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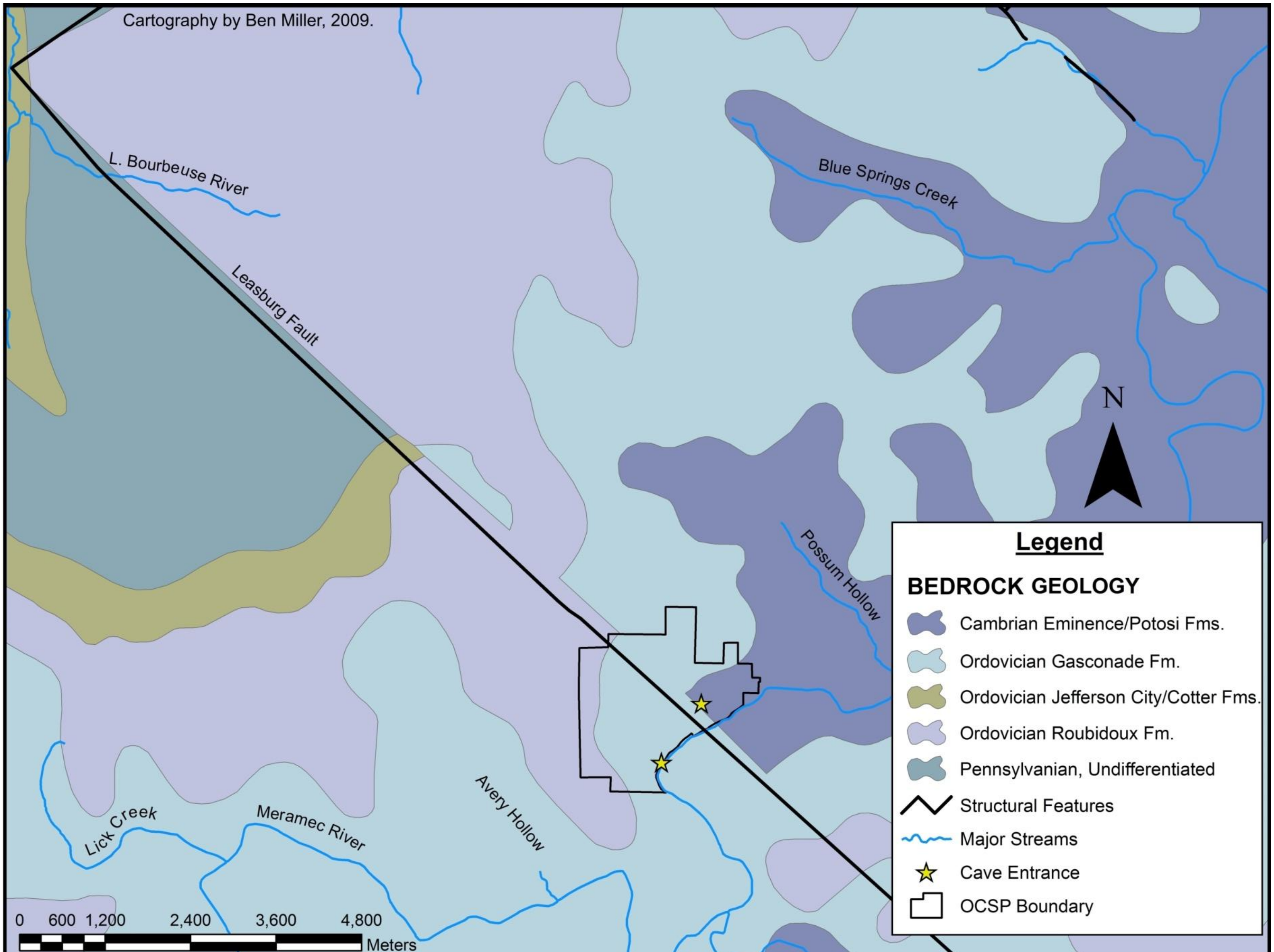
Delineating Recharge Areas for Onondaga & Cathedral Caves using Groundwater Tracing Techniques



MAP 1: GEOLOGIC MAP OF ONONDAGA AND CATHEDRAL CAVE AREA.

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Cover: "Narcissus Dye-Tracing His Visage" (Ben Miller injecting fluorescein into Campground Creek, November 11, 2003.)

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Delineating Recharge Areas for Onondaga and Cathedral Caves Using Groundwater Tracing Techniques

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&

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Abstract

Onondaga Cave and Cathedral Cave are two large, significant cave systems with active streams located along the Meramec River in the Ozarks ecoregion of Missouri. Groundwater dye tracing has delineated recharge areas for both caves in order to aid in the management of the cave systems by Onondaga Cave State Park (OCSP). Dye injection techniques ranged from direct pouring of the dye into streamways to the use of dry sets, and the assistance of fire department tanker trucks. Monitoring of discharge features utilized charcoal receptors placed directly in the discharge feature or stream. Onondaga Cave has a recharge area of approximately 24 km^2, while Cathedral Cave has a recharge area of approximately nine km^2. Each of the cave systems receives the majority of their recharge from losing streams. Onondaga Cave receives recharge largely from Possum Hollow, to the north of the cave. Cathedral Cave receives recharge from tributaries along the eastern side of Avery Hollow. Land uses that may present a threat to water quality in the cave streams, such as intensive row crop production, impervious surfaces, or urbanization, currently account for a minor proportion of impacting land uses. The knowledge gained from this research was incorporated into the cave management plans developed by OCSP personnel. The management plans will guide future land acquisitions and allow for educational programs and materials to be targeted to landowners within the recharge areas. In addition, future changes in land use that may threaten the water quality of the cave streams can be minimized (via negotiation with or education of landowners), or actively opposed by OCSP. The goal of this study is to improve the overall management and preservation of Onondaga Cave and Cathedral Cave as Outstanding Water Resources in the State of Missouri.

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FIGURE 1: GENERAL LOCATION OF ONONDAGA CAVE STATE PARK.

Introduction

Onondaga Cave and Cathedral Cave are two cave systems located in the northern Ozarks of Missouri, which are the centerpiece of Onondaga Cave State Park (OCSP). Both of the cave systems have active streams with perennial flow that act as significant habitats for both endemic and endangered species. Some previous dye tracing in these caves' recharge areas had been attempted, but much of the dye was lost following injection. In addition, the documentation of this work was incomplete, or missing altogether.

In the winter of 2003, a dye tracing project was initiated by park staff to begin delineating the recharge areas for each of these significant cave systems. This research helped to identify what areas directly affect the water quality in the caves, and how much of these areas lay outside the boundaries of the Park. This project was a collaboration between the Missouri Division of State Parks, the United States Department of Agriculture's Agricultural Research Service, and the Missouri Geological Survey. The information obtained from this work assisted the park in managing their cave and karst resources, as well as guiding future land acquisition and education efforts.

Setting and environments

Geographic Setting

Onondaga Cave and Cathedral Cave are located within the Meramec River basin, south of the village of Leasburg in Crawford County, Missouri (Figure 1, page 6). The Meramec River is a large, perennially flowing river which controls the base-level water table of the region. The two caves are located approximately 3.5 kilometers downstream of the confluence of the Meramec River and two of the river's primary tributaries, Huzzah and Courtois Creeks. The entire study area is located in the Ozarks ecoregion (Commission for Environmental Cooperation, 1997) on the Salem Plateau, an expansive plateau largely comprised of Ordovician dolomites and sandstones. The terrain is characterized by steep hills, rock bluffs, and incised stream channels, with a total local relief of approximately 120 meters. Onondaga Cave and Cathedral Cave are in close proximity to one another, with Onondaga Cave to the northeast of Cathedral (Figure 2, page 8). The caves are the focal point of Onondaga Cave State Park, created in 1981 and managed by the Missouri Department of Natural Resources, Division of State Parks (MoDNR, 2008). The 1,317-acre park consists of two management units preserving 5.3 square kilometers (km^2) of land, 28 caves, and multiple springs.

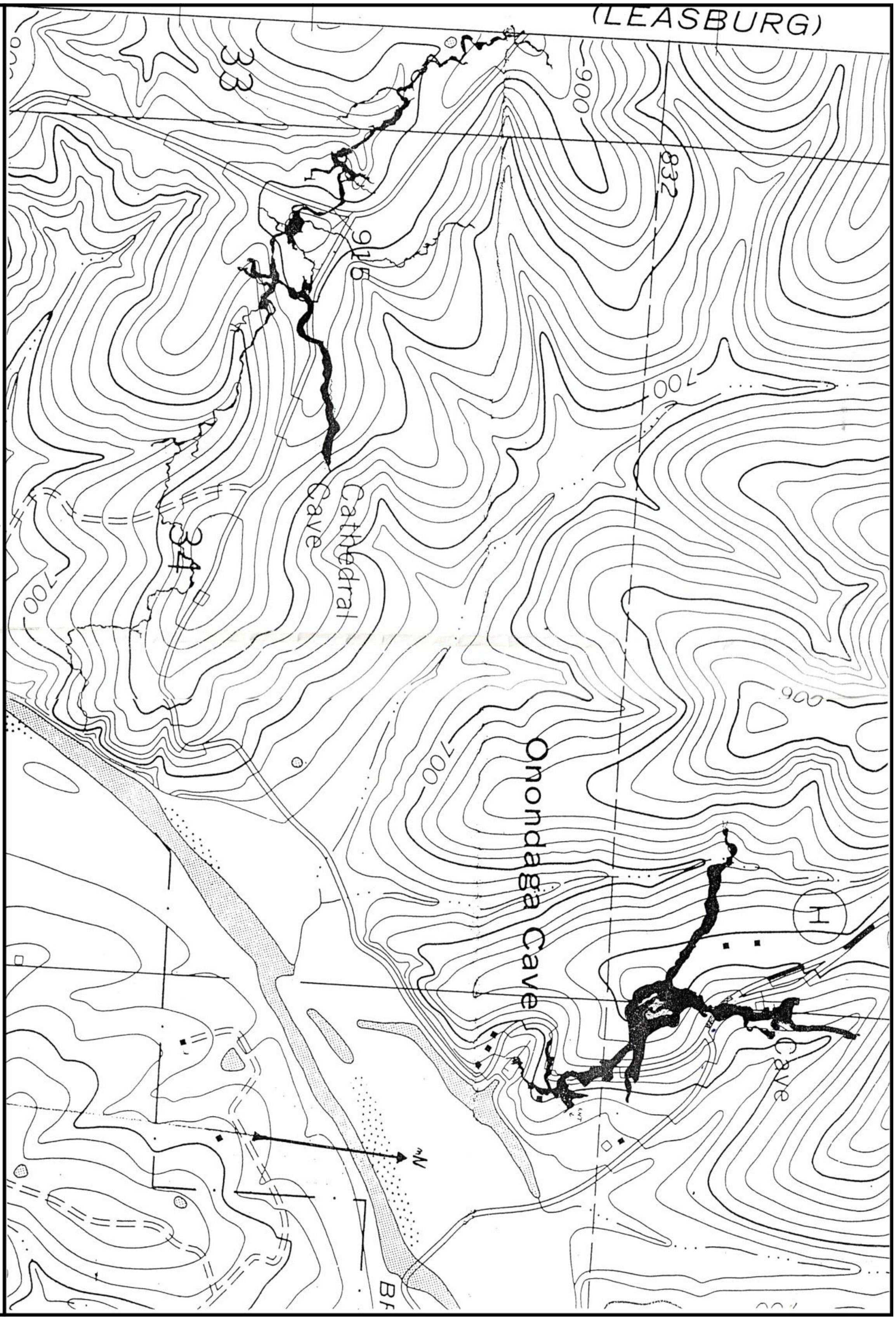


Figure 2: Topographic overlay of Onondaga Cave and Cathedral Cave.

Geologic Setting

The area surrounding Onondaga and Cathedral Caves is dominated by Ordovician and Cambrian dolomites and sandstones (Map 1, page 2). The ridgetops have a thick residuum underlain by the Ordovician-age Roubidoux Formation. The Roubidoux is predominantly a sandstone unit, with intercalated dolomite and chert beds. The Roubidoux Formation lies unconformably on top of the Gasconade Dolomite, a prominent dolomite unit up to 213 meters thick. The Gasconade Dolomite is a medium to coarsely crystalline dolomite with numerous chert beds interspersed throughout the unit (Thompson, 1995). The Gasconade is commonly split into three distinct members: the Upper Gasconade, the Lower Gasconade, and the Gunter Sandstone. Members of the formation vary by grain size, percentage of chert, and mineral composition. Both Onondaga Cave and Cathedral Cave are primarily formed within the Gasconade Dolomite. The Gunter Sandstone at the base of the Gasconade Formation lies unconformably on top of the Cambrian-age Eminence Formation. The Eminence is a massively bedded dolomite with some chert blocks, which can reach a total thickness of 107 meters.

Within the study area, and in close proximity, are several structural features. These range from a complex, crypto-explosive features, such as the Crooked Creek Structure, to simpler features like the Cuba Graben. One significant structural feature, the Leasburg Fault, runs for 20 kilometers through the study area, oriented northwest-southeast, before changing strike north of Leasburg and extending for another 40 kilometers (McCracken, 1971). The fault has an offset of 13.7 meters in the vicinity of Onondaga and Cathedral Caves (Froning, 1971). There are typically few surface expressions of the Leasburg fault, with the exception of a few outcrops and one cave with some visible distortion in the Huzzah Conservation Area.

Cave and Karst Features

Onondaga Cave and Cathedral Cave are significant cave systems, both in terms of length of passage and biodiversity. Onondaga Cave contains approximately 2.9 kilometers of mapped passage, one of the largest rooms in the state of Missouri, and is profusely decorated with speleothems (NSS Geo2 Long & Deep Cave Lists, 2011). Onondaga Cave also contains a large stream called Lost River, which has an average daily base flow rate of 195 liters per second (L/s), or 6.9 cubic feet per second (ft^3/s) (Flynn et al., 2009). This stream discharges from the natural entrance of the cave system to flow down a spring branch to the Meramec River. Cathedral Cave is an extensive stream cave with approximately 4.8 kilometers of passage, large passage dimensions, and a variety of speleothem deposits. An active cave stream flows through the majority of the cave system, with a base flow of 11 L/s (0.4 ft^3/s) (Flynn et al., 2009).

All of the surrounding study area near Onondaga and Cathedral Caves is karst topography. More than 60 caves have been documented within a five-kilometer radius of Cathedral Cave, ranging in length from 15.2 meters to more than 2.8 kilometers (MSS Cave

Database, 2011). Springs are also common in the area. Many of these springs are smaller, less than 14 L/s (0.5 ft^3/s), and discharge from cave entrances (personal observation). However ,there are a few larger springs in the study area, namely Saranac Spring, McKee Spring, and Blue Spring. Each of these larger springs has substantial recorded flow that can range upward of 43-198 L/s (1.5-7 ft^3/s), depending on the individual spring (Vineyard and Feder, 1974). Sinkhole development is not as common, and appears to be primarily restricted to isolated features on ridgetops. One prominent sinkhole is Snake Pit (Figure 3, page 15), near Leasburg, which is a large collapse sinkhole formed at the contact of the Gasconade Dolomite and the overlying Roubidoux Formation. It may be related to the Leasburg Fault. One of the more distinctive characteristics of the Onondaga karst area is the large number of losing streams, many of which only have visible surface flow in flood stage. Some of these losing streams have some flow in portions of the streambed, but these extents typically are restricted to only a few hundred meters before the stream loses again. Avery Hollow is an example of this type of setting (personal observation). The areas near Onondaga Cave and Cathedral Cave are a complex system of recharge and discharge features, all contributing to the overall karst hydrology of the region.

Statement of problem

In managing a resource such as a cave, knowing and understanding the hydrology of the cave as well as the surrounding area is crucial. Too often, land managers only manage the entrance of the cave, or only the area above known cave passages. However, in karst topography, factors such as agriculture and urban development can affect the water quality of caves or springs from several kilometers away. Maintaining a high level of water quality is necessary to ensuring the health and diversity of fragile cave biota.

In the case of Onondaga Cave and Cathedral Cave, the streams in the caves have been designated Outstanding Water Resources by the State of Missouri, a designation that recognizes the importance of these cave streams as habitat for cave-adapted organisms. To properly manage and preserve the caves and their water resources, park staff decided to delineate the recharge area of both cave systems using dye tracing techniques. In the event of a dramatic drop in water quality or a loss of biological diversity, this information would provide the park with an area to examine for potential contamination sources. The results of this project were then used to develop cave management plans that could focus landowner education efforts and future land acquisition within the delineated recharge areas.

Methodology

A simple karst hydrologic inventory was completed at the onset of each round of dye tracing to investigate any major resurgences and also to identify potential injection locations that might have visible stream flow. Since outside funding was not obtained to support this work, the number of monitoring locations had to be limited. Major recharge or discharge features were marked on topographic quadrangles, their locations logged by a hand-held GPS unit, and in many cases photographed. Depending on the proximity of discharge features to the injection site, charcoal receptors were installed at the site (Map 2, page 18). Receptors were also placed downstream from any injection location in order to determine if the dye stayed in the stream channel or was lost through the streambed to the sub-surface. Stream reaches with perennial flow or segmented flow were noted on topographic quadrangles to aid in determining injection sites. Stream channels were also observed across seasons and following rain events, to determine responses to flooding and the potential for injecting dye following such events.

Injections utilized three common groundwater tracing dyes: fluorescein, eosine, and rhodamine WT. These dyes were injected into recharge features such as losing streams and sinkhole swallets. Injection locations at the onset of the project were in close proximity to the cave sites. As the project progressed, injection sites were located at increasingly greater distances from the caves to determine the potential maximum extent of the recharge area. Injection methods varied, depending on the characteristics of the injection site. The most common method was a direct pouring of the dye into a flowing reach of stream channel. In the event the stream channel was completely dry but accessible by road, tanker trucks from the local Leasburg Volunteer Fire Department were used to flush the dye into the subsurface (Figure 11, page 22), using approximately 7,600 liters of fresh water for each injection.

In sites with dry streambeds that were not accessible by road, dry sets were used. Dry sets consisted of a one-meter-long piece of 18-centimeter-in-diameter PVC pipe, anchored to the streambed with baling wire and large nails. Dry, powdered dye was placed inside the PVC pipe. When a rain event occurred substantial enough to create overland stream flow, the dye was injected with the run-off from the storm event. In several cases, makeshift dry sets utilized culverts under roadbeds instead of the PVC piping method (Figure 7, page 20). To prevent cross-contamination between injection sites, latex gloves were worn at every injection. Chlorine bleach was employed to clean boots, skin, or other equipment contaminated with dye.

Monitoring locations utilized receptors containing crushed coconut charcoal, each receptor containing 4-5 grams of charcoal. These charcoal receptors were placed in discharge features and were typically anchored to streambanks using baling wire or vinyl-coated wiring (Figure 10, page 21). Receptors were changed periodically to determine approximate travel time from injection point to resurgence. At each collection of receptors, a new pair of latex gloves were worn to prevent cross-contamination between sites. Any sites which required standing in water were always approached from downstream. Individual receptors were placed in Ziploc bags, then stored in a refrigerator to await transport to the laboratory in Rolla, Missouri.

Analysis of charcoal packets for the presence of sorbed dyes was completed by the Missouri Department of Natural Resources, Division of Geology and Land Survey, Environmental Geology Section, in Rolla, Missouri. A 0.5 gram portion of each charcoal receptor was individually eluted with a mixture of ammonium hydroxide and ethanol. The eluent was then analyzed using a synchronously scanning Hitachi F-4500 Fluorescence Spectrophotometer. Once a sample fluorescence spectrum graph was produced, a qualified lab technician identified the dyes present in the sample. Based on this analysis, positive traces were confirmed or discounted.

Description of Dye Injections

Over the course of the project 21 dye injections were executed at 19 locations. A summary of each injection event follows, as well as a description of the individual injection location. The dye injections are also listed in Table 1 (page 31) and plotted on Map 2 (page 18).

Round 1: November 11, 2003

1st Injection: Campground Creek upstream of OCSP Campground.

Dye used: Fluorescein, 0.9 kilograms (two pounds). By walking upstream from the Onondaga Cave State Park campground and staying in the main channel, a perennial pool is reached just below a waterfall ledge. This location is nearly on the northern boundary of the Park. Approximately one kilogram of fluorescein dye powder was injected directly into this pool (photo, cover). Post-injection, noticeable flow was detected moving downstream in the pool, as well as in a small trickle of water which immediately sank into the gravel streambed.

2nd Injection: "Dead Frog Hollow", drainage behind seasonal housing at OCSP

Dye used: Rhodamine WT, 0.9 kilograms (two pounds). As with the first injection, a small puddle of water approximately 0.4 meters across was found by traveling upstream until an elevation of 233 meters (765 feet) above mean sea level was reached. Approximately one kilogram of liquid rhodamine WT was poured into this small puddle, then slightly covered up by leaves to prevent dye degradation by solar radiation (Figure 4, page 16).

Round 2: February 24, 2004

1st Injection: Possum Hollow Creek at Spring Lake Lane

Dye used: Rhodamine WT, 1.4 kilograms (three pounds). This injection took place at a road crossing high in the watershed of Possum Hollow Creek, in a large, intermittent stream valley north of OCSP. This stretch of creek nearly always has stream flow, as it did on the injection date. The dye was placed directly into the stream and immediately began flowing downstream.

2nd Injection: Avery Hollow Creek at Highway H

Dye used: Eosine, 1.8 kilograms (four pounds). Avery Hollow Creek crosses Highway H at the bottom of Knight's Hill, southeast of Leasburg. This stretch of Avery Hollow Creek has perennial flow which loses within the next half mile, before crossing Davis Valley Road. Using the road easement, the dye was injected into Avery Hollow Creek. Dye remained visible in the stream channel for several hours, but disappeared completely by the next day.

Round 3: January 18, 2005

1st Injection: Snake Pit

Dye used: Fluorescein, 1.4 kilograms (three pounds). Snake Pit (Figure 3, page 15) is a large swallet sinkhole located in an upper tributary of Avery Hollow. The location was chosen in part due to local legends about the water in the base of the pit connecting to Onondaga Cave, and also because of a previous failed trace, attempted prior to the current research, when dye was injected into a non-flowing puddle. For this attempt, after descending into the pit cave on a ladder, researchers injected fluorescein dye into a deep pool located on the south side of the cave (Figure 8, page 21). At the time of the injection, an active stream was flowing into the pit cave and sinking immediately into residuum at the base of the drop.

2nd Injection: Avery Hollow at Highway H

Dye used: Rhodamine WT, 1.4 kilograms (three pounds). Avery Hollow Creek was retraced, since the previous injection of dye had not been detected at any of the monitoring stations. Several new monitoring sites were added pre-injection. Also there was concern about potential solar degradation of the dye during the previous trace and the level of detectability of eosine, considering the fluorescein levels in the system. Approximately 1.4 kilograms of rhodamine WT were injected into the flowing creek at the road easement of Highway H. The injection was done after sunset to reduce potential solar degradation of dye.

Round 4: April 15, 2005

1st Injection: Little Bourbeuse River at Springfield Road

Dye used: Rhodamine WT, 1.4 kilograms (three pounds). The headwaters of the Little Bourbeuse River, a tributary of the Bourbeuse River, begin in the village of Leasburg. The river flows roughly west before making a sharp turn to the north. The normally dry stream channel crosses Springfield Road roughly 2 kilometers (1.25 miles) outside of Leasburg. On the date of the injection, however, local weather conditions allowed for injecting the dye into a temporarily flowing streamway. Dye was introduced directly into the stream channel. Less than 24 hours later, the stream section where injection took place was dry.

2nd Injection: Lick Creek at Kitchen Road

Dye Used: Fluorescein, 1.4 kilograms (three pounds). Lick Creek, a tributary of the Meramec River, is a perennially flowing stream in the western portion of the study area. Lick Creek is fed by a number of springs issuing from the numerous caves along Lick Creek. The dye was injected directly into Lick Creek on the downstream side of Kitchen Road, the upper-most road crossing the watershed. The dye was immediately mobilized by the flowing stream. It was not visible at the road crossing four hours later.

3rd Injection: Tributary to Blue Springs Creek

Dye Used: Eosine, 2.3 kilograms (five pounds). Blue Springs Creek is a perennially flowing stream in the easternmost portion of the study area. The creek is fed primarily by Blue Springs, a large spring with an average base flow of 164 L/s (5.8 ft^3/s) (Vineyard and Feder, 1982). Due to a lack of access to the streamway and the ability to find accessible portions with flow, the injection was done in a tributary of Blue Springs Creek, approximately 150 meters above the tributary's confluence with the main creek. The tributary crosses Highway N at a large bridge, which is where the injection took place. Approximately 2.3 kilograms of powdered eosine dye were injected into the small creek. Later that day, orange dye was reported by local citizens in the main channel of Blue Springs Creek.

Round 5: November 14, 2005

1st Injection: Possum Hollow Creek on Possum Hollow Lake property

Dye used: Eosine, 1.8 kilograms (four pounds). This injection site was located 2.8 kilometers further downstream from the first injection location in Possum Hollow Creek. This injection location hoped to pinpoint the furthest downstream losing portion of the stream. The streambed has no visible flow, is completely dry, and has a hummocky appearance. The remoteness of the site precluded assisting the injection with an artificial flush of water. A low spot along the southern bank of the stream was chosen, and 1.8 kilograms of liquid eosine were poured into the streambed sediments. This location is just upstream of a large, artificial lake known as Possum Hollow Lake. A subdivision on the western portion of the lake owns the property where the injection took place.

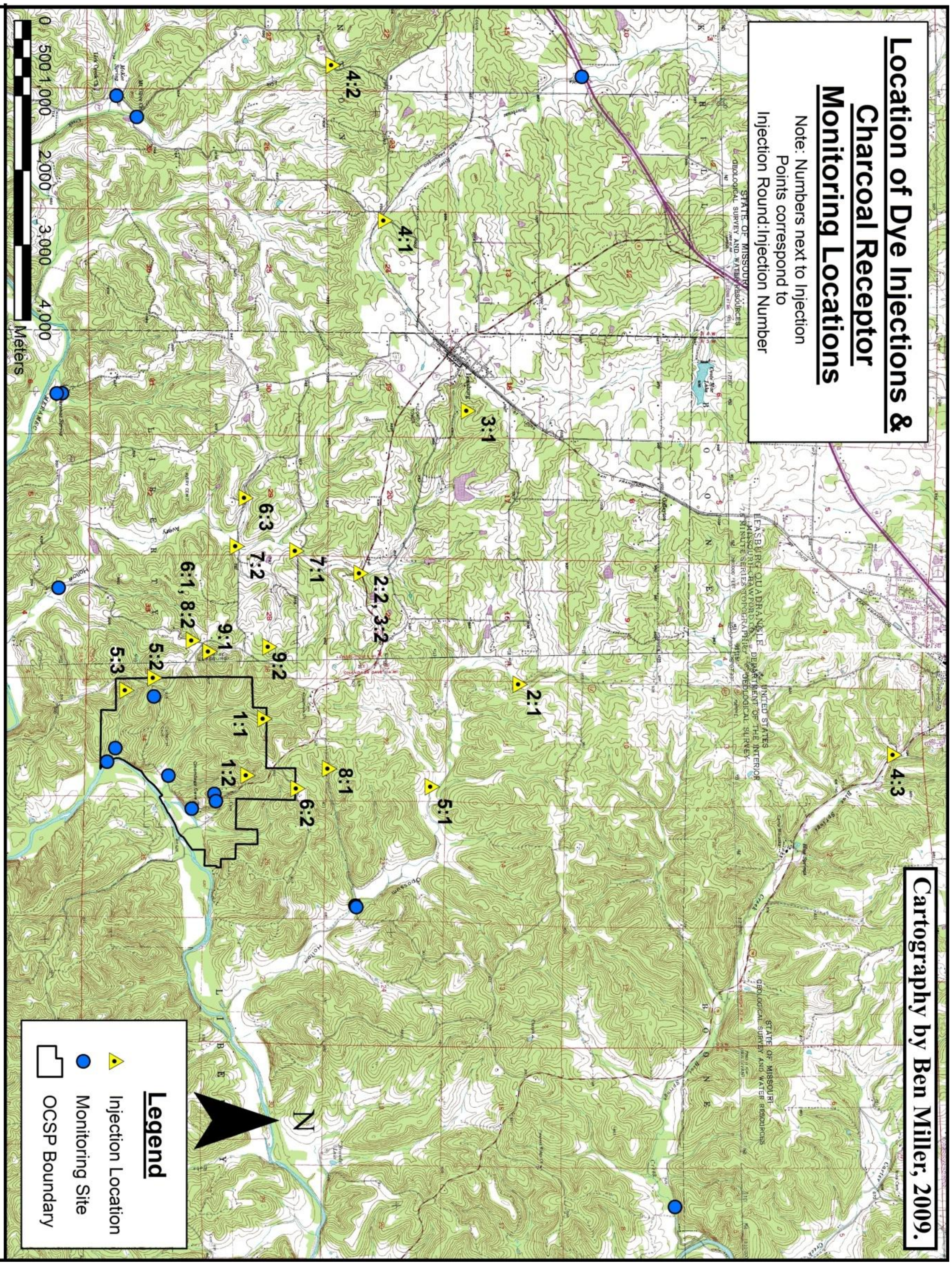
Dye used: Rhodamine WT, 1.4 kilograms (three pounds). This tributary to Avery Hollow is located on the west side of Avery Hollow Creek. It crosses Land Town Loop Road approximately 0.8 kilometers (0.5 miles) west of the main creek. The tributary has the unique characteristic of having stream flow at the road, but the channel entirely disappears before the stream reaches Avery Hollow Creek. Dye was injected directly into flowing water around sunset to prevent solar degradation of the dye. The next morning, no dye was visible in the streambed.

FIGURE 3: BEN MILLER AT SNAKE PIT, SITE OF ROUND 3, INJECTION 1

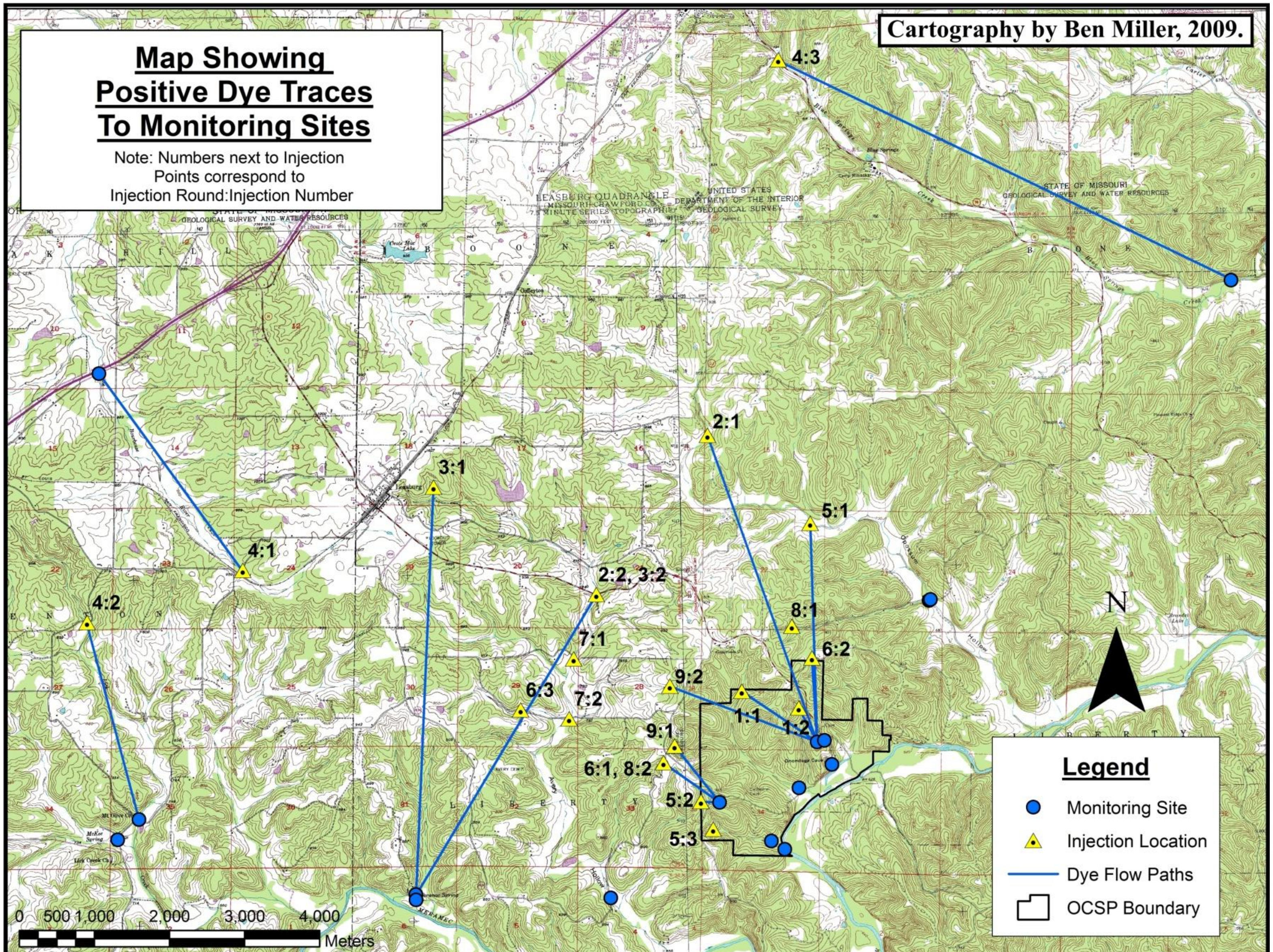
Snake Pit, near Leasburg, is a recharge feature for Saranac Spring. Note stream flowing into pit in lower right corner of photo.

FIGURE 4: BEN MILLER INJECTING RHODAMINE WT INTO "DEAD FROG" HOLLOW, 11/11/2003.

FIGURE 5: BEN MILLER & BOB LERCH SET UP DRY SET OF FLUORESCEIN IN AVERY HOLLOW TRIBUTARY ON OCSP, 11/14/2005.


Location of Dye Injections &
Charcoal Receptor
Monitoring Locations
Note: Numbers next to Injection
Points correspond to
Injection Round:Injection Number
Cartography by Ben Miller, 2009.
Legend
Injection Location
Monitoring Site
OCSP Boundary
N
0 500 1,000 2,000 3,000 4,000
Meters
4:2
4:1
3:1
6:3
7:2
7:1
2:2, 3:2
6:1, 8:2
9:1
9:2
5:2
5:3
2:1
1:1
1:2
8:1
6:2
5:1
4:3

MAP 2



Map Showing
Positive Dye Traces
To Monitoring Sites
Note: Numbers next to Injection Points correspond to Injection Round:Injection Number
Cartography by Ben Miller, 2009.
4:3
4:1
4:2
3:1
2:1
5:1
2:2, 3:2
8:1
7:1
6:2
9:2
6:3
7:2
1:1
1:2
9:1
6:1, 8:2
5:2
5:3
N
Legend
Monitoring Site
Injection Location
Dye Flow Paths
OCSP Boundary
0
500
1,000
2,000
3,000
4,000
Meters

Map 3

Figure 6: Injecting rhodamine WT into Avery Hollow at Land Town Loop Road, 11/1/2006.

Figure 7: Bob Lerch beside culvert dry set along Nixon School Road, 2/3/2006.

Figure 8: Ben Miller injects fluorescein into Snake Pit, 1/18/2005.

Figure 9: Fluorescein dye in Avery Hollow near Davis Valley Road, 10/27/2006.

Figure 10: Ben Miller changes a charcoal receptor in Lost River, within Onondaga Cave.

Figure 11: Injecting rhodamine WT with the use of fire department tanker truck, 11/26/2007.

Figure 12: Injecting fluorescein near Nixon School Road, 11/26/2007.

2nd Injection: Eastern tributary to Avery Hollow on portion of OCSP

Dye Used: Fluorescein, 0.9 kilograms (two pounds). This tributary to Avery Hollow begins on a western portion of Onondaga Cave State Park. The injection location is just inside the western boundary of the park, just upstream of a power line easement. At the time of the injection there was no overland flow in the channel for this small stream, so a dry set was utilized (Figure 5, page 17). A 15-centimer diameter PVC pipe, filled with 0.9 kg of fluorescein, was staked to the bottom of the streambed using large nails and baling wire. After the dry set, placement rain continued throughout the day and into the night. By the next morning, dye could be seen flowing from the PVC pipe.

3rd Injection: Tributary to the Meramec River on OCSP property near the Group Campground

Dye Used: Rhodamine WT, 0.45 kilograms (one pound). The injection location was just below the convergence of several small first-order drainages in a tributary to the Meramec River. The stream is located on OCSP property and is normally a dry channel. Because of this condition, a dry set had to be utilized. Due to the close proximity of the site to Cathedral Cave, a smaller amount of dye was used. Light drizzle was falling at the time of injection. By the next morning, dye was seen moving downstream from the dry-set tube.

Round 6: February 3, 2006

1st Injection: Eastern tributary to Avery Hollow off of Nixon School Road

Dye Used: Eosine, 1.4 kilograms (three pounds). This injection used a road culvert in order to achieve a dry-set injection (Figure 7, page 20). The injection was into a first-order stream located near the intersection of Nixon School Road and Riverbend Road. The culvert had a small amount of water flowing through it on the day of injection. The 1.4 kilograms of powdered eosine dye was placed in the culvert to decrease solar degradation. Dye continued to seep out of the culvert over the next week.

2nd Injection: Culvert off of Keyes Road

Dye Used: Fluorescein, 0.9 kilograms (two pounds). The injection was similar to the injection off of Nixon School Road, in that a road culvert was utilized for a dry-set injection. The powdered dye was placed inside the culvert. The water flowing out of the culvert immediately turned a bright green color. Dye was completely flushed from the culvert within 48 hours.

3rd Injection: Western tributary to Avery Hollow off of Land Town Loop

Dye used: Rhodamine WT, 1.4 kilograms (three pounds). This tributary to Avery Hollow is located on the west side of Avery Hollow Creek. It crosses Land Town Loop Road approximately 0.8 kilometers (0.5 miles) west of the main creek. The tributary has the unique characteristic of having stream flow at the road, but the channel entirely disappears before the stream reaches Avery Hollow Creek. Dye was injected directly into flowing water around sunset to prevent solar degradation of the dye. The next morning, no dye was visible in the streambed near the injection location.

Round 7: October 27, 2006 & November 1, 2006

1st Injection: Avery Hollow Creek at Davis Valley Road, October 27, 2006

Dye used: Fluorescein, 1.4 kilograms (three pounds). The injection took place following a heavy rain which created visible flow in the normally dry streambed. The channel at this location has largely a fractured bedrock surface. Directly following the flood pulse,1.4 kilograms of fluorescein were injected into the creek (Figure 9, page 21). Flow in the creek at the time of injection was estimated to be 57-85 L/s (2-3 ft^3/s).

2nd Injection: Avery Hollow Creek at Land Town Loop Road, November 1, 2006

Dye used: Rhodamine WT, 1.8 kilograms (four pounds). This injection was at the next downstream road crossing of Avery Hollow Creek from the previous injection location. This portion of the creek is always dry, except for very large flood events. Because the streambed was dry on the date of the injection, a fire department tanker truck provided a flush of 7,600 liters of fresh water. The tanker truck was opened and once the flow started down the streambed the dye was added to the flow (Figure 6, page 20). Flow from the tanker truck lasted for five to ten minutes. The remaining water had disappeared two hours after injection.

Round 8: November 26, 2007

1st Injection: Western tributary to Possum Hollow Creek, off Possum Hollow Road

Dye used: Rhodamine WT, 0.9 kilograms (two pounds). The tributary begins and runs directly next to Possum Hollow Road on the west side of Possum Hollow Creek. The small drainage crosses the road several times before converging with the main stream. The dye injection took place at the first upstream road crossing of this small stream. The streambed at the injection location is dry but easily accessible by road, so a 7,600-liter fire department tanker truck was used to create a temporary pulse to facilitate injection of the dye (Figure 11, page 22). The stream ran to a discrete point of the land surface, then sank into the substrate less than 100 meters from the injection location.

2nd Injection: Tributary to Avery Hollow Creek, off of Nixon School Road

Dye used: Fluorescein, 0.9 kilograms (two pounds). A previous trace from this location had been attempted by placing eosine dye in a road culvert (see Round 6, Injection 1). No positive trace had resulted from this injection. Due to proximity to Cathedral Cave, it was decided to repeat the trace. However, this round would use fluorescein dye and flush with water provided by a fire department tanker truck (Figure 12, page 20). After the tanker truck flow was initiated the dye was observed to run down the channel of this first-order drainage and then sink just below its confluence with another first-order drainage.

Round 9: April 30, 2008

1st Injection: Western tributary to Campground Creek, on OCSP property

Dye used: Rhodamine WT, 0.9 kilograms (two pounds). This tributary flows into Campground Creek which, in turn, flows through the main campground at Onondaga Cave State Park. The main Campground Creek had been previously traced to Onondaga Cave (see Round 1, Injection 1). The injection at this second location was to delineate any potential flow from this area that might go to Cathedral Cave, which was much closer to the injection point than Onondaga Cave. The injection was just above a small waterfall over which the stream flows before sinking into residuum at the base of the ledge.

2nd Injection: Tributary to Avery Hollow Creek, between Land Town Loop Road and Davis Valley Road

Dye used: Fluorescein, 0.9 kilograms (two pounds). This location is a tributary to Avery Hollow located on the eastern side of the drainage. As several other eastern tributaries had been previously traced to Cathedral Cave, this drainage was chosen, since it is in close proximity to Cathedral Cave. Since the location was high on the ridge, there was no overland stream flow at the time of the injection. Consequently, a dry set was used as the injection method. A PVC pipe with fluorescein dye was staked to the streambed and filled with 0.9 kilograms of dry fluorescein powder.

Results and Positive Traces

Dye traces made from injection points to established monitoring locations are considered positive traces and are described below. Instances where dye was lost will be described in more detail in the Issues Encountered section. Maps showing all injections and the positive traces to monitoring sites are included on pages 18 and 19.

Round 1

Recovery Site: Onondaga Cave. Dye Recovered: Fluorescein. Date Recovered: 11/20/2003. Fluorescein dye injected into Campground Creek was detected, via charcoal packet receptors, in the main cave stream of Onondaga approximately eight days after injection. This was the first positive trace to Onondaga Cave. Dye came through in high concentrations.

Recovery Site: Onondaga Cave. Dye Recovered: Rhodamine WT. Date Recovered: 12/4/2003. Rhodamine WT was recovered approximately 22 days after injection into "Dead Frog" Hollow. Though the injection site was closer to Onondaga Cave than the fluorescein trace, the smaller drainage area of the creek may not have provided enough flow to force the dye into the cave system until a storm event.

Round 2

Recovery Site: Onondaga Cave. Dye Recovered: Rhodamine WT. Date Recovered: 3/5/2004. Dye injected into Possum Hollow Creek at Spring Lake Lane was recovered via charcoal receptors in Onondaga Cave's main stream ten days post-injection. This injection dramatically increased the size of the Onondaga recharge area. It remains the farthest trace to the cave in the project, a 4.34-kilometer (2.69-mile) straight-line distance.

Round 3

Recovery Site: Saranac Spring. Dye Recovered: Fluorescein. Date Recovered: 2/22/2005. Dye injected into Snake Pit in Leasburg was recovered at Saranac Spring approximately 35 days post-injection. This trace represents the farthest positive trace to Saranac Spring, a 5.44-kilometer (3.38 mile) straight-line distance.

Recovery Site: Saranac Spring. Dye Recovered: Rhodamine WT. Date Recovered: 2/22/2005. This was a repeat of an earlier trace done from Avery Hollow Creek at Highway H. In the previous trace, Saranac Spring had not been monitored. Monitoring the spring on this round provided a travel time of roughly 35 days from injection site to the spring. Another smaller spring, approximately 100 meters south of Saranac Spring, was monitored but showed no fluorescence from these traces.

Round 4

Recovery Site: Little Bourbeuse River at Interstate 44. Dye Recovered: Rhodamine WT. Date Recovered: 5/4/2005. Rhodamine WT was injected into the upper portion of the Little Bourbeuse River drainage off of Springfield Road outside of Leasburg. This dye was recovered, via charcoal receptors, at the Interstate 44 bridge approximately 3.6 kilometers downstream of the injection site. Travel time is probably much faster than the receptor change-out indicates, 19 days post-injection, since the dye likely stayed within the stream channel and did not go subsurface.

Recovery Site: Lick Creek at Lick Creek Road. Dye Recovered: Fluorescein. Date Recovered: 5/17/2005. Fluorescein dye injected into Lick Creek at Kitchen Road was recovered 32 days later where Lick Creek crosses Lick Creek Road, 3.3 kilometers downstream of the injection site. The longer travel time, compared to the Little Bourbeuse River travel time, may be a result of the stream water sinking and eventually resurging from a large spring 0.7 kilometers upstream of Lick Creek Road. This hypothesis is only speculative, as the large spring was not known at the time of injection and thus was not monitored.

Recovery Site: Blue Springs Creek near Blue Springs Conservation Area. Dye Recovered: Eosine. Date Recovered: 5/5/2005. Dye was injected into a short tributary of Blue Springs Creek above Blue Springs. Dye was recovered 7.75 kilometers downstream near Blue Springs Conservation Area 18 days post-injection. Travel time may have been faster than receptor change-out indicates. We believe the dye stayed in the streambed and did not sink into the subsurface.

Round 5

Recovery Site: Cathedral Cave main stream. Dye Recovered: Fluorescein. Date Recovered: 11/30/2005. A dry set with fluorescein powder was used to inject dye into a tributary to Avery Hollow located on the property of Onondaga Cave State Park. Dye was recovered in the main stream of Cathedral Cave 15 days later. Dye concentration was extremely high. It is believed the dye entered the subsurface almost immediately after flow was introduced to the dry set. This was the first positive trace to Cathedral Cave.

Recovery Site: Onondaga Cave. Dye Recovered: Eosine. Date Recovered: 11/30/2005. Liquid eosine dye was injected into the streambed of Possum Hollow near Possum Hollow Lake and was detected at Onondaga Cave approximately 15 days following injection. This injection represents the furthest downstream portion of Possum Hollow Creek which has been traced to Onondaga Cave.

Round 6

Recovery Site: Onondaga Cave. Dye Recovered: Fluorescein. Date Recovered: 3/13/2006. A dry set using fluorescein dye was placed in a culvert off of Keyes Road very close to the northeastern boundary of Onondaga Cave State Park. Dye was recovered via charcoal receptors 39 days post-injection.

Round 7

No dye was recovered from the two injections in Round 7.

Round 8

Recovery Site: Cathedral Cave. Dye Recovered: Fluorescein. Date Recovered: 2/20/2008. Fluorescein dye was injected into a side tributary of Avery Hollow off of Nixon School Road. Because the trace had been attempted before without success, a fire department tanker truck was utilized to flush the dye, which resulted in a positive trace to Cathedral Cave. The dye was recovered from charcoal receptors 86 days post-injection. The long travel time is not indicative of the actual travel time since charcoal packet retrieval was greatly delayed by a regional-scale ice storm, which prevented access to monitoring sites. Actual dye travel time was probably much less than 86 days.

Round 9

Recovery Site: Onondaga Cave. Dye Recovered: Fluorescein. Date Recovered: 5/8/2008. A dry set of fluorescein dye was placed in the streambed of a tributary to Avery Hollow. Dye from this dry set was recovered in Onondaga Cave approximately eight days after placing the dry set. Frequent rain events immediately after setup facilitated quick injection of the dye.

Recovery Site: Cathedral Cave. Dye Recovered: Rhodamine WT. Date Recovered: 5/8/2008. Dye injected in a small stream tributary of Campground Creek in Onondaga Cave State Park appeared in Cathedral Cave eight days post-injection. This tributary had been considered part of the Onondaga Cave recharge area prior to this injection. The positive trace indicates a previously unknown drainage divide between Cathedral and Onondaga Caves within the Campground Creek drainage basin.

Discussion

A total of 21 dye injections resulted in six positive traces to Onondaga Cave, three positive traces to Cathedral Cave, and two positive traces to Saranac Spring. This tracing work allowed for the delineation of recharge areas for both Onondaga Cave and Cathedral Cave. Onondaga Cave currently has a recharge area of approximately 24 km^2, or 9.3 square miles (mi^2), and Cathedral Cave has a recharge area of 2.9 km^2 (1.1 mi^2). The vast majority of both recharge areas is outside the boundaries of Onondaga Cave State Park (Map 4, page 35). Because Saranac Spring was not the focus of this research and access to the site was not available during most of the project, a recharge area has not been delineated for this spring. Recharge area maps were created using the positive traces and following topographic ridges upstream of injection locations. The downstream extents were commonly drawn to the lowest elevation that water could make it to the upstream end of the cave streams.

Both Onondaga and Cathedral Cave streams are provided recharge by the many losing stream segments within their recharge areas. Losing reaches of Possum Hollow Creek and Campground Creek provide the largest amount of recharge to Onondaga Cave. Small tributaries along the eastern side of Avery Hollow Creek primarily provide recharge to Cathedral Cave; however, one of these tributaries was traced to Onondaga Cave. Each cave has individual sub-basins, based on injection locations, within the total recharge area for that cave (Map 5, page 36). Onondaga Cave, for instance, has a total of five sub-basins within the total recharge area of the cave, the largest of which is Possum Hollow Creek. Cathedral Cave has three sub-basins within the recharge area, the largest being the southernmost Avery Hollow sub-basin.

With the recharge areas delineated for both Onondaga and Cathedral Caves, the current land use patterns within the recharge areas could be examined. Land use data from 2005, acquired from Missouri Resource Assessment Partnership (MSDIS Data), was clipped to the recharge areas for both caves. Land use classes for the various areas were then used to determine percentage of the land area in specific uses (Table 2, page 32). In both recharge areas, land use is dominated by deciduous forest, followed by grassland and deciduous woody/herbaceous woodlands. Deciduous forest encompasses 81.6 % of the land use in the Cathedral Cave recharge area, and 67.2 % in the Onondaga Cave recharge area (Map 5, page 36). Land uses which might be detrimental to the water quality of the cave streams, such as cropland and impervious surfaces are minimal within both recharge areas. Impervious land use, such as roadways, buildings, and parking lots, accounts for only 0.62 % of the land use in the Onondaga recharge area and 1.04 % in the Cathedral recharge area. Cropland accounts for an even smaller percentage of the land uses with only ~0.2% of the recharge areas used for row crop production.

While urban development of the recharge areas appears small, other less obvious threats to water quality do exist within these recharge areas. For example, sinkhole and streamside dumps are common in the area. The lack of sewer infrastructure implies that any homes or businesses within the recharge area utilize on-site wastewater treatment. In addition, much of the grassland in the recharge areas is used as pasture for grazing cattle. On-site wastewater treatment and cattle-grazing operations could be sources of nutrients and fecal bacteria in the cave streams. Since the majority of the land use is deciduous forest, it appears that the threats to water quality in these recharge areas are much less than for karst recharge areas with significant row crop production, confined animal feeding operations (CAFOs), or urbanization (Butler, 1987; Boyer and Pasquarell, 1996; Currens, 2002; Lerch et al., 2005; Frueh et al., 2008; Lerch, 2009; Owen and Pavlowsky, 2010).

Issues Encountered & Future Work

A common problem with dye tracing is the inability to account for the injected dyes. There were a total of six traces in which the dye was not recovered. Many of these injections were in Avery Hollow and its tributaries or in one tributary to Possum Hollow. The unrecovered Avery Hollow dye traces were believed to have connected to Saranac Spring. However, access to Saranac Spring was prohibited by the landowner early in the project, so these traces could not be confirmed. The establishment of additional monitoring sites could also have aided in identifying locations where the dye may have traveled.

Some dye-tracing work remains to be done in the Onondaga and Cathedral Cave area. Additional tributaries to Avery Hollow, especially north of Davis Valley Road, seem likely to be recharge sources to either Onondaga or Cathedral. In some cases, low flow conditions may have prevented detection of dyes in the caves. The dry set upstream of the group campground in OCSP may be such a site, along with the tributary to Possum Hollow that was attempted in Round 8. If Saranac Springs were available as a monitoring site, several traces could likely have been confirmed, possibly resulting in the delineation of the three major recharge areas in the region: Onondaga Cave, Cathedral Cave, and Saranac Spring. Additional work would refine the exact boundaries of the recharge areas for both cave systems, especially in basins already traced to the caves.

Conclusion

Onondaga Cave and Cathedral Cave are two large, significant cave systems with active streams located along the Meramec River in the Ozarks ecoregion of Missouri. Groundwater dye tracing has delineated recharge areas for both caves in order to aid in the management of the cave systems by Onondaga Cave State Park. Onondaga Cave has a recharge area of approximately 24 km^2, while Cathedral Cave has a recharge area of approximately nine km^2. Dye injection techniques ranged from direct pouring of the dye into streamways to the use of dry sets, and the assistance of fire department tanker trucks. Monitoring of discharge features utilized charcoal receptors placed directly in the discharge feature or stream. Each of the cave systems receive the majority of their recharge from losing streams. Onondaga Cave receives recharge largely from Possum Hollow, to the north of the cave. Cathedral Cave receives recharge from tributaries along the eastern side of Avery Hollow. Land uses that may present a threat to water quality in the cave streams, such as intensive row crop production, impervious surfaces, or urbanization, currently account for a minor proportion of the land uses. The knowledge gained from this research was incorporated into the cave management plans developed by OCSP personnel. The management plans will guide future land acquisitions and allow for educational programs and materials to be targeted to landowners within the recharge areas. In addition, future changes in land use that may threaten the water quality of the cave streams can be minimized (via negotiation or education of landowners) or actively opposed by OCSP. Thus, the impact of this work was to improve the overall management and preservation of Onondaga Cave and Cathedral Cave as Outstanding Water Resources in the State of Missouri.

Table 1: Summary table of dye injections & positive traces to monitored features.

Round # : Injection#	Date	Location Description	UTM- NAD 83 Easting/Northing	Elev. meters(ft.)	Dye Injected	Amt. Injected	Positively Traced To
1:1	11/12/03	Along Campground Creek upstream of C.G., on OCSP	E: 654263 N: 4214901	229 (750)	Fluorescein	0.9 kg. (2 lbs.)	Onondaga Cave
1:2	11/12/03	"Dead Frog" Hollow directly west of Hwy H, on OCSP	E: 655026 N: 4214661	233 (765)	RhodamineWT	0.9 kg. (2 lbs.)	Onondaga Cave
2:1	2/24/04	Possum Hollow, at Spring Lake Ln.	E: 653803 N: 4218313	241 (790)	RhodamineWT	1.4 kg. (3 lbs.)	Onondaga Cave
2:2	2/24/04	Avery Hollow, at Hwy H	E: 652321 N: 4216198	244 (800)	Eosine	1.8 kg. (4 lbs.)	Saranac Spring
3:2	1/18/05	Avery Hollow, at Hwy H	E: 652321 N: 4216198	244 (800)	RhodamineWT	1.4 kg. (3 lbs.)	Saranac Spring
3:1	1/18/05	Snake Pit, swallet near Leasburg	E: 650161 N: 4217616	287 (940)	Fluorescein	1.4 kg. (3 lbs.)	Saranac Spring
4:1	4/15/05	Little Bourbeuse River, at Springfield Road	E: 647619 N: 4216512	293 (961)	RhodamineWT	1.4 kg. (3 lbs.)	L. Bourbeuse River
4:2	4/15/05	Lick Creek, at Kitchen Rd.	E: 645536 N: 4215825	250 (820)	Fluorescein	1.4 kg. (3 lbs.)	Lick Creek
4:3	4/15/05	Blue Springs Creek, at Hwy N	E: 654753 N: 4223317	227 (746)	Eosine	2.3 kg. (5 lbs.)	Blue Springs Creek
5:2	11/14/05	Eastern trib. to Avery Hollow on OCSP	E: 653711 N: 4213422	253 (830)	Fluorescein	0.9 kg. (2 lbs.)	Cathedral Cave
5:1	11/14/05	Possum Hollow Creek, on Lake property	E: 655141 N: 4217162	216 (710)	Eosine	1.8 kg. (4 lbs.)	Onondaga Cave
5:3	11/14/05	Side trib. to Meramec River, on OCSP	E: 653886 N: 4213046	226 (740)	RhodamineWT	0.45 kg. (1 lb.)	n/a
6:1	2/3/06	Eastern trib. to Avery Hollow Creek, off Nixon School Rd.	E: 653225 N: 4213933	274 (900)	Eosine	1.4 kg. (3 lbs.)	n/a
6:2	2/3/06	Culvert off Keyes Road into hollow west of Hwy H	E: 655202 N: 4215342	244 (800)	Fluorescein	0.9 kg. (2 lbs.)	Onondaga Cave
6:3	2/3/06	Western trib.to Avery Hollow, off Land Town Loop	E: 651321 N: 4214640	238 (780)	RhodamineWT	1.4 kg. (3 lbs.)	n/a
7:1	10/27/06	Avery Hollow Creek, at Davis Valley Road	E: 652020 N: 4215341	235 (770)	Fluorescein	1.4 kg. (3 lbs.)	n/a
7:2	11/1/06	Avery Hollow Creek, at Land Town Loop, used fire truck	E: 651959 N: 4214533	229 (750)	RhodamineWT	1.8 kg. (4 lbs.)	n/a
8:1	11/26/07	Side trib. to Possum Hollow, at Possum Hollow Road	E: 654931 N: 4215765	253 (830)	RhodamineWT	0.9 kg. (2 lbs.)	n/a
8:2	11/26/07	Eastern trib. to Avery Hollow, at Nixon School Rd.	E: 653225 N: 4213933	274 (900)	Fluorescein	0.9 kg. (2 lbs.)	Cathedral Cave
9:1	4/30/08	Tributary to Campground Creek on OCSP	E: 653373 N: 4214159	256 (840)	RhodamineWT	0.9 kg. (2 lbs.)	Cathedral Cave
9:2	4/30/09	Eastern tributary to Avery Hollow south of Davis Valley Rd.	E: 653309 N: 4214959	268 (880)	Fluorescein	0.9 kg. (2 lbs.)	Onondaga Cave

Table 2: Land use in the Onondaga & Cathedral Cave recharge areas.

Land Use Type	Onondaga %	km^2	Cathedral %	km^2
Impervious Surface-Rds, Bldgs, P.Lots	0.62	0.149	1.04	0.031
Barren or Sparsely Vegetated	0.11	0.026	0.06	0.002
Cropland	0.19	0.046	0.24	0.007
Grassland	21.45	5.153	12.37	0.364
Deciduous Forest - Over 60% Cover	67.18	16.139	81.59	2.400
Evergreen Forest - Over 60 % Cover	0.69	0.166	0.15	0.004
Deciduous Woody/ Herbaceous - <60% Cover	7.94	1.908	4.49	0.132
Herbaceous Dominated Woodland - Floodplain	0.03	0.007	0.00	0.000
Open Water	1.79	0.430	0.06	0.002

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The MSS was incorporated as a not-for-profit organization under the laws of Missouri in 1956. It is administered by a Board of Directors selected by affiliate organizations and members, and served by a President, Vice-President, Secretary and Treasurer selected by the Board. The

Board meets three times a year to formulate the policies of the MSS, which are then acted upon by the officers and appointed committees.

The MSS is supported by Missouri chapters of the National Speleological Society, local caving clubs, other agencies, and individuals who are interested in supporting cave research. Funds for the operation of the survey come primarily from the sale of publications, from grants and gifts, and from membership and affiliation fees.

The Missouri Department of Natural Resources, Geological Survey and Resources Assessment Division, and the National Speleological Society (NSS) have supported the MSS since its inception. The Geological Survey and Resources Assessment Division provides a permanent repository and reproduction service for cave maps and maintains a cooperative cave file. The Society provided grants and technical assistance in the early years of the MSS. During recent years the MSS has worked with the National Park Service, the United States Forest Service, the Missouri Department of Conservation, the Nature Conservancy, the United States Army Corps of Engineers, planning commissions, other local, state, and federal agencies, as well as with individuals and landowners.

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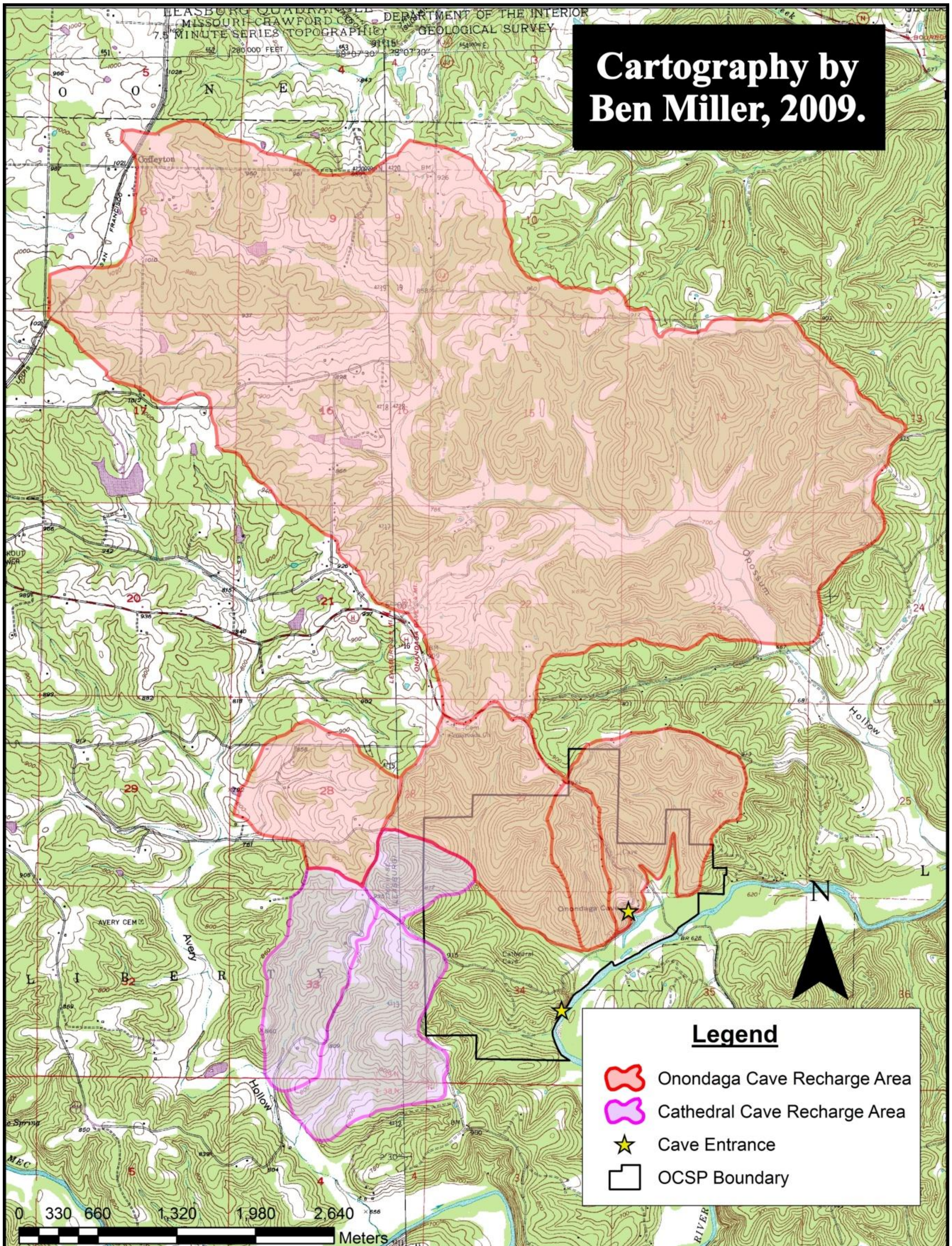
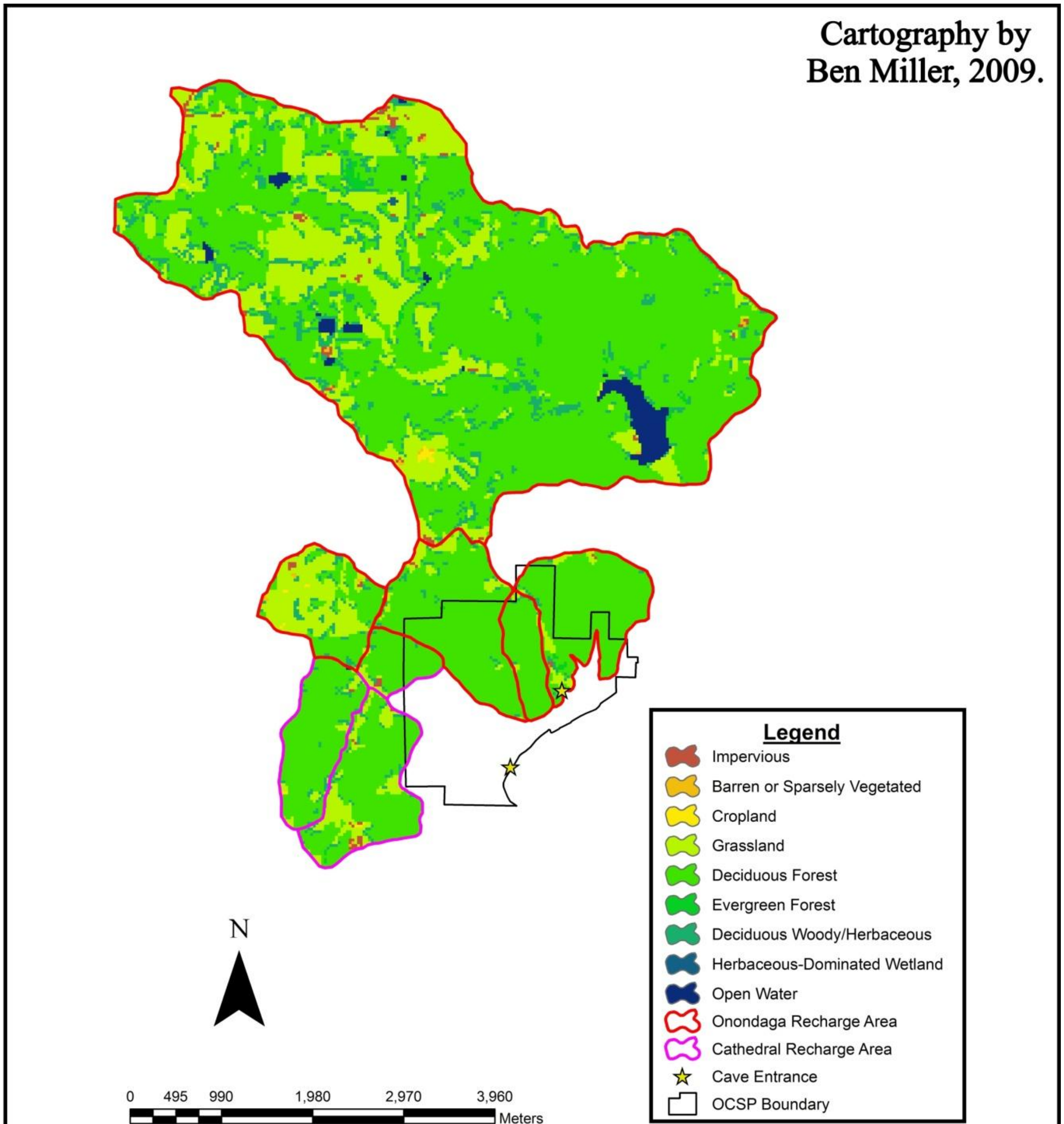
James R. Cooley, Editor
Missouri Speleology
February, 2011



MAP 4: RECHARGE AREAS FOR ONONDAGA & CATHEDRAL CAVES.



MAP 5: LAND USE IN THE ONONDAGA AND CATHEDRAL CAVE RECHARGE AREAS

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