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

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Scientific Investigations Map 3506
Sheet 2 of 2

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 site 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 conducted 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 mi^2 (4.48 km^2) 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 mi^2 (4.48 km^2) 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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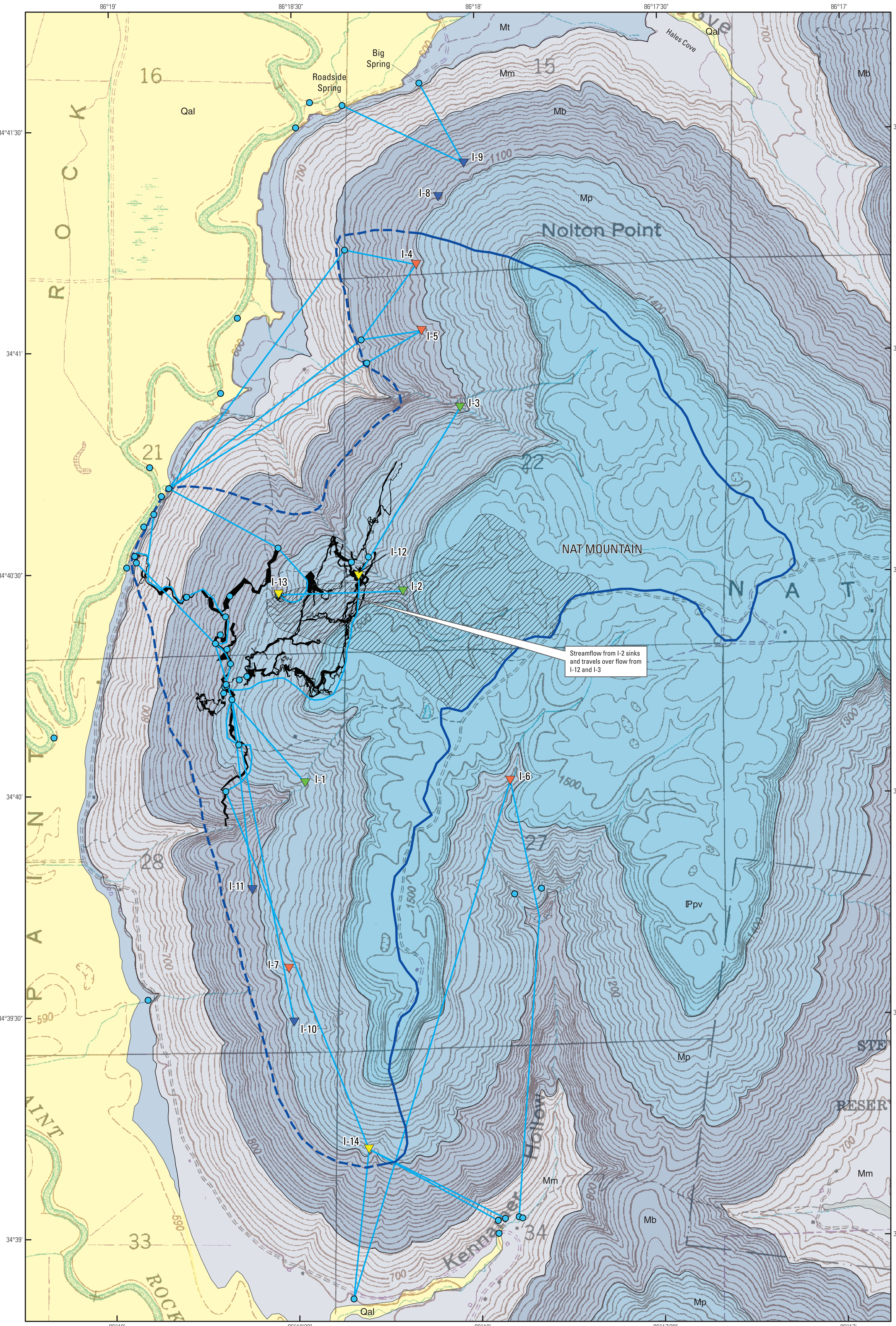

Figure 4. Locations of dye injections, positive dye traces, recharge areas, and surficial bedrock geology. Geology modified from Osborne and others (2013).

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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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