U.S. Department of the Interior
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Prepared in cooperation with the
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Scientific Investigations Map 3506
Sheet 1 of 2

Abstract

Fern Cave in Jackson County, Alabama, is a 15.6-mile-long (25.1-kilometer) cave system, managed by the U.S. Fish and Wildlife Service and Southeastern Cave Conservancy, that has the second highest biodiversity of any cave in the southeastern United States. Groundwater in karst ecosystems is known to be susceptible to impacts from human-induced land-use activities in watersheds that contribute recharge to the groundwater system. To provide the U.S. Fish and Wildlife Service with necessary baseline information on the groundwater flow system in Fern Cave, the U.S. Geological Survey and the Kentucky Geological Survey conducted a series of dye traces during 2019–21 to delineate the watershed recharging the cave system. The dye traces identified two separate streams that flow through the cave and a recharge area of 1.73 square miles (4.48 square kilometers) draining to the cave system. Current land use within the recharge area is dominated by deciduous forest with minimal additional land use types, indicating a low potential for undesirable effects to the cave by anthropogenic sources.

Introduction

Karst aquifers have long been noted to have high hydraulic connectivity between the surface-water system and groundwater system (Palmer, 1990; Priebe and others, 2018). Matrix and fracture flow paths result in longer storage within the aquifers, whereas dissolution enhanced flow paths result in rapid recharge (Toran and others, 2007; Mudarra and others, 2019). As a result of this rapid flow, karst groundwater systems are highly susceptible to contamination from surface sources, such as human-induced impacts from land-use activities (Fields, 1993; Urich, 2002).

Researchers have suggested that as habitat availability in cave systems increases, so does cave biodiversity (Christman and Culver, 2001). Recent efforts at documenting biodiversity in caves of the southeastern United States have begun to confirm both their high biodiversity and high endemism (Culver and others, 2000; Niemiller and Zigler, 2013). As a result, it is crucial to understand the recharge area of cave systems, which delivers water that can affect or negatively impact these sensitive ecosystems. In fluviokarst settings, understanding the recharge area for a cave or spring is critical to mitigate contamination potential and maintain water quality and quantity for sensitive cave biota.

A cooperative project between the U.S. Geological Survey (USGS), U.S. Fish and Wildlife Service (USFWS), and the Kentucky Geological Survey (KGS) was established in December 2019 to conduct dye traces focused on delineating a recharge area for the Fern Cave system in Jackson County, Alabama, to aid in management and preservation of these cave and karst resources. This study took place from December 2019 to May 2021. This report documents the mapping of karst groundwater flow paths and delineation of recharge areas for Fern Cave, Alabama, through the use of dye tracing.

Setting

Fern Cave is located in Nat Mountain in the Paint Rock Valley of Jackson County, Alabama (fig. 1). Nat Mountain is a highly dissected lobe of the Cumberland Plateau (Fenneman, 1938), bounded on the north and west by the Paint Rock River and bordered to the south by Yellow Branch in Peters Cove. The study area extends along the western portion of Nat Mountain from Hales Cove (to the north) to Splitrock Mountain (to the south). The base level stream for the area is the Paint Rock River, which forms the western border of the study area and has a drainage area of approximately 300 square miles (mi^2; 777 square kilometers [km^2]) upstream from the stream resurgences that flow from Fern Cave (U.S. Geological Survey, 2019b). The gage at the Paint Rock River at Woodville (USGS station number 03574500; U.S. Geological Survey, 2019c, 2020) had a stage range from 1.53 to 18.61 feet (ft) above datum (datum of gage is 570.95 ft above the National Geodetic Vertical Datum of 1929 [NGVD 29]), between December 2019 and May 2021, the duration of this study. Higher stage levels indicate large flood events and result in major changes in hydrologic gradients between the surface and groundwater systems (U.S. Geological Survey, 2019c, 2020). The vertical relief of Nat Mountain is approximately 1,000 ft (305 meters [m]), ranging from 590 to 1,600 ft (180–488 m) above NGVD 29 (U.S. Geological Survey, 1997). Land use on Nat Mountain is dominated by deciduous forests (Dewitz and U.S. Geological Survey, 2019).

The geology of Nat Mountain was mapped and described by the Geological Survey of Alabama (Osborne and others, 2013). Nat Mountain is capped by the Pottsville Formation of Early Pennsylvanian age, a 200-ft-thick (61-m) quartzose sandstone that is occasionally conglomeratic with interbeds of shales. Beneath the Pottsville Formation is the Pennington Formation of Late Mississippian age, a lithologically variable unit that consists of interbeds of sandstone, limestone, chert, dolomite, and shale that is approximately 300 ft (91 m) thick beneath Nat Mountain. The presence of carbonate interbeds within the Pennington Formation creates karstified intervals, which result in springs discharging from the base of the formation at its contact with the underlying Bangor Limestone. The Bangor Limestone (Upper Mississippian) is a 300-ft-thick (91 m) unit beneath Nat Mountain that may have interbeds of chert in the upper part and shale in the lower part. The Hartselle Sandstone (Upper Mississippian) underlies the Bangor Limestone; however, it is absent or so thin in the study area that it is typically unmapped. There does appear to be some hydrologic control from the Hartselle Sandstone at locations along the flanks of Nat Mountain where its presence and limited vertical permeability may create small springs that issue from the upper contact of the formation and that sink into the subsurface a short distance from the point of issuance. The Monteagle Limestone (Upper Mississippian) underlies the Hartselle Sandstone and is a 180- to 220-ft-thick (55–67 m), massively bedded limestone that is extensively karstified throughout the study area. The Tuscumbia Limestone of Middle Mississippian age underlies the Monteagle Limestone and forms the base of Nat Mountain and the valley floor of Hales Cove. The Tuscumbia Limestone contains chert nodules and stringers, and only has 20–40 ft (6–12 m) of exposure thickness in the study area.

The Fern Cave system (fig. 2) is the longest mapped cave in Alabama, with a total surveyed length of 15.6 mi (25.1 km) and a depth of 536 ft (163 m) (Gulden, 2021). The cave is comanaged by the U.S. Fish and Wildlife Service and the Southeastern Cave Conservancy Inc. The cave has five entrances and a diversity of passage morphologies that provide a wide range of subterranean environments for native biota. The cave is known for two primary features, a 437-ft (133-m) deep, voluminous pit that is popular with recreational cavers; and the largest known Myotis grisescens (gray bat) hibernacula in the world, containing over 1.5 million bats (Martin, 2007). Much of the cave is dry; however, there are at least three distinct subsurface streams (Lower North Cave Stream, Surprise Stream, and Bottom Cave Stream) within the cave system that originate as surface streams from different areas on top of the Cumberland Plateau and that issue to springs along the east bank of the Paint Rock River. Although many of the passages in Fern Cave have floors with steep gradients, Bottom Cave and its associated stream are relatively flat-lying and contain flood debris, suggesting backwater inundation flooding from the Paint Rock River in the lower portions of the system. Because of the variety of its niche habitats, Fern Cave has recently been recognized as having the second highest troglobitic diversity of any cave in the southeastern United States, second only to that of Mammoth Cave in Kentucky (T. Inebnit, oral commun., 2021; M. Niemiller, written commun., 2022). Currently, 113 taxa, including 25 cave obligates, are known to inhabit the Fern Cave system. Species that are susceptible to impacts from water quality and of particular concern to managers are the Orconectes australis (southern cave crayfish), Typhilichthys subterraneus (southern cavefish), and the endangered Palaemonias alabamae (Alabama cave shrimp) (Niemiller and others, 2019).

Methods

A detailed inventory of hydrologic features in the Fern Cave area was conducted at the beginning of the study to identify springs, seeps, and sink points that might be important sites for dye traces, including dye detection monitoring and injection locations (table 1). Sites selected for dye detection (fig. 3 and table 1) were monitored using weighted receptors containing activated coconut charcoal tied to a wire and placed directly in the flow of the stream or feature being monitored. These receptors were changed intermittently, at daily to weekly intervals, following dye injections to aid in determining the approximate travel time from each dye injection point to recovery location.

Once monitoring sites were identified, initial dye-injection locations were chosen with the goal of identifying flow paths into and through Fern Cave and those that flow away from the cave. Subsequent dye-injection locations were chosen on the basis of the results of the previous dye injection rounds, with each location chosen with the goal of understanding the potential boundaries of the drainage area feeding Fern Cave. Dye injections (table 2) utilized four nontoxic fluorescent dyes (fluorescein, eosine OJ, rhodamine WT, and sulphorhodamine B) that were injected into losing streams, swallets, cave streams, and one as a dry set, where dry, powdered dye was placed in a polyvinyl chloride (PVC) pipe that was staked to the streambed. The dry set was left in place for subsequent rainfall to wash the dye into the groundwater system. The dyes used in this study are commonly used in karst groundwater-tracing studies, because each dye fluoresces at a unique wavelength when exposed to light, and the fluorescence wavelength can be identified through laboratory analyses at concentrations as low as 5 parts per billion (Currens, 2013).

Following retrieval of the dye receptors, processing and analysis were conducted at the Kentucky Geological Survey Water Laboratory in Lexington, Kentucky, on a Cary Eclipse fluorescence spectrometer using established protocols (Currens, 2013). Once positive traces were confirmed, results were plotted in a geographic information system (GIS) spatial framework to begin delineating the recharge area of the cave. Additional information related to methods used for the study is included as part of the metadata within a separate USGS data release of the dye-tracing data for this study (Miller and others, 2023).

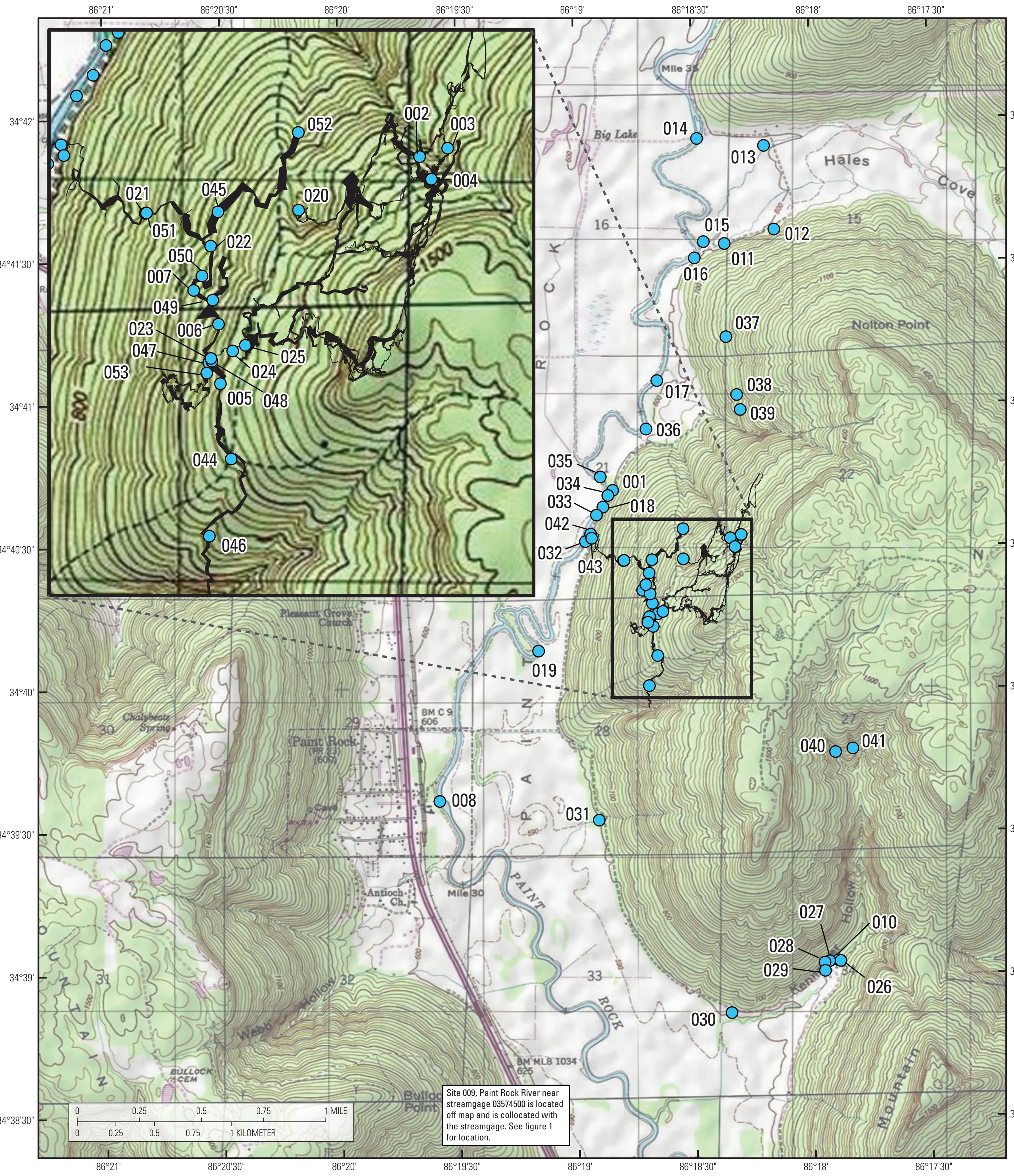
From these dye traces, a recharge area, also known as a groundwater basin for Fern Cave was delineated by following topographic divides between the injection points for positive traces in Fern Cave and positive traces that were detected at monitoring locations outside of the cave system. When dye from an injection was not detected in Fern Cave but was detected at an adjacent monitored discharge feature, then that point was used as a groundwater basin divide. Following delineation of a recharge area, boundaries were drawn with both defined and interpreted boundaries. Defined boundaries surround areas underlain by relatively insoluble strata (sandstone or shale) and indicate areas unlikely to be karstified, thus the boundaries follow topographic boundaries. Interpreted boundaries lie along portions of the recharge area boundary underlain by soluble bedrock (limestone) and where groundwater recharge may not follow topographic boundaries because of karstification of the underlying bedrock. Although dye tracing is a proven method for delineating groundwater basins in karst terrain, this method may be limited by hydrologic conditions that occur during tracing, such as precipitation heterogeneity and changes in groundwater or stream levels that can cause basin divides to shift laterally depending on ambient conditions.

In addition to the work focused on delineating the groundwater basin(s), a round of dye injections was conducted in May 2021 to identify the connection between streams within Fern Cave. For these injections, dye was injected directly into the Surprise Stream and Lower North Stream, and cave streams downstream from the injection sites were monitored throughout the cave system (table 2). Some subsurface flow paths were able to be accurately represented using cave survey data provided by the Fern Cave Project (Steve Pitts, written commun., 2021). The Fern Cave Project had conducted surveys of the cave system using handheld instruments, fiberglass tapes, and had manually collected data related to passage dimensions and speleological features present at the time of survey. These data were then used by this project to determine cave stream pathways and accurately gain elevational data for the monitoring sites established in the cave. At the time of publication, these data were not publicly available (Steven Pitts, Fern Cave Project, written commun., 2021).

Table 1. Monitoring sites (Miller and others, 2023).

[Elevations are referenced to the National Geodetic Vertical Datum of 1929. CV, cave stream; SP; spring; ST, surface stream, Hwy, highway; ft, foot]

Site number	Site name	Site type	Elevation (ft)
001	Haley Spring	SP	585
002	Lower North Cave stream at base of 155 pit	CV	857
003	Lower North Cave site 2, at small infeeder, mid-site	CV	843
004	Lower North Cave stream above cascades	CV	840
005	Bottom Cave main stream at reed torches	CV	604
006	Bottom Cave main stream at station PU12	CV	600
007	Bottom Cave side tributary stream at PU19	CV	600
008	Paint Rock River at Paint Rock Canoe and Kayak take out	ST	580
009	Paint Rock River near streamgage 03574500	ST	575
010	Kennamer Spring	SP	615
011	Roadside Spring	SP	600
012	Big Spring	SP	605
013	Boiling Spring	SP	595
014	Paint Rock River at Jones Bridge	ST	595
015	Hales Cove failsafe	ST	590
016	Paint Rock River downstream of Hales Cove	ST	590
017	Paint Rock River due west of Nolton Point	ST	588
018	Lower North/Bottom Cave Spring	SP	585
019	Paint Rock River at Log Jam Island	ST	583
020	Surprise Karst Window spring	SP	1,140
021	Bottom Cave stream downstream from last tributary	CV	591
022	Bottom Cave main stream, mid-site	CV	591
023	Bottom Cave tributary. Waterfall Dome Route & North Cave streams	CV	595
024	Unnamed stream dropping into 100 ft pit in Jericho Passage	CV	717
025	Dripping dome in Jericho Pit, West Room	CV	752
026	Kennamer Hollow upstream from Kennamer Spring	ST	615
027	Small spring with dam near Kennamer Spring	SP	612
028	Waterfall stream near Kennamer Spring	ST	630
029	Kennamer Hollow, downstream of road	ST	610
030	Nat Overflow Spring	SP	600
031	Unnamed wet weather stream downstream from road	ST	600
032	Paint Rock River downstream from Fern Overflow Springs	ST	585
033	Paint Rock River upstream from Fern Overflow Springs	ST	585
034	Paint Rock River downstream from Haley Spring, upstream from 018	ST	585
035	Paint Rock River upstream from Haley Spring	ST	585
036	Paint Rock River downstream from 017	ST	585
037	Northern perched spring near Nolton Point	SP	860
038	Central perched spring near Nolton Point	SP	840
039	Southern perched spring near Nolton Point	SP	840
040	West branch of Kennamer Hollow	ST	1,180
041	East branch of Kennamer Hollow	ST	1,140
042	Fern Overflow Spring 1	SP	590
043	Fern Overflow Spring 2	SP	595
044	Bottom Cave main stream, 500 ft upstream from Reed Torches	CV	618
045	Disappointment Passage, Bottom Cave side	CV	578
046	Bottom Cave main stream, 1,500 ft upstream from Reed Torches	CV	527
047	Bottom Cave main stream upstream from 023	CV	595
048	Bottom Cave main stream downstream from datalogger	CV	595
049	Bottom Cave main stream at entrance to large side passage on right	CV	598
050	Unnamed left side tributary to Bottom Cave main stream	CV	604
051	Unnamed right side tributary to Bottom Cave main stream	CV	591
052	Surprise Stream at climbdown past Earthquake Room	CV	578
053	Wilson Dome stream	CV	616



Base from U.S. Geological Survey digital data 2022, 1:24,000
Universal Transverse Mercator projection, zone 16
North American Datum of 1983

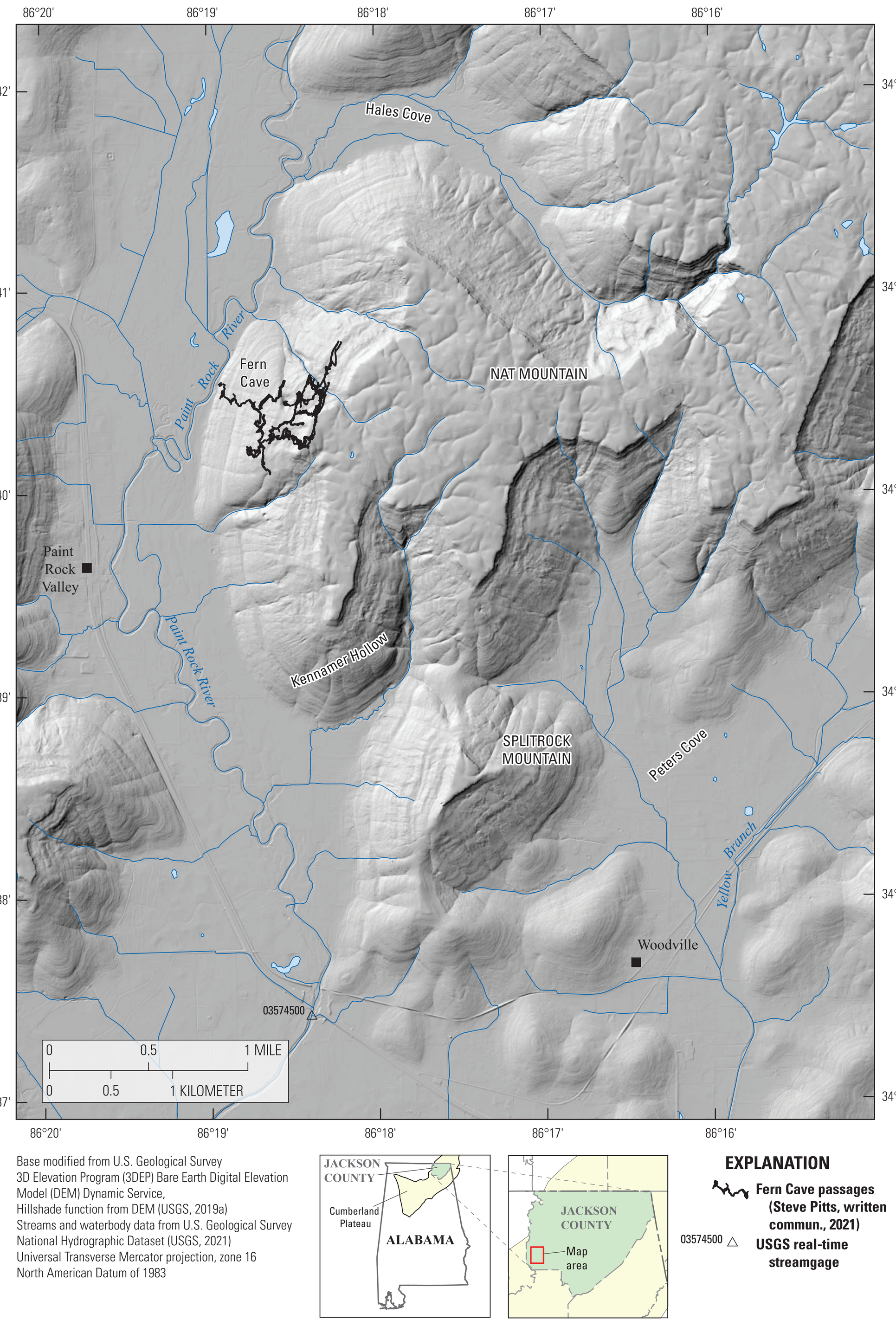
Fern Cave survey data provided by Steve Pitts (Fern Cave Project, written commun., 2021)

EXPLANATION

Fern Cave passages (Steve Pitts, written commun., 2021)

030 Monitoring site and number

Figure 3. Locations of monitoring sites utilized for this study. Site numbers correspond to those listed in table 1.



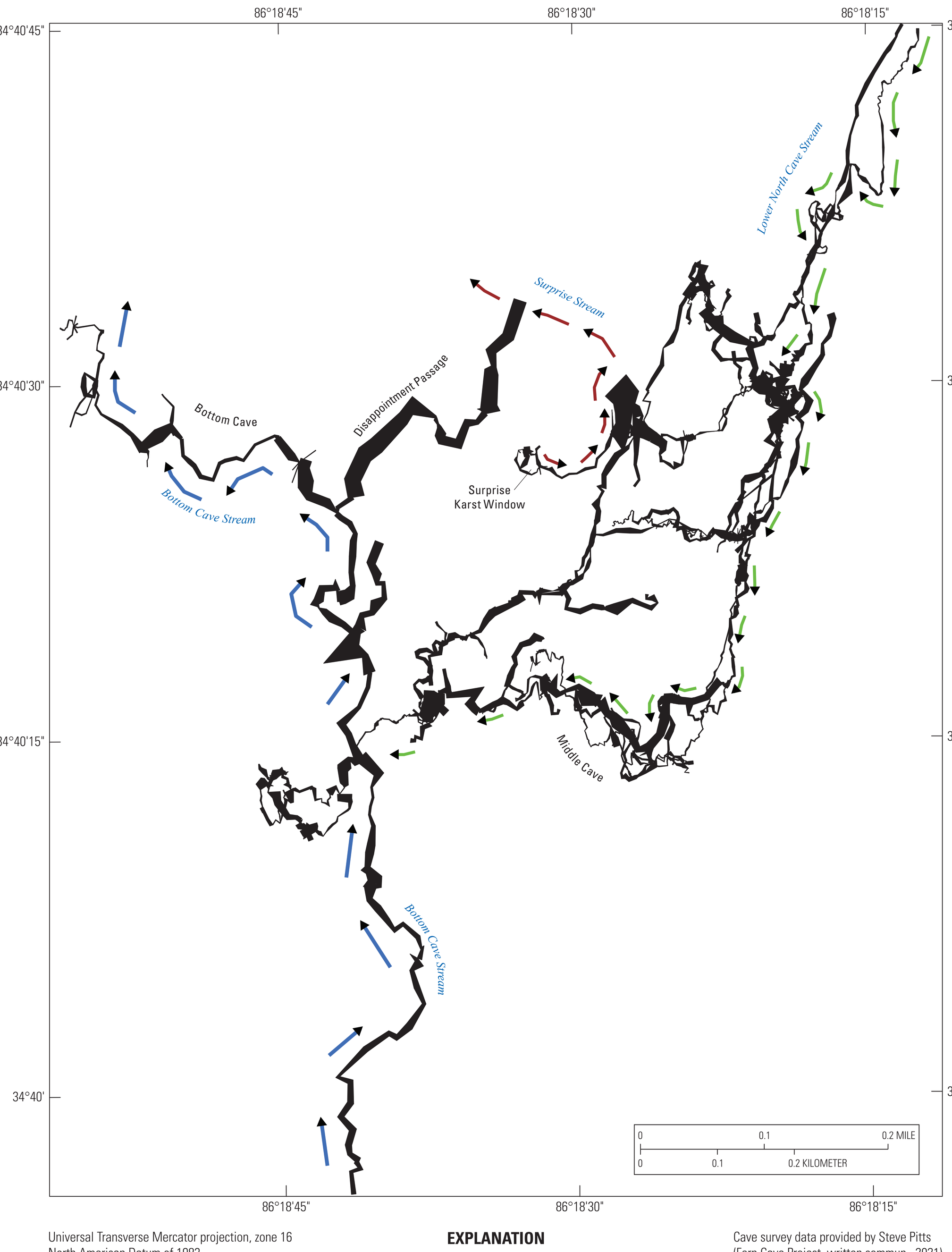
Base modified from U.S. Geological Survey
3D Elevation Program (3DEP) Bare Earth Digital Elevation Model (DEM) Dynamic Service,
Hillshade function from DEM (USGS, 2019a)
Streams and waterbody data from U.S. Geological Survey National Hydrographic Dataset (USGS, 2021)
Universal Transverse Mercator projection, zone 16
North American Datum of 1983

EXPLANATION

Fern Cave passages (Steve Pitts, written commun., 2021)

03574500 USGS real-time streamgage

Figure 1. General location of study area.



Universal Transverse Mercator projection, zone 16
North American Datum of 1983

Cave survey data provided by Steve Pitts (Fern Cave Project, written commun., 2021)

EXPLANATION

Fern Cave passages (Steve Pitts, written commun., 2021)

Flow direction
Lower North Cave stream
Surprise stream
Bottom Cave stream

Figure 2. Generalized layout of Fern Cave passages showing locations and flow directions of major cave streams.

Table 2. Dye injections and positive traces (Miller and others, 2023).

[Elevations are referenced to the National Geodetic Vertical Datum of 1929. Dates are shown in month, day, year format. lb, pound; kg, kilogram; ft, foot; m, meter; us, upstream; ds, downstream; nr, near; h, hour; min., minute; >, greater than; --, not applicable]

Round number	Injection ID	Injection setting	Elevation (ft)	Elevation (m)	Strata	Injection date	Flowing water present	Dye injected	Amount injected (lb)	Amount injected (kg)	Recovery sites (site numbers)	Elevation (ft)	Elevation (m)	Strata	Date recovered	Dye concentration
1	I-1	Streambed, small seep, sinking immediately	1,200	365.8	Pennington Formation	12/9/2019	Yes	Sulphorhodamine B	2	0.9	Bottom Cave sites (005,022), Fern Cave Overflow Spring 2 (043)	604–591	184–180	Pennington - Tuscumbia	2/16/2020	>10x background intensity
1	I-2	Streambed, flowing, sinking 50 ft ds	1,400	426.7	Pennington Formation	12/9/2019	Yes	Eosine OJ	2	0.9	Surprise Karst Window Spring (020), Haley Spring (001)	1,140–585	347–178	Pennington - Tuscumbia	12/16/2019	>10x background intensity
1	I-3	Streambed, flowing, sinking 100+ ft ds	1,060	323.1	Bangor Limestone	12/10/2019	Yes	Rhodamine WT	2	0.9	Lower North Cave Stream (004), Lower North/Bottom Cave Spring (018)	840–585	259–178	Bangor - Tuscumbia	2/18/2020	>10x background intensity
2	I-4	Streambed, seep, us from open swallet/cave	1,100	335.3	Bangor Limestone	3/14/2020	Yes	Eosine OJ	3	1.35	Northern Perched Spring (037), Central Perched Spring (038), Haley Spring (001)	850–585	259–178	Monteagle - Tuscumbia	3/15/2020	>10x background intensity, visual confirmation at 001
2	I-5	Cave stream, dropped 20+ ft in elevation down crack	1,050	320.0	Bangor Limestone	3/14/2020	Yes	Sulphorhodamine B	2	0.9	Central Perched Spring (038), Southern Perched Spring (039), Haley Spring (001)	850–585	259–178	Monteagle - Tuscumbia	4/28/2020	>10x background intensity, visual confirmation at 001
2	I-6	Streambed, flowing,	1,400	426.7	Pennington Formation	3/14/2020	Yes	Rhodamine WT	1.5	0.675	Kennamer Spring (010), Nat Overflow Spring (030)	615–600	187–183	Pennington - Tuscumbia	4/28/2020	>10x background intensity
2	I-7	Streambed, flowing, sinking immediately	1,160	353.6	Pennington Formation	3/14/2020	Yes	Fluorescein	1	0.45	Not detected at any monitoring sites	--	--	--	--	--
3	I-8	Dry streambed, dry set utilized	1,100	335.3	Bangor Limestone	7/28/2020	No	Fluorescein	1	0.45	Not detected at any monitoring sites	--	--	--	--	--
3	I-9	Swallet, no flow, 20 ft deep	1,040	317.0	Bangor Limestone	7/28/2020	No	Rhodamine WT	2	0.9	Big Spring (012), Roadside Spring (011)	605–600	184–183	Bangor - Tuscumbia	9/24/2020	>10x background intensity
3	I-10	Streambed, nonflowing pool	1,140	347.5	Pennington Formation	7/28/2020	No	Eosine OJ	3	1.35	Bottom Cave sites (005,021,022)	604–591	184–180	Monteagle - Tuscumbia	8/8/2020	>10x background intensity
3	I-11	Streambed, nonflowing pool	1,090	332.2	Bangor Limestone	7/28/2020	No	Sulphorhodamine B	2	0.9	Bottom Cave sites (005,021,022)	604–591	184–180	Bangor - Tuscumbia	8/8/2020	>10x background intensity
4	I-12	Cave stream, Lower North Cave Stream nr Cascades	840	256.0	Bangor Limestone	5/18/2021	Yes	Rhodamine WT	2	0.9	Bottom Cave sites (021,022, 047, 049), Fern Cave Overflow Spring 1 (042), Lower North/Bottom Cave Spring (018)	598–585	182–178	Monteagle - Tuscumbia	5/19/2021	>10x background intensity, Visual confirmation at 042, 047
4	I-13	Spring that immediately sinks into swallet	1,140	347.5	Pennington-Bangor	5/19/2021	Yes	Fluorescein	0.5	0.225	Disappointment Passage stream (052), Haley Spring (001)	585	178	Monteagle - Tuscumbia	5/19/2021, 2 h 47 min[1]	>10x background intensity, Visual confirmation at 001, 052
4	I-14	Small karst window, spring flows 40 ft into swallet	1,140	347.5	Bangor Limestone	5/22/2021	Yes	Eosine OJ	2	0.9	Bottom Cave sites (005,021,022,023,046), Nat Cave (030), Waterfall Stream (027), Small Spring with Dam (028)	630–591	192–180	Monteagle - Tuscumbia	6/23/2021	>10x background intensity

[1]Time period for dye trace was short enough to require the use of hours and minutes.

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U.S. Geological Survey, 2019, USGS water-year summary 2019—03574500 Paint Rock River near Woodville, AL, in USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN. [Site information directly accessible at https://nwis.waterdata.usgs.gov/nwis/wys_rpt?dv_ts_ids=&2629&adr_begin_date=2018-10-01&adr_end_date=2019-09-30&site_no=03574500&agency_cd=USGS.]

U.S. Geological Survey, 2020, USGS water-year summary 2020—03574500 Paint Rock River near Woodville, AL, in USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN. [Site information directly accessible at https://nwis.waterdata.usgs.gov/nwis/wys_rpt?dv_ts_ids=&2629&adr_begin_date=2019-10-01&adr_end_date=2020-09-30&site_no=03574500&agency_cd=USGS.]

Mapping Karst Groundwater Flow Paths and Delineating Recharge Areas for Fern Cave, Alabama, Through the Use of Dye Tracing

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Results

From December 2019 through May 2021, four rounds of dye injections, encompassing 14 individual dye injections, were conducted to delineate the recharge area for the Fern Cave system. The first round of dye injections (injections I-1 to I-3; fig. 4, tables 1 and 2) focused on areas directly adjacent to known cave system passages. Three injections were conducted during December 9–10, 2019, with dye injections taking place north, south, and east of known cave passages. Injection I-1 (south of the cave) was conducted at a small seep in a losing stream that was traced to two sites along Bottom Cave Stream (fig. 3, sites 005 and 022) then to Fern Cave Overflow Spring 2 (site 043). Injection I-2 was conducted from a ravine east of the known cave, where flowing water was located above a sinking waterfall. This site was positively traced to the spring at Surprise Karst Window (site 020) and then traced to Haley Spring (site 001). Injection I-3 was conducted along a losing stream with flowing water located north of the known cave. This site was positively traced to the Lower North Cave Stream (site 004) and then to a wet weather spring located ~ 500 ft (~150 m) downstream from Haley Spring along the east bank of the Paint Rock River (site 018).

The second round of dye injections was conducted on March 14, 2020 (injections I-4 to I-7; fig. 4, tables 1 and 2). These traces focused on extending the recharge area boundaries north and south of the cave system, while also attempting to determine if any hydrologic connection exists between the upper reaches of Kennamer Hollow and Fern Cave. Injection I-4, located north of I-3, was conducted at a seep within a ravine directly upslope from an open swallet accepting all streamflow. Injection I-5, located south of I-4 and north of I-3, was conducted at a flowing cave stream 50 ft below land surface. Dye from both I-4 and I-5 was observed discharging from Haley Spring (site 001) less than 24 hours post-injection, confirmed both visually (fig. 5) and later with spectrofluorometric analysis. Additionally, these two injections (I-4 and I-5) were traced to a series of perched springs (sites 037, 038, 039) on the hillslope ~200 ft below the injection sites. Injection I-6 was located in the western arm of Kennamer Hollow and the dye was later observed sinking into an open swallet. Injection I-6 was positively traced to Kennamer Spring (site 010) and Nat Overflow Spring (site 030), indicating that the area is within a different groundwater basin from the Fern Cave system, delineating a recharge area boundary southeast of the cave. Injection I-7 was conducted at a small karst window ~3,100 ft (945 m) south of injection I-1. This injection was not positively traced to any of the established monitoring sites both in-cave or on the surface.

Figure 5. Visual confirmation of eosine OJ and sulphorhodamine B (determined via charcoal packets) at Haley Spring (monitoring site 001), March 15, 2020. Photograph by Ben Miller, U.S. Geological Survey.

The third round of dye injections was conducted on July 28, 2020 (injections I-8 to I-11, fig. 4, tables 1 and 2). These traces were conducted to establish extensions of the recharge area with coupled injection sites north and south of the previously delineated area. The northern sites (I-8 and I-9) are both located in wet-weather stream ravines northwest of Nolton Point. Because of the dry conditions present at the time of injection, a dry set was utilized at site I-8, and dye was placed in the bottom of a dry stream swallet at I-9. Dye from injection I-8 was not recovered at any of the monitoring sites in the study area. Site I-9 was positively traced to both Big Spring (site 012) and Roadside Spring (site 011). This trace provided the necessary information to delineate the northern boundary for the Fern Cave recharge area. The southern injection sites (I-10 and I-11) are located south of the previously delineated recharge area, and dye was injected into small pools at each site (fig. 6). Injections I-10 and I-11 were both positively traced to the Bottom Cave stream in Fern Cave (sites 005, 021, 022). These traces extended the recharge area for the cave system to the southern end of Nat Mountain and nearly to the southwestern topographic divide with Kennamer Hollow.

Figure 6. Injection of fluorescent dye at injection site I-10, July 28, 2020. Photograph by Ben Miller, U.S. Geological Survey.

The fourth and final round of injections was conducted during May 18–22, 2021 (Injections I-12 to I-14; fig. 4, tables 1 and 2), to define some of the hydrologic connections within the Fern Cave system, and to expand the recharge area and better define a groundwater basin divide with the Kennamer system. Injection I-12 was conducted in the Lower North Cave Stream, downstream from monitoring site 004 (Lower North Cave Stream above cascades) (fig. 7). Dye from I-12 was visually confirmed the next day at points in Bottom Cave Stream, at sites downstream from Waterfall Dome Route confluence (sites 018, 021, 022, 042, 047, 049). Injection I-13 was conducted in flowing water immediately downstream from the spring resurgence at Surprise Karst Window (fig. 8). Directly following the injection, the research team travelled in-cave to Bottom Cave Stream and to a flowing stream near the end of the Disappointment Passage (site 052) where the dye was highly visible 2.8 hours post-injection. The dye was also visually confirmed at Haley Spring, 21.4 hours post-injection. Injection I-14 was conducted at a small karst window with flowing water located south of injection I-10. Injection I-14 was positively traced to multiple sites in the Bottom Cave Stream of Fern Cave (sites 005, 021, 022, 023, 046) and to three sites within the Kennamer system (sites 027, 028, 030), though not to Kennamer Spring. This trace provided the first and only identified hydrologic connection between the Fern Cave system and the springs found within the Kennamer system.

Figure 7. In-cave dye injection of rhodamine WT into Lower North Cave Stream (injection site I-12), May 18, 2021. U.S. Geological Survey (USGS) scientists followed all appropriate safety protocols and requirements for working near, on, in, or over water consistent with approved USGS Job Hazard Analysis. Photograph by Brian Ham, used with permission.

Results from the 14 dye injections resulted in a delineated recharge area of 1.73 mi² (4.48 km²) for the Fern Cave system (fig. 4). This system is fed largely by allogenic recharge from the siliciclastic Pottsville Formation above the underlying limestone formations. Because of the lack of karst development in the Pottsville Formation, the eastern portion of the recharge area along the ridgetop was drawn to account for the surface watershed that contributes flow to the dye injection points, with defined boundaries using the topographic divides on the ridgetop. The western boundary of the Fern Cave recharge extends from defined boundaries to the Paint Rock River, encompassing all of the known passages and resurgences for the cave system. This portion of the recharge area is drawn with an interpreted boundary because the underlying limestone is subject to dissolution and may be more likely to deviate from topographic boundaries. The recharge area for the Fern Cave system is bounded on the southeast side by the Kennamer system, with the interpreted location of this boundary confirmed and delineated by traces from injections I-1, I-10, I-11, and I-14. Only one of the injection sites (I-14) was positively traced to both the Fern Cave system and the Kennamer system, implying a small, overlapping section of recharge area for both systems. The Fern Cave recharge area is bounded to the north by recharge areas for Roadside Spring and Big Spring that discharge into Hales Cove, which was confirmed by injection I-9 (Miller and others, 2023).

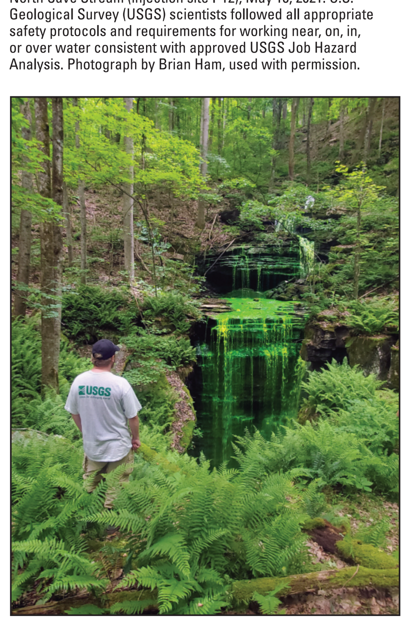

Figure 8. Injection of fluorescein dye into Surprise Karst Window (injection site I-13), May 19, 2021. U.S. Geological Survey (USGS) scientists followed all appropriate safety protocols and requirements for working near, on, in, or over water consistent with approved USGS Job Hazard Analysis. Photograph by Ben Miller, U.S. Geological Survey.

Discussion

The 1.73 mi² (4.48 km²) recharge area for the Fern Cave system is dominated by deciduous forest (98.8 percent of recharge area) with less than 1 percent of the area recognized as shrub/scrub and hay/pasture (Dewitz and U.S. Geological Survey 2021), the next two highest percentage land-use types in the recharge area (table 3). This suggests that there is currently minimal risk for contamination of the karst groundwater system from the current land use types. The dye traces show that most of the drainage area to the Fern Cave system occurs along the western slope of Nat Mountain (fig. 4). Results suggest that multiple perched routes, roughly parallel to the ridgeline, ultimately flow westward to the Paint Rock River and emerge at one of two main springs (sites 001, 018) or to one of the additional two high flow springs (sites 042, 043).

Table 3. Land-use and land cover for the Fern Cave recharge area (Dewitz and U.S. Geological Survey, 2021).

Land use and land cover	Percent of recharge area
Deciduous forest	98.76
Evergreen forest	0.08
Mixed forest	0.22
Shrub/scrub	0.40
Herbaceous	0.16
Hay/pasture	0.38

The in-cave dye injections helped to define the internal stream network in the Fern Cave system. The in-cave trace in the Lower North Cave Stream (injection I-12) confirmed that the stream flows south, descending through the Middle Cave level to join with the Waterfall Dome Route Stream and finally to join the Bottom Cave Stream (figs. 2 and 4), creating the largest stream in the cave system. The dye injection into the Surprise Karst Window (injection I-13) confirmed the connection between Surprise Karst Window (site 020), Disappointment Passage (site 052), and Haley Spring (site 001), and the complete separation of this flow path from the Bottom Cave Stream. The source of the water at Surprise Karst Window was confirmed through an earlier trace from injection site I-2. From site I-2, the water passes over known cave passages, including the stream of Lower North Cave, before resurging at the spring at the upstream end of Surprise Karst Window. Based on this flow configuration, the recharge area for the Surprise Karst Window and Surprise Stream is an isolated portion of the overall Fern Cave recharge area (fig. 4) that is surrounded by the recharge areas for Bottom Cave stream (which includes the Lower North Cave Stream recharge area).

The Surprise Karst Window injection also gave insights into the variability of groundwater velocity in karst systems. For injection I-13, dye was injected into the karst opening at 12:40 p.m. on May 19, 2021. Following this injection, dye was visually observed at the Disappointment Passage at concentrations of 445 parts per billion, 2.8 hours post-injection. The distance the dye traveled from the injection site to the observation point was approximately 0.5 mi (800 m), providing an average velocity of approximately 880 feet per hour (0.07 meters per second). When the team exited the cave and arrived at Haley Spring 9 hours post-injection, the known resurgence point for the stream, dye was not visible and analysis of the dye packets retrieved at this time confirmed the dye had not arrived. The following morning, 21.4 hours post-injection, there were visible dye concentrations in Haley Spring. The straight-line distance from Disappointment Passage to Haley Spring is approximately 0.39 mi (627 m), which indicates a travel time for the dye of between 9 and 18.6 hours. This results in a velocity range of 96–228 feet per hour (0.008–0.019 meter per second). The maximum velocity through this section is only 26 percent of the velocity observed along the upper portion of the total flow path. This variability in velocity may be the result of a lower hydrologic gradient between the two sections of the total flow path. Another potential cause of variable velocity was a series of small storm events that caused the Paint Rock River to rise during the study. Anecdotal evidence, including water level data and river debris in lower portions of the cave stream, suggest that backflooding from the river may reduce flow velocity rates in the lower section of the cave during these storm events. Although this backflooding did not impact the dye trace results, the direct causes of these variances in groundwater velocities are unknown. This behavior within a single cave stream illustrates the dynamic nature of flow in karst groundwater systems.

Summary

A 1.73-square-mile (4.48-square-kilometer) recharge area was delineated for the Fern Cave system in Jackson County, Alabama, using the results from a series of 14 dye traces conducted during 2019–21. The recharge area primarily lies along the western escarpment of Nat Mountain, with the system draining to multiple springs along the Paint Rock River and bounded by the Kennamer system to the southeast and small springs in Hales Cove to the north. Recharge to the system appears to be through a combination of surface-water runoff from the ridgetop of Nat Mountain and groundwater discharging from the Pennington Formation that then sinks immediately into the Bangor Limestone.

In general, land-use types in the recharge area appear to represent a low risk to the water quality and quantity within Fern Cave system, primarily to the biota living within the cave streams and pools. However, future land-use changes, such as increased logging, could require assessment to determine if mitigations are necessary to minimize risk to stream biota. In addition to potential threats from land-use changes on Nat Mountain, further study of the relationship between the Paint Rock River and the lower sections of Fern Cave would help provide a better understanding of how the proximity of a surface stream to these passage impacts biota and affects conditions present in the deepest portion of the cave system. Flow velocity data coupled with anecdotal evidence of backflooding into the cave system suggest that the stygian habitat in the lower portion of the cave may be influenced significantly by the water quality and stage of the Paint Rock River.

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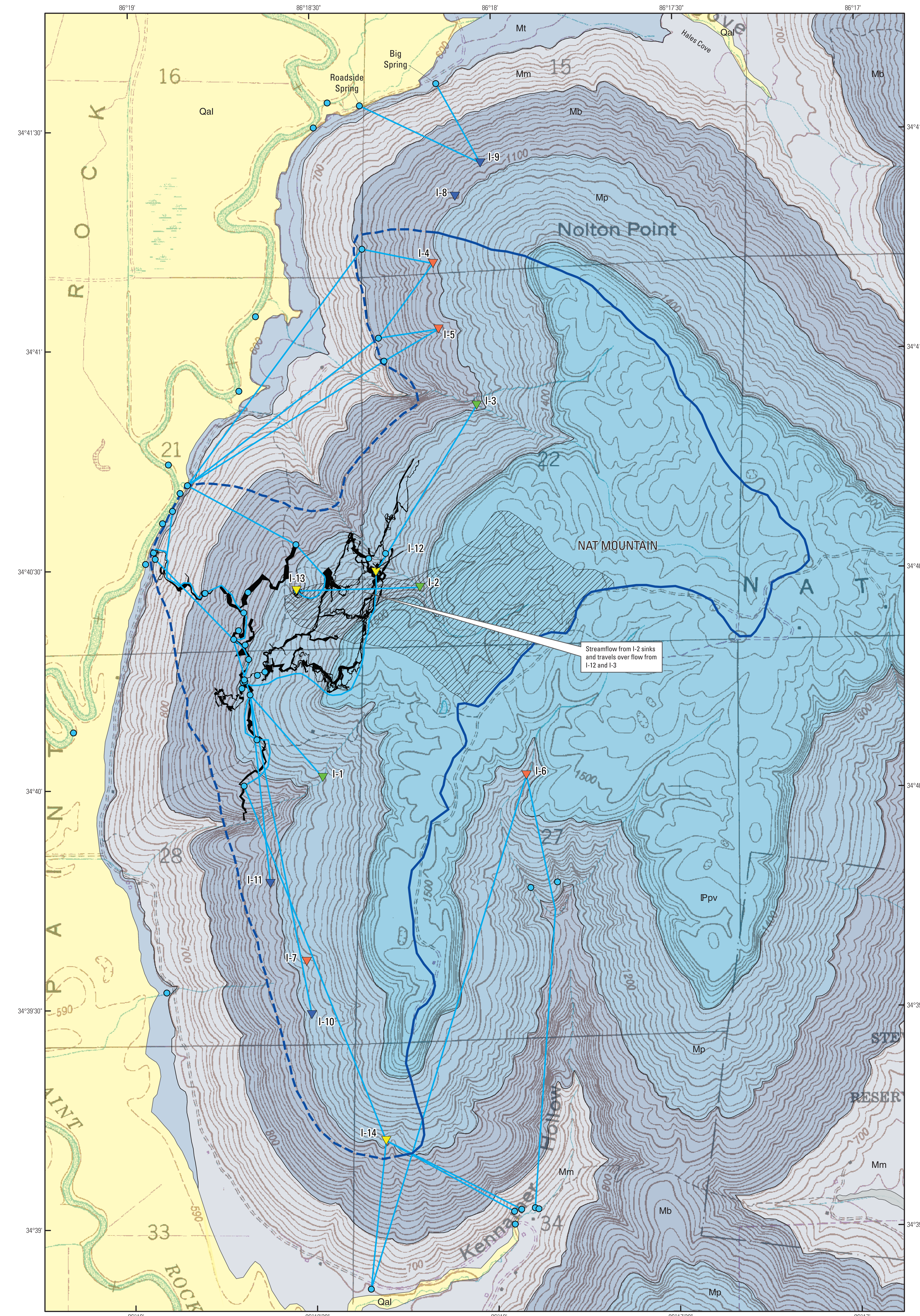

Base from U.S. Geological Survey digital data 2022, 1:24,000
USA topo map copyright 2013 National Geographic
Universal Transverse Mercator projection, zone 16
North American Datum of 1983

0 0.25 0.5 MILES
0 0.25 0.5 KILOMETERS

Fern Cave survey data from Steve Pitts (written commun., 2021);
Bedrock geology modified from Osborne and others, 2013

EXPLANATION

- Surprise Stream recharge area
- **Bedrock Unit**
  - Qal — Alluvium (Quaternary)
  - Ppv — Pottsville Formation (Lower Pennsylvanian)
  - Mp — Pennington Formation (Upper Mississippian)
  - Mb — Bangor Limestone (Upper Mississippian)
  - Mh — Hartselle Sandstone (Upper Mississippian)
  - Mm — Monteagle Limestone (Upper Mississippian)
  - Mt — Tuscumbia Limestone (Middle Mississippian)
- **Fern Cave passages (Steve Pitts, written commun., 2021)**
- **Dye flow path**
- **Fern Cave recharge boundary**—dashed where interpreted
- **Contact**
- **Monitoring site**
- I-2 **Round 1 injection and identifier**
- I-7 **Round 2 injection and identifier**
- I-10 **Round 3 injection and identifier**
- I-14 **Round 4 injection and identifier**

Figure 4. Locations of dye injections, positive dye traces, recharge areas, and surficial bedrock geology. Geology modified from Osborne and others (2013).

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Mapping Karst Groundwater Flow Paths and Delineating Recharge Areas for Fern Cave, Alabama, Through the Use of Dye Tracing

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2023

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