) for Big Spring and 1.09 $mi^2/ft^3/s$ for Alley Spring (table 7). A figure is not available for Round Spring because a recharge area for the spring has not been defined separate from the Current River Springs Complex. Both these figures are close to the estimate of approximately 1 $mi^2/ft^3/s$ for Ozark springs (Aley, 1976) because this estimate probably was used as a guideline when the recharge areas were estimated. Most of the other springs in table 7 also have a spring recharge area per unit of estimated annual mean spring discharge that is close to 1 $mi^2/ft^3/s$. The exception is Blue Spring (Jacks Fork) for which a large recharge area was estimated because its recharge area is contained in the Alley Spring recharge area (Aley, 1976).

There are some indications, though not conclusive, that some spring recharge areas and annual mean discharges are overestimated. The spring recharge area per unit low base-flow spring discharge (2006 measurements) is 1.25 $mi^2/ft^3/s$ for Big Spring and 1.52 $mi^2/ft^3/s$ for Alley Spring (table 7). Each of these springs has a recharge area that is based on a mean annual discharge derived from a long-term gage record. Several springs have values substantially larger than this (table 7), which may indicate that the recharge area (the numerator in this calculation) and the annual mean discharge are overestimated. Also, for Big Spring and Alley Spring, each of which has a reliable mean annual discharge because of a long term gage record, the percentage of 2006 low base-flow discharge to annual mean discharge was 77 percent and 72 percent (table 7). Several springs have a percentage that varies from 43 percent to 49 percent. These lower percentages suggest that the annual mean discharge (the denominator in this calculation), and, hence, the recharge area, may be overestimated. Aley (1976) made a similar calculation for three gaged springs on the Current River and four gaged springs on the Eleven Point River (fig. 1) using 1966 low base-flow measurements and observed that the larger the spring discharge, the larger



Base from U.S. Geological Survey digital data, 1995, 1:24,000 and 1:100,000
Universal Transverse Mercator projection, Zone 15

Spring recharge areas reproduced or modified from Aley and Aley, 1987; Imes and others, 2007; Keller, 2000; and Vandike, 1997. Losing streams modified from Missouri Department of Natural Resources, 2007

0 5 10 15 20 25 MILES

0 5 10 15 20 25 KILOMETERS

EXPLANATION

- Spring recharge area
- Area of two overlapping spring recharge areas
- Area of three overlapping spring recharge areas
- Groundwater basin (defined by potentiometric surface)
- Surface-water basin
- Losing stream

Figure 22. Surface-water basin and groundwater basin of the Current River at Big Spring and the Big Spring and upstream spring recharge areas.

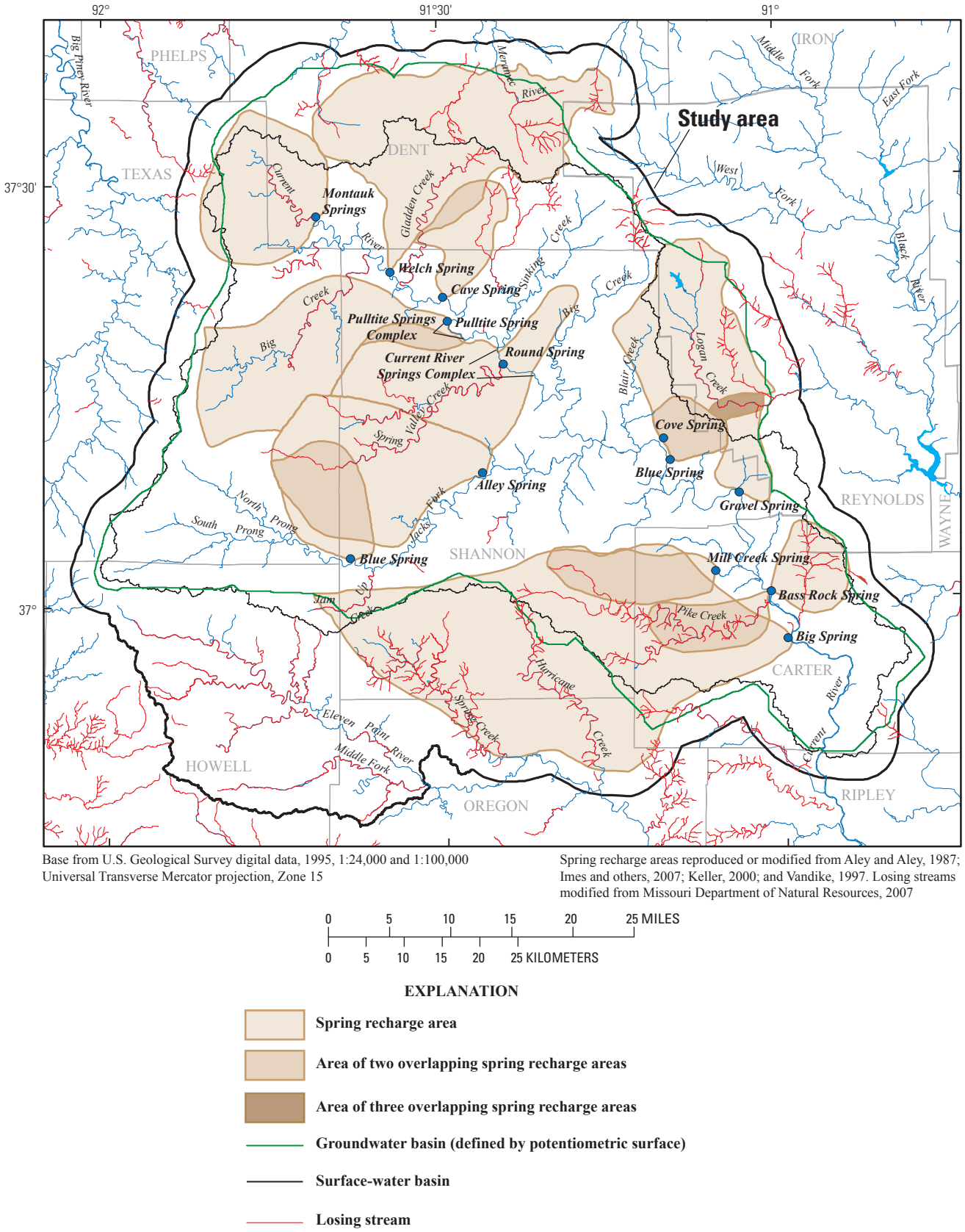


Figure 23. Surface-water basin and groundwater basin of the Current River at the downstream end of the Ozark National Scenic Riverways and upstream spring recharge areas.

the percentage of the USGS 1966 low base-flow discharge to annual mean discharge. This also is observed for the gaged springs, Alley Spring and Big Spring, using 2006 low base-flow discharge data (table 7). Because of this trend, the lower percentages of 2006 low base-flow discharge to annual mean discharge for the smaller nongaged springs (Cave Spring and Blue Spring on Jacks Fork) may reflect realistic estimates of annual mean discharge, but larger springs (Montauk Springs and Welch Spring) may have smaller percentages because the annual mean discharge, and, hence, the recharge area, are overestimated. Despite these indications that some annual mean discharges and recharge areas may be overestimated, there may be other geohydrologic factors that affect the statistics in table 7, and further study, including additional dye tracing to better define recharge area, would be needed before further modifying recharge areas or annual mean discharge estimates.

Landscape Characteristics

This section describes landscape characteristics that potentially affect how precipitation that falls on the study area moves to the Current River, Jacks Fork, and springs of the ONSR. Some landscape characteristics are geohydrologic, that is, they are natural characteristics of the landscape. Other landscape characteristics are anthropogenic, that is, they are characteristics of man's impact on the landscape, or lack thereof. Data for landscape characteristics for each spring recharge area, including two springs (Greer Spring and Mammoth Spring) that have part of their recharge area in the study area but are not in the ONSR are given in table 9. Some of the landscape characteristics given in table 9 are described in this section and comparisons are made between spring recharge areas (but not the recharge areas for Greer Spring or Mammoth Spring). Landscape characteristic data for that portion of the study area that is not in a spring recharge area, and for the entire study area, also are given in table 9. Also, a series of landscape characteristic maps are presented (figs. 24 through 34) which show the gridded (800-m analysis cells) distribution of each characteristic throughout the study area. Each map shows where a landscape characteristic, sinkholes, for example, are most likely to affect the recharge of water to the groundwater system. Each map shows the spring recharge areas described in this report, which allows for a visual comparison of recharge areas.

The landscape characteristic maps help explain by visual representation how the groundwater system is recharged, but the system is very complex and the characteristics represented in these maps relate to only part of how the groundwater system is recharged. Aley (1975, 1976) discussed how the groundwater system is recharged in the Hurricane Creek Basin, which is in the southern part of the study area in the Big Spring recharge area (fig. 4); he distinguished discrete recharge, which is rapid and concentrated recharge, from diffuse recharge, which is slower, less concentrated recharge. He estimated that about 63 percent of the groundwater recharge is discrete recharge, and about 37 percent is diffuse recharge. He further estimated that sinkholes [which he assumed to account for about 10 percent of the land area (table 9 shows a smaller percentage for the 13 springs in the study area for which recharge areas have been estimated)] account for about 10 percent of the recharge, losing streams about 11 percent of the recharge, and nonvalley discrete recharge with little or no surface expression (for example, solution-enlarged fractures and macropores) accounts for about 42 percent of the recharge. Aley (1975, 1976) also estimated that most of the diffuse recharge occurs in valleys rather than on hillsides and slopes, and that diffuse recharge in valleys is more important than discrete recharge in valleys (for example, losing streams). These figures are only estimates, and no effort has been made in this report to make any other estimates; whatever the actual figures, there likey is substantial recharge to the groundwater system by other means than through sinkholes and losing streams. The difficulty with showing all these recharge mechanisms as landscape characteristics is that only sinkholes and losing streams have a recognizable surficial expression. A spring recharge area is a way of showing where all these mechanisms can be expected to affect recharge to a spring system. Of course sinkholes, for example, may account for only a small amount of recharge, but they are important where they occur, and the landscape characteristic maps are intended to show this.

Sinkholes are important to groundwater recharge, not only because they can channel runoff to the subsurface, but also because their existence is an expression of an underlying subsurface conduit system. This conduit system can collect recharge that has entered the subsurface through a sinkhole and in other ways. The spring recharge areas with the largest number of sinkholes are Big Spring (339), Alley Spring (312), and Welch Spring (284) (table 9). The spring recharge areas with the largest number of identified sinkholes per square mile of recharge area are Alley Spring (2.12), Blue Spring (Jacks Fork) (1.74), Welch Spring (1.33), and Round Spring and the Current River Springs Complex (1.02). The locations of sinkholes are shown in figure 3, and as a landscape characteristic in figure 24. The pattern on figure 24, which reflects the pattern of sinkholes on figure 3, shows that spring recharge areas to the northeast (Welch Spring) and west of the Current River are more characterized by sinkholes than recharge areas east of the Current River. The sinkhole density in 800-m analysis cells ranges from zero to nine sinkholes per cell. The cells with the largest sinkhole density are in the Big Spring and Alley Spring recharge areas. Sinkholes vary in size, and considering sinkhole area gives greater weight to larger sinkholes. Sinkhole areas were obtained from data compiled by the DGLS (Missouri Department of Natural Resources, 2007), and modified to remove the two large topographic depressions in creeks that were removed from the sinkhole location map. The spring recharge areas with the largest sinkhole area are Big Spring (1.5 mi^2) and Alley Spring (1.3 mi^2) and the spring

Table 9. Landscape characteristics for spring recharge areas.

[mi², square mile; mi, mile]

Spring recharge area	Area (mi²)	Sinkholes[1] (count)	Sinkholes per square mile of recharge area (count/mi²)	Sinkhole area[1] (mi²)	Sinkhole area per square mile of recharge area (mi²/mi²)	Sinkhole drainage area (mi²)	Sinkhole drainage area per square mile of recharge area (mi²/mi²)	Losing streams[1] (mi)	Losing stream miles per square mile of recharge area (mi/mi²)	Losing stream drainage area (mi²)	Losing stream drainage area per unit recharge area (mi²/mi²)
Springs contributing water to the Ozark National Scenic Riverways											
Montauk Springs	99	39	0.39	0.1	0.001	0.4	0.004	12.7	0.13	67.7	0.69
Welch Spring	214	284	1.33	.9	.004	5.3	.025	87.7	.41	180	.84
Cave Spring	40	18	.45	.1	.003	.4	.011	12.0	.30	32.8	.83
Pulltite Springs Complex	145	110	.76	.3	.002	2.0	.014	14.5	.10	116	.80
Round Spring and Current River Springs Complex	119	121	1.02	.3	.003	1.5	.013	29.0	.24	59.4	.50
Blue Spring (Jacks Fork)	56	97	1.74	.8	.013	3.5	.062	6.8	.12	24.9	.45
Alley Spring	147	312	2.12	1.3	.009	7.8	.053	33.9	.23	77.4	.53
Cove Spring	29	5	.17	0	0	0	0	5.3	.18	8.8	.30
Blue Spring (Current River)	137	28	.21	0	0	.2	.001	39.2	.29	91.9	.67
Gravel Spring	29	2	.07	0	0	0	0	5.9	.20	11.7	.40
Mill Creek Spring	48	17	.36	0	.001	.1	.002	8.5	.18	28.4	.60
Bass Rock Spring	70	12	.17	0	0	.1	.001	69.3	.99	55.1	.79
Big Spring	430	339	.79	1.5	.004	13.1	.030	246	.57	354	.82
Springs not contributing water to the Ozark National Scenic Riverways											
Greer Spring[4]	348	358	1.03	2.0	.006	14.7	.042	134	.39	252	.73
Mammoth Spring[4]	290	712	2.46	2.0	.007	33.0	.114	106	.37	31.2	.11
Other areas											
Portion of Study Area not in a Spring Recharge Area	1,440	409	.28	1.0	.001	24.3	.017	215	.15	322	.22
Study Area	3,140	2,007	.64	7.2	.002	51.7	.016	856	.27	1,610	.51

Table 9. Landscape characteristics for spring recharge areas. —Continued

[mi², square mile; mi, mile]

Spring recharge area	Springs[1] (count)	Streams (mi)	Land use/Land cover							Publicly owned land[2] (mi²)	Area of publicaly owned land per unit recharge area(mi²/mi²)
			Water[2] (mi²)	Forested[2] (mi²)	Area of forested per unit recharge area (mi²/mi²)	Cultivated[2] (mi²)	Open[2] (mi²)	Area of open land per unit recharge area (mi²/mi²)	Urban[2] (mi²)		
Springs contributing water to the Ozark National Scenic Riverways											
Montauk Springs	7	368	0.2	57.2	0.58	0.6	40.3	0.41	0.5	0.9	0.01
Welch Spring	6	812	.3	117	.55	2.5	91.6	.43	1.9	28.5	.13
Cave Spring	1	148	0	34.2	.86	.1	5.2	.13	.1	4.6	.12
Pulltite Springs Complex	5	565	.3	112	.77	.7	32.1	.22	.6	24.6	.17
Round Spring and Current River Springs Complex	7	456	.2	108	.91	.2	9.9	.08	.2	69.3	.58
Blue Spring (Jacks Fork)	1	213	.1	25.6	.46	.5	28.7	.51	1.0	.3	.01
Alley Spring	2	578	.2	87.5	.59	1.1	57.1	.39	1.5	31.0	.21
Cove Spring	1	114	0	26.3	.91	.3	2.3	.08	.1	14.8	.51
Blue Spring (Current River)	9	532	.5	122	.89	1.7	12.3	.09	.6	35.3	.26
Gravel Spring	1	113	0	26.6	.91	.3	2.2	.08	.1	19.8	.68
Mill Creek Spring	4	181	0	44.4	.93	.1	3.0	.06	.1	40.3	.85
Bass Rock Spring	6	278	.1	57.0	.82	.5	11.0	.16	1.1	16.7	.24
Big Spring	33	1,680	.5	346	.81	2.4	76.6	.18	4.0	255	.59
Springs not contributing water to the Ozark National Scenic Riverways											
Greer Spring[4]	28	1,350	1.2	196	.56	2.7	141	.40	7.3	19.6	.06
Mammoth Spring[4]	21	1,100	.4	119	.41	3.3	153	.53	13.9	3.7	.01
Other areas											
Portion of Study Area not in a Spring Recharge Area	176	5,540	10.2	1,800	1.25	16.5	536	.37	19.2	424	.29
Study Area	272	12,100	11.6	2,330	.74	21.5	743	.24	30.8	903	.29

Table 9. Landscape characteristics for spring recharge areas. —Continued

[mi², square mile; mi, mile]

Spring recharge area	Population[2] (count)	U.S. highway[2] (mi)	State highway[2] (mi)	State route[2] (mi)	County roads and streets[2] (mi)	Railroad[2] (mi)	Pipeline[3] (mi)	Airport[2] (count)	Certified wells[1] (count)	Public drinking water wells[1] (count)
Springs contributing water to the Ozark National Scenic Riverways										
Montauk Springs	1,617	0	25.1	21.0	82.6	0	8.2	0	163	4
Welch Spring	3,090	0	36.5	60.9	193	0	8.9	1	438	6
Cave Spring	189	0	9.2	3.9	29.0	0	0	0	48	0
Pulltite Springs Complex	1,029	0	18.9	22.5	88.2	0	10.1	0	180	0
Round Spring and Current River Springs Complex	365	0	7.6	10.7	82.4	0	0	0	68	1
Blue Spring (Jacks Fork)	1,253	0	12.3	16.9	72.9	0	7.2	0	142	4
Alley Spring	1,767	0	25.5	43.4	118	0	9.1	0	207	4
Cove Spring	128	0	10.1	3.2	22.6	0	0	0	13	0
Blue Spring (Current River)	572	0	16.0	30.1	73.1	0	0	0	42	1
Gravel Spring	131	0	4.2	1.7	26.0	0	0	0	14	1
Mill Creek Spring	231	0	3.5	4.4	69.1	0	0	0	22	2
Bass Rock Spring	1,148	22.3	6.3	11.9	66.5	0	0	1	61	1
Big Spring	5,355	39.1	32.3	55.3	480	0	0	0	416	11
Springs not contributing water to the Ozark National Scenic Riverways										
Greer Spring[4]	10,004	47.3	32.4	60.4	388	11.3	24.6	2	781	11
Mammoth Spring[4]	20,506	52.6	22.7	62.0	469	41.1	19.7	1	1,000	28
Other areas										
Portion of Study Area not in a Spring Recharge Area	22,162	48.9	138	297	1,350	11.4	22.5	1	1,773	62
Study Area	47,277	144	341	617	2,940	24.6	87.1	5	4,202	104

[1]Modified from data from Missouri Department of Natural Resources (2007).

[2]Modified from data compiled by Missouri Spatial Data Information Service (2007).

[3]Modified from data supplied by Pipelines and Hazardous Materials Safety Administration (written commun., 2007).

[4]Data are for entire recharge area, not just area inside study area.

recharge areas with the largest sinkhole area per unit recharge area are Blue Spring (Jacks Fork) (0.013 mi^2/mi^2) and Alley Spring (0.009 mi^2/mi^2) (table 9). A density representation of sinkhole area (fig. 25) shows a pattern of cells that is similar to the pattern of figure 24. The sinkhole area density in 800-m analysis cells ranges from 0 to 4,737 10-m cells per 800-m analysis cell (out of a maximum 6,400 10-m cells). Also, the runoff that potentially can be captured by a sinkhole is a larger area than the area of the sinkhole because runoff can travel some distance downslope before entering a sinkhole. The spring recharge areas with the largest sinkhole drainage area (total area draining to sinkholes) are Big Spring (13.1 mi^2), Alley Spring (7.8 mi^2), and Welch Spring (5.3 mi^2), and the spring recharge areas with the largest sinkhole drainage area per unit recharge area are Blue Spring (Jacks Fork) (0.062 mi^2/mi^2) and Alley Spring (0.053 mi^2/mi^2). It is interesting to note that for each spring the sinkhole drainage area is less than 10 percent of the recharge area, which is the number Aley (1975, 1976) estimated for the percent of the Hurricane Creek Basin land surface that is sinkhole area. A landscape characteristic map of the density of sinkhole area in each 800-m analysis cell is shown in figure 26. More cells in figure 26 have a value greater than zero than in figure 24 or figure 25, reflecting the larger area of influence sinkholes have when upslope drainage into sinkholes is considered. The sinkhole drainage area density in 800-m analysis cells ranges from 0 to 6,400 (100 percent) 10-m cells per 800-m analysis cell.

Losing streams are important discrete groundwater recharge features, and occur where a local subsurface opening or zone of high permeability (for example, a gravel-filled sinkhole or solution-enlarged fractures in the stream) directs surface water to subsurface conduits of the groundwater system. As previously stated, there are losing streams that are not shown on figure 4 because a study has not been conducted by the DGLS to determine if they are losing. Also, many intermittent streams, some of which are too small to be shown on USGS topographic maps, flow in response to storm runoff but lose flow downstream. While attributing some of this to discrete groundwater recharge (losing streams) Aley (1975), without quantifying, emphasized that a substantial amount of this loss of flow in intermittent streams is diffuse recharge of valley alluvium and residuum. Despite the limitations of not having all losing stream reaches inventoried, table 9 shows data for known losing streams by spring recharge area. While the Big Spring recharge area has the largest number of miles of losing stream (246 mi), the Bass Rock Spring recharge area has the largest number of miles of losing stream per unit recharge area (0.99 mi/mi^2). The density representation of losing streams (fig. 27) helps to visually portray where known losing streams are likely to be most important to recharging ONSR spring systems. The pattern of colored cells follows the locations of identified losing streams, but the cell values vary depending on the length of losing stream segments in each cell. The losing stream density in 800-m analysis cells ranges from 0 to 350 10-m cells per 800-m analysis cell. Also, a losing stream has a larger area of influence than just its location because precipitation falling upslope potentially can be directed to the losing stream and then to subsurface conduits of the groundwater system. The losing stream drainage area for each stream is the area draining to the lowest point on the stream that has been identified as losing. The losing stream drainage area per unit recharge area ranges from 0.30 to 0.84 mi^2/mi^2 (table 9). A density representation of losing stream drainage areas shows large areas where all 800-m analysis cells have a maximum density (6,400 10-m cells) surrounded by a fringe of cells with lower densities (fig. 28). The map does not indicate that all precipitation falling in these areas will necessarily be directed to the subsurface through a downstream losing stream reach, only that these areas are within the drainage area of a losing stream reach, which increases the potential for capture by subsurface conduits. A substantial portion of each spring recharge area contains a large area where 800-m cells have the maximum density, and areas of maximum density also are outside spring recharge areas. This does not warrant a revision of recharge areas on this basis alone, as it is not known if precipitation falling in these areas actually moves downstream to a losing stream reach to be lost to subsurface conduits.

The slope of the land surface is another landscape characteristic that can affect how water reaches the Current River or Jacks Fork, by surface flow or by flow to springs. A higher slope will result in less infiltration of precipitation and more runoff than a lower slope. Conversely, a lower slope likely will result in more infiltration to the groundwater system and less runoff. A landscape characteristic map of land slope is shown in figure 29. Larger values indicate larger mean slopes where there is a greater propensity for precipitation to run off rather than infiltrate the land surface and recharge the groundwater system. Of course, as noted above, surface-water runoff may still become groundwater recharge at losing streams. The areas with the largest slope are along the larger streams, including the Current River and Jacks Fork. The mean slope in 800-m analysis cells ranges from 1 to 20 degrees. Land slope was computed from the 10-m raster grid of topographic elevation. For each cell of the topographic elevation grid, the slope from the cell of interest to the lowest of the eight surrounding cells was calculated, and the slope value assigned to the cell was the slope computed between these two cells. The 10-m grid of slopes then was aggregated up to the 800-m grid cell using the mean function and divided into 10 classes.

A landscape characteristic map of the density of stream segments in the study area is shown in figure 30. The location of the streams (and their vector representation) from 1:24,000 scale USGS topographic maps are cartographically defined, and as such, have no uniformity as to where the stream was represented on the topographic map. Stream lines could start very near the drainage divide in one area of the map and be quite some distance from the divide in other areas. Density based on this type of data could be biased to map areas where longer stream segments were cartographically represented on the topographic map sheets. To standardize the stream density characteristic, a vector representation of the drainage network

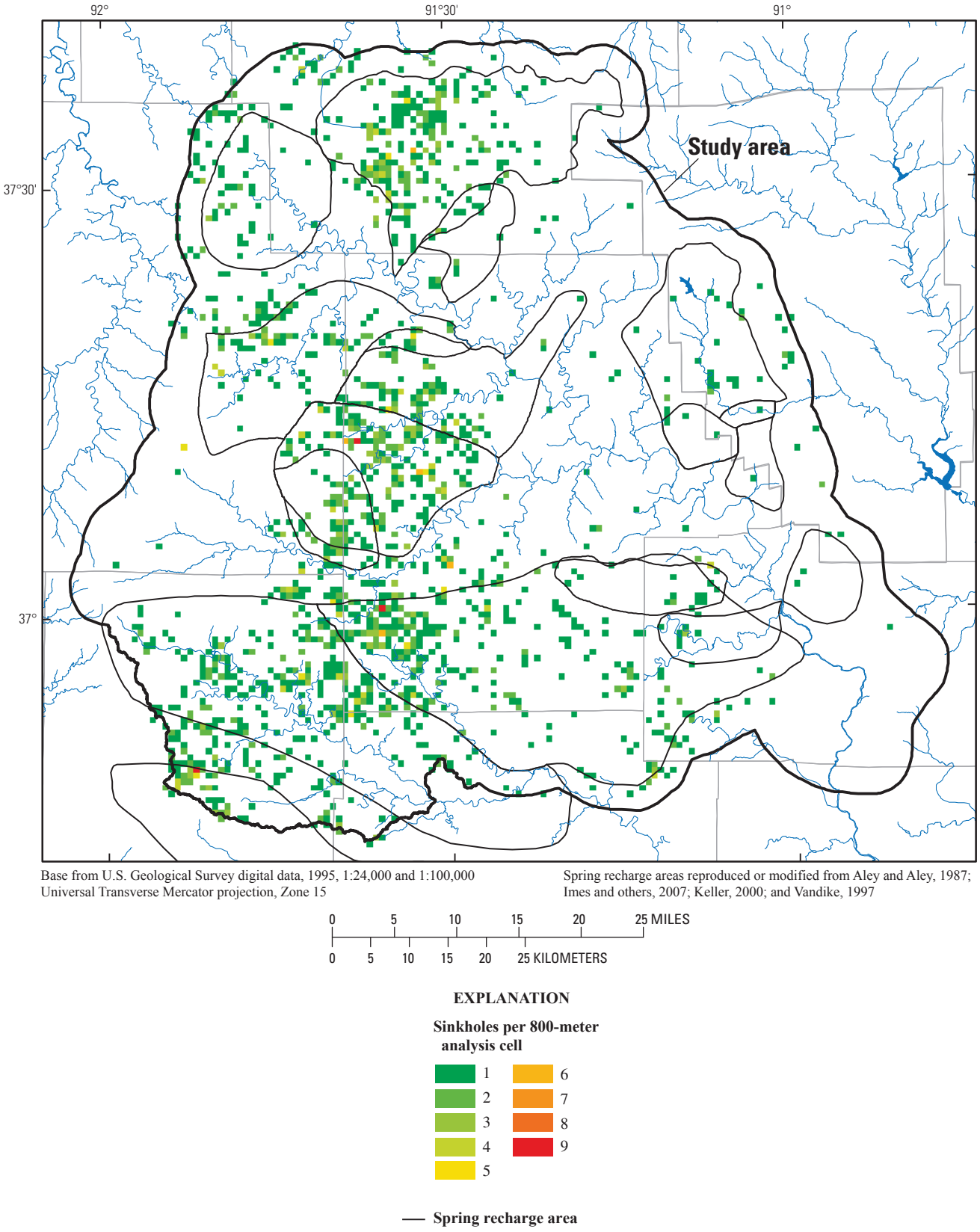
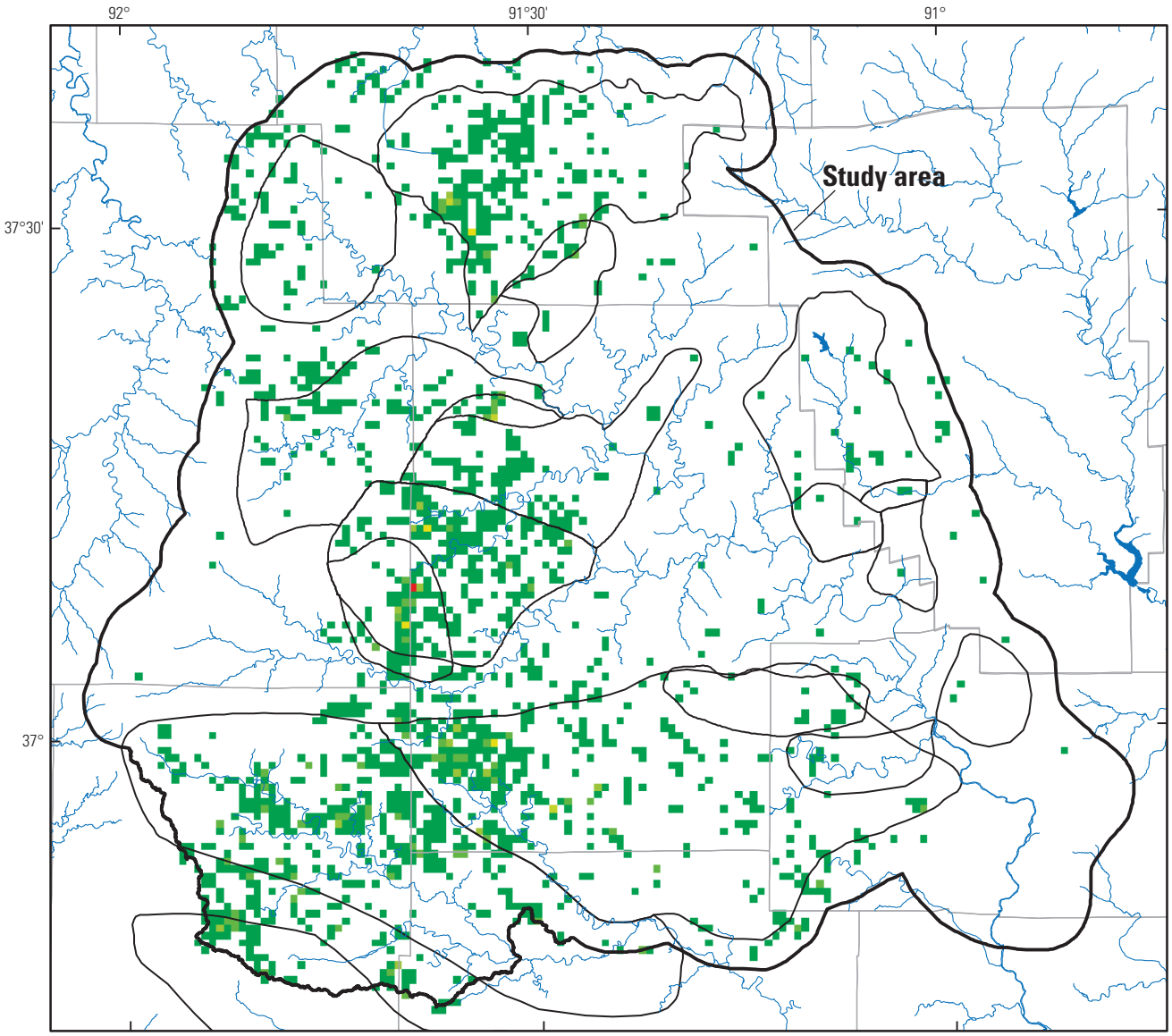


Figure 24. Density distribution of sinkholes.



Base from U.S. Geological Survey digital data, 1995, 1:24,000 and 1:100,000
Universal Transverse Mercator projection, Zone 15

Spring recharge areas reproduced or modified from Aley and Aley, 1987; Imes and others, 2007; Keller, 2000; and Vandike, 1997

0 5 10 15 20 25 MILES

0 5 10 15 20 25 KILOMETERS

EXPLANATION

Number of 10-meter cells in the area of sinkholes (defined by the topographic expression of sinkholes) per 800-meter analysis cell (out of a maximum possible 6,400 10-meter cells)

1 to 475	2,370 to 2,843
476 to 948	2,844 to 3,316
949 to 1,422	3,317 to 3,790
1,423 to 1,895	3,791 to 4,263
1,896 to 2,369	4,264 to 4,737

Spring recharge area

Figure 25. Density distribution of sinkhole area.

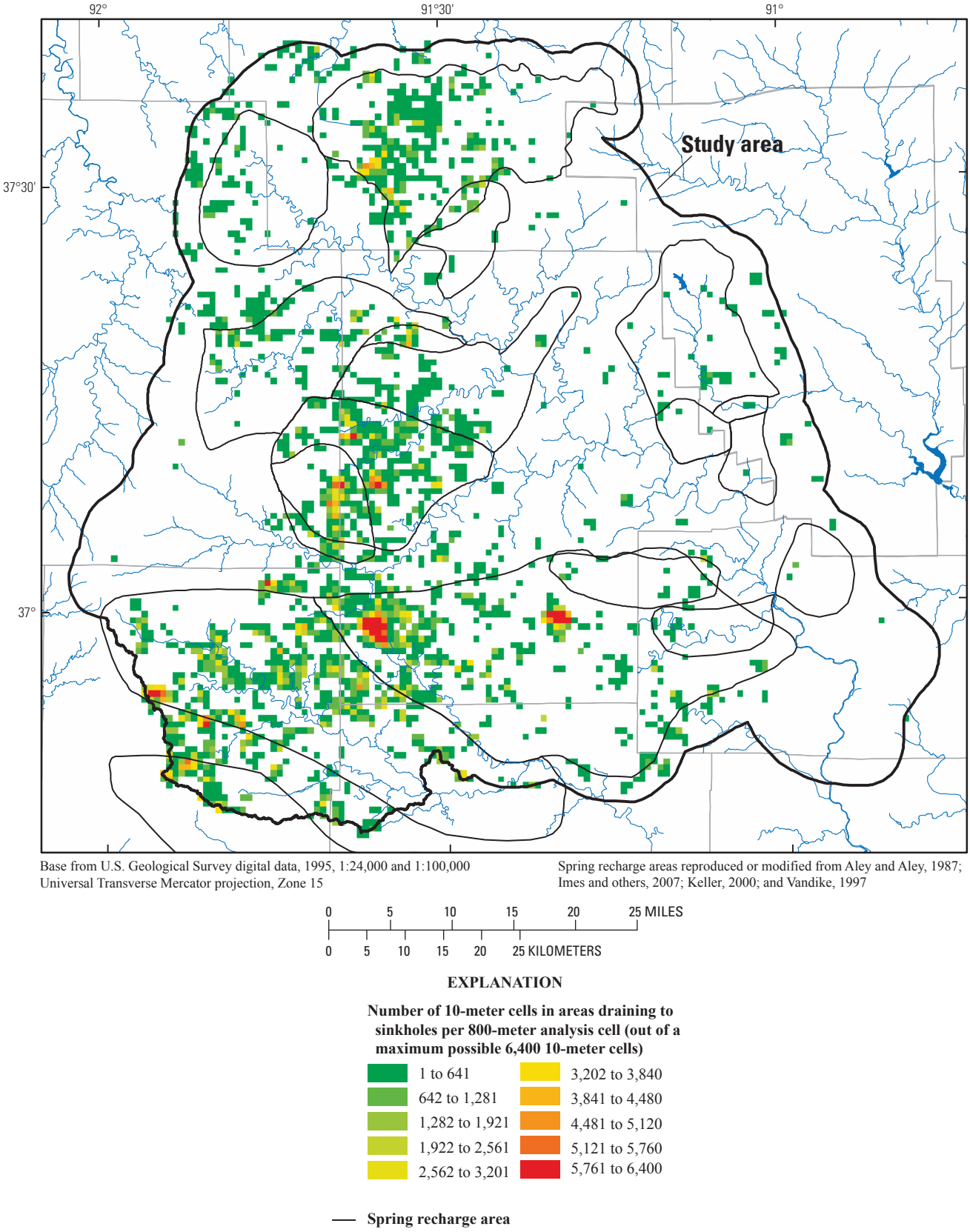


Figure 26. Density distribution of sinkhole drainage area.

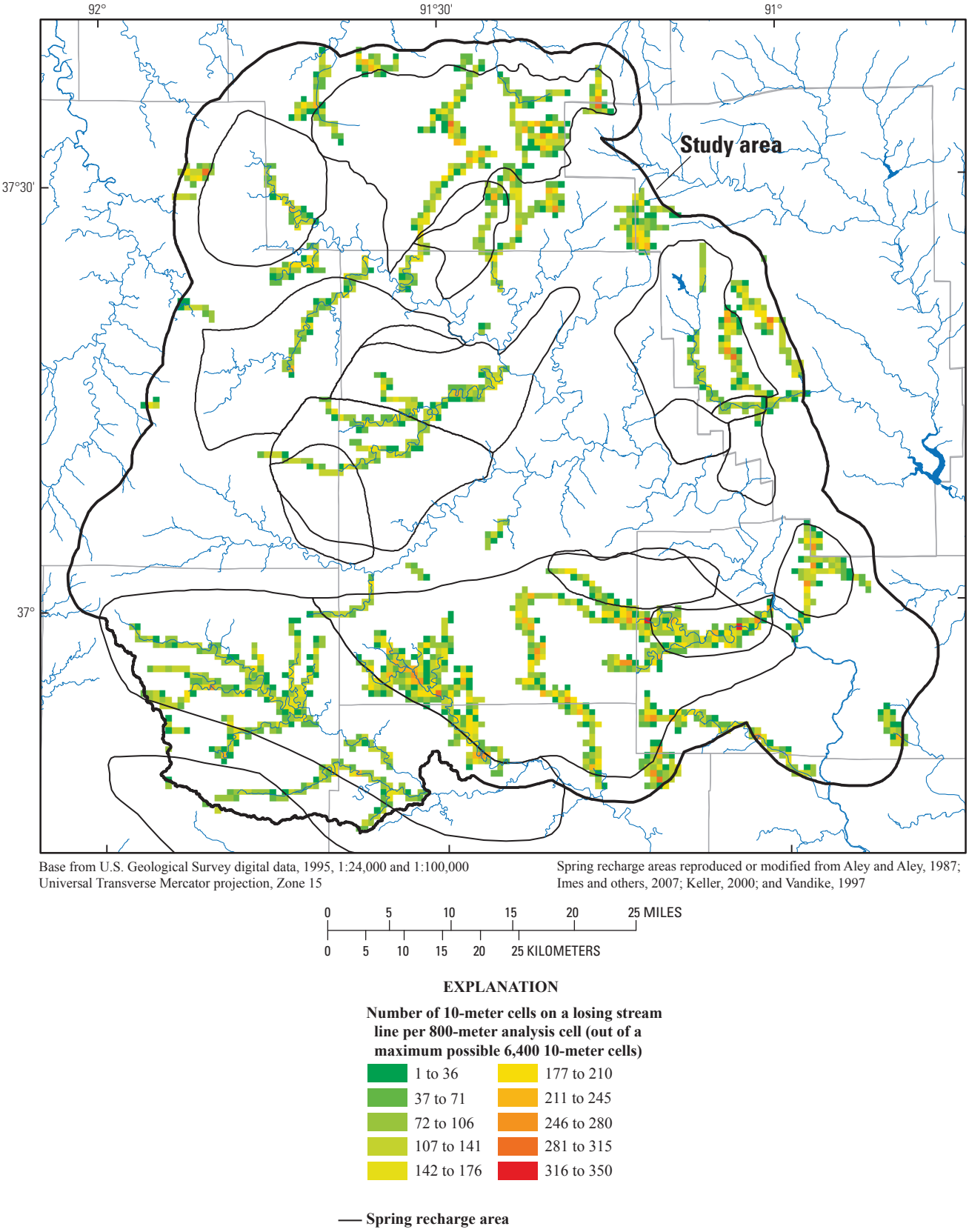


Figure 27. Density distribution of losing streams.

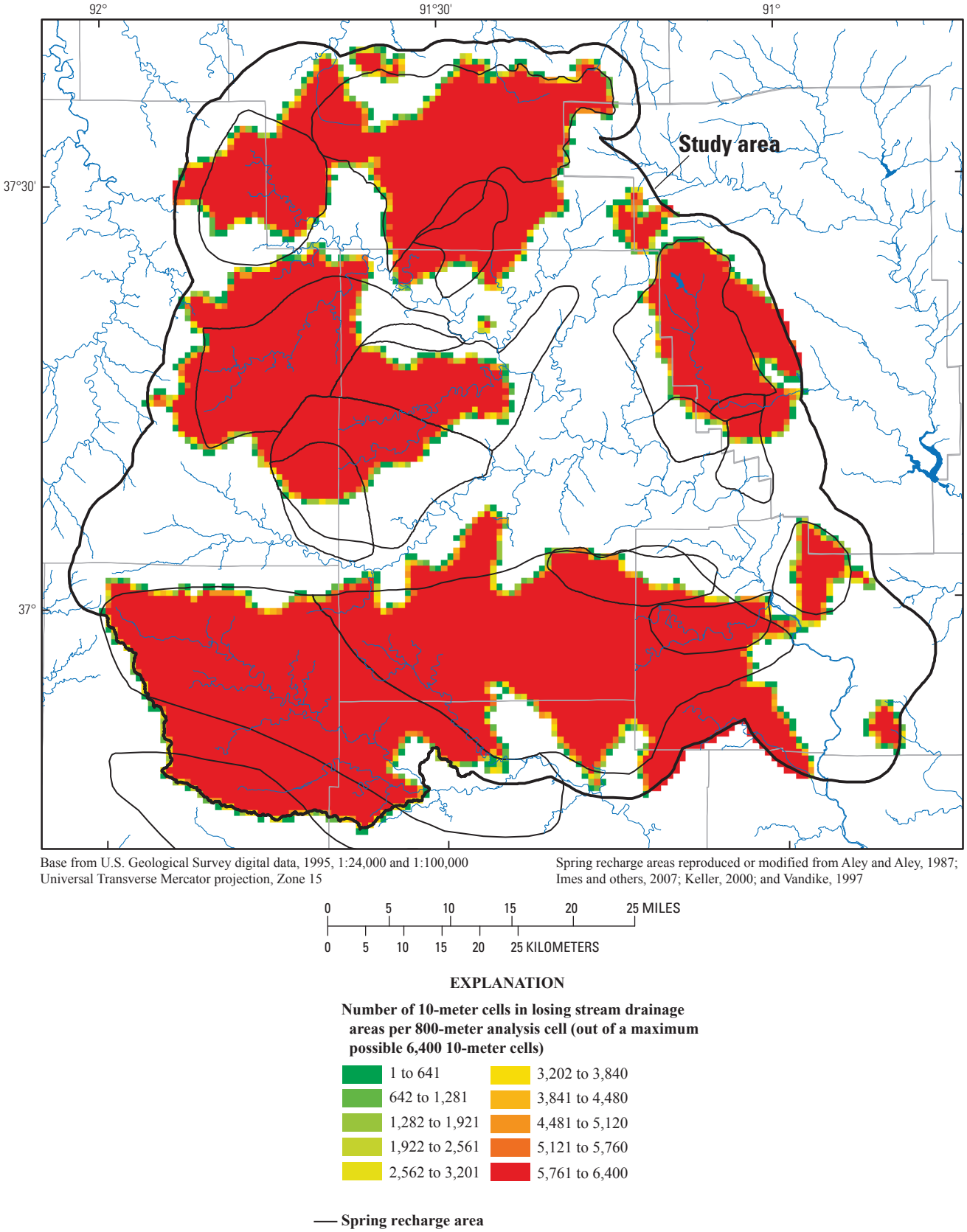
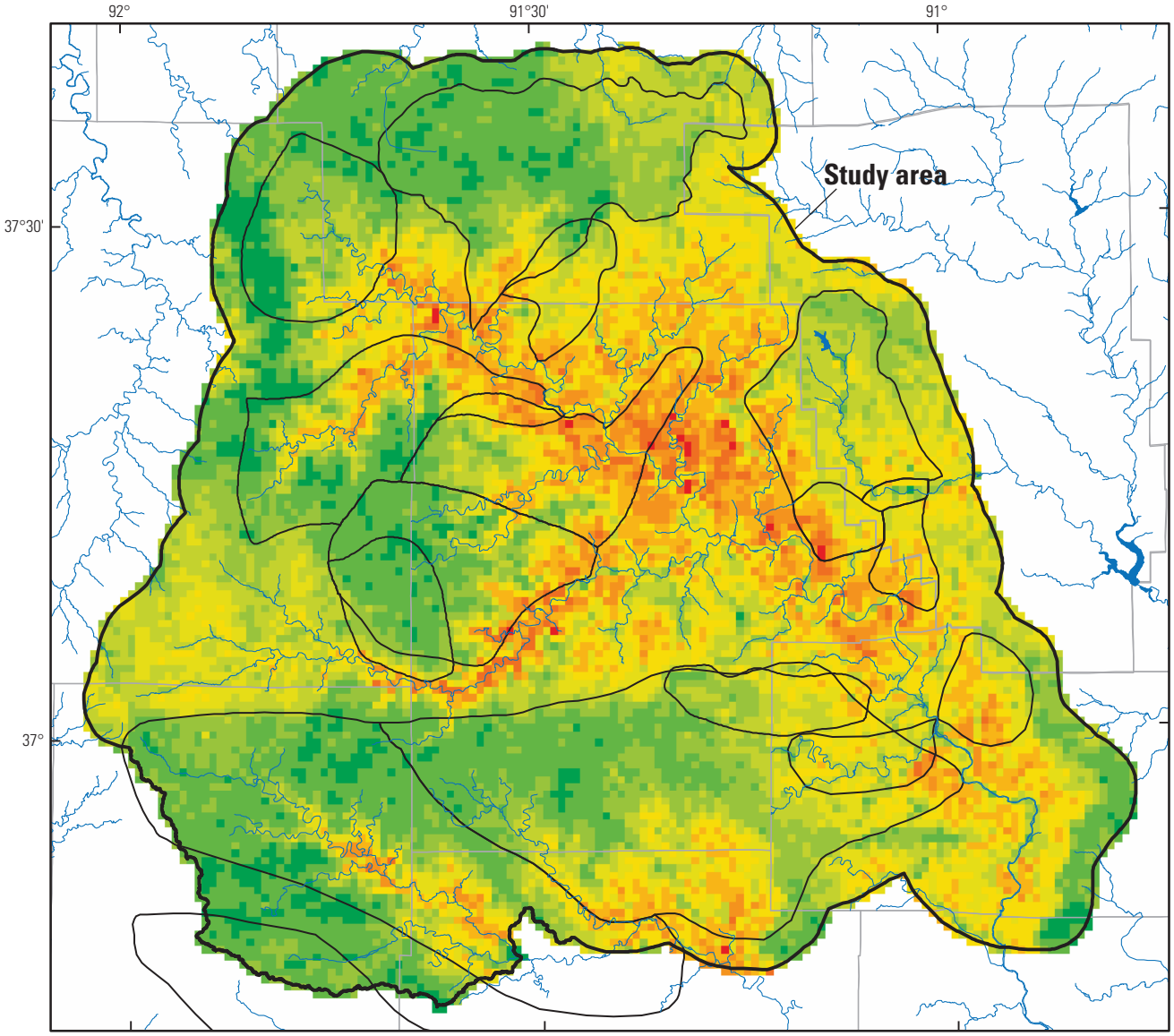


Figure 28. Density distribution of losing stream drainage area.



Base from U.S. Geological Survey digital data, 1995, 1:24,000 and 1:100,000
Universal Transverse Mercator projection, Zone 15

Spring recharge areas reproduced or modified from Aley and Aley, 1987; Imes and others, 2007; Keller, 2000; and Vandike, 1997

0 5 10 15 20 25 MILES

0 5 10 15 20 25 KILOMETERS

EXPLANATION

Mean land-surface slope of 800-meter analysis cells, in degrees

0.6 to 2.6	10.4 to 12.2
2.7 to 4.5	12.3 to 14.2
4.6 to 6.4	14.3 to 16.1
6.5 to 8.4	16.2 to 18.0
8.5 to 10.3	18.1 to 20.0

Spring recharge area

Figure 29. Mean land-surface slope.

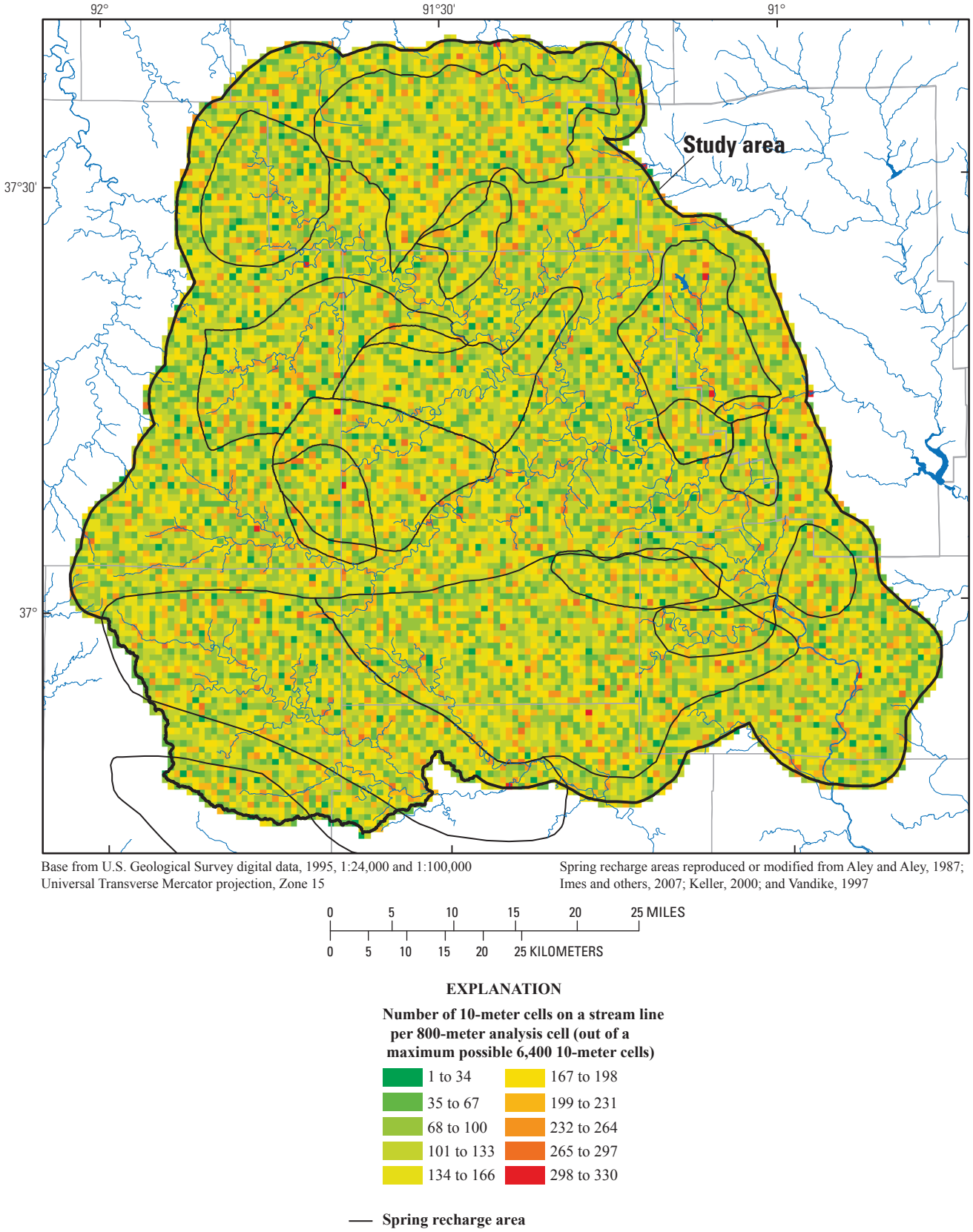


Figure 30. Stream density distribution.

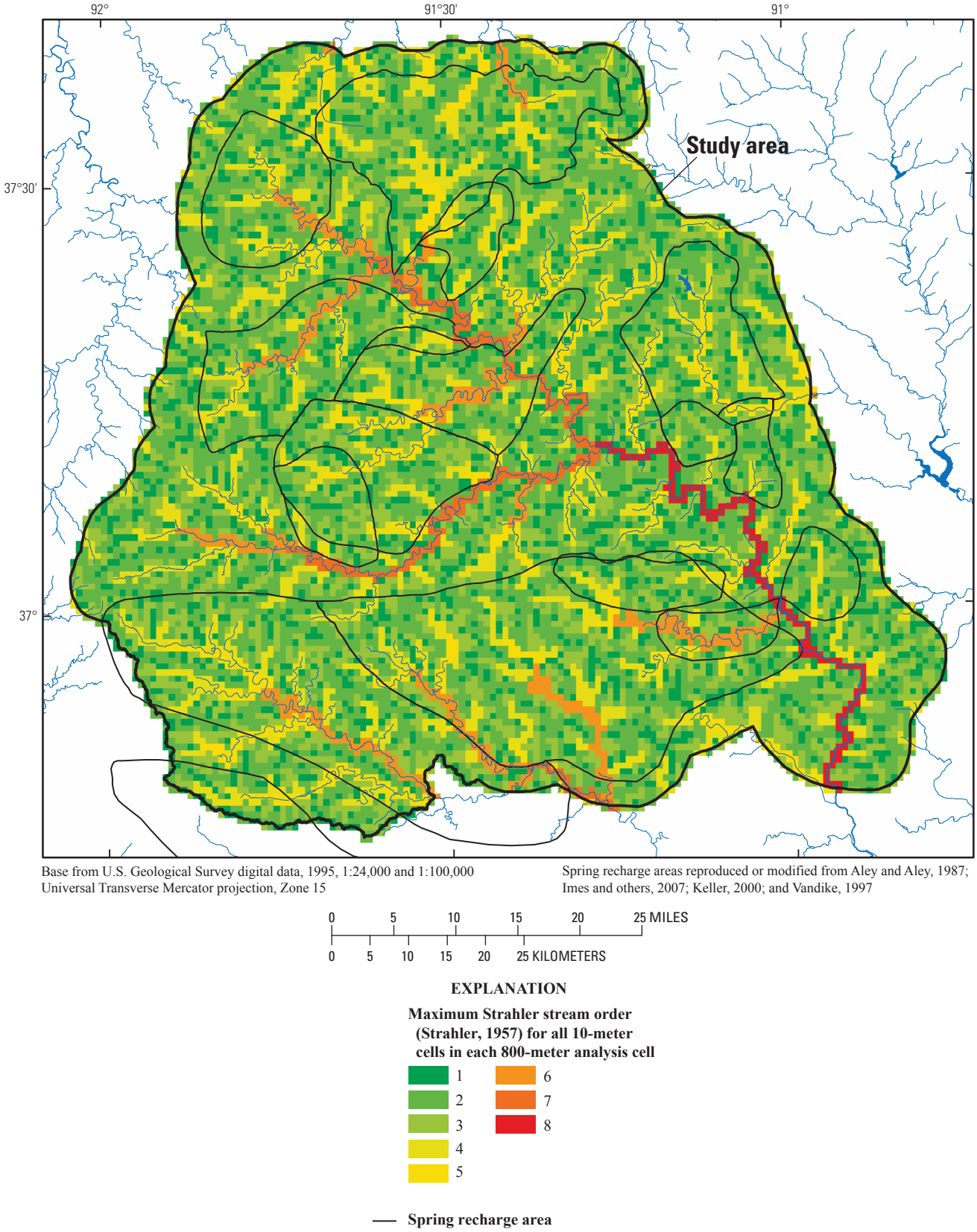


Figure 31. Maximum Strahler stream order.

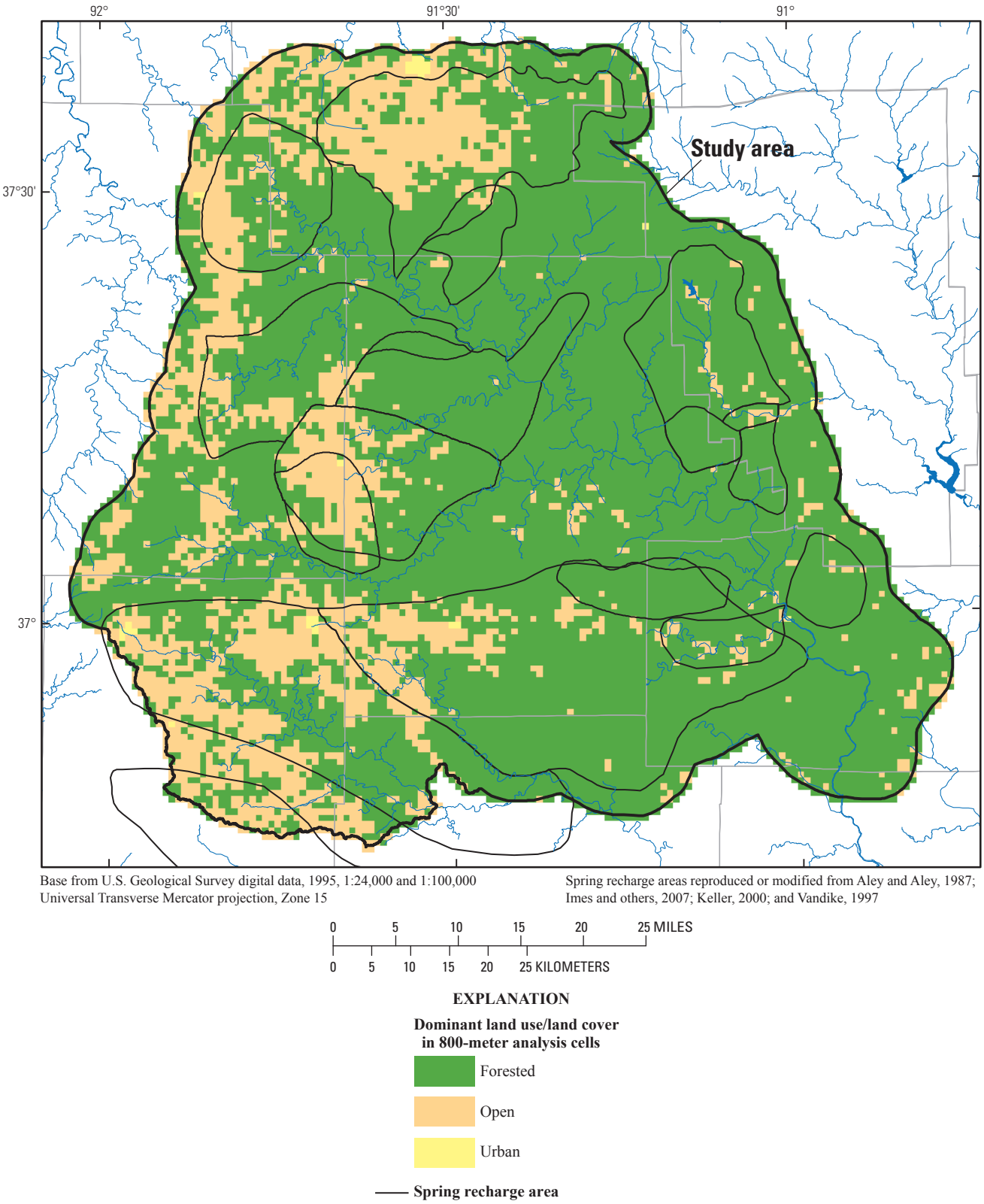


Figure 32. Dominant land use/land cover.

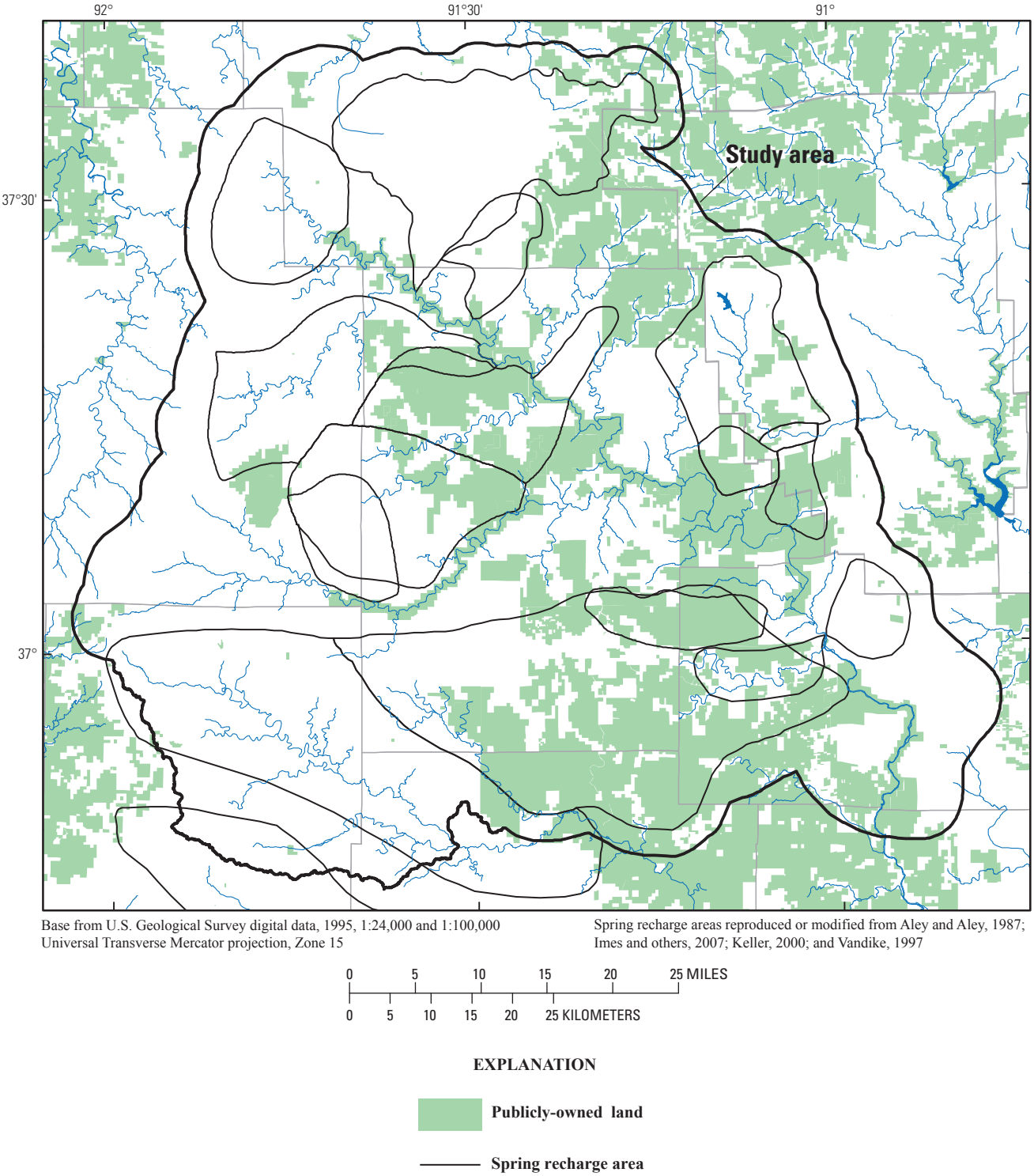


Figure 33. Public land ownership.

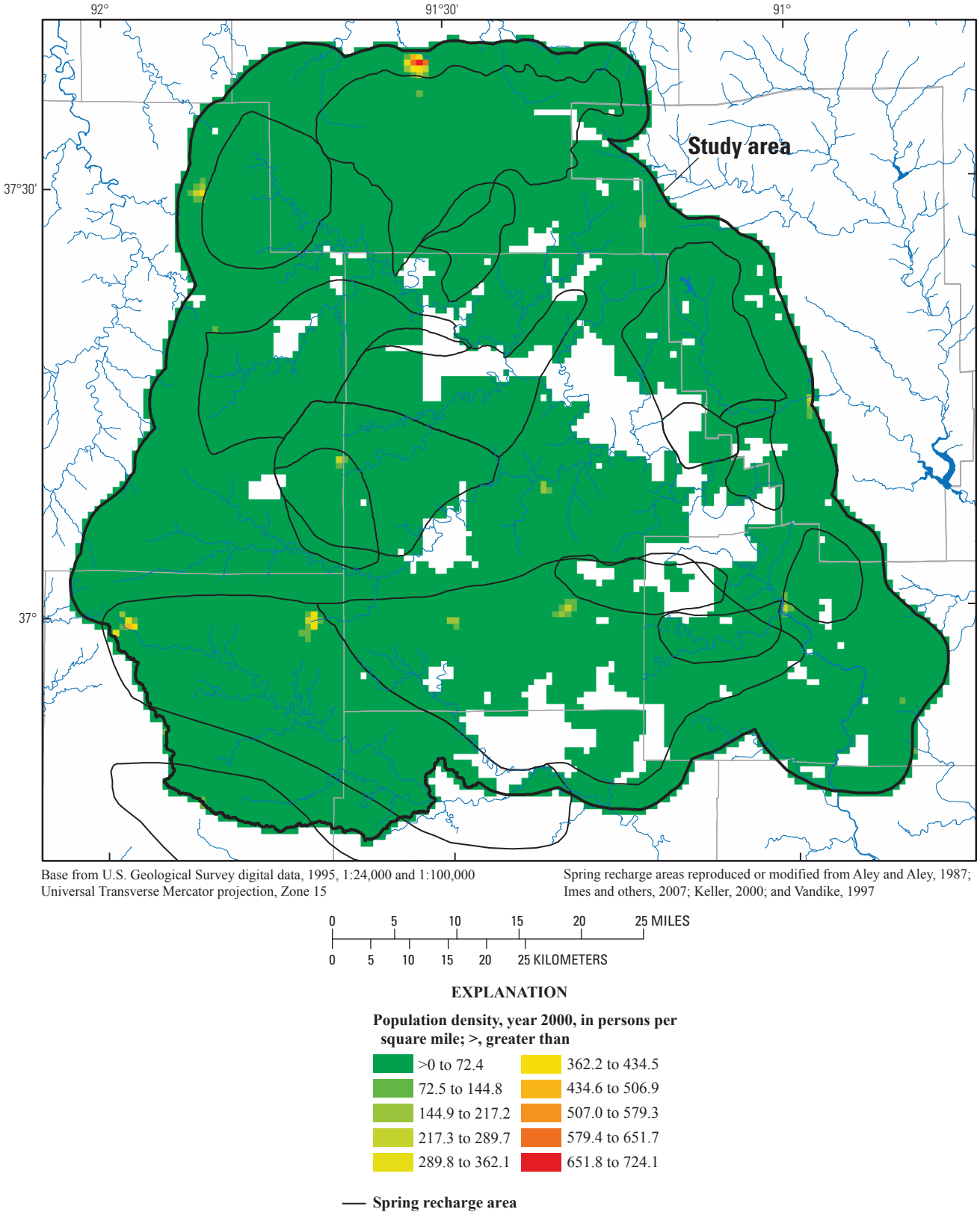


Figure 34. Population density distribution.

was developed from the 10-m grid of topographic elevation. In this representation, every vector stream line begins at the same contributing drainage area (in this case, 809 10-m cells or about 20 acres). This stream representation is uniform over the entire study area. The vector streams generated from the topographic elevation grid then were rasterized at 10 m, aggregated by summing to the 800-m cell size, and divided into 10 classes. The relevance of this landscape characteristic is that 800-m analysis cells with a greater density of stream segments can move more surface water to the Current River or Jacks Fork than cells with a lower stream density. This is true even for a losing stream, which, depending on rainfall intensity and streambed characteristics, may not lose all its flow and can still move some water downstream, particularly during heavy runoff events. The miles of streams in each spring recharge area are given in table 9. The stream density in 800-m analysis cells ranges from 1 to 330 10-m cells on a stream line per 800-m analysis cell (fig. 30). Stream density, however, does not take into account the size of the stream, and treats a small tributary in the headwaters of a stream the same as the stream itself. Stream order is a way of classifying streams based on their number of tributaries and describes the relative stream size and position in the stream network. The Strahler (1957) method was used to assign numeric order to the vector streams generated from the topographic elevation grid. In the Strahler method, the most upstream segments are assigned order 1. The order of the stream increases when streams of the same order intersect. For example, the intersection of two first-order streams will create a second-order stream. The intersection of two streams of different order will not increase the order, but the highest order will be retained. The ordered streams were rasterized to a 10-m grid, aggregated using the maximum function, and divided into 10 classes to be consistent with other landscape characteristic maps. The highest stream order is 8. A landscape characteristic map for maximum Strahler stream order is shown in figure 31.

Land use/land cover is an anthropogenic landscape characteristic, and while not geohydrologic in nature, its portrayal in a landscape characteristic map further characterizes the study area, and spring recharge areas in particular. Although, land use and land cover are not the same thing, land cover can be used as a surrogate for land use. For example, much of the land cover classified as open probably has a land use as pasture. The area of each of five types of land use/land cover (water, forested, cultivated, open, and urban), based on interpretation of spectral reflectance data by the University of Missouri, School of Natural Resources, Missouri Resource Assessment Partnership (Missouri Spatial Data Information Service, 2007) is given in table 9. The area of forested and open land per unit recharge area also are given in table 9. The spring recharge areas with the most open land and the least forested land per unit recharge area are Blue Spring (Jacks Fork), Welch Spring, Montauk Springs, and Alley Spring. A map of the 2005 land use/land cover in the study area shows the dominant land use/land cover in 200-m cells (fig. 5). For consistency with other 800-m maps, figure 32 shows the dominant land use/land cover in 800-m cells and spring recharge areas. Open land is more prominant in the spring recharge areas listed above and in the western part of the Big Spring recharge area than in other spring recharge areas (fig. 32).

Public land ownership, which is the combination of the public lands shown in figure 1, is shown in figure 33. This is not a rasterized map like the other landscape characteristic maps. Public lands include lands owned by Federal and State agencies. The publicly owned land area and publicly owned land area per unit recharge area for each spring recharge area are given in table 9. The spring recharge areas with the least amount of publicly owned land per unit recharge area are Montauk Springs, Blue Spring (Jacks Fork), Cave Spring, Welch Spring, and the Pulltite Springs Complex.

Aside from a few small towns with concentrated population, most of the study area is sparsely populated and nonpopulated in places. A population density map, based on the 2000 United States Census data compiled by the University of Missouri, Department of Geography, Geographic Resource Assessment Center (Missouri Spatial Data Information Service, 2007) is shown in figure 34. Population in each census block (represented by irregularly shaped vector area features in the source data) was normalized by the area of each census block. The vector area features were rasterized to a 10-m grid and aggregated up to the 800-m grid by summing and divided into 10 classes. Large areas with low values and cells with higher values clustered at towns are shown in figure 34. The largest town in the study area is Salem (fig. 1) with a 2000 population of 4,854. Large parts of the study area, particularly along the Current River, a smaller portion along Jacks Fork, and Hurricane Creek, are nonpopulated.

Summary and Conclusions

The Ozark National Scenic Riverways (ONSR) is a narrow corridor that stretches for approximately 134 mi (miles) along the Current River and Jacks Fork in southern Missouri. Most of the water flowing in the Current River and Jacks Fork is discharged to the rivers from springs within the ONSR, and most of the recharge area of these springs is outside the ONSR. The karst terrain of the study area is characterized by many sinkholes, springs, caves, and losing streams, which are linked by a complex and poorly understood underground drainage system of fractures and conduits. Springs range in size from small springs that may flow intermittently to Big Spring, the largest spring in Missouri with an annual mean discharge of 446 ft^3/s (cubic feet per second). To improve understanding of the geohydrology and landscape characteristics in and outside the ONSR, the U.S. Geological Survey (USGS) conducted a study during 2006–08 in cooperation with the National Park Service.

Water-level measurements were made in 119 wells and two springs to map the potentiometric surface of the Ozark

aquifer north of Jacks Fork and east of the Current River. A seepage run, consisting of 255 measurements and estimates of discharge and observations of no discharge, was conducted on the Current River, Jacks Fork, and Sinking Creek. A temperature profile was conducted along an 85-mi reach of the Current River from Akers Ferry to Cataract Landing to determine if previously unknown springs exist in the streambed. Two dye tracer tests were conducted to better define discrete groundwater flow in an area between Logan Creek and the Current River. A series of maps was created to display the variability of landscape characteristics throughout the study area. These landscape characteristics were quantified by dividing the study area into 800-m (meter) analysis cells and, for most characteristics, creating a raster representation of the density of each characteristic in each cell.

Potentiometric-surface contours were interpreted north of Jacks Fork and east of the Current River in this investigation, and were joined to a previously constructed potentiometric-surface map of the southern part of the study area to complete the potentiometric-surface map of the study area for 2000–07. The potentiometric-surface map shows the general pattern of high hydraulic head in upland areas and progressively lower head closer to streams, which mimics the land-surface topography in a general way. In some places, notably along Logan Creek and the northeastern part of the study area, the groundwater divide extends outward beyond the surface-water divide, indicating interbasin transfer of groundwater between surface-water basins. A low hydraulic gradient, as indicated by widely spaced potentiometric contours, occurs in much of the upland area west of the Current River, associated with areas of high sinkhole density. The density of sinkholes indicates the presence of a network of subsurface karst conduits, which depresses the water table and causes a low hydraulic gradient. Groundwater troughs can reflect the presence of subsurface karst conduits, and show the convergence of flow to springs. This is probably best demonstrated by the Welch Spring and Blue Spring (Current River) recharge areas.

A seepage run was conducted in 2006 during low base-flow conditions when stream discharge represented the maximum groundwater component, or base flow of the stream discharge, with little additional inflow from surface-water runoff. The streamflow conditions for the 2006 seepage run were low but not at historic low-flow conditions as compared with historic low-flow instantaneous discharges recorded at USGS gages. In general, the seepage run showed gaining conditions, that is, the Current River, Jacks Fork, and Sinking Creek gained flow with increasing distance downstream. Most of the gain was from discharge from identified springs, and a smaller amount of gain was from tributaries whose discharge probably originated as spring discharge, or from springs or diffuse groundwater discharge in the streambed.

Results of the temperature profile indicate a general increase in river bottom and surface temperature with increasing distance downstream. Average bottom temperatures were lowest within or immediately downstream from inflows of springs such as Cave Spring [15.6 degrees Celsius (ºC)], Fire Hydrant Spring, which is part of the Pulltite Springs Complex, (14.0 ºC), Blue Spring (16.8 ºC), Bass Rock Spring (14.0 ºC), and Big Spring (14.4 ºC). The warmest bottom water temperatures were measured at the mouth of Sinking Creek (average bottom temperature of 24.7 to 26.6 ºC), and an average bottom temperature of 27.4 ºC measured in a slough at the mouth of Pine Valley Creek. The general increase in temperature with distance downstream is caused by the longer residence time of water in the stream that allows for warming by contact with the warmer summer air temperatures and exposure to sunlight during the daytime hours in which the temperature profile was done. No temperature anomalies were noted along the reach identified as the Current River Springs Complex.

Using a mass-balance on heat calculation and assuming equilibrium mixing, the discharge of groundwater from Blue Spring was estimated at 94 ft^3/s using the measured discharge upstream from Blue Spring, and 90 ft^3/s using the measured discharge downstream from Blue Spring. A large temperature decrease was detected within a pool just upstream from Van Buren, locally referred to as “Bass Rock”, and herein named “Bass Rock Spring”. Using the mass-balance on heat calculation, the discharge of Bass Rock Spring was estimated to be 34.1 ft^3/s, which compares favorably with 43 ft^3/s calculated by subtracting upstream from downstream Current River discharge measurements. This estimated discharge ranks Bass Rock Spring as the sixth largest spring in the Current River basin. Bass Rock Spring is similar to Pulltite Spring and Blue Spring in that its specific conductance value [295 microsiemens per centimeter at 25 ºC (µS/cm)] was smaller than the specific conductance of the Current River upstream from the spring (330 µS/cm). In contrast, the specific conductance values of Cave Spring, Gravel Spring, and Big Spring were larger than the Current River upstream from these springs.

The first of the two dye tracer tests conducted by the USGS in 2006 was unsuccessful because dye was not recovered at any of the dye packet locations. The second dye trace was successful with dye recovery at Blue Spring.

The 13 springs in the study area for which recharge areas have been estimated accounted for 82 percent (867 ft^3/s of 1,060 ft^3/s) of the discharge of the Current River at Big Spring during the 2006 seepage run. Including discharge from other springs, the cumulative discharge from springs was over 90 percent of the river discharge at most of the spring locations, and was 92 percent at Big Spring and at the lower end of the ONSR.

The discharge from Montauk Springs measured in the 2006 seepage run was 48.6 ft^3/s, which represented 99 percent of the flow in the Current River at that location. The discharge from Welch Spring measured in the 2006 seepage run was 100 ft^3/s, which represented 57 percent of the discharge in the Current River at that location. The estimated Welch Spring recharge area is almost entirely outside the surface-water basin for the Current River at Welch Spring. The discharge from Cave Spring measured in the 2006 seepage run was 16.6 ft^3/s, which represented 9 percent of the flow in the Current River at that location. The discharge from the 1.9-mile long Pulltite

Springs Complex measured in the 2006 seepage run was 88 ft^3/s, which represented 32 percent of the discharge in the Current River at the lower end of the complex. The discharge was 77 ft^3/s from the first approximately 0.25 mi of the Pulltite Springs Complex and then 11 ft^3/s from the next 1.4 mi of the complex.

Round Spring has an annual mean discharge of 46.9 ft^3/s based on 25 years of record at a USGS gage (1928–1939 and 1965–1979). Because of excessive watercress, a discharge measurement was not obtained for Round Spring during the 2006 seepage run. It has been estimated that the annual mean discharge from the Current River Springs Complex is 125 ft^3/s, based on an apparent discharge of 50 ft^3/s during a 1966 USGS seepage run. However, a reinterpretation of the 1966 seepage run data shows that the discharge from the Current River Springs Complex instead was about 12.6 ft^3/s, and the annual mean discharge is estimated to be 32 ft^3/s, substantially less than 125 ft^3/s. The 2006 seepage run showed a gain of only 12 ft^3/s from the combined Round Spring and Current River Springs Complex from the mouth of Sinking Creek to 0.7 mi upstream of Root Hollow. Also, the 2006 temperature profile measurements did not indicate any influx of spring discharge throughout the length of the Current River Springs Complex.

The discharge from Blue Spring (Jacks Fork) measured during the 2006 seepage run was 10.6 ft^3/s, which represented 27 percent of the discharge of Jacks Fork at that location. The discharge from Alley Spring measured in the 2006 seepage run was 97 ft^3/s which represents 71 percent of the discharge of Jacks Fork at that location. The annual mean discharge from Alley Spring is 135 ft^3/s, based on a USGS gage that was at Alley Spring from 1928 to 1939 and 1965 to 1979.

The combined discharge of Cove Spring and Powder Mill Spring was 7.9 ft^3/s in the 2006 seepage run. The discharge from Blue Spring (Current River) measured in the 2006 seepage run was 93 ft^3/s, which represented 15 percent of the discharge in the Current River at that location. The annual mean discharge from Blue Spring is estimated to be about 127 ft^3/s based on a previously calculated average of 115 discharge measurements. Most of the recharge area for Blue Spring is along Logan Creek in the Black River Basin, outside the Current River Basin, and Blue Spring is an excellent example of interbasin transfer of groundwater. The discharge from Gravel Spring was not directly measured during the August 2006 seepage run, and the mass-balance on heat calculation was used to estimate its discharge at 12.9 ft^3/s. The discharge from Mill Creek Spring measured in the 2006 seepage run was 3.47 ft^3/s. The 34.1 ft^3/s discharge estimated for Bass Rock Spring using the mass-balance on heat calculation represents approximately 5 percent of the discharge of the Current River at that location.

Big Spring is the largest spring in Missouri with an annual mean discharge of 446 ft^3/s based on data recorded continuously at a USGS gage from 1921 to 1966 and 2000 to present (2008). The discharge measured in the 2006 seepage run was 343 ft^3/s, which represents 32 percent of the discharge in the Current River at that location. About 56 percent of the Big Spring recharge area is outside the surface-water basin.

The spring recharge areas with the largest number of identified sinkholes are Big Spring (339), Alley Spring (312), and Welch Spring (284). The spring recharge areas with the largest number of sinkholes per square mile of recharge area are Alley Spring (2.12), Blue Spring (Jacks Fork) (1.74), Welch Spring (1.33), and Round Spring and the Current River Springs Complex (1.02). The spring recharge areas with the largest sinkhole area are Big Spring (1.5 mi^2) and Alley Spring (1.3 mi^2), and the spring recharge areas with the largest sinkhole area per unit recharge area are Blue Spring (Jacks Fork) (0.013 mi^2/mi^2) and Alley Spring (0.009 mi^2/mi^2). The spring recharge areas with the largest sinkhole drainage area are Big Spring (13.1 mi^2), Alley Spring (7.8 mi^2), and Welch Spring (5.3 mi^2), and the spring recharge areas with the largest sinkhole drainage area per unit recharge area are Blue Spring (Jacks Fork) (0.062 mi^2/mi^2) and Alley Spring (0.053 mi^2/mi^2). Using the currently known locations of losing streams, the Big Spring recharge area has the largest number of miles of losing stream (246), and the Bass Rock Spring recharge area has the largest number of miles of losing stream per unit recharge area (0.99 mi/mi^2). The spring recharge areas with the most open land and the least forested land per unit recharge area are Blue Spring (Jacks Fork), Welch Spring, Montauk Springs, and Alley Spring. The spring recharge areas with the least amount of publicly owned land per unit recharge area are Montauk Springs, Blue Spring (Jacks Fork), Cave Spring, Welch Spring, and the Pulltite Springs Complex.

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