Characteristics of Thermal Springs and the Shallow Ground-Water System at Hot Springs National Park, Arkansas

Prepared in cooperation with the
National Park Service

Scientific Investigations Report 2006-5001

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

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U.S. Department of the Interior
Gale A. Norton, Secretary

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Conversion Factors, Vertical Datum, and Abbreviations,

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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

°F = (1.8 x °C) + 32

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

Characteristics of Thermal Springs and the Shallow Ground-Water System at Hot Springs National Park, Arkansas

By Daniel S. Yeatts

Abstract

The thermal springs of Hot Springs National Park have been valued for the recreational and therapeutic benefits of the thermal baths, as a source of drinking water, and a destination of attraction since the history of the area was first recorded. The future of the park and the city of Hot Springs depends greatly on maintaining and protecting this unique natural resource from degradation and contamination. To maintain and protect the thermal springs, it is imperative to understand the character of the springs, monitor changes in spring characteristics, and evaluate the source of the thermal springs.

The thermal springs are situated in the Ouachita Mountains of central Arkansas. The springs emerge in a gap between Hot Springs Mountain and West Mountain in an area about 1,500 feet long by 400 feet wide. The springs predominantly are composed of a deep thermal ground water component with a lesser but qualitatively substantial component of shallow cold ground water. Currently, there are 43 thermal springs in the park that are presumed to be flowing. Thermal water from 33 of the thermal springs is collected and monitored at a central reservoir, which distributes the combined discharge for public use and consumption.

The average collection system discharge over the period of record 1990 through 1995 and 1998 through 2005 was 658,000 gallons per day and ranged from 518,000 to 763,000 gallons per day, not including about 131,000 gallons per day from springs 43 and 43a that emerge from the bottom of the collection system reservoir. The overall pattern of the collection system discharge from 1990 through 2005 shows an increasing rate of discharge. Changes in the collection system temperature showed a positive relation to changes in discharge from 1990 through 1995, and an inverse relation to changes in discharge from 1998 through 2005. The collection system usually increases in discharge during rainfall events.

Continuous water temperature monitoring at the collection system reservoir inflow pipe shows that there has not been a substantial long-term temperature change during the past 15 years. The daily water temperature ranged from 59.1 to 62.1 degrees Celsius and the average daily temperature was 61.4 degrees Celsius. The collection system water temperature shows a strong seasonal pattern, with highs and lows about 1 month delayed from air temperature highs and lows. The collection system temperature also shows strong response to rainfall.

The water temperatures at four thermal springs were monitored from August 2000 through June 2005, and four additional thermal springs and one thermal spring collection box were monitored from September 2003 through June 2005. Springs of relatively higher elevation (defined as group 1) generally showed a greater temperature response to changes in air temperature and rainfall. Springs of relatively lower elevation (defined as group 2) generally showed a smaller temperature response to changes in air temperature and rainfall. Springs 17 and 46 were exceptions that displayed unique water temperature responses that differed somewhat from group 1 and 2 springs.

Rock types exposed in the vicinity of the thermal springs are shale, chert, novaculite, sandstone, and conglomerate. Shale units generally impede ground-water movement, while fractured chert, novaculite, and sandstone units generally support ground-water movement. The thermal-water component hypothetically enters the ground-water system as regionally derived recharge from rainfall and flows to estimated depths of 4,500 to 7,500 feet, where the water is heated and rises along fault and fracture conduits. The cold-water component enters the ground-water system primarily as locally derived recharge from rainfall and flows along shallow northeast trending faults, joints, and fractures to the thermal springs. The thermal springs are bounded on the southwest, southeast, and northwest by shale barriers. The lower member of the Arkansas Novaculite is probably the primary aquifer of shallow ground-water flow. Ground-water levels generally indicate that ground-water flow is towards Hot Springs Creek.

The size of the shallow cold-water recharge area was estimated from the general concept of the hydrologic budget, where the average annual ground-water recharge (input) is equal to the average annual cold-water discharge (output) of the thermal springs. Based on the thermal springs estimated cold ground-water baseflow discharge of 17.8 million gallons per year, and an estimated ground-water recharge rate of 5 to 10 inches per year, the estimated size of the shallow cold-water recharge area computes to 0.10 to 0.20 square mile. The shallow cold-water recharge area appears to be bounded on three sides by low-permeability barriers, and extends approximately to the topographic divide. The estimated shallow ground-water recharge area based on the boundaries is about 0.14 square mile.

Rhodamine dye released on Hot Springs Mountain, about 1,000 feet east of Central Avenue, was detected above background levels at several thermal water recovery sites over a period of several weeks. The flow path of the rhodamine dye to

the thermal springs is probably along the western boundary contact with the Stanley Shale or along northeast-trending fractured lineaments. Presence of the dye verifies that this area is part of the recharge area and that surface water enters the ground-water system at some point along the pathway of the rhodamine dye. Time of travel from the release point to the thermal springs was 1 to 3 weeks, depending on where the dye was detected.

Introduction

The thermal springs of Hot Springs National Park (HSNP) have been valued for the recreational and therapeutic benefits of the thermal water baths, as a source of drinking water, and as a destination of attraction since the history of the area was first recorded. After becoming a territory in 1803, the Arkansas Territorial Legislature recognized the importance of the thermal springs resource and requested in 1820 that the springs and adjoining mountains be set aside as a Federal reservation. The value of the thermal springs received national recognition when President Andrew Jackson signed legislation in 1832 to set aside "...four sections of land including said (hot) springs, reserved for the future disposal of the United States (which) shall not be entered, located, or appropriated, for any other purpose whatsoever." The Federal reservation was designated as a national park on March 4, 1921. In 2004, about 1.4 million people made recreational visits to HSNP, more than 100,000 people bathed in the thermal waters, and additional tens of thousands of people collected water for drinking. The thermal springs of today provide the stimulus and attraction that form the base for local tourism and businesses.

HSNP is situated in the Ouachita Mountains of central Arkansas; about 55 miles southwest of Little Rock and about 80 miles east of the Oklahoma State line (fig. 1). The mountains of HSNP divide the city of Hot Springs into northern and southern areas: the northern area lying in a valley on the southern edge of the Zigzag Mountains; and the southern area lying on the northern border of the Mazarn Basin, which drains to the Ouachita River. The north and south areas are connected by a pass between West Mountain and North and Hot Springs Mountains. This pass is the only throughway for drainage of the northern valley area to the southern Mazarn Basin area via Hot Springs Creek, and for vehicular and pedestrian traffic between the two areas. It is also the area of occurrence for 43 thermal springs of HSNP.

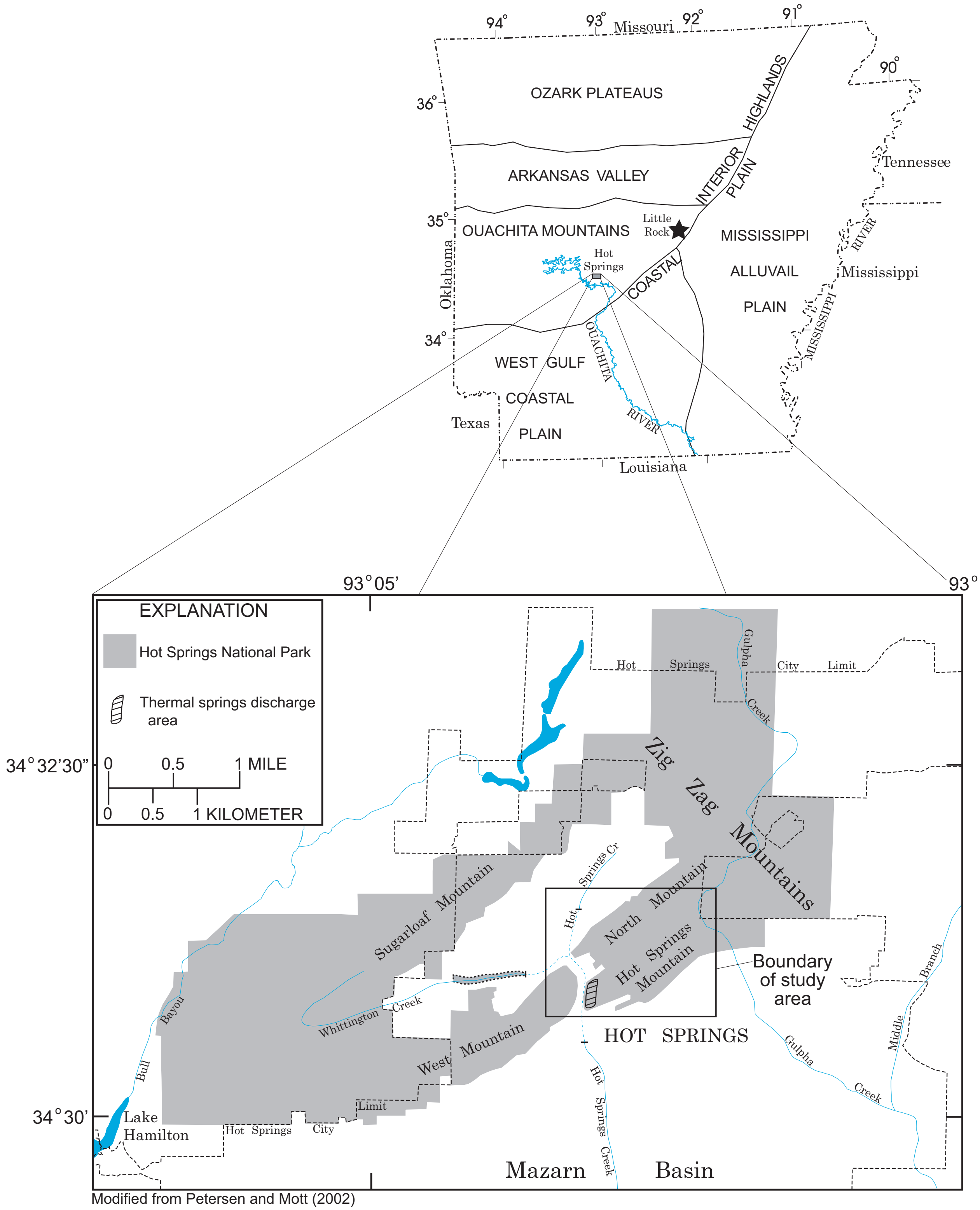
Flow from the thermal springs originates in two distinct recharge areas that yield water from two flow paths in HSNP. The predominant component of flow from the springs is supplied from thermal water that takes 4,000 years or more to move from the recharge area to the discharge point at the springs (Bedinger and others, 1979). Another component of flow is derived from a short, shallow flow path representing a locally recharged, cold-water component of flow that is more readily susceptible to contamination from development and land use in the area. The exact location and extent of this recharge area are unknown. An investigation conducted in 2000 and 2001 by the USGS has provided temperature and geochemical data that confirms the presence of a substantial locally derived cold-water component from recharge (Richard W. Bell and Phillip D. Hays, U.S. Geological Survey, written commun., 2005). The recharge area for the cold-water component is within or in proximity of an urban environment. Potential sources of contamination occurring in an urban setting include leaking sewer systems; leaking underground storage tanks; chemical-intensive commercial activities where spills or improper disposal may occur; and chemically-charged non-point source runoff from lawns, parking lots, roads, and other surfaces.

Direct infiltration of contaminants from above and adjacent to the springs is also a concern because of the past construction history of the springs and the park. The springs today have been disturbed by intensive excavation throughout the spring discharge area to reroute the path of Hot Springs Creek, renovate spring catchments, and construct the bathhouses and pedestrian walkways. Excavations and thermal spring catchments that have altered tufa and other surficial formations allow pathways for surface water to infiltrate into the springs (Charles G. Stone, Arkansas Geological Commission, written commun., 2005). Hot Springs Creek, which drains a large urban area, flows about 50 feet (ft) west of some thermal springs at the base of Hot Springs Mountain, and the water level in the creek can rise above the level of the thermal springs during storm events, posing a concern for lateral infiltration into the springs.

The future of HSNP and the city of Hot Springs depends greatly on maintaining and protecting the thermal springs from degradation. Types of degradation that could affect the park and the city include: (1) increased contributions of colder surface water into the thermal water system affecting temperature, (2) introduction of contaminants from point and non-point sources affecting water quality, and (3) changes in ground-water hydraulics affecting the discharge of the springs. To maintain and protect the thermal springs, it is imperative to understand the character of the springs, monitor changes in spring characteristics over time, and evaluate the source of the thermal springs and the thermal springs system. In October 2003, a 2-year study was initiated in cooperation with the National Park Service to monitor and trace local, shallow ground-water flow to the thermal springs and estimate its recharge area.

Purpose and Scope

The purpose of this report is to describe the characteristics of the thermal springs and shallow ground-water system, and approximate the size and boundaries of the recharge area for the cold-water component of the thermal springs. Several sources of information and techniques were used to achieve this purpose. Geologic and structural data from previous studies (Purdue, 1910; Bryan, 1922; Arndt and Stroud, 1953; Bedinger and others, 1979), topographic data from existing maps, and data collected in the field were inventoried, compiled, and reviewed to determine the surficial controls on drainage and infiltration,



Modified from Petersen and Mott (2002)

Figure 1. Location of Hot Springs National Park, Arkansas.

the ground-water flow paths, and the boundaries to ground-water flow. Four wells were logged using borehole geophysics to provide more detailed information on lithology, distribution of permeability, fracture orientation, and thermal flow within the shallow ground-water system. The water temperature at eight thermal springs and a collection box, the water temperature and discharge at the collection system reservoir, the rainfall in downtown Hot Springs, and the ground-water levels at two wells were monitored to identify and evaluate the relation between water temperature, discharge, precipitation, and ground-water level. Geochemical data from previous or contemporaneous studies were evaluated to quantify and characterize the nature of the cold-water component of the thermal springs (Richard W. Bell and Phillip D. Hays, U.S. Geological Survey, written commun., 2005; Bedinger and others, 1979). Dye tracing was performed to identify flow paths from points of release to points of dye recovery and to approximate the time of travel between release and recovery points.

Acknowledgments

Appreciation is extended to the staff of the National Park Service for accompanying and assisting USGS personnel on many of our trips to HSNP, and for their understanding in dealing with the delicate nature of the Hot Springs thermal resource. Appreciation is especially expressed to Steve Rudd and Leonard Lawson for their coordination of the project and their patience. Special thanks to Sharon Shugart, the museum curator of HSNP, for the plethora of information she maintains and for her kind assistance.

The author would like to acknowledge the assistance of other USGS personnel that made this study possible: to Rene Freret and Marsha Gipson for installing, operating, and maintaining the gage station network; to Greg Stanton and Brian Clark for conducting the geophysical logging, and processing and interpreting the logs; and to personnel of the reports unit for preparing the illustrations and editing the report. The author also is grateful to Charlie Stone and Doug Hansen of the Arkansas Geological Commission for their kind assistance in supplying information for the report, for their field assistance, and for their wealth of knowledge about Hot Springs geology.

Thermal Springs Development

The importance of the thermal springs resource was first recognized when Congress created the Hot Springs Reservation in 1832; the first Federal reservation established to protect natural resources for public enjoyment. The presence of the Hot Springs Reservation attracted people and businesses that developed into the city of Hot Springs, incorporated in 1876. Accounts of development of the thermal springs began some time before 1877, describing that some springs were walled in and covered by masonry arches to protect them from contamination (Scully, 1966).

In 1883, excavation and reconstruction began on Hot Springs Creek to contain and cover the creek. This tunnel, known as “the creek arch,” still exists and extends about 4,600 ft through a gap between Hot Springs Mountain and West Mountain. The creek arch conveys the normal flow of Hot Springs Creek and has sufficient volume to contain stormflows of 3-year recurrence interval (U.S. Army Corps of Engineers, 1993). Five thermal springs that were reported to rise from the bed of Hot Springs Creek were covered by the creek arch (Purdue and Miser, 1923). Only one thermal spring, Alum Spring, was reported to issue from the west bank of the creek (Bryan, 1922; Haywood, 1902), across from the Hale Bathhouse. Alum Spring was captured with stone walls in 1885, refurbished in 1914, and capped in 1921 (Shugart, 2000). All other thermal springs issue from the east side of the creek arch, at the base of the southwest sloping Hot Springs Mountain.

Extensive development of the thermal springs and area continued through the 1900’s. By 1901, most of the thermal springs were covered and a complex system of piping evolved to supply hot water to the bathhouses. Major development took place from 1912 to 1922 to construct eight bathhouses. In 1931, some springs were deepened and the collection system was reconstructed. Bedinger and others (1979) reported that the collection system diverted the flow of 44 springs to the central reservoir system. Some springs and the spring distribution system were reconstructed again in three phases: Arlington Lawn area, 1976; upper promenade, 1979; and lower promenade, 1981. No major construction has taken place since then, with the exception of the present ongoing reconstruction of the bathhouses.

An attempt was made to inventory the correct number of thermal springs and assess their condition and use, but the results should be considered with some uncertainty because many of the springs and collection system components were buried, secured, or unmarked, and available information was difficult to decipher. According to the author’s assessment, a total of 55 thermal springs have been identified since 1901 (table 1). Interestingly, 12 of the 55 springs have been abandoned and are either covered or destroyed (12, 14, 16, 18, 20, 21, 30, 35, 36, 37, 40, 41), while 11 new springs were identified after 1901 (4a, 6a, 6b, 6c, 9a, 21c, 43a, 47, 48, 49, 50). Therefore, there are presently 43 thermal springs that are presumed to still be flowing. Of these 43 springs, the present collection system consists of 33 springs, 2 of which (43, 43a) discharge directly from the bottom of the collection system reservoir (Jacobs, 1988).

The present collection system carries thermal water through 2- to 6-inch pipes into collection boxes that lead to the collection main in the creek arch (Jacobs, 1988). The collection main carries the thermal water to the collection system reservoir under the Park Administrative Building on Reserve Avenue. Ten springs that are not collected are drained to the creek arch, including several display springs (27, 28, 29, 32, 33, and 34), Haywood Spring (31, used for water fountain), Maurice Bathhouse Spring (50), Army and Navy Spring (39), and Cave Spring (10).

Table 1. Thermal springs identified in Hot Springs National Park .

Spring number	Spring name	Condition	Water use
1	Egg	Reconstructed 1980	Collection system
2	Arsenic South	Reconstructed 1977	Collection system
3	Arlington	Reconstructed 1980	Collection system
4	Cliff	Reconstructed 1977	Collection system
4a	Cliff New	Constructed 1977	Collection system
5	Avenue	Reconstructed 1980	Collection system
6	Boiler House North	Reconstructed 1977	Collection system
6a	Cooler North	Reconstructed 1977	Collection system
6b	Cooler South	Reconstructed 1977	Collection system
6c	Boiler House South	Constructed 1977	Collection system
7	Imperial North	Reconstructed 1980	Collection system
8	Crystal	Reconstructed 1980	Collection system
9	Rector	Reconstructed 1977	Collection system
9a	Rector North	Constructed 1977	Collection system
10	Cave	Covered with fill material	Drains to creek arch
11	Little Iron North	Reconstructed 1977	Collection system
12	Little Geyser	Abandoned	Not collected
13	Little Iron South	Reconstructed 1977	Collection system
14	Ral	Abandoned	Not collected
15	Big Iron	Reconstructed 1977	Collection system
16	Imperial South	Abandoned	Not collected
17	Arsenic North	Reconstructed 1977	Collection system
18	Hitchcock	Abandoned	Not collected
19	Superior Bath	Reconstructed 1977	Collection system
20	Superior North	Abandoned	Not collected
21	Alum	Abandoned	Not collected
21c	Alum East	Constructed 1980	Collection system
22	Superior South	Reconstructed 1980	Collection system
23	Twin North	Reconstructed 1980	Collection system
24	Twin South	Reconstructed 1980	Collection system
25	Hale Bath	Reconstructed 1980	Collection system
26	Palace	Reconstructed 1980	Collection system
27	Tunnel	Display tunnel	Drains to creek arch
28	Maurice	Covered	Drains to creek arch
29	Dripping	Display fountain	To fountain and creek arch
30	Arch	Abandoned	Not collected
31	Haywood	Reconstructed 1980	To fountain and creek arch
32	Noble	Display spring	Drains to creek arch

Table 1. Thermal springs identified in Hot Springs National Park—Continued.

Spring number	Spring name	Condition	Water use
33	Lamar	Display spring	Drains to creek arch
34	Wiley	Display spring	Drains to creek arch
35	Hardin	Abandoned	Not collected
36	Eisele	Abandoned	Not collected
37	Stevens	Abandoned	Not collected
38	Horseshoe	Reconstructed 1980s	Collection system
39	Army and Navy	Drilled and cased	Drains to creek arch
40	W.J. Little	Abandoned	Not collected
41	Mud	Abandoned	Not collected
42	Quapaw Bath	Reconstructed 1980s	Collection system
43	Reservoir North	In collection reservoir	Collection system
43a	Reservoir South	In collection reservoir	Collection system
46	Fordyce Bath	Reconstructed 1980s	Collection system
47	New North	Reconstructed 1980	Collection system
48	New South	Reconstructed 1980	Collection system
49	USGS	Reconstructed 1980	Collection system
50	Maurice Bath	Reconstructed 1980s	Drains to creek arch

Previous Literature

Numerous scientific investigations directly or indirectly involved the thermal springs at HSNP. Although each study generally had a different specific objective, most addressed the issue of the origin of the thermal spring waters. Several theories on the source of the thermal water and the source of the heat for the thermal waters have been proposed, but only a few survived subsequent inquiries. The earliest recorded theory on the origin of the heat source dates back to the Lewis and Clark expedition in 1804. As part of this expedition to explore the Ouachita Mountains, William Dunbar suggested the heat resulted from chemical reactions in the water because he saw no evidence of volcanic activity in the vicinity (Bergfelder, 1976). Owen (1860) rejected the chemical theory proposed by Dunbar and attributed the cause of the high water temperature to the internal heat of the earth. Branner (1892), Arkansas State Geologist, also discounted the chemical reaction theory among other less proven theories, and added that the probable cause of the water being hot is from contact with masses of hot rocks; the cool edges of which may or may not be exposed at the surface.

Haywood (1902) and Weed (1902) performed the most comprehensive early investigations of the thermal springs, measuring the temperature and discharge of all accessible thermal springs and performing a thorough chemical analysis on each spring. Weed (1902) supported the theory that the heat source was from a “great body of still heated igneous rocks.” Weed (1902) strengthened this hypothesis with evidence of surficial volcanic occurrences at Potash Sulfur Springs and at Magnet Cove, and the occurrence of intrusive dikes at various locations around the thermal springs. The dikes trend below Hot Springs to a possible source of heat. From the chemical analyses, Haywood (1902) and Weed (1902) also deduced that because the thermal springs contain so little mineral matter, particularly silica, and the gases given off closely correspond to the ratio of gases in atmospheric air, that the thermal waters are of meteoric origin, or waters derived from rainfall.

Purdue (1910) supported that the thermal waters were of meteoric origin, based on Weed’s studies and the general consensus of geologists. Purdue (1910) went further to suggest that the Bigfork Chert in the anticlinal valley between North Mountain and Sugarloaf Mountain is the most probable collection area for the meteoric water that is “conducted through the Bigfork Chert beneath the North Mountain syncline, and forced up into the Hot Springs anticline, at the western end of which it emerges in the hot springs.”

Bryan (1922 and 1924) distinguished between an east and west body of the Hot Springs Sandstone Member of Stanley Shale based on the extreme difference in strike and dip orientation of the two bodies, and postulated that a thrust fault separated them. The west body contained the thermal springs and the east body contained a new well with mostly thermal water. Bryan (1922) also postulated that there are four lines of open joints where the thermal springs emerge that are parallel to the postulated thrust fault.

Arndt and Stroud (1953) contributed to the understanding of stratigraphy and structure in the vicinity of the HSNP through field studies conducted in 1952. The authors described two major thrust faults, called Alpha and Beta, between which the thermal springs emerged, and defined structural features in more depth than in previous studies. The authors theorized that the thermal waters rose from juvenile water and mixed with artesian meteoric cold water in the lower member of the Arkansas Novaculite before emerging along the faults, fissures, and joints at the thermal springs.

Fellowes (1968) expanded on the geology of the Hot Springs area with more detailed field investigations, geologic mapping, and petrographic analyses. His findings generally agreed with Arndt and Stroud (1953) where their studies overlapped. Fellowes further hypothesized that the position of the thermal springs near the southwest-plunging nose of the Hot Springs Mountain Anticline suggests a possible relation between the structural trend and ground-water flowpaths. Fellowes also introduced an abnormally high geothermal gradient as an alternative hypothesis for the source of the heat to the thermal springs.

Perhaps the most comprehensive study of the thermal springs was conducted by Bedinger and others (1974 and 1979). The authors' findings supported the meteoric origin of the thermal water and the flow pathway through the Bigfork Chert as presented by Purdue (1910). The high temperature of rocks is attributed to the normal geothermal gradient, which is estimated to be between 0.006 and 0.01 degree Celsius (°C) per foot. The minimum depth of fluid circulation would range from 4,500 to 7,500 ft for the geothermal gradient theory to work. Silica analyses made on samples collected in 1901, 1952, and 1972 suggested that the spring source temperature had been decreasing at a rate of about 0.08 °C per year since 1901.

Bedinger and others (1974 and 1979) presented evidence of a secondary cold-water component to the thermal springs through their studies. Tritium and carbon-14 dating of the thermal springs indicated that the water is a mixture of a small amount of water less than 20 years old and a preponderance of water about 4,400 years old. In addition, the study indicated that a component of flow to some cold-water springs and wells in the Hot Springs area showed evidence of contamination, such as elevated concentrations of nitrate and chloride.

More recent studies presented further evidence of a cold-water component. C. Shane Barks (U.S. Geological Survey, written commun., 1995) indicated that storm events strongly affected thermal springs discharge and temperature. Using data collected during storms, calculations showed that water from locally derived recharge areas might contribute 25 percent of the total flow to the thermal springs during and after storm events. Richard W. Bell and Phillip D. Hays (U.S. Geological Survey, written commun., 2005) performed chemical analyses at nine thermal springs and two cold water springs in 2000 and 2001 to determine the influence of locally derived cold water recharge on the thermal springs. They estimated that the proportion of cold-water recharge ranged from 0 to 16 percent during baseflow conditions and 21 to 31 percent during stormflow conditions, based on silica concentrations.

Description of Study Area

The local study area for this report includes Hot Springs Mountain and adjacent area (fig. 2). The thermal springs are situated in the gap between Hot Springs Mountain and West Mountain. The thermal springs emerge at the base of Hot Springs Mountain in a belt about 1,500 ft long, between Reserve Avenue and Fountain Street, and about 400 ft wide from Central Avenue to the lower part of Hot Springs Mountain Drive (fig. 3). The altitude is 600 ft above National Geodetic Vertical Datum of 1929 (NGVD 1929) at the corner of Reserve and Central Avenue, which is about the lowest surface point in the area of occurrence of the thermal springs, and is also the southern end of the block of bathhouses known as "Bathhouse Row." Some springs along Bathhouse Row have been excavated and emerge below ground surface. Altitudes of the thermal springs range from 576 ft above NGVD 1929 in the collection system reservoir (springs 43 and 43a) at the extreme southern end of occurrence, to 683 ft above NGVD 1929 at springs 47 and 5 at the extreme northeastern end of occurrence (Hamilton and Blood, 1931).

Methods of Investigation

Methods of investigation for this report included monitoring the thermal springs characteristics, performing a hydrogeologic assessment to define the physical characteristics of the thermal springs system, estimating the cold-water recharge area of the thermal springs, and conducting dye tracing to verify inferred cold-water recharge area boundaries.

Thermal and Hydrologic Monitoring

Several types of monitoring equipment were used to collect information on the physical characteristics of the thermal springs and study area to assist in defining the hydrogeology and estimating the recharge area. The monitoring equipment consisted of nine water-temperature probes with recorders, two ground-water observation well recorders, a rain gage, and a monitoring station at the collection system reservoir that monitored inflow, overflow, water level, and water temperature at the inflow of the reservoir (fig. 3).

Nine water-temperature probes were placed at eight thermal springs and at collection box 1 (CB1). Four of the probes were installed in August 2000 at thermal springs 8, 17, 25, and 46. Five additional probes were installed in September 2003 at thermal springs 15, 19, 42, 49, and at CB1. CB1 monitored the composite temperatures of thermal springs 1, 3, 47, and 48. All temperature probes remained in place from installation through

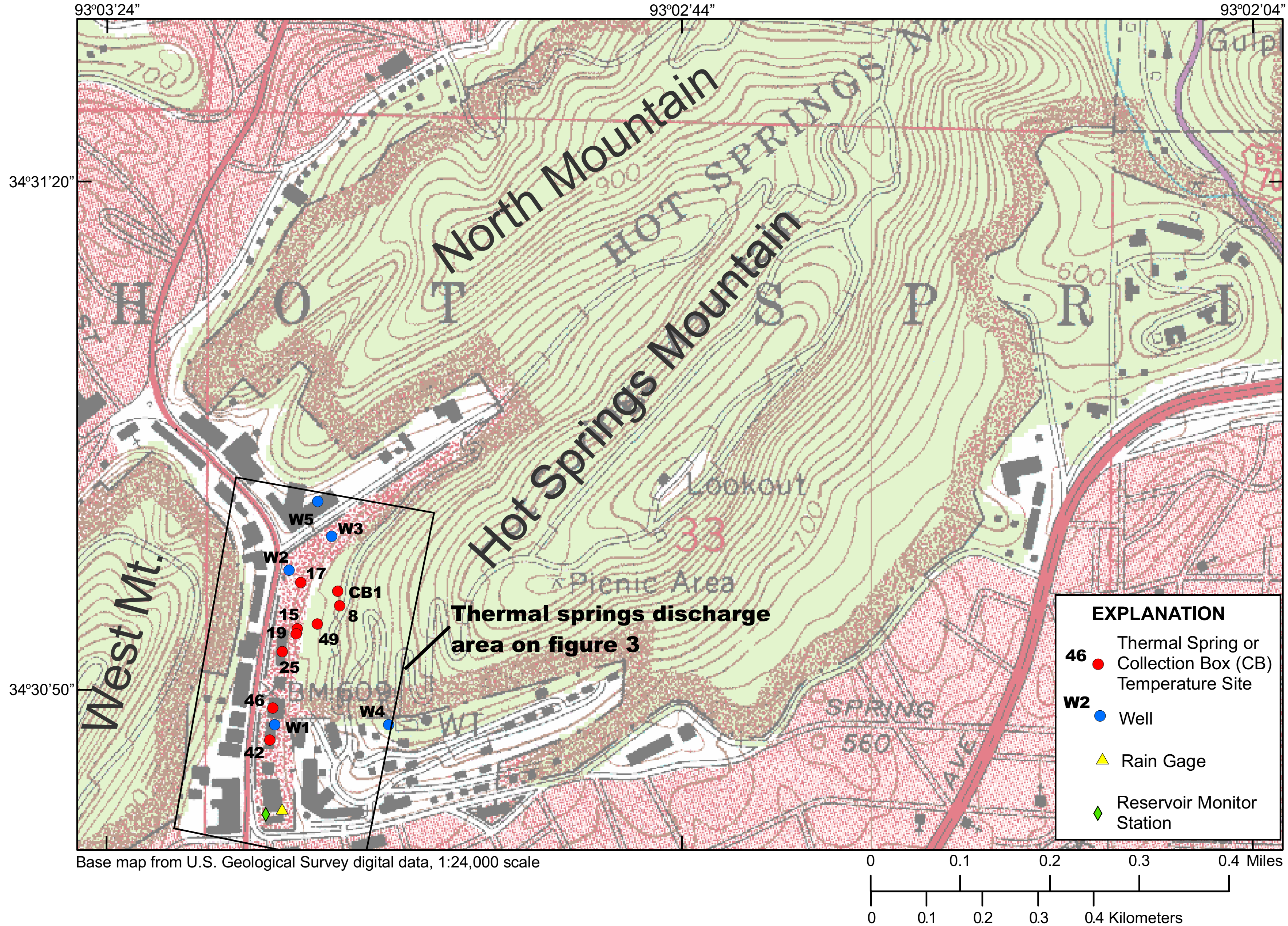
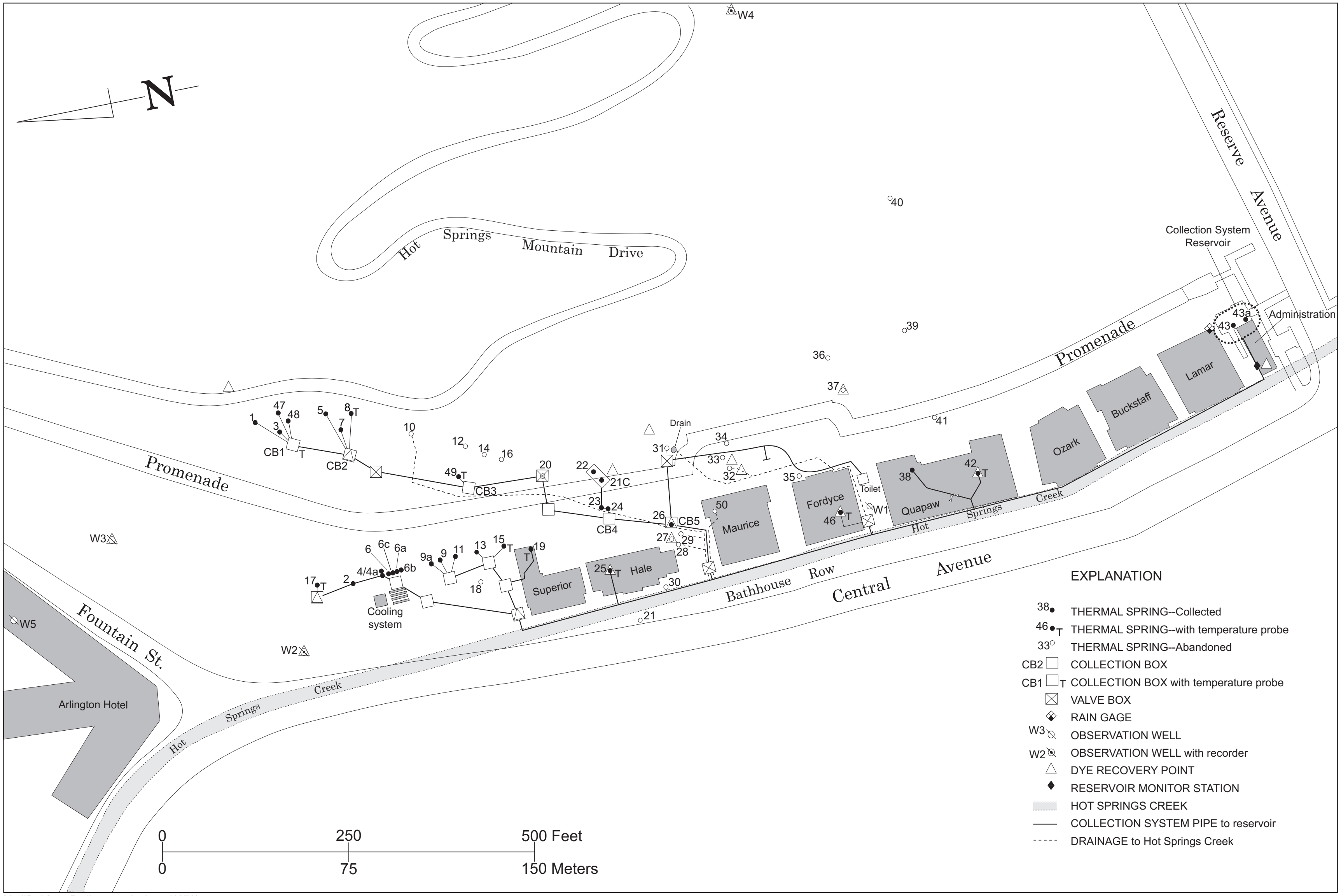


Figure 2. Study area and monitoring sites, Hot Springs National Park, Arkansas.



Modified from Bedinger and others (1979)

Figure 3. Location of thermal springs, collection system, and monitoring sites, Hot Springs National Park, Arkansas.

June 2005, although there are some gaps in data because of equipment malfunction and onsite disturbances such as construction activities. All temperatures were measured to one-hundredth of a degree Celsius using a thermistor, and digital recorders collected data at 15-minute intervals. The temperature probes were checked periodically using a calibrated digital thermometer. Recorder data were corrected to the temperature taken with the calibrated digital thermometer. The methods used followed the guidelines by Wagner and others (2000), and Radtke and others (1998).

Of the two ground-water level recorders, one was placed in a well above and east of the thermal springs (W4 in fig. 3), and one was placed in a well at the base of Hot Springs Mountain, just north of the thermal springs (W2 in fig. 3). The ground-water observation well with recorder at the upper well (W4) has been monitoring continuously from October 1996 through June 2005 and uses a float attached to an encoder that translates water-level measurements to digital format. The ground-water observation well with recorder at the lower well (W2) was operated from June 2004 through May 2005, and consisted of a transducer that monitored water pressure converted to water level. Both water-level recorders measured the water levels to one-hundredth of a foot and recorded values at 1-hour intervals. Data periodically were downloaded and the water level checked using a calibrated steel or electrical tape. The methods used followed Garber and Koopman (1968) and the Quality-Assurance Plan for Ground-Water Level Activities of the U.S. Geological Survey (Arkansas Water Science Center, U.S. Geological Survey, written commun., 2002).

The rain gage was operated from September 25, 2003, through June 2005 on the southeastern corner of the roof of the Lamar Bathhouse (fig. 3). The gage consisted of a single automatic tipping bucket connected to the collection reservoir recorder in the basement of the adjacent park administration building. Data were transmitted by satellite from this recorder to the USGS Arkansas Water Science Center in Little Rock. Rainfall was measured to one-hundredth of an inch and values recorded at 15-minute intervals. Rainfall data prior to September 25, 2003, was obtained from Hot Springs Memorial Field Airport (Elizabeth Sanders, Southern Regional Climate Center, written commun., 2005).

The monitoring station located in the basement of the park administration building has been monitoring collection system discharge from October 1988 through June 2005 and temperature from October 1990 through June 2005. The monitoring station consists of a weir to measure the inflow from the collection system to the collection reservoir; a float device to measure the water level in the reservoir; a weir to measure the overflow from the reservoir to Hot Springs Creek; and a temperature probe located at the inflow weir to measure water temperature from the thermal springs. The inflow and overflow weirs were identical in design and construction and were installed side by side, but were oriented in opposite directions and at different elevations. The weirs were calibrated in a flume for discharges from 0.01 to 2.12 cubic feet per second (ft^3/s), or 4.5 to 952 gallons per minute (gal/min), and rating equations were established to convert the water level in the weir boxes to discharge of water passing through the weirs. The water levels in the weirs and the reservoir were measured to one-hundredth of a foot, and the temperature measured to one-hundredth of a degree Celsius. All data were recorded at 15-minute intervals and transmitted every 4 hours. The methods used for measuring discharge followed Rantz and others, (1982), and the methods used for measuring temperature followed Wagner and others (2000).

The total discharge of the thermal springs for the period from October 1990 through June 2005 was determined by adding the total inflow to the collection reservoir and the estimated discharge from springs 43 and 43a that emerge from the open bottom of the collection reservoir. The discharge from springs 43 and 43a was estimated from three reservoir recovery tests conducted in 1989 (C.S. Barks, U.S. Geological Survey, written commun., 1989). The tests were conducted by diverting collection-system inflow to Hot Springs Creek and pumping down the water in the reservoir, allowing only springs 43 and 43a to discharge into the reservoir. The total discharge of springs 43 and 43a were calculated from the recovery of the reservoir water level.

The historical total discharge and average temperature of the thermal springs were determined from investigations conducted in 1901 (Haywood, 1902) and 1976 (Jacobs, 1988). The total discharge of the thermal springs was determined by adding the discharge of each spring measured. The average temperature of the thermal springs was determined by calculating the average of each spring's discharge-weighted temperature. The discharge-weighted temperature of each spring is the product of the spring discharge and temperature, divided by the total discharge of all the thermal springs measured.

Hydrogeologic Assessment

The first step in delineating the cold-water recharge area for the thermal springs was to develop a conceptual model of the hydrogeology. Features of the conceptual model that define the hydrogeology include the rock type and physical properties, the orientation and thickness of rock units, structural features such as folds and faults, and the capacity of the rock and soil to hold, transmit, and deliver water. This information was obtained from geologic maps that show rock types, lithologic boundaries, faults and fractures; topographic maps that show surface relief, drainage pattern, and direction of surface-water flow; drillers' logs and geophysical logs that show subsurface hydrogeologic features; aquifer tests that help define subsurface porosity and permeability; geochemical analyses that characterize the makeup and source of the ground water; and ground-water levels that infer the direction of ground-water flow.

Additional field mapping and geophysical logging were conducted for the investigation of this report. Field mapping was conducted to identify surface rock types and determine the orientation of rock units, determine release and collection points for dye tracing, and also inventory the location of all thermal springs, cold springs, and wells in the study area (fig. 3). Geophysical logging was conducted on four wells in the study area: Wells W1, W2, W3, and W4. These logs provided information about the lithology, distribution of permeability, fracture orientation, and thermal flow within the ground-water system. The geophysical measurements included well caliper, fluid specific conductance and temperature, natural gamma, long (64 inch) and short (16 inch) normal resistivity, single-point resistivity, electromagnetic induction resistivity, spontaneous potential, and secondary porosity/structural features using an acoustic televiewer.

Estimating Cold-Water Recharge Area

The size of the cold-water recharge area was estimated from the general concept of the hydrologic budget (input=output), where the average annual ground-water recharge (input) is equal to the average annual cold-water discharge (output) of the thermal springs. If ground-water recharge is the amount of rainfall over an area that recharges the water table, then the recharge area for the cold-water discharge of the thermal springs can be expressed as:

$$A = (3.5 \times 10^{-8})\, Q / R \tag{1}$$

Where A is the cold-water recharge area, in square miles;
Q is the annual cold-water discharge from the thermal springs, in cubic feet per year;
R is the annual ground-water recharge from rainfall, in feet per year; and
3.5×10^{-8} converts square feet to square mile.

The cold-water discharge of the thermal springs (Q) was determined during baseflow or low-flow conditions following the methods of Brahana (1997) and Quinlan and Ray (1995). Baseflow discharge is generally a better estimator of the total recharge area of a spring than stormflow because stormflow generally is derived near the discharge point of the springs and may consist of some unsaturated flow and surface runoff, whereas, baseflow generally is derived from ground-water storage.

Total annual baseflow of the thermal springs first was estimated from the total discharge of the collection system and springs 43 and 43a during low-flow conditions in September 2000. Then, the cold-water component of the total thermal springs discharge was estimated from the average silica concentration of water samples collected from nine thermal springs (springs 8, 9, 17, 25, 33, 42, 46, 47, and 49) during low flow from September 18 to 22, 2000 (Richard W. Bell and Phillip D. Hays, U.S. Geological Survey, written commun., 2005). Silica concentration of water can be used as a measure of the maximum temperature reached by the water (Fournier and Rowe, 1966). The average silica concentration of the nine thermal springs then was compared to the silica concentration typical of cold-water springs and wells (8 mg/L of silica), representing the cold-water component, and the maximum thermal spring silica concentration measured (47 mg/L of silica), representing the thermal-water component. A binary mixing equation for silica was used to estimate the proportion of cold water in the thermal springs samples:

$$X_{mix} = (X_a)f_a + (X_b)f_b \tag{2}$$

Where X_{mix} is the silica concentration or isotopic composition of the mixture, in milligrams per liter;
X_a is the silica concentration or isotopic composition of the cold-water component (a) contributing to the mixture, in milligrams per liter;
f_a is the proportion of the cold-water component (a) present in the mixture;
X_b is the silica concentration or isotopic composition of the thermal-water component (b) contributing to the mixture, in milligrams per liter; and
f_b is the proportion of the thermal-water component (b) present in the mixture.

The proportion of cold water in the thermal springs samples then was applied to the total annual baseflow discharge of the thermal springs to obtain the annual cold-water discharge from the thermal springs.

The average annual ground-water recharge (R) was estimated by Dugan and Peckenpaugh (1985) using a soil-moisture computer model with input of soil properties, vegetation types, monthly rainfall, and monthly potential evapotranspiration. The average annual recharge in the general area north of Hot Springs for woodland and range conditions was estimated to be 10 to 15 inches. The factors used for the model were generalized and the actual ground-water recharge for the study area is presumed to be less than 10 inches because of the steep gradient on Hot Springs Mountain (20 percent) and extensive road drainage for HSNP not considered in the model. Recharge values (R) of 5 to 10 inches per year (in/yr) were considered in equation 1 to compute a range of sizes for the recharge area.

The cold-water recharge area boundaries were delineated based on the lithology, structure, and hydrology of the study area. The boundaries define the shape of the recharge area. The size of the recharge area determined from the recharge boundary assessment also was computed using Geographical Information System (GIS) tools. The size of the recharge area determined from the recharge area boundary was compared to the size of the recharge area as estimated using the hydrologic budget.

Dye Tracing

Dye tracing was conducted from December 2004 through March 2005 in an attempt to verify inferred cold-water recharge area boundaries and identify shallow ground-water flow paths. Fluorescent dyes certified for use in drinking water were released at three locations (fig. 4) to trace the flow path of the

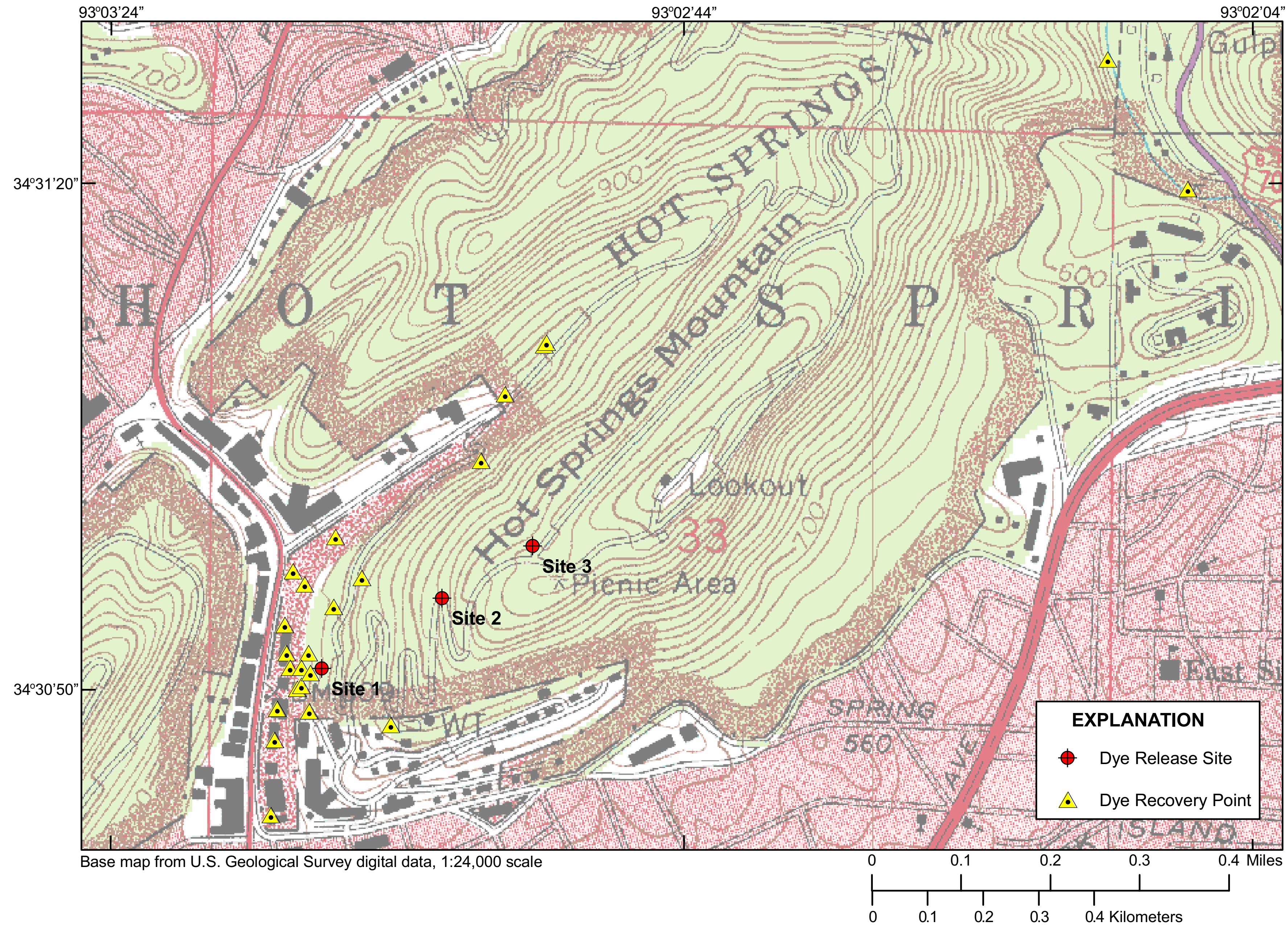


Figure 4. Dye release sites and dye recovery points, Hot Springs National Park, Arkansas.

ground water. The general methods used are described in Mull and others (1988).

The lithology and surface structure in the area of the thermal springs did not present favorable conditions to transmit the dyes in the quantities needed and in the amount of time feasible for the investigation. The lithology consisted of well-cemented, fine-grained chert, sandstone, and shale that supported diffuse ground-water flow rather than conduit flow. Structural faults and fractures that could present conduit flow, if present in the subsurface, were weathered and covered by vegetation and soil on the surface. The few visible areas of surface structure along drainage features dictated where the dye release points were placed.

Three types of fluorescent dyes were released consecutively into surface-drainage features at three different points upgradient from the thermal springs. The three dyes (and color index) used were Eosine OJ (acid red 87), Rhodamine WT (acid red 388), and Fluorescein (acid yellow 73) released at sites 1, 2, and 3 respectively (fig. 4). One liter of 10 percent concentration eosine dye, 2 liters of 5 percent concentration rhodamine dye, and 4 liters of 10 percent fluorescein dye were released. The quantities of dyes desired for detection were reduced to minimize the likelihood of discoloring the public water system supplied by the thermal springs. Reducing dye quantities also reduced the quantities of dye detected at recovery points.

Activated charcoal was used as a dye receptor at 24 recovery points (selected springs, wells, creeks, and drainageways) around Hot Springs Mountain (fig. 4) based on accessibility and location. Activated charcoal is a passive detector that indicates if dye was present, but is not used to quantify the concentration of the dyes. Charcoal packets were fabricated by placing the charcoal in nylon mesh screen that was stapled together. Prior to releasing the dyes, the charcoal packets were placed at the recovery points for about 1 week to obtain background florescence readings. New charcoal packets were placed at the recovery sites 1 day prior to releasing the dyes, and the packets were replaced about weekly after the dye release.

The charcoal packets were placed in the center of flow, suspended on string and wire at spring boxes, drainageways, creeks, and wells. Four spring box lids were fabricated and installed on collection boxes and thermal springs (fig. 5) to provide access for the charcoal packets and protect the spring source from contamination. Upon collection of the charcoal packets, the packets were rinsed and dried, then immersed in a solution of 90 percent isopropyl alcohol and 10 percent ammonium hydroxide for 2 to 6 hours to extract the dyes from the charcoal (Imes and Fredrick, 2002). Presence or absence of fluorescence in the solution was analyzed using a spectrofluorophotometer (fluorometer) as described by Wilson and others (1986). The three dyes fluoresce at different wavelengths, and therefore, could be differentiated when present.

Several laboratory tests were performed on the capability of the charcoal to absorb and retain dyes in hot water. The tests showed that the dyes were absorbed and retained similar to how they would have been retained in cold water. Heated solutions (about 90 °C) of dye concentration greater than 1 microgram per liter (μg/L) were detected by the fluorometer. Solutions of dye concentration less than 1 μg/L showed low detection peaks, or no peaks at all. The results varied depending on the type of dye used, length of time the charcoal packet was exposed to the dye solution, and time exposed to hot distilled water after absorbing the dye.

Figure 5. Collection box 2 with fabricated lid to provide access for dye trace monitoring, Hot Springs National Park, Arkansas.

Geologic Setting

The exposed rock types in the vicinity of the thermal springs are sedimentary rocks of Mississippian to Ordovician age (table 2), with the exception of younger igneous rocks (Cretaceous age) exposed in two small areas about 6 and 11 miles southeast of the thermal springs (Potash Sulphur Spring and Magnet Cove, respectively), and in many very small dikes and sills (Bedinger, 1979). Most dikes are less than 5 ft wide (Purdue and Miser, 1923). Purdue (1910) noted 80 dikes about 4 miles southeast of Hot Springs, on and near the Ouachita River. There is no indication that igneous rock occurs where the thermal springs discharge.

Lithology

The sedimentary rocks in the vicinity of the thermal springs consist of shale, chert, novaculite, sandstone, and conglomerate (fig. 6). The Womble Shale is the oldest geologic unit that underlies all other exposed units. It is exposed a few miles northeast of the study area. It is black, hard, and argillaceous shale, with interbedded lenses of limestone 20 ft or more in thickness (Purdue and Miser, 1923). The Bigfork Chert overlies the Womble Shale and consists almost entirely of chert and silty chert in layers 2 to 12 inches thick, separated by minor thin beds of black shale. The chert is very brittle and intensely fractured from folding (Purdue, 1910).

The Polk Creek Shale and Missouri Mountain Shale overlie the Bigfork Chert and generally consist of shale with minor thin layers of quartzitic sandstone. The contact between the Missouri Mountain Shale and Polk Creek Shale at Hot Springs is inconspicuous. The Polk Creek Shale is a black, fissile, graphitic shale. The Missouri Mountain Shale varies in color, and is soft and argillaceous (Purdue and Miser, 1923).

The Arkansas Novaculite consists of lower, middle, and upper members. The lower member is a massive fractured novaculite, and is the dominant member on Hot Springs Mountain, with a thickness of about 275 ft. The middle member is a black clay shale interbedded with novaculite, about 10 ft thick on Hot Springs Mountain (Purdue and Miser, 1923). The upper member is chiefly a massive, highly calcareous light gray to black novaculite. It reaches a maximum thickness of 180 ft in the study area, and the rock weathers to a soft, porous, fine-grained material (Purdue and Miser, 1923).

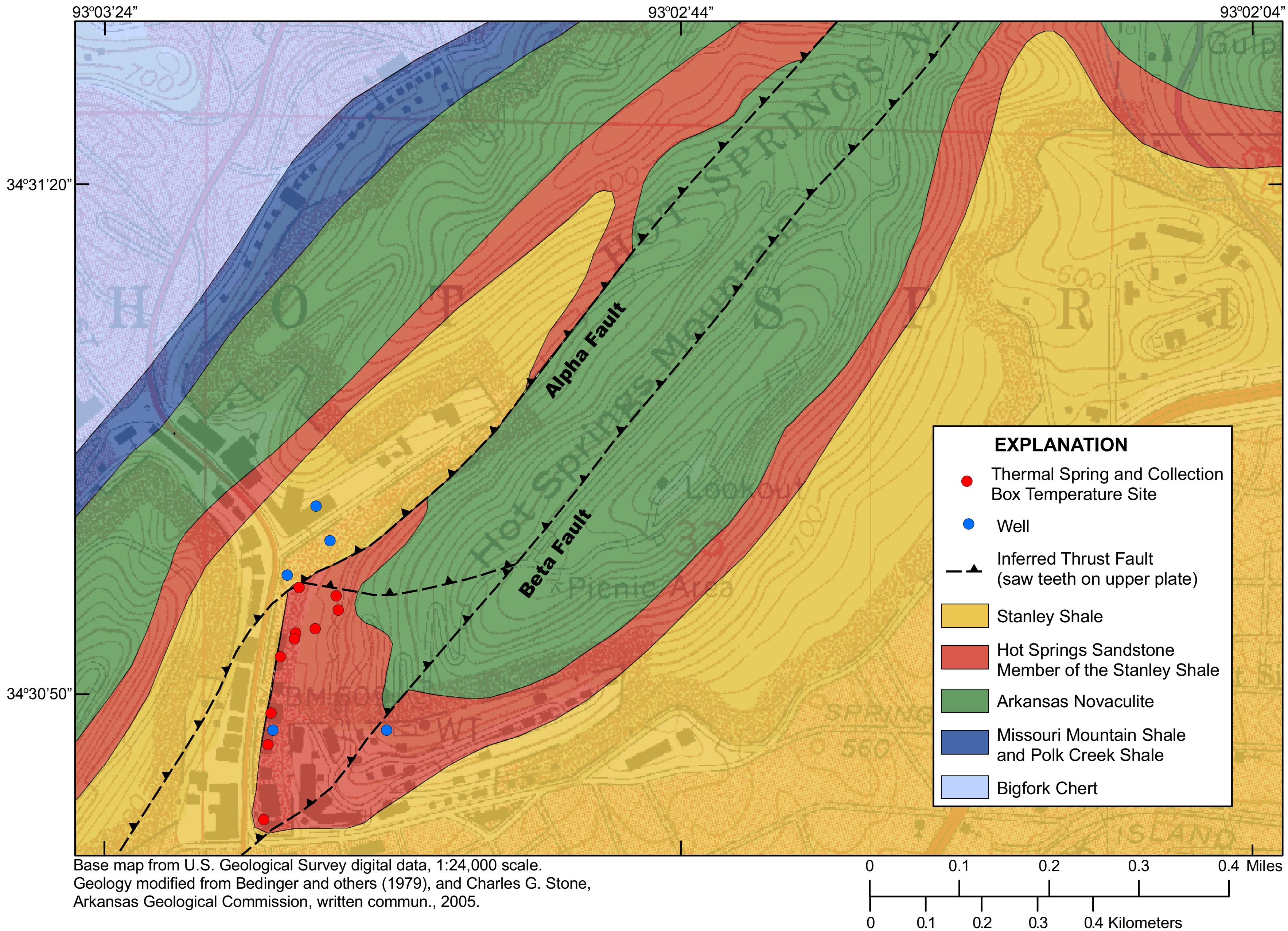
The Hot Springs Sandstone Member of the Stanley Shale, hereafter referred to as the Hot Springs Sandstone, consists of fine- to medium-grained sandstone with some shale and conglomerate. The sandstone is gray, hard and quartzitic, reaching thicknesses up to 6 ft. The shale predominantly occurs at the top of the unit, and the principal bed of the conglomerate occurs at the bottom (Purdue and Miser, 1923).

The Stanley Shale is predominantly a clayey, thinly fissile, black to green shale, with large amounts of sandstone interbedded throughout the formation. The sandstone, when freshly exposed, is a hard, fine-grained, feldspathic, silty sandstone, but weathers easily to a soft, clayey porous material ranging from green to brown in color (Purdue and Miser, 1923). Almost all of the low-lying areas in the city of Hot Springs are composed of the Stanley Shale, and it surrounds Hot Springs Mountain on the south, east, and west sides.

Table 2. Generalized stratigraphy of sedimentary rocks in the vicinity of the thermal springs (modified from Bedinger and others, 1979).

System	Unit	Character of rocks	Maximum thickness in Hot Springs area[1] (feet)
Mississippian	Stanley Shale	Bluish-black shale, and gray sandstone	2,500
	Hot Springs Sandstone Member of the Stanley Shale	Hard, gray, quartzitic sandstone, and conglomerate	200
Mississippian / Devonian	Arkansas Novaculite	Massive and thin bedded novaculite interbedded with black argillaceous and siliceous shale.	465
Silurian / Ordovician	Missouri Mountain Shale, Polk Creek Shale	Green to black shale, and few thin sandstones	225
Ordovician	Bigfork Chert	Thin-bedded chert, highly fractured, and interbedded thin shale	700
	Womble Shale	Black shale, and thin bedded lenses of limestone	1,200

[1]Charles G. Stone, Arkansas Geological Commission, written commun., 2005.



Base map from U.S. Geological Survey digital data, 1:24,000 scale.
Geology modified from Bedinger and others (1979), and Charles G. Stone, Arkansas Geological Commission, written commun., 2005.

Figure 6. Geology in the vicinity of Hot Springs Mountain, Hot Springs National Park, Arkansas.

Structure

Rocks in the Hot Springs area have undergone at least three episodes of compressional deformation, resulting in a series of thrust faults and overturned complexly folded strata trending in a northeast-southwest direction (Bedinger and others, 1979). The thermal springs emerge from the plunging crest line of a large overturned anticline in the Zigzag Mountains of the Ouachita anticlinorium. The overturned anticline plunges toward the southwest into the Mazarn Basin.

Arndt and Stroud (1953) and Fellowes (1968) recognized two major thrust faults trending nearly parallel to fold axes that define the northern and southern limits of the thermal springs discharge area (fig. 6). The southern fault, identified as Beta Fault, extends northeastward about 9,000 ft roughly along the axis of the Hot Springs anticline, and dips about 44 degrees north. The northern fault, identified as Alpha fault, extends nearly parallel to Fountain Street northeastward about 9,200 ft onto the southeast flank of North Mountain, and dips about 26 degrees north. At the northern extent of the thermal springs, Alpha fault is suggested to form along the bedding contact of the Hot Springs Sandstone and Stanley Shale, with the Stanley Shale forming the hanging wall of the fault. Bedinger (1979) proposed a fault that splits away from Beta fault, trends west and connects with Alpha fault (fig. 6). A natural ravine trends along the location of this fault.

Extensive cracks, joints, and fissures in the Bigfork Chert, Arkansas Novaculite, and the Hot Springs Sandstone produce the primary permeability in the thermal springs area. Purdue (1910) attributed the intensely fractured and brittle nature of the Bigfork Chert as a primary factor in defining it as the most probable recharge area for meteoric water infiltration. Bedinger and others (1979) observed that jointing is common in the few exposures of Hot Springs Sandstone in the thermal springs discharge area, and that these are associated with thrust faults, normal faults, and joints on the plunging anticline of Hot Springs Mountain. Bryan (1922) observed strong, nearly vertical jointing in the northeasterly direction in outcrops of the Hot Springs Sandstone on the hillside behind the bathhouses. He suggested that there are at least four lines of jointed systems that are arranged along lines of thermal springs, and parallel to a postulated thrust fault, later recognized as Beta fault by Arndt and Stroud (1953). Arndt and Stroud (1953) believed that jointing and shattering of Arkansas Novaculite in the North Mountain Syncline and adjacent to faults created preferred channels for migration of water directly into the thermal springs area, and that water in the lower member, confined by middle member shales of the Arkansas Novaculite, was then forced upward to the thermal springs through fissures.

Characteristics of Thermal Springs

The water temperature and discharge of the thermal springs were monitored infrequently prior to continuous monitoring in 1988. However, a rough comparison between the results of the 1901 (Haywood, 1902) and 1976 (Jacobs, 1988) investigations indicates that temperature and discharge did not change substantially from 1901 to 1976 (table 3). The total discharge estimated in 1901 (826,000 gal/d) was about equal to the total discharge estimated in 1976 (829,000 gal/d). The average discharge-weighted water temperature in 1901 was 58.8 °C, and the average discharge-weighted water temperature in 1976 was 59.9 °C. The lower temperature in 1901 may be attributed to several factors unrelated to the source of the thermal water. The 1901 investigation included several springs of lower temperature (such as springs 27-30 and 32-37) that did not exist or were not of sufficient discharge to be measured in 1976. Also, the 1901 temperatures were measured in January, during the winter season, whereas, the 1976 temperatures were measured at unspecified times, but probably during warmer periods.

Collection System Discharge and Water Temperature

To better understand the condition of the thermal springs, a system of weirs, water level, and temperature devices were installed at the collection system reservoir in 1988 to monitor the combined discharge and temperature of all thermal springs collected. The discharge and temperature have been monitored continuously from October 1, 1990 through September 30, 1995 and October 1, 1998 through June 10, 2005. The period from October 1, 1995 through September 30, 1998 was not monitored. By accurately and continuously monitoring the combined discharge and temperature of the collected springs over a long period of time, response to natural and man-induced effects may be documented and temporal patterns evaluated.

Discharge

The average daily discharge at the inflow of the collection system reservoir was 658,000 gal/d and ranged from 518,000 to 763,000 gal/d from 1990 through 1995, and 1998 through 2005, not including springs 43 and 43a that emerge from the open bottom of the collection system reservoir. The discharge from springs 43 and 43a was calculated in 1989 to be 131,000 gal/d (C. Shane Barks, U.S. Geological Survey, written commun., 1989). Adding springs 43 and 43a discharge to the collection system discharge gives an average daily discharge of 789,000 gal/d and range of discharge from 649,000 to 894,000 gal/d.

The overall pattern of the collection system discharge from 1990 through 2005 shows an increasing rate of discharge, although the majority of increase in discharge took place during the period from 1990 through 1995, and the discharge pattern during the period not monitored from 1995 through 1998 is unknown (fig. 7). The discharge appears to increase and decrease cyclically at a 4-5 year interval during the period from 1990 through 2005, although data are insufficient to substantiate this observation.

Table 3. Historical record of thermal springs temperature and discharge.

[e, estimated; °C, Celsius; gal/d, gallons per day; w/spring number, included with spring indicated; --, no data]

		1890 (Branner, 1892)	1900 (Haywood, 1902)	1901[1] (Haywood, 1902)		1931 (Hamilton, 1932)		1952 (Kuroda, 1953)	1972 (Bedinger, 1979)	1976[2] (Jacobs, 1988)		2005[3] (current study)
Spring number	Spring Name	Temperature (°C)	Temperature (°C)	Temperature (°C)	Discharge (gal/d)	Temperature (°C)	Discharge (gal/d)	Temperature (°C)	Temperature (°C)	Temperature (°C)	Discharge (gal/d)	Temperature (°C)
1	Egg	62.6	61.9	61.7	28,800	--	9,600	62.0	54.6	58.9	33,100	--
2	Arsenic South	--	51.9	53.9	w/17	54.4	--	--	--	55.0	w/17	--
3	Arlington	--	61.7	61.3	19,938	60.0	w/5	62.2	52.2	60.0	28,800	--
4	Cliff	--	55.9	52.4	3,600	57.2	--	--	--	60.6	17,300	--
4a	new spring 1	--	--	--	--	--	--	--	--	w/4	w/4	--
5	Avenue	--	61.4	61.9	17,280	61.1	21,800	61.7	--	60.6	10,200	--
6	Boiler House	--	57.5	58.3	32,400	57.2	--	58.6	--	61.1	2,600	--
6a	Cooler North	--	--	--	--	--	--	--	--	60.0	2,300	--
6b	Cooler South	--	--	--	--	--	--	--	--	54.4	3,700	--
6c	new spring 2	--	--	--	--	--	--	--	--	w/6	w/6	--
7	Imperial North	--	60.1	60.8	18,514	--	1,760	62.2	59.3	59.4	3,300	--
8	Crystal	--	35.2	36.2	e2,000	61.1	w/5	--	--	53.9	9,400	61.5
9	Rector	59.6	61.1	62.4	51,840	62.2	18,000	61.2	--	54.4	17,400	--
9a	new spring 3	--	--	--	--	--	--	--	--	w/0	w/9	--
10	Cave	--	57.4	57.2	18,514	60.0	14,400	--	--	--	--	--
11	Little Iron North	--	--	56.8	w/9	64.4	32,400	61.2	--	w/9	w/9	--
12	Little Geyser	--	36.2	36.2	524	--	0	--	--	--	--	--
13	Little Iron South	--	--	56.3	w/9	w/11	w/11	61.2	--	w/9?	w/9?	--
14	Ral	59.6	60.9	62.8	8,640	--	0	--	--	--	--	--
15	Big Iron	63.6	63.9	63.9	201,600	64.4	--	61.2	--	66.7	201,600	65.0
16	Imperial South	--	60.8	60.9	w/7	--	0	--	--	--	--	--
17	Arsenic North	--	55.4	56.4	10,800	--	--	56.9	56.0	57.2	10,400	51.1
18	Hitchcock	--	57.3	57.3	e35,000	52.8	90,000	59.6	--	--	--	--
19	Superior Bath	--	56.4	56.1	13,292	--	--	--	--	62.8	10,400	64.3
20	Superior North	--	46.3	44.5	3,677	44.4	1,690	--	--	--	--	--
21	Alum	46.6	43.3	46.0	1,152	--	--	--	--	--	--	--
21c	new spring 4	--	--	--	--	--	--	--	--	--	900	--
22	Superior South	--	57.1	56.5	1,723	56.1	2,460	--	--	--	2,900	--
23	Twin North	--	62.0	62.4	w/24	50.0	2,500	59.6	56.2	62.8	1,400	--
24	Twin South	--	62.3	60.3	10,800	57.8	2,500	54.3	--	63.9	3,300	--

Table 3. Historical record of thermal springs temperature and discharge.—Continued

[e, estimated; °C, Celsius; gal/d, gallons per day; w/spring number, included with spring indicated; --, no data]

		1890 (Branner, 1892)	1900 (Haywood, 1902)	1901[1] (Haywood, 1902)		1931 (Hamilton, 1932)		1952 (Kuroda, 1953)	1972 (Bedinger, 1979)	1976[2] (Jacobs, 1988)		2005[3] (current study)
Spring number	Spring Name	Temperature (°C)	Temperature (°C)	Temperature (°C)	Discharge (gal/d)	Temperature (°C)	Discharge (gal/d)	Temperature (°C)	Temperature (°C)	Temperature (°C)	Discharge (gal/d)	Temperature (°C)
25	Hale Bath	61.6	62.7	62.9	e35,000	--	--	63.3	--	60.6	39,300	62.9
26	Palace	--	63.4	61.4	25,847	63.3	10,950	--	--	63.3	11,500	--
27	Tunnel	--	--	51.9	800	--	--	59.2	--	--	--	39.3 (pool)
28	Maurice	--	--	59.8	e21,000	--	--	60.0	--	--	--	--
29	Dripping	--	57.1	57.8	2,618	--	--	61.1	--	--	--	--
30	Arch	--	53.9	51.9	--	--	--	--	--	--	--	--
31	Haywood	--	51.4	51.4	7,200	54.4	130	54.0	--	57.8	21,000	--
32	Noble	--	46.0	46.5	28,800	45.0	--	52.5	52.5	--	--	54.5
33	Lamar	--	48.3	49.2	w/31	--	--	--	57.6	--	--	58.0
34	Wiley	--	47.9	47.3	28,800	--	--	57.5	--	--	--	--
35	Hardin	--	39.0	43.0	2,469	--	--	--	--	--	--	--
36	Eisele	--	48.9	48.8	9,600	--	--	--	--	--	--	--
37	Stevens	--	52.9	52.6	5,760	--	--	--	--	--	--	--
38	Horseshoe	--	58.8	59.8	e40,000	w/42	w/42	60.3	--	w/42	w/42	--
39	Army and Navy	--	61.4	61.4	35,000	--	--	--	--	--	--	--
40	W.J. Little	--	48.9	48.9	4,320	--	--	--	--	--	--	--
41	Mud	--	46.8	48.3	e4,000	--	--	--	--	--	--	--
42	Quapaw Bath	51.6	--	58.3	e50,000	60.6	12,000	60.8	61.3	62.8	90,700	61.0
43	Reservoir North	--	46.3	46.1	e20,000	50.0	140,000	--	--	50.0	165,600	--
43a	Reservoir South	--	--	--	--	--	--	--	--	w/43	w/43	--
46	Fordyce Bath	--	51.5	51.5	e25,000	57.2	32,200	--	58.3	60.0	30,700	56.4
47	New North	--	no flow	--	--	58.6	13,500	61.7	--	64.4	28,300	--
48	New South	--	no flow	--	--	w/47	w/47	62.2	60.0	62.2	24,000	--
49	USGS	--	no flow	--	--	--	--	61.0	61.8	64.4	44,500	61.1
50	Maurice Bath	--	no flow	--	--	62.8	--	--	53.3	57.2	14,400	--
Total				58.8[4]	826,308[5]					59.9[4]	829,000[5]	

[1]Spring 30 discharge could not be estimated; springs 47-50 were not discharging at the time of analyses.
[2]Springs 43 and 43a temperatures are from Hamilton (1932); spring 13 included with spring 9 is not certain.
[3]Temperatures in 2005 were measured on March 8, 2005, except for springs 27, 32, and 33 which were measured on October 6, 2004.
[4]Discharge-weighted average temperature of all measured springs.
[5]Total estimated discharge of all measured springs.

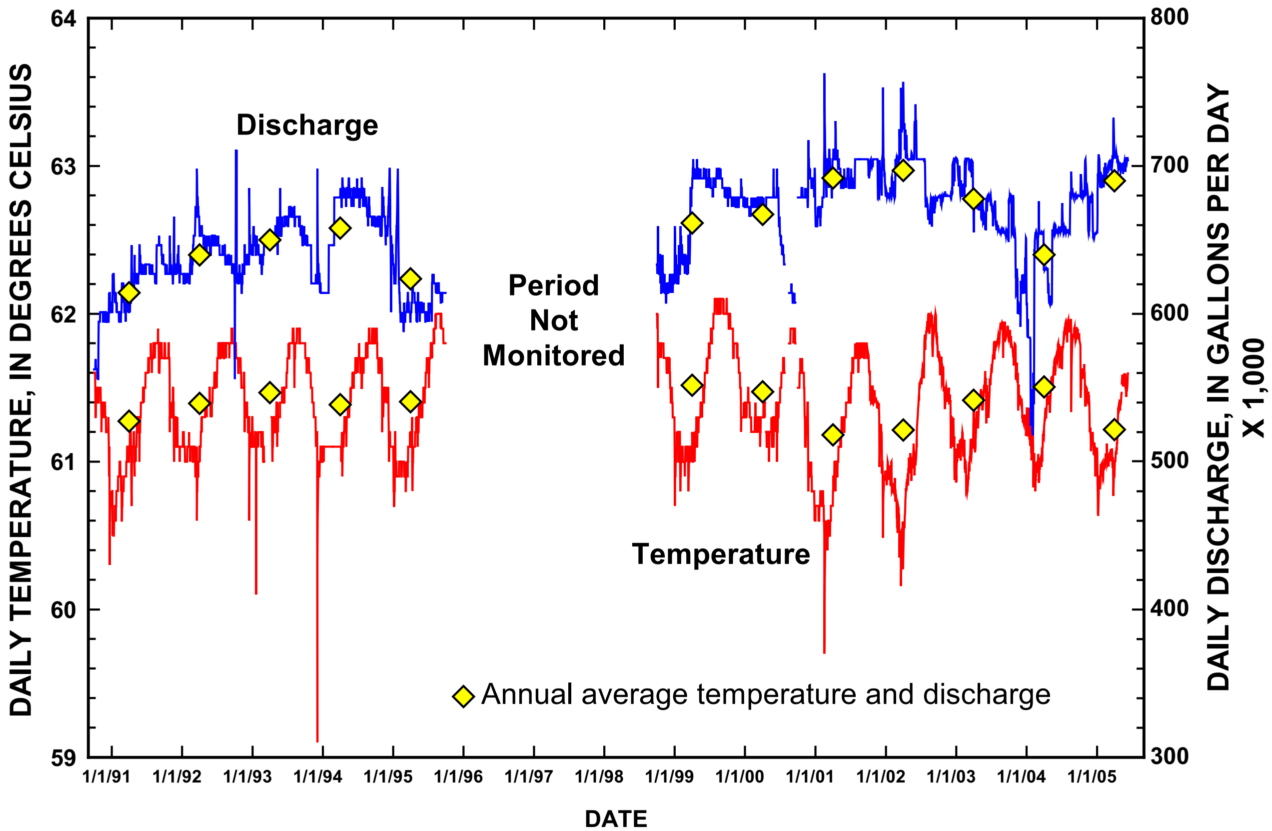


Figure 7. Daily and annual average discharge and temperature of the thermal springs at the inflow of the collection system reservoir.

The annual average discharge and temperature show how the annual cycle has changed over the period of record (fig. 7). Of particular interest is how the annual discharge changed in comparison to the annual temperature. During the period from 1990 through 1995, the temperature generally showed a positive relation to discharge. This would suggest that increased discharge in the thermal water component relative to the cold-water component of the thermal springs caused increased water temperature during this period, because increased discharge in the cold-water component would have an inverse effect on the water temperature. One possible explanation is that more thermal water was added to the system through man-induced changes such as collection system upgrades or adding thermal spring flow to the system. Another possible explanation may be that thermal spring discharge shifted from the upper springs to the lower springs. Hamilton (1932) reported that discharge of the upper springs decreased from 167,000 gal/d in 1901 to 124,000 gal/d in 1931. If discharge did shift to the lower springs, there should be an overall increase in spring discharges because the springs would be subjected to less elevation pressure head. Monitoring discharge and temperature at selected individual springs would better show when changes are natural or man-induced. Currently (2005), only temperature is monitored at selected springs.

During the period from 1998 through 2005, the annual average temperature showed a strong inverse relation to the annual average discharge. This would suggest that increased discharge in the cold-water component relative to the thermal component of the thermal springs caused decreased water temperature during this period. This is the result that would be expected if cold-water recharge from rainfall was the main cause of change to thermal spring discharges.

The collection system daily discharge showed a noticeable immediate short-term response to rain events, increasing in discharge when rainfall contributed recharge to the ground-water system. The discharge increased by as much as 100,000 gal/d (15 percent) in response to major rain events. Water temperature also decreased considerably, indicating that the increase in discharge during rain events was primarily, if not wholly, from increase in the cold-water component of flow, although infiltration through collection system piping (leaks) also may contribute.

Water Temperature

Continuous water temperature monitoring conducted by the USGS from 1990 through 1995 and 1998 through 2005 at the collection system reservoir inflow pipe shows that there has not been a long-term temperature change during the past 15 years (fig. 7). The daily water temperature ranged from 59.1 to 62.1 °C and the average daily temperature was 61.4 °C for the period of record. The 1976 average discharge-weighted temperature was 59.9 °C at the thermal springs. The 15-year collection system temperature does not include the water from springs 43 and 43a that emerge from the bottom of the reservoir, while the 1976 temperature calculation does include temperature from these springs. If springs 43 and 43a temperatures of 50.0 °C (Hamilton, 1932) discharging at 131,000 gal/d (C. Shane Barks, U.S. Geological Survey, written commun., 1989) were included in the collection system temperature, the average discharge-weighted collection system temperature would be about 59.5 °C. Heat loss between the spring source and the collection system reservoir during transmission is one of many variables that could account for the recent collection system temperature being lower than the water temperature measured at the springs in 1976.

The collection system temperature shows a strong seasonal pattern, with maximum temperatures occurring from August through October and minimum temperatures occurring from January through March, about one month delayed from air temperature highs and lows. This suggests that air temperature influences the thermal springs and the shallow ground water that mixes with the thermal water. Seasonal change in temperature at the reservoir inflow also may be from heat loss in the collection system. Disregarding short-term fluctuations in water temperature, the seasonal temperature varied about 1 °C, from about 60.9 to 61.9 °C.

The collection system temperature also shows substantial response to rainfall. One of the largest responses recorded was on February 16, 2001 (fig. 8), when the hourly temperature decreased from 60.7 to 58.6 °C, while hourly inflow increased from 705,000 to 812,000 gal/d, in response to heavy rainfall; 3.5 inches of rain was measured on February 15-16, 2000, at Hot Springs Memorial Field Airport, about 3 miles southwest of the thermal springs (Elizabeth Sanders, Southern Regional Climate Center, written commun., 2005).

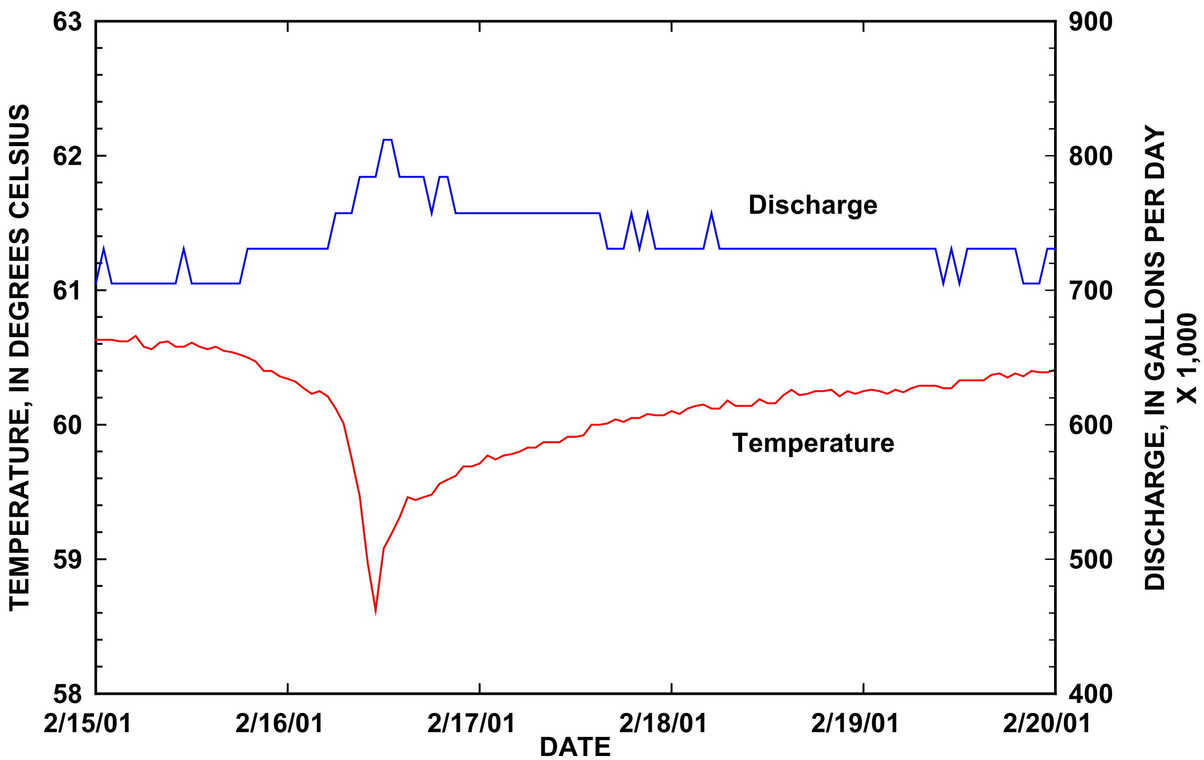


Figure 8. Thermal springs collection system hourly temperature and discharge response to 3.5 inches of rainfall on February 15-16, 2001.

Thermal Springs Temperature Monitoring

The water temperature of eight thermal springs and one thermal springs collection box was monitored during the period of investigation from 2000 through 2005. Springs 8, 17, 25, and 46 were monitored from August 2000 through June 2005, and springs 15, 19, 42, 49, and collection box 1 were monitored from September 2003 through June 2005 (fig. 3). Collection box 1 (CB1) collected flow from springs 1, 3, 47, and 48. Each spring displayed different temperature magnitudes ranging from about 50 to 65 °C and showed a unique response to environmental influences, such as air temperature and rainfall. General similarities among springs above the promenade that differed from springs on Bathhouse Row suggest that the springs may be grouped for evaluation purposes. The springs in group 1 (spring 17 and promenade springs 8, 49, and CB1) generally showed strong seasonal patterns and sharp responses to rainfall and air temperature. The springs in group 2 (Bathhouse Row springs 15, 19, 25, 42 and 46) generally showed more stable temperatures with less response to rainfall and air temperature. Springs 17 and 46 displayed unique temperature responses, but were grouped with the other springs based on the seasonal pattern of the springs.

Diurnal and annual air temperature fluctuations (fig. 9) affect the water temperature of the springs. Thermal springs respond to air temperature because air temperature affects the ground temperature at the point of emergence, and air temperature affects the water temperature of shallow ground water that mixes with the thermal spring water. Some springs that emerge at depths below the land surface, such as the bathhouse springs and excavated springs, are less likely to be affected by surface temperatures.

The effects of rain events are evident at each spring to varying degrees. Recharge from rainfall generally causes downward spikes in water temperature. The response of the water temperature to rain events is the most direct evidence that cooler ground water is mixing with the thermal water of the springs. Decreases in thermal spring temperature show a poor linear relation to rainfall events, though, because there are other factors involved in how the thermal springs respond, such as antecedent soil saturation conditions and the temperature, intensity, duration, and areal distribution of rainfall during a rain event.

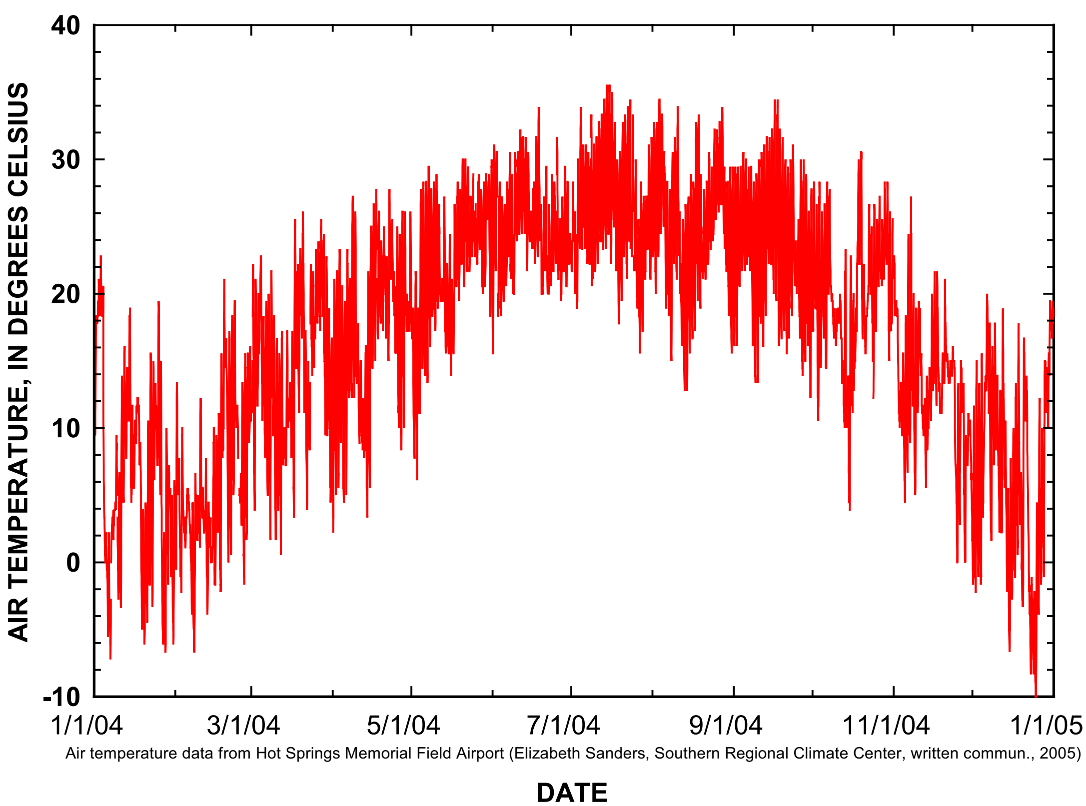


Figure 9. Hourly air temperature at Hot Springs Memorial Field Airport, Hot Springs, Arkansas, 2005.

Group 1 Thermal Springs

Group 1 springs 8, 17, 49, and CB1 (composite flow from springs 1, 3, 47, 48) share several common attributes. All group 1 springs lie near the north-northeastern boundary of the thermal springs area. Springs 8, 49, and CB1 are located in the same general area on the lawn above the promenade, and are the highest and most northeastern thermal springs in the study area. Spring 17 is the most northwestern spring in the study area, lying about 50 ft directly downgradient from CB1. Group 1 springs generally show strong seasonal patterns and sharp responses to rainfall events and diurnal air temperature (fig. 10).

The temperature at spring 17 on Bathhouse Row is considerably lower than the temperature at springs 8, 49, and CB1 above the promenade. Springs 8 and 49 are about the same temperature, averaging 61.5 °C. CB1 temperatures generally are 2 °C lower than temperatures of springs 8 and 49, although the actual temperatures at the springs that CB1 collects probably are higher because of heat loss during transmission to CB1. Spring 17 on the northern edge of the thermal springs area exhibits the lowest temperatures of all the thermal springs monitored, averaging about 52.7 °C. Spring 17 lies about 150 ft from well W2; well W2 predominantly is influenced by cold water, with temperatures near the surface ranging from 20 to 25 °C (June 2004 through May 2005). Recent (2000-2005) temperatures measured at spring 17 also are lower than have been reported in the recorded past (table 3), suggesting that colder shallow ground-water influence increased sometime after 1976 when the recorded temperature was 57.2 °C.

All group 1 springs show strong seasonal water temperature patterns that coincide with air temperature. Group 1 shows temperature highs from August through September and lows from February through March, about one month later than air temperature highs and lows. The differences between the seasonal high and low spring temperatures ranged from about 1.0 °C difference at springs 8 and 49, to about 4.0 °C at spring 17.

Springs 8, 49, and CB1 responded to most rain events that contributed recharge to ground water, while spring 17 response was more gradual and of less magnitude. After large rain events, the water temperature monitored hourly at spring 17 decreased about 0.2 °C, spring 49 decreased about 0.5 °C, CB1 decreased about 1.0 °C, and spring 8 dropped several degrees Celsius. Spring 8 hourly temperature decreased more than 5.0 °C during at least eight rain events for the period of record from August 2000 through June 2005. The largest hourly temperature decrease at spring 8 for the same period of record was about 20 °C on February 16, 2001. During the same rain event, spring 17 showed a gradual decrease of only a few tenths of a degree Celsius over a 2-3 day period. This suggests that recharge from rainfall may take a longer ground-water path to spring 17 and is more thoroughly mixed than at the other springs. This spring also may be influenced by subsurface flow from Hot Springs Creek.

Hourly variations in spring temperatures because of daily air temperature changes are evident in group 1. Springs 8 and CB1 show daily temperature fluctuations of about 0.10 and 0.20 °C, respectively, with highs and lows coinciding similarly to daily air temperature highs and lows (fig. 11). Daily temperature fluctuations at springs 17 and 49 are less evident, although apparent fluctuations between daily highs and lows of about 0.05 °C were observed.

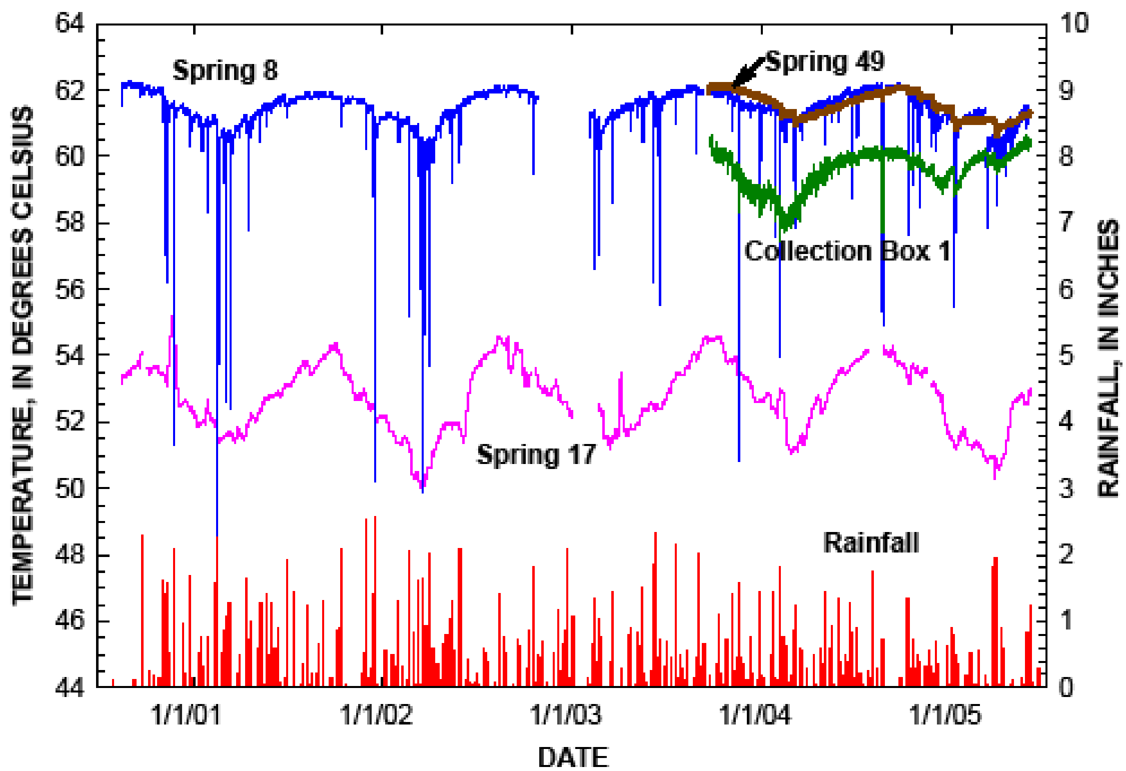


Figure 10. Daily average water temperature of group 1 springs and rainfall, 2000-2005.

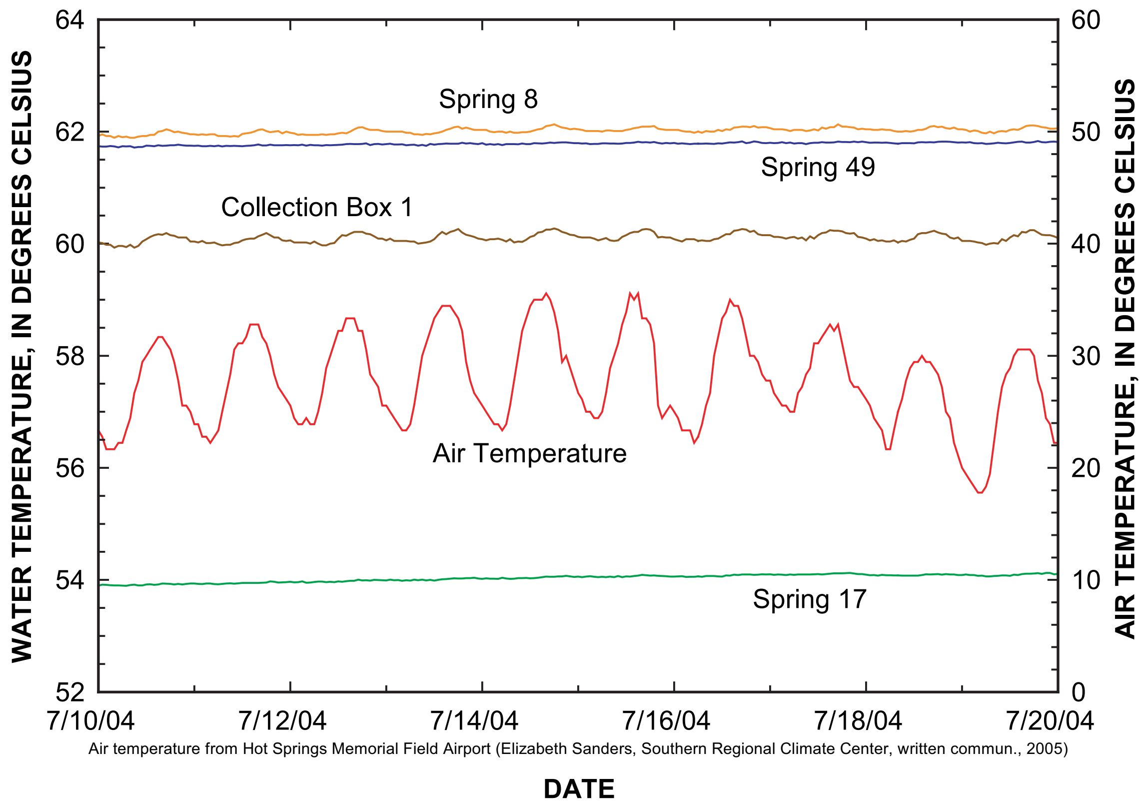


Figure 11. Hourly air temperature fluctuations compared to hourly water temperature at group 1 springs, July 10-20, 2004.

Group 2 Thermal Springs

Group 2 springs 15, 19, 25, 42, and 46 share several common attributes. All Group 2 springs are located along bathhouse row. Four of the springs (19, 25, 42, and 46) are in bathhouses. Springs 15, 19, 25, and 42 discharge large quantities of water with the highest and most stable temperatures monitored. Group 2 springs generally show less response than group 1 springs to seasonal effects and environmental influences (fig. 12). Spring 46 differs from other springs in group 2 because of a lower water temperature and larger responses to diurnal temperature changes and rainfall events. Spring 46 also shows responses to man-induced changes in the distribution system and spring chamber that did not occur at the other springs.

The average water temperature for the period of record in group 2 decreases towards the south except for spring 46. Spring 15 is the most northerly spring in group 2 and exhibits the highest average temperature of 64.9 °C. Spring 19, located about 35 ft south of spring 15, shows a slightly lower average temperature of 64.5 °C. The average water temperature continues to decrease towards the south with spring 25 at 63.1 °C, and spring 42 at 61.3 °C. Spring 46, located between springs 25 and 42, does not follow the same pattern, showing a lower average temperature of 55.4 °C. The lower temperature at spring 46 suggests it may be influenced by another cold-water source, possibly Hot Springs Creek. The decreasing pattern from spring 15 to springs 19, 25, and 42 in a southerly direction may be the cumulative effect of cold-water recharge as it collects at the base of Hot Springs Mountain and continues to accumulate as the cold-water recharge flows south along Central Avenue and Hot Springs Creek.

All group 2 springs show subdued seasonal water temperature patterns with peaks 2 to 5 months delayed from the air temperature cycle. The differences in spring seasonal high and low water temperatures range from about 0.2 °C at spring 19 to about 0.5 °C at spring 42. Springs 15, 19, 42, and 46 show temperature highs around September and lows around March, which is about 2 months later than air temperature highs and lows. Spring 25 exhibited a more delayed seasonal cycle of about 5 months, with highs in December and lows in June. The delayed seasonal responses at the springs suggest that the seasonal cycle also may be affected by seasonal rainfall through shallow ground-water paths. The delayed seasonal pattern at spring 25 may suggest that shallow ground water takes a longer pathway or has a larger recharge area than at springs 15, 19, 42, and 46. Spring 25 also may be more affected by subsurface flow along Hot Springs Creek, which is about 50 ft west of spring 25.

The seasonal temperature response at spring 46 is hard to discern because of responses to artificial changes in the distribution system and spring chamber, but the response to seasonal temperature probably is lessened at this spring because it is located in the basement of the Fordyce bathhouse, well insu-

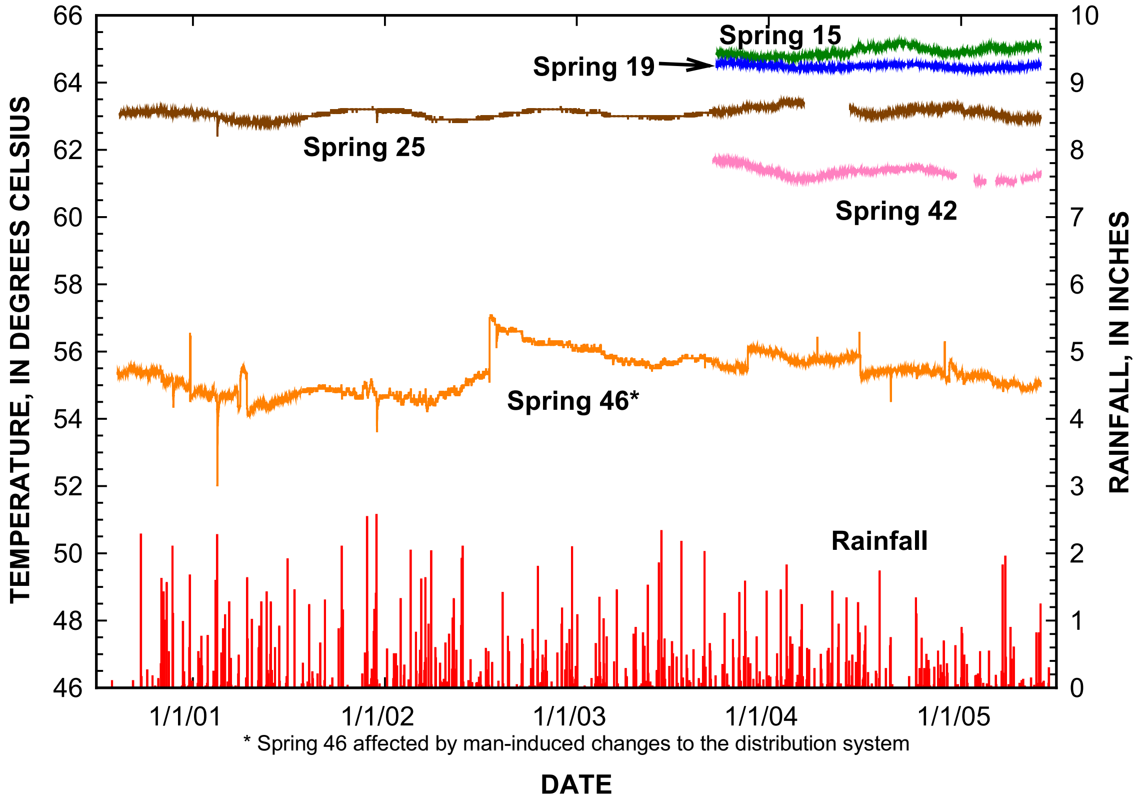


Figure 12. Daily average water temperature of group 2 springs and rainfall, 2000-2005.

lated from the outside changing environment. Springs 19, 25, and 42 also are located in the basement of bathhouses, probably lessening the seasonal influence of these springs. Spring 15 is not located in a bathhouse, but the spring emerges from about 15 ft below the land surface, probably providing an insulating effect at this spring as well.

Short-term variations in spring temperatures because of diurnal air temperature changes and rain events are small or negligible in group 2 springs. Springs 42 and 46 show slight daily temperature fluctuations of about 0.02 °C and 0.05 °C, respectively, which roughly coincide with daily air temperature changes. Springs 15, 19, and 25 do not appear to show a daily pattern. None of the group 2 springs show discernible responses to moderate rain events. During heavy rainfall of several inches, springs 15, 19, and 42 decreased less than 0.1 °C, usually over a several-day period. Springs 25 and 46 may drop in temperature several tenths of a degree Celsius during heavy rainfall. Two responses at springs 25 and 46 are especially evident during rain events on February 16 and December 16, 2001. The largest temperature decrease occurred on February 16, 2001, when spring 25 decreased 0.6 °C and spring 46 decreased 2.3 °C. Temperature responses at springs 25 and 46 occurred during the wet season and after several inches of rain had fallen in previous days. This indicates that these two springs appear to only respond during saturated soil conditions. Both springs 25 and 46 are about 50 ft from Hot Springs Creek, and the elevation of the springs is below the top of the underground creek arch, which fills beyond capacity about every 3 years (U.S. Army Corps of Engineers, 1993) and near capacity annually. Infiltration through fill material between the creek and springs or overland during flooding are possible pathways of flow to the springs.

Characteristics of the Shallow Ground-Water System

The thermal springs consist of two components of flow: deep thermal-water flow and shallow cold-water flow. The purpose of this report is to describe the shallow ground-water system, although, because the deep and shallow ground-water systems are connected and interact near the surface, a brief discussion of the deep ground-water system also will be presented.

According to the hypotheses of past investigators, the thermal-water component at HSNP enters the ground-water system as meteoric water from regional recharge areas in the fractured, permeable Bigfork Chert and Arkansas Novaculite (Bedinger and others, 1979; Arndt and Stroud, 1953; Purdue, 1910). These formations outcrop in exposed anticlinal structures to the west, north, and east of the thermal springs. The waters migrate to estimated minimum depths of 4,500 to 7,500 ft and are heated in the deep section of the flow path before rising through overlying geological units along fault and fracture conduits (Bedinger and others, 1979). Under artesian pressure, the thermal waters rise and emerge through the Hot Springs Sandstone between the traces of two thrust faults, along several northeast-trending lineaments (Bedinger and others, 1979; Bryan, 1922) (fig. 13).

There are several theories of how the thermal waters are heated. The one presented by Bedinger and others (1979) assumes that the waters are heated by geothermal gradient. The recharge area in the anticlinal structure to the northwest of the thermal springs is about 1 mile from the thermal springs, which is a short distance for the Alpha and Beta faults to reach depths of 4,500 to 7,500 ft. Recharge areas to the east-northeast are more probable for the geothermal model to work (illustrated by the arrows of flow from the right in figure 13). Although, alternative theories of the heat source, such as uncooled masses of igneous rock (Purdue, 1910; Bryan, 1922), juvenile waters rising and heating shallower meteoric waters (Arndt and Stroud, 1953), and an abnormally high geothermal gradient (Fellowes, 1968) could be used to explain how recharge from the northwest anticlinal structure contributes to the thermal springs.

The ground-water composition of the shallow, cold-water component of the thermal springs is probably similar in origin to cold-water wells and cold-water springs in the immediate area of HSNP. Cold water enters the ground-water system as locally derived recharge from rainfall and primarily flows along faults, joints, and fractures to the thermal springs. Cold-water recharge from losing streams in the study area (Hot Springs Creek and Happy Hollow Creek) appears less likely based on topography, stratigraphy, and faults, except during large rain events when water levels are abnormally high. Surface and unsaturated flow probably also contribute recharge during storm events.

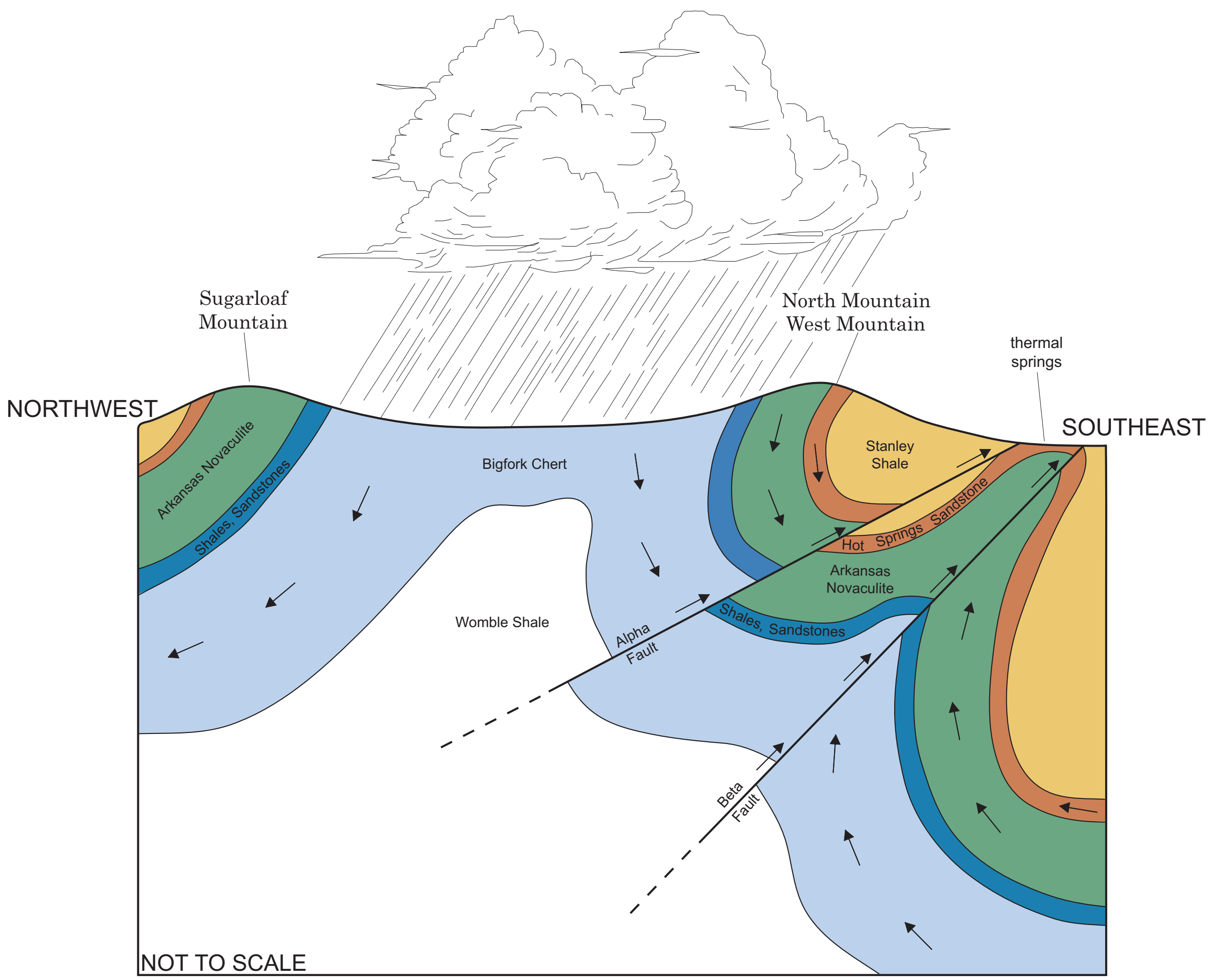


Figure 13. Conceptual model of the thermal water flow system.

Hydrologic Properties of Local Lithologies

Formations composed predominantly of shale generally may be considered to impede ground-water movement, contribute small quantities to recharge, and yield meager quantities to wells (Bedinger and others, 1979). Shale formations in the vicinity of HSNP include the Womble Shale, Missouri Mountain Shale, Polk Creek Shale, and Stanley Shale. The emergence of the thermal springs from the Hot Springs Sandstone above the contact with the Stanley Shale supports the concept that the Stanley Shale serves as a low-permeability barrier. Ground-water studies in Arkansas show the Stanley Shale generally yields only a few gallons per minute (Halberg and others, 1968).

Ground-water flow in the vicinity of the thermal springs occurs primarily in formations that are dense and hard; tending to crack or break under stress. These formations include the Bigfork Chert, Arkansas Novaculite, and Hot Springs Sandstone. The Bigfork Chert is not exposed on or adjacent to Hot Springs Mountain. Therefore, the contribution of the Bigfork Chert to cold-water recharge to the thermal springs is less likely, but possible from distant artesian sources.

The Arkansas Novaculite is highly resistant to erosion and supports the ridge of Hot Springs Mountain. It is locally intensely jointed (Bedinger and others, 1979) especially in the lower massive and dense member of the formation, which is presumed to be the major water-bearing unit of the formation (Arndt and Stroud, 1953). The lower member makes up the majority of surficial geology on Hot Springs Mountain and, therefore, probably represents a major recharge area on Hot Springs Mountain. The middle member of the Arkansas Novaculite consists mostly of shales with thin chert beds and may act as a barrier between the lower and upper members of the formation, creating conditions for a confined aquifer in the lower member (Arndt and Stroud, 1953). The upper member of the formation is less densely fractured chert with increased intergranular permeability, interbedded with minor shale and conglomerate. There is a thin shale zone between the top of the upper member and the basal conglomerate of the overlying Hot Springs Sandstone in Gulpha Gorge east of Hot Springs Mountain (Arndt and Stroud, 1953). However, fracturing and faulting probably supply some conduits of flow between the upper member and Hot Springs Sandstone.

Like the Arkansas Novaculite, the Hot Springs Sandstone is highly resistant to erosion with locally intense joints and fractures that increase permeability. The basal contact with the Arkansas Novaculite consists of conglomerate pebbles and cobbles in a dense siliceous matrix. The upper part of the Hot Springs Sandstone grades into the Stanley Shale by an increase in the amount of shale (Arndt and Stroud, 1953). Surface exposures of the Hot Springs Sandstone are enclosed by the Stanley Shale on all sides of Hot Springs Mountain except toward the northeast topographic divide.

Principal Conduits and Barriers

The principal conduits of shallow ground-water flow appear to occur along lines of southwest-northeast trending faults, joints, and fractures. Evidence of minor and major faults trending northeast have been documented by Bryan (1922), Arndt and Stroud (1953), Bedinger and others (1979), and Bedinger (1994). The two major faults, Alpha and Beta (Arndt and Stroud, 1953) that trend along the northern and southern boundaries of the thermal springs area are theorized to represent the permeable conduits through which the thermal water rises to shallow depths. Thermal water is distributed to the thermal springs through joints and fractures in the Hot Springs Sandstone and Arkansas Novaculite. The faults, joints, and fractures also represent pathways where adjacent cold ground water could mix with the thermal water. How much mixing occurs would depend on the head of the thermal water in relation to that of the cold water and dynamics of the system.

The shallow ground-water system associated with the thermal springs is bounded on three sides—southwest, southeast, and northwest—by shale barriers aligned to the structural trend of folds and faults. To the southwest, the Stanley Shale forms a barrier over the southwest plunging Hot Springs Sandstone. To the southeast, the Stanley Shale also forms a barrier below the southeast limb of the overturned Hot Springs anticline, and Beta fault trends between the southeast limb and the thermal springs area. The final barrier to shallow ground-water flow lies to the northwest along the northeast-trending Alpha fault. North of the thermal springs, Alpha fault lies along the contact between the Stanley Shale and Hot Springs Sandstone (Bedinger, 1994; Arndt and Stroud, 1953). Alpha fault probably developed in the less competent shale beds of the Stanley Shale, thrusting the overturned Stanley Shale over the Hot Springs Sandstone (fig 6). The emergence of the thermal springs from the Hot Springs Sandstone near to the contact with the Stanley Shale implies that the low permeability of the Stanley Shale creates a barrier that directs the springs to emerge in the Hot Springs Sandstone (Bedinger, 1994).

Shallow Aquifers and Cold-Water Recharge

The lower member of the Arkansas Novaculite is probably the primary aquifer that contributes a continuous supply of shallow, cold ground water to the thermal springs area. It is the thickest of the exposed rock units with relatively large outcrops on Hot Springs Mountain and North Mountain and with extensive jointing and fracturing. The underlying Missouri Mountain Shale and the overlying shales of the middle member of the Arkansas Novaculite also may seal off the lower novaculite aquifer, creating confined conditions. If the lower novaculite is saturated sufficiently, the resulting pressure head may force confined water upward from depth, through fractures to the thermal springs at the surface (Arndt and Stroud, 1953).

It is unclear how much ground-water flow from the Arkansas Novaculite and Hot Springs Sandstone on the southeast limb of the Hot Springs anticline reach the thermal springs area. Cold ground water on the southeast flank of Hot Springs Mountain was reported to emerge at the contact of the Hot Springs Sandstone and Stanley Shale in seepages and some small springs (Kirk Bryan, U.S. Geological Survey, written commun., 1922). Well W4 was drilled in 1922 in an effort to capture this water. However, the well encountered predominantly thermal water reaching temperatures of up to 54 °C throughout the well except for a small quantity of cold water reported in the upper part of the well (Kirk Bryan, U.S. Geological Survey, written commun., 1922). Therefore, it is evident that thermal water leaks into the ground-water system and mixes with cold ground water at least in the vicinity of the well. Thermal water probably migrated from the thermal springs area and possibly from Beta fault on the southern limits of the thermal springs area.

Recharge directly around the spring catchments and recharge to the Hot Springs Sandstone and Arkansas Novaculite directly upgradient from the thermal springs contribute an unknown amount of cold water to the thermal springs during rain events. Temperature monitoring at selected thermal springs indicates the water temperature decreases within minutes to hours of recharge from rainfall. This is especially true of the higher thermal springs on Hot Springs Mountain, which are less sheltered from weather than the lower springs. The lower thermal springs are commonly covered by the bathhouses or increased ground cover over the spring source.

Ground-Water Levels

The altitudes of the water table in wells W2, W3, and W5 (well depths 200, 190, and 202 ft, respectively) were measured simultaneously on July 7, 1993, prior to aquifer testing (Bedinger, 1994). The wells are located just north of the thermal springs discharge area. The water-table altitudes were 604.17 ft (W2), 608.96 ft (W3), and 612.35 ft (W5) above NGVD 1929. Based on these three data points, the direction of ground-water flow was south-southwest, generally towards Hot Springs Creek. Temperatures, silica and sulfate concentrations, and the specific conductance of samples from wells W2 and W3 were between those of the thermal springs and typical cold-water springs, whereas, the chemistry of well W5, a few hundred feet farther north from the thermal springs area, was more similar to cold-water springs (Pearson, 1994).

The altitude of the water level at well W4 (well depth 336 ft) on Hot Springs Mountain was considerably higher than the other wells, at about 629 ft above NGVD 1929 on July 7, 1993. This would be expected if the direction of ground-water flow followed the slope of the mountain southwest, towards Hot Springs Creek. Well W4 appears to respond to similar hydrologic conditions as well W2, according to the water-level measurements recorded at the two wells in 2004-2005 (fig. 14). The water level at well W2 is considerably more responsive to atmospheric conditions than well W4, probably because the depth of water at W2 is near land surface, whereas, the depth of water at

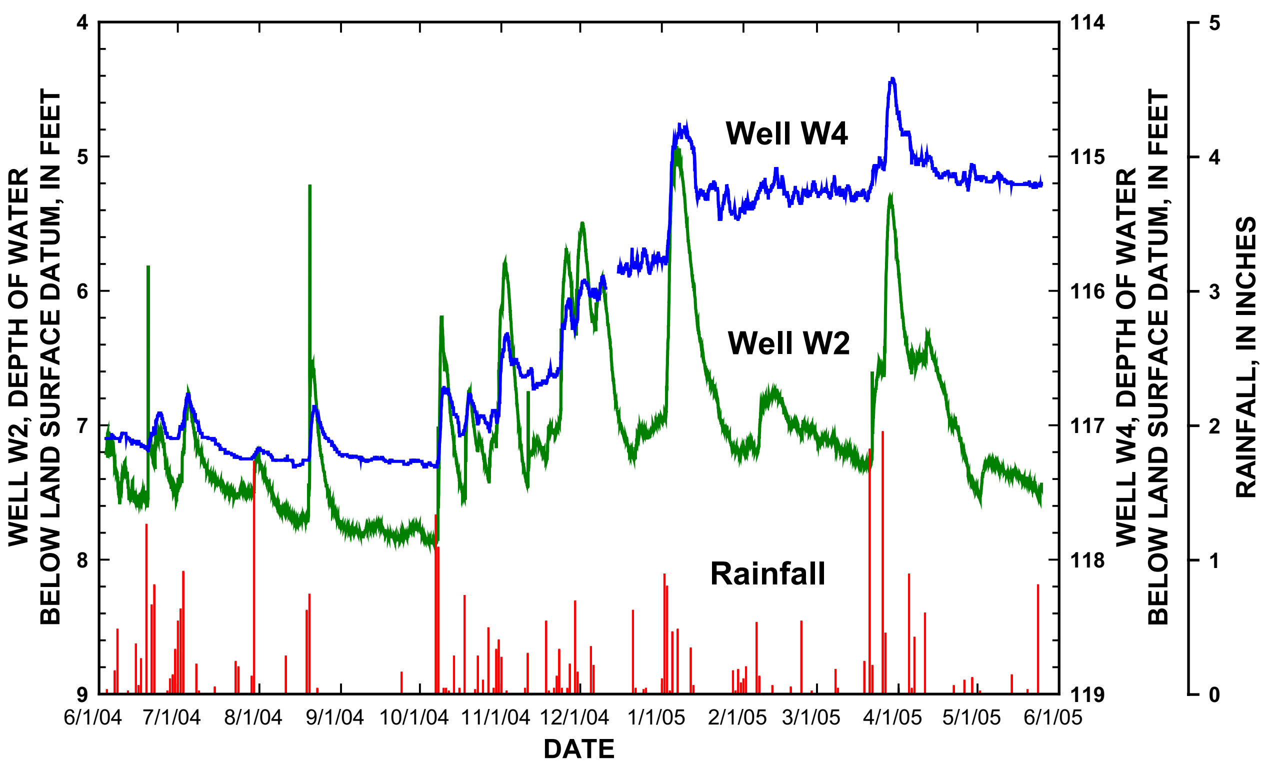


Figure 14. Hourly water levels in wells W2 andW4 and daily rainfall, 2004-2005.

W4 is about 100 ft deeper. The hydraulic head in well W4 increased more than well W2 over the recorded period. This suggests that the sources of recharge to W4 are more continuous or retained longer, as opposed to the more flashy response to recharge at W2.

Thermal Springs Hydraulic Connection

There are several examples that show how many of the thermal springs are in hydraulic connection. Kirk Bryan (U.S. Geological Survey, written commun., 1922) reported that thermal springs 37 and 40 ceased to flow after spring 39, converted to a well, began to be used. Bryan also reported that spring 49, created during spring collection systems excavations, caused the drying up of adjacent springs. Other springs that were reported to develop as a result of excavation include springs 5, 7, 16, 37, 47, and 48 (Weed, 1902). Springs 12 and 14 reportedly lost most of their outflow when spring 16 was deepened (Weed, 1902). Weed (1902) also reported that spring 36 did not flow when water was pumped from the well on the military reservation (Hot Springs Rehabilitation Center on Reserve Avenue). Bedinger (1994) assessed during aquifer tests that wells W2, W3, and W5 were all hydraulically connected. Furthermore, Bedinger (1994) attributed a recharge boundary indicated by the drawdown plot at well W2 "to a partial hydraulic connection between the aquifer at the west well (W2) and Hot Springs Creek."

A hydraulic connection appears to be present between the lower springs on Bathhouse Row and the upper springs above the promenade, as evidenced by a decrease in the number of upper springs and increase in the number of lower springs over the last 100 years, presumably because of excavating and other earth-moving activities. Hamilton (1932) reported a decrease in discharge of the upper group of springs from about 167,000 gal/d in 1901 to 124,000 gal/d in 1931. Three old springs in the group had gone dry and others showed a decrease in flow. Hamilton (1932) commented that "It seems clear that the drilling of wells or the opening of new springs under certain bathhouses has lessened the flow from this group of springs."

Alternative Sources of Cold-Water Recharge

Although the source of shallow ground-water flow to the thermal springs has been proposed to originate on or adjacent to Hot Springs Mountain, alternative paths of ground-water flow are plausible. First, vertical infiltration through fill material around the spring catchments is possible if the fill material is not properly sealed. Most of the entire hillside that lies east of Central Avenue has been excavated at some time for construction of the Hot Springs Creek arch, new bathhouses, walkways, and new spring catchments and distribution lines.

Second, lateral infiltration of water from Hot Springs Creek to adjacent springs on Bathhouse Row is possible. This is a concern because Hot Springs Creek drains a large urban area that may contain potentially harmful chemicals, substances, and biological hazards. The creek arch was constructed over 100 years ago with an open floor and fill material between the creek and some of the springs. Four thermal springs collected for public use (springs 25, 42, 43, 46) and well W2 are within 45 to 60 ft of the creek. Bedinger (1994) presents results from an aquifer test on well W2 that indicates the well is in hydraulic connection with the Hot Springs Creek and that the creek is a source of recharge, supplying water to the well during the aquifer test. Heavy rainfall events are more of a concern because the water level in the creek rises above the level in many springs and flooding may inundate some of the springs.

Third, ground-water flow in the Stanley Shale across Central Avenue is possible along major faults, such as the Alpha and Beta faults discussed. Arndt and Stroud (1953) and Bedinger and others (1979) proposed that the Alpha and Beta faults do extend across Central Avenue and further southwest, although there is no evidence to suggest that sufficient permeability and pressure head exists in the Stanley Shale to conduct flow into the thermal springs area.

Fourth, it is entirely possible that deeper, cold-water flow paths exist, that are harder to identify and evaluate. One such flow path may be the same path as the proposed thermal water flow path through the Bigfork Chert, but instead of meteoric water traveling to deep, heated depths, some meteoric water may take shorter, shallower flow paths across the Alpha fault that extends into the massive lower Arkansas Novaculite, providing a pathway to the surface (Arndt and Stroud, 1953). Another flow path may be from the flanks of North and Hot Springs Mountains through preferred channels in the trough of the plunging North Mountain syncline and adjacent faults, directing flow into the thermal springs area.

Cold-Water Recharge Areas

Delineating the cold-water recharge area to the thermal springs involves numerous factors such as the hydrologic boundaries, soil properties, vegetation types, rainfall frequency and distribution, runoff, evapotranspiration, spring discharge, and surface-water influence. Many of these factors and their associated processes are not well defined for the study area, and it was beyond the scope of this investigation to evaluate all of the factors involved. Therefore, the information for estimating the recharge area was simplified from previous studies to make a preliminary estimate of the recharge area possible. Further study that adds to the knowledge and understanding of any of these factors will help to better define the recharge area.

As discussed previously, the thermal-water component of the thermal springs is theoretically derived from distant sources, and travels to depths greater than 4,500 ft over periods greater than 4,000 years; whereas, the cold-water component of the thermal springs is derived locally and travels to shallow depths over relatively short periods of time. Therefore, the size and boundaries of the cold-water recharge area should be analogous to the shallow ground-water recharge area. This cold-water recharge area is delineated by, first, estimating the recharge area size; second, approximating the recharge area boundaries; and third, testing the delineated recharge area using dye-tracing techniques.

Recharge Area Size

The size of the cold ground-water recharge area was estimated from a general form of the hydrologic budget in equation 1 that utilizes the cold ground-water baseflow discharge of the thermal springs and the amount of recharge from rainfall. The cold ground-water baseflow discharge was estimated from equation 2 using silica concentrations and the average daily discharge from the collection system and springs 43 and 43a. Using the average silica concentration of nine thermal springs (44.4 mg/L sampled in September 2000) for X_{mix}, the estimated proportion of cold-water discharge (f_a) during baseflow conditions computes to 6.6 percent. The average daily discharge from the collection system and springs 43 and 43a during September 2000 was 738,000 gal/d. The total cold-water discharge component is 6.6 percent of 738,000 gal/d, or about 48,700 gal/d. This computes to about 17.8 million gallons per year (Mgal/yr).

Dugan and Peckenpaugh (1985) estimated the average annual ground-water recharge in the general area north of Hot springs for woodland and range conditions to be 10 to 15 inches. The actual annual ground-water recharge for the study area is presumed to be less than 10 inches because of the steep gradient on Hot Springs Mountain (20 percent) and the extensive road drainage system not applied specifically for HSNP in the model used. Recharge values ranging from 5 to 10 in/yr were considered more representative of the study area. Applying 5 to 10 in/yr recharge from rainfall and 17.8 Mgal/yr cold-water discharge from the thermal springs to the hydrologic budget equation 1, the cold-water recharge area computes to a range from 0.10 to 0.20 mi^2. Recharge rates greater than 10 in/yr would decrease the estimated size of the recharge area and rates less than 5 in/yr would increase the estimated size of the recharge area that contributes to the shallow ground-water component of the thermal springs.

Recharge Area Boundaries

Subsurface bedding attitude departs from surface topography on the southeast limb of Hot Springs Mountain and along at least two faults that displace subsurface bedding, creating a cold (shallow) ground-water recharge area that deviates from the surface drainage area of the thermal springs (the surface drainage area was inferred from topographic contours). Four ground-water boundaries are recognized to form the estimated recharge area for shallow ground-water flow to the thermal springs: southeast, west, northwest, and northeast boundaries (fig. 15). On the southeast boundary, the southeast limb of Hot Springs anticline is overturned and dips to the northwest towards the thermal springs, potentially extending the ground-water recharge boundary past the topographic divide, to include the overturned Arkansas Novaculite and Hot Springs Sandstone, up to the boundary of the Stanley Shale that acts as a barrier. The western ground-water boundary parallels the surface drainage boundary along Bathhouse Row, and acts as a barrier at the contact with the Stanley Shale. Most springs emerge at or above this contact in the Hot Springs Sandstone, although a few springs probably follow fractured conduits a short distance into the Stanley Shale. The northwest ground-water boundary is a fault (Alpha fault) that forms a barrier along the contact of the Stanley Shale that has been overthrust adjacent to the Hot Springs Sandstone and Arkansas Novaculite on the northwest limb of the Hot Springs anticline. The northeast ground-water boundary does not appear to have barriers to ground-water flow, and is presumed to closely conform to the surface drainage boundary, extending the recharge area to the topographic divide at the peak of Hot Springs Mountain near lookout point. The approximate size of the shallow ground-water recharge area based on these boundaries computes to 0.14 mi^2.

The absence of thermal water influence and the presence of cold-water sources just outside the projected boundaries of the thermal springs recharge area present further evidence of the location of the recharge boundaries. On the northwest faulted boundary, cold water at Happy Hallow Spring and at well W5 are evidence that thermal water does not substantially cross the fault. On the west boundary, limited discharge of thermal water through the Stanley Shale in Hot Springs Creek is evidence that thermal water does not substantially flow southwest of the springs. On the southeast boundary, cold-water springs have been reported to seep or flow along the boundary contact with the Stanley Shale (Kirk Bryan, U.S. Geological Survey, written commun., 1922).

Dye Tracing

Dyes were released on December 4, 2004, at three sites in the estimated recharge area above the thermal springs (fig. 16). Dyes at sites 1 and 3 were not sufficiently detected above background levels at thermal-water sites to indicate these dyes were in the thermal springs. The rhodamine dye released at site 2 was detected above background levels at several thermal water sites over a period of several weeks (table 4). The levels of dye detected were low because low concentrations of dyes were released to prevent the water in the public water system from discoloring.

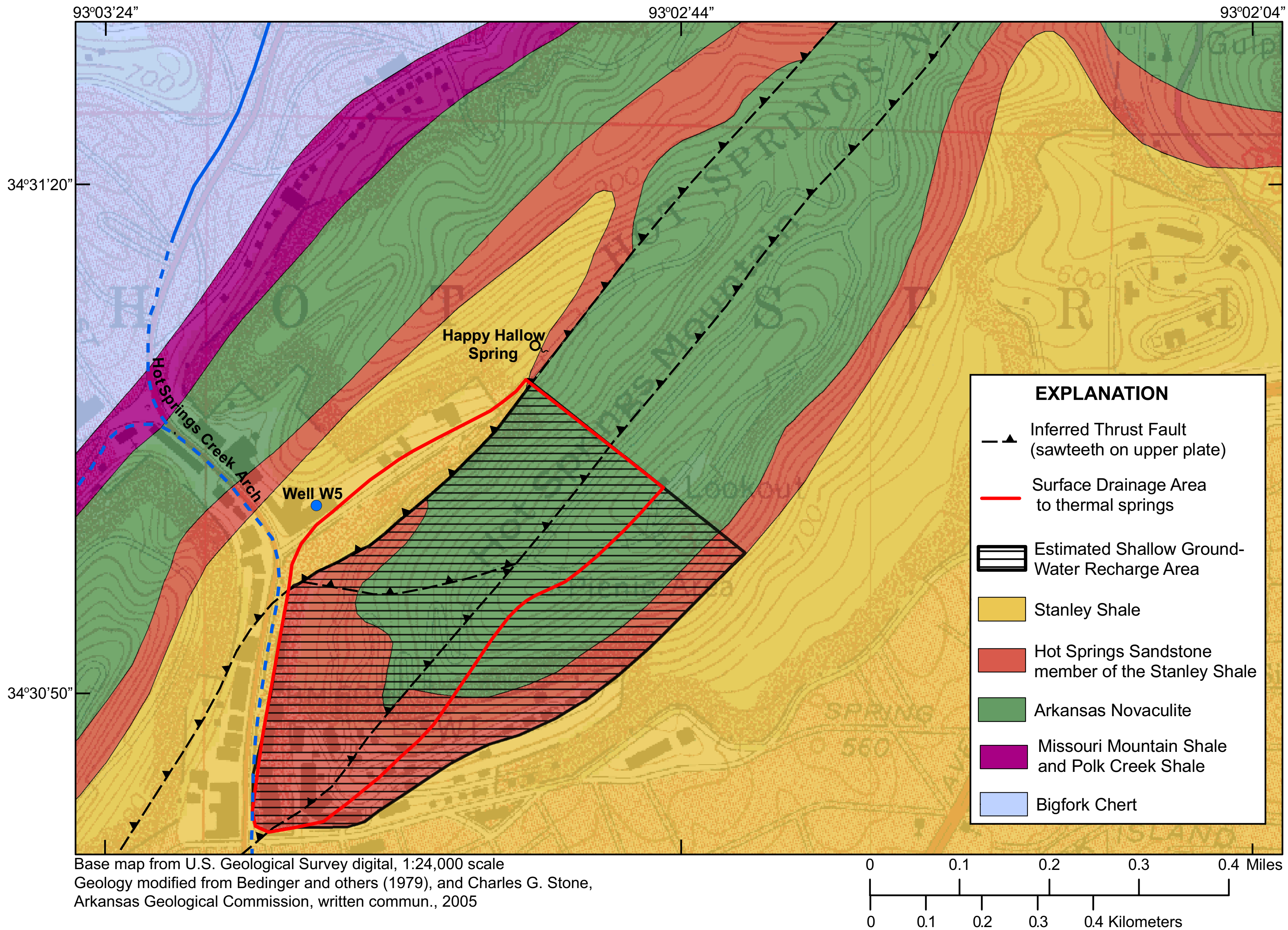


Figure 15. Estimated recharge area for shallow ground-water contribution to the thermal springs.

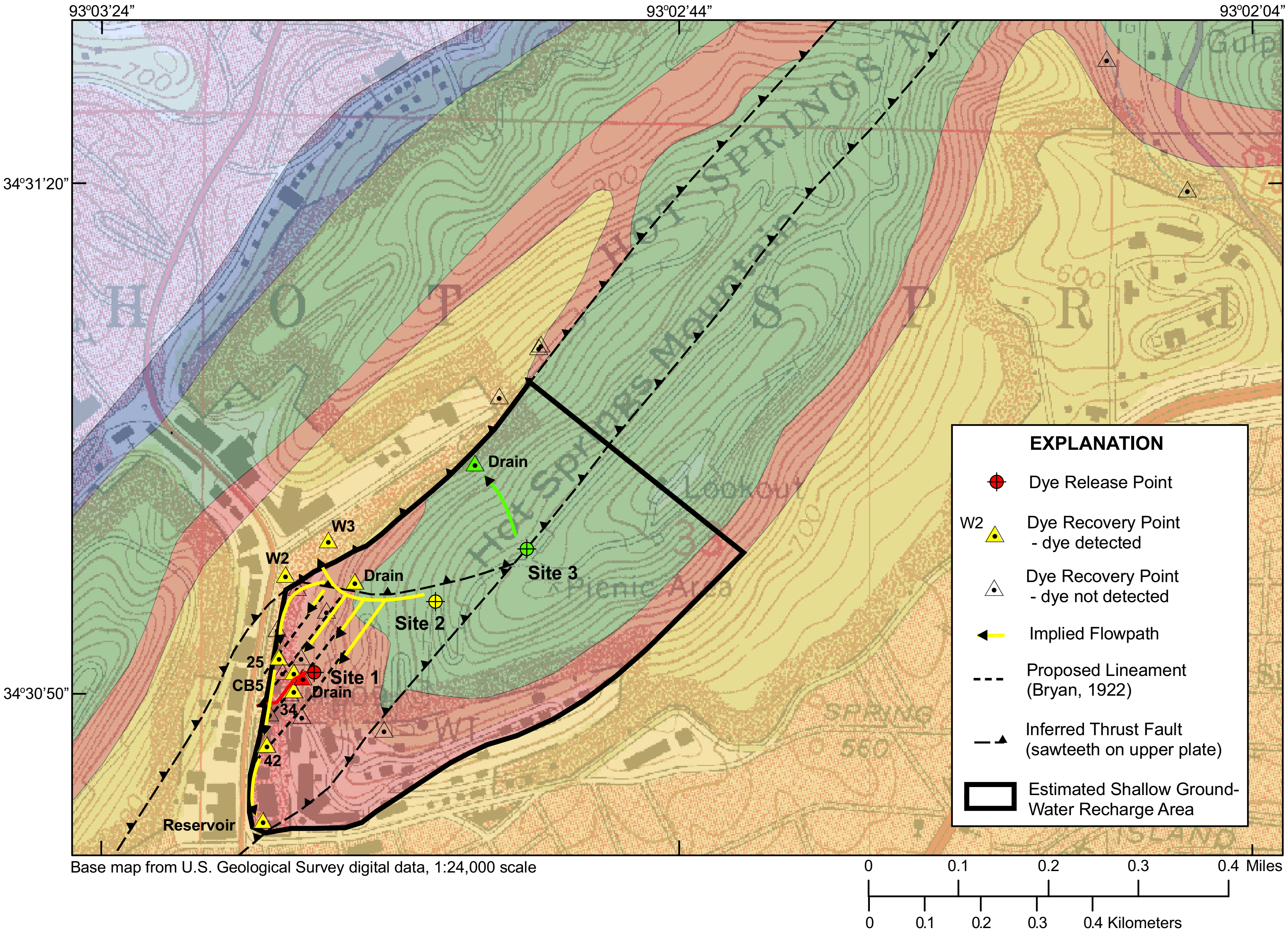


Figure 16. Dye release and detection points and implied flow paths of the dyes.

Table 4. Results of rhodamine dye release at site 2 on December 4, 2004.

[Res., collection reservoir inflow; W2, Arlington lawn well west; W3, Arlington lawn well east; CB5, collection box 5; Rainfall is total rainfall for period between date charcoal packet installed and date charcoal packet removed]

Date charcoal packet installed	Date charcoal packet removed	Sites where dye was detected	Rainfall (inches)
12/03/04	12/09/04	Res., W3	0.56
12/09/04	12/15/04	W3	0
12/15/04	12/22/04	Res., W2, W3, Springs 25, 34, 42, CB5	0.66
12/22/04	12/28/04	Res., W3, Springs 25, 42	0.07
12/28/04	01/06/05	Res., Springs 34, 42	2.28
01/06/05	01/14/05	not detected	0.88
01/14/05	01/20/05	not detected	0
01/20/05	02/04/05	not detected	0.76
02/04/05	03/03/05	not detected	1.37

Eosine dye (1 liter, 10 percent concentration) was released at site 1 about 100 ft above spring 31 in a partially paved natural drainageway for road drainage. About 30 ft above spring 31, the drainageway flows into a culvert, then underground past display springs 32 and 33, between the Fordyce and Maurice bathhouses, and to Hot Springs Creek. Positive identification of the eosine dye was detected in the surface drainage at the culvert entrance, but detection levels were not sufficiently above background levels at thermal water sites to conclusively determine presence of the dye.

Fluorescein dye (4 liters, 10 percent concentration) was released at site 3 about 1,500 ft east of Central Avenue in a natural drainageway below Hot Springs Mountain Drive. Surface drainage flows northwest until Hot Spring Mountain Drive, where drainage flows underground to Fountain Street drainage, then to Hot Springs Creek. Positive identification of the fluorescein dye was detected in the surface drainage near the bottom of Hot Springs Mountain, but dye was not detected at any of the thermal water recovery sites. Dye release site 3 was the site farthest from the thermal springs and it is possible that more dye or more time was needed to reach detection levels at the recovery sites.

Rhodamine dye (2 liters, 5 percent concentration) was released at site 2 about 1,000 ft east of Central Avenue in a partially paved natural drainageway used for road drainage (fig. 17). The drainageway lies near and perhaps along a fault proposed by Bedinger and others (1979). The flow path of the dye was probably along drainage west until Hot Springs Mountain Drive just above the upper thermal springs. At that point, the drainage flows into a culvert and underground, apparently to Fountain Street drainage and Hot Springs Creek. It was observed by the author that the culvert had open gaps between sections where water could filter into the ground. The culvert terminates in the area of wells W2 and W3. The dye could have either flowed to wells W2 and W3 through the culvert across the fault, or the dye could have seeped into the fault, which intercepted wells W2 and W3 downdip.

The flow path of the rhodamine dye to the thermal springs is probably along the western boundary contact with the Stanley Shale. Bedinger (1994) suggested that this contact is a thrust fault. It also is possible that the dye flowed into northeast trending fractured lineaments higher up on the mountain that lead to the thermal springs. Bryan (1922) proposed four such lineaments that appear to run along lines of thermal spring occurrence (fig. 16). The dye did show up at springs near each of the four proposed lineaments.

Figure 17. Rhodamine dye release at site 2 on Hot Springs Mountain, Hot Springs National Park, Arkansas.

Presence of the rhodamine dye at the thermal springs, wells, and reservoir verifies that this area is part of the recharge area and that runoff from this area enters the ground-water system at some point along the pathway of the rhodamine dye. Several implications can be drawn from this conclusion. The drainage for the dye also drains runoff from the road. Therefore, road drainage enters the ground-water system that is connected to the thermal springs. Time of travel from release point to the thermal springs was 1 to 3 weeks, depending on where the dye was detected (table 4). Time of travel also would be dependent on other environmental conditions such as the soil saturation condition, and the amount, intensity, and duration of rainfall. The dye was detected only at well W3 and the collection reservoir after the first week of observation. Well W3 is not part of the thermal water collection system, therefore, the dye that was detected at the collection system reservoir must have come through a spring that was not monitored with a charcoal packet.

Summary

The thermal springs of Hot Springs National Park have been valued for the recreational and therapeutic benefits of the thermal baths, as a source of drinking water, and a destination of attraction since the history of the area was first recorded. The future of the park and the city of Hot Springs depends greatly on maintaining and protecting this unique natural resource from degradation and contamination. To maintain and protect the thermal springs, it is imperative to understand the character of the springs, monitor changes in spring characteristics, and evaluate the source of the thermal springs.

The thermal springs are situated in the Ouachita Mountains of central Arkansas. The springs emerge in a gap between Hot Springs Mountain and West Mountain in an area about 1,500 feet long by 400 feet wide at altitudes from 576 to 683 feet. The springs predominantly are composed of a deep thermal ground water component with a lesser but qualitatively substantial component of shallow cold ground water. Currently, there are 43 thermal springs in the park that are presumed to be flowing. Thermal water from 33 of the thermal springs is collected and monitored at a central reservoir, which distributes the combined discharge for public use and consumption.

Rock types exposed in the vicinity of the thermal springs are shale, chert, novaculite, sandstone, and conglomerate. Shale units generally impede ground-water movement, while fractured chert, novaculite, and sandstone units generally support ground-water movement.

The average daily collection system discharge over the period of record 1990 through 1995 and 1998 through 2005 was 658,000 gal/d and ranged from 518,000 to 763,000 gal/d, not including 131,000 gal/d from springs 43 and 43a that emerge from the bottom of the collection system reservoir. The overall pattern of the collection system discharge from 1990 to 2005 shows an increasing rate of discharge; the majority of the increase took place from 1990 through 1995. Changes in the collection system temperature showed a positive relation to changes in discharge from 1990 through 1995, and an inverse relation to changes in discharge from 1998 through 2005. The period 1995 through 1998 was not monitored. The collection system discharge shows a good response to rain events, increasing in discharge when rainfall contributes recharge to the ground-water system.

Continuous water temperature monitoring conducted by the USGS from 1990 through 1995 and from 1998 through 2005 at the collection system reservoir inflow pipe shows that there has not been a significant long-term temperature change during the past 15 years. The daily water temperature ranged from 59.1 to 62.1 °C and the average daily temperature was 61.4 °C. The collection system water temperature shows a strong seasonal pattern, with highs and lows about 1 month delayed from air temperature highs and lows. The collection system temperature also shows strong response to rainfall.

The water temperatures were monitored at four thermal springs from August 2000 through June 2005, and at four additional thermal springs and one thermal spring collection box from September 2003 to June 2005. Springs 8, 17, 49, and CB1 (group 1) generally showed strong seasonal patterns and sharp responses to changes in air temperature and rainfall. Group 1 showed water temperature highs from August through September and lows from February through March, about 1 month later than air temperature highs and lows. Springs 8, 49, and CB1 water temperature responded to practically all rain events that contributed recharge to ground water, while spring 17 response was more gradual and of less magnitude. Spring 8 water temperature dropped several degrees Celsius after large storm events. Springs 8, CB1, 17, and 49 showed daily water temperature fluctuations of about 0.10, 0.20, 0.05, and 0.05 °C, respectively, with highs and lows coinciding similarly to air temperature highs and lows.

Springs 15, 19, 25, 42, and 46 (group 2) generally showed more stable water temperatures and less response to changes in air temperature and rainfall than group 1. The water temperatures in group 2 decreased towards the south except for spring 46. Springs 15, 19, 42, and 46 show water temperature highs around September and lows around March, which is about 2 months later than air temperature highs and lows. Spring 25 water temperature exhibited a more delayed seasonal cycle of about 5 months, with highs in December and lows in June. Short-term variations in spring water temperatures because of diurnal air temperature changes and rain events are small or negligible in group 2 springs. Springs 42 and 46 showed daily water temperature fluctuations in response to diurnal air temperature changes of about 0.02 °C and 0.05 °C, respectively. Springs 25 and 46 may drop in water temperature several tenths of a degree Celsius during heavy rainfall.

The source of the thermal water component of the thermal springs hypothetically enters the ground-water system as rainfall from regional recharge areas in the fractured, relatively permeable Bigfork Chert, Arkansas Novaculite, and Hot Springs Sandstone. The meteoric water migrates to estimated minimum depths of 4,500 to 7,500 ft and achieves high temperatures in

the deep section of the flow path before rising along fault and fracture conduits. Under artesian pressure, the thermal waters rise and emerge through the Hot Springs Sandstone between the traces of two thrust faults, along several northeast-trending lineaments.

The cold-water component enters the ground-water system as locally derived recharge from rainfall, and flows primarily along shallow northeast trending faults, joints, and fractures to the thermal springs. The thermal springs are bounded on the southwest, southeast, and northwest by shale barriers. The lower member of the Arkansas Novaculite is probably the primary aquifer of shallow ground-water flow. Water-level observations made at four wells in the thermal springs area indicate that shallow ground-water flow generally follows the slope of Hot Springs Mountain, flowing southwest and towards Hot Springs Creek. A hydraulic connection appears to be present between the lower and upper thermal springs, as evidenced by a decrease in the number of upper springs over the last 100 years, presumably because of excavation and other earth-moving activities at or near the thermal springs.

Alternative sources of cold-water recharge that are plausible include: (1) vertical infiltration through fill material around the spring catchments, (2) lateral infiltration of water from Hot Springs Creek to adjacent springs on bathhouse row, (3) ground-water flow in the Stanley Shale across Central Avenue along major faults, and (4) longer, cold-water flow paths such as the proposed thermal water flow path through the Bigfork Chert, but taking shallower flow paths to the thermal springs.

The size of the cold-water recharge area was estimated from the general concept of the hydrologic budget, where the average annual ground-water recharge (input) is equal to the average annual cold-water discharge (output) of the thermal springs. Based on the thermal springs estimated cold ground-water baseflow discharge of 17.8 Mgal/yr, and an estimated ground-water recharge rate of 5 to 10 in/yr, the estimated size of the shallow ground-water recharge area computes to 0.10 to 0.20 mi^2. The shallow ground-water recharge area appears to be bounded on three sides by low-permeability barriers, and extends approximately to the topographic divide. The shallow ground-water recharge area based on the boundaries is about 0.14 mi^2.

Dyes were released at three sites in the proposed recharge area above the thermal springs. Two of the dyes were not sufficiently detected above background levels to indicate the dyes were in the thermal springs. Rhodamine dye released at site 2, about 1,000 ft east of Central Avenue, was detected above background levels at several recovery sites over a period of several weeks. The flow path of the rhodamine dye to the thermal springs is probably along the western boundary contact with the Stanley Shale or along northeast-trending fractured lineaments. Presence of the dye verifies that this area is part of the recharge area and that surface water enters the ground-water system at some point along the pathway of the rhodamine dye. Time of travel from the release point to the thermal springs was 1 to 3 weeks, depending on where the dye was detected.

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