HYDROGEOLOGICAL CHARACTERISTICS OF DELINEATED RECHARGE AREAS FOR 40 BIOLOGICALLY SIGNIFICANT CAVE AND SPRING SYSTEMS IN MISSOURI, ARKANSAS, OKLAHOMA, AND ILLINOIS

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Abstract

This paper summarizes the results from recharge-area delineations of cave and spring systems providing habitat for federally, listed threatened and endangered aquatic species in Missouri, Arkansas, Oklahoma, and Illinois. These include 24 sites for the Ozark Cavefish (*Amblyopsis rosae*), the only known site for the Tumbling Creek cavesnail (*Antrobia culveri*), four sites for the Benton Cave crayfish (*Cambarus aculabrum*), one site for the Hell Creek Cave crayfish (*Cambarus zophonastes*), seven sites for the Illinois Cave amphipod (*Gammarus acherondytes*), and three known or potential sites for Hine's emerald dragonfly (*Somatochlora hineana*).

Epikarstic zones known or presumed to provide habitat for Ozark cavefish populations are associated with 79% of the delineated cavefish sites, all of the Benton Cave crayfish sites, and the only known site for the Tumbling Creek cavesnail. All of the studied fens providing known or potential habitat for Hine's emerald dragonfly receive their groundwater supplies from the epikarstic zone rather than deeper groundwater systems.

Seventy-five percent or more of the lands in the recharge areas for the Tumbling Creek Cavesnail, the Illinois Cave Amphipod, the Hell Creek Cave Crayfish, and the Grotto Sculpin are ranked as having High or Extremely High Vulnerability to groundwater pollution. For the 36 sites with one or more of the federally listed cave species, only 7 (19%) are ranked as being highly defensible over the next 30 years.

The delineated recharge areas for the aforementioned species encompass a total area of 764 km^2 (295 mi.^{2}). About 95% of this land is in private ownership. Lands encumbered by right-of-ways for county, state, and federal roads in these recharge areas are estimated to almost equal the amount of land owned by conservation agencies, not-for-profit conservation entities, or that are included in conservation easements.

Key words: hydrogeology, karst recharge areas, cave biology, Missouri, Arkansas, Oklahoma, Illinois, contaminants

Introduction

The recharge area for a cave or spring is the land area that contributes water to the feature. During the past 30 years the Ozark Underground Laboratory has used groundwater tracing and other hydrogeologic data to delineate recharge areas for a large number of significant cave and spring systems. Included in these delineations were the recharge areas for 40 biologically significant cave and spring systems in Missouri, Arkansas, Oklahoma, and Illinois that provide habitat for at least one federally-listed endangered or threatened aquatic species. Several of these sites also provide habitat for one or more other species of conservation concern.

Federally-listed threatened and endangered species for which we have delineated recharge areas include 24 sites for the Ozark cavefish (*Amblyopsis rosae*), the only known site for the Tumbling Creek cavesnail (*Antrobia culveri*), four sites for the Benton Cave crayfish (*Cambarus aculabrum*), one site for the Hell Creek Cave crayfish (*Cambarus zophonastes*), seven sites for the Illinois Cave Amphipod (*Gammarus acherondytes*), and three known or potential sites for Hine's emerald dragonfly (*Somatochlora hineana*). Six other recharge areas have been delineated for other species of conservation concern; these have included one site in Missouri for the Spring cavefish (*Forbesichthys agassizi)* and five other biologically significant cave systems providing habitat for other cavefish or cave crayfish. Finally, recharge area delineation work is underway for five sites for the Grotto Sculpin (*Cottus* sp., similar to *C. carolinae*). This fish is distinctly different from surface-dwelling sculpins and is found only in cave systems in Perry County, Missouri.

This paper has two major objectives. First, to summarize data developed as a part of the recharge area delineations. The delineation studies have been reported in contract reports, but little of this information has reached the technical literature prior to this paper. The second objective is to illustrate the scale of the challenges that must be overcome if groundwater quality is to be protected in these recharge areas and loss of individual populations and extinctions are to be prevented.

Over 430 groundwater traces have been conducted in delineating these recharge areas and this tracing work is continuing with major projects underway in Perry County, Missouri and southwestern Illinois.

Several cavefish populations have been heavily collected in the past for purposes of limited scientific value or for public or private display purposes. Most of the studied sites are on private property and, in some cases, information on the locations of the sites is restricted at the request of property owners or others concerned with the protection of the populations. As a result we will identify most sites based only on the county in which they are located and will not routinely provide site or owner names in this paper. Where sites are protected well we will identify them in the discussions as appropriate. We believe this approach will provide land managers and scientists the information they need while maximizing protection of the populations and honoring property owner requests.

Geologic Settings

All of the sites for the Ozark cavefish are in Mississippian age limestone units. These include the Burlington and Keokuk Limestones in Missouri, the similar Boone Formation of Arkansas and Oklahoma, and the St. Joe Limestone of Arkansas that has sometimes been mapped as a unit of the Boone Formation. In much of the area where the Ozark cavefish populations occur the Mississippian age units are separated from underlying Ordovician dolomites by shale units including the Northview Formation and the Chattanooga Shale. It is possible that the existence of these shales explain the absence of Ozark cavefish in the Ordovician units.

The only known site for the Tumbling Creek cavesnail is within the Cotter Formation of Ordovician age.

The entrance to Hell Creek Cave, the only studied site for the Hell Creek Cave crayfish, is in the lower portions of the Ordovician Plattin Limestone. In or near this cave there are numerous karst features within the underlying Joachim Dolomite and in the overlying Plattin, Kimmswick, and Fernvale Limestones. A second site for the Hell Creek Cave crayfish is now known, but the authors of this paper do not know its precise geologic setting.

All of the Benton Cave crayfish sites are within the Boone Formation and the underlying St. Joe Limestone. One of the Benton Cave crayfish sites also provides habitat for Ozark cavefish.

The Spring cavefish population is located in the Plattin Limestone.

The Hine's emerald dragonfly sites are calcareous fens fed by small springs discharging from the epikarstic zone of dolomitic bedrock.

The Illinois Cave amphipod is found in caves formed in the St. Louis Limestone.

The Grotto Sculpin populations in Perry

County, Missouri are restricted to cave streams in the Joachim Dolomite.

Role of the Epikarstic Zone

The epikarst (or epikarstic zone) is the weathered, upper part of calcareous bedrock units. Common thicknesses of the epikarstic zone are about 10 meters (33 feet) (Ford and Williams 1989), but this value is highly variable and ranges from nearly 0 to 100 m (328 ft.) (Aley 1997). The extent and nature of epikarstic development varies substantially among geologic units. Unsaturated epikarstic development often can be seen in road cuts and quarry faces, but these exposures give only limited insight into the extent, nature, and thickness of the seasonally or perennially saturated epikarstic zones lying adjacent to or beneath valleys. It is these valley-associated epikarstic zones that provide habitat for some of the species discussed in this paper.

Williams (2003) estimates that about 80% of all carbonate dissolution occurs within the upper 10 m (33 ft.) or so of the top of the carbonate bedrock. This extensive and localized solution can produce intensive epikarstic development. The intensity of epikarstic development can be expressed as a percent of the bedrock that has been removed by solution. It can range from less than 1% to more than 50% (Aley 1997). In many epikarstic zones sediments partially or almost completely fill most or all of the voids within the bedrock; in other cases many of the voids are largely free of sediment.

Epikarstic zones with "likely habitat" known or presumably habitable for Ozark cavefish populations are associated with 79% of the delineated cavefish sites, all of the Benton Cave crayfish sites, and at the only known site for the Tumbling Creek cavesnail.

Dye tracing and specific-conductance monitoring has been conducted of springs in the studied fens providing "likely habitat" for Hine's emerald dragonfly. Specific conductance measurements vary dramatically over relatively short periods of time, and dye concentrations from groundwater traces can vary substantially at springs located relatively close together within a particular fen. These findings, plus rapid groundwater travel rates, demonstrate that groundwater for the fens is derived from the epikarstic zone rather than deeper groundwater sources.

Four of the Ozark Cavefish sites are hand-dug wells in which cavefish were sometimes or routinely sighted; one of these sites has two dug wells in which cavefish have been seen. All of the hand-dug wells bottom in the epikarstic zone. These sites are located in Greene, Newton, and Lawrence Counties, Missouri and in Benton County, Arkansas. Most of the hand-dug wells were constructed at points where groundwater initially discharged to the surface during wet periods of the year. In one case a backhoe was used to excavate a spring discharging into a small perennial stream. The backhoe excavated a trench about 30 m (100 ft.) long extending from the bank of the stream to a point where water was rising through a solutionally widened joint in the limestone bedrock. The landowner reported that several cavefish were excavated during the construction of this trench.

Epikarstic development in the Mississippian age limestones commonly yields cutters and pinnacles (Fellows, 1965). The openings resulting from bedrock solution produce a grid-work maze of preferential solutional openings along joints plus interconnecting openings along bedding planes. Fellows (1965) notes that networks of cutters in the Burlington Limestone of Greene County, Missouri, form dendritic patterns. One important cavefish site in Delaware County, Oklahoma, includes small caves in the epikarst that are large enough for a person to enter for short distances. These caves clearly illustrate a grid-work maze of openings. Insufficient bedrock exposures exist in this area to clearly determine if there is a dendritic pattern.

Most of the epikarstic zone sites are located on or near the floor of perennial stream valleys, but there are important exceptions. One of the hand-dug wells providing Ozark Cavefish habitat is on the bank of a small stream that drains a surface area of about 162 ha (400 ac). This site is located about 2.87 km (9,400 ft.) from the nearest stream with perennial flow; this stream is created by the spring that discharges water that passes through the bottom of the hand-dug well. This spring is also a known cavefish site.

Important portions of many Ozark cavefish sites are within the epikarstic zone beneath perennial streams and some intermittent streams. The flow of water through such epikarstic systems is complex and varies with time. Unlike the case with a single karst conduit, pollutants unevenly impact epikarstic zones. This has been demonstrated by dye traces through the epikarstic zone where dye concentrations at different sampling points in the epikarstic zone can vary by two or more orders of magnitude. Even if aquatic life kills do occur from a pollutant following particular flow routes through an epikarstic zone, there are adjacent areas where the pollutant concentrations are lower or even non-existent. These areas can help re-populate affected portions of the epikarstic zone. As a result, aquatic fauna sites that include epikarstic zones are likely to be less subject to acute aquatic life kills that destroy much or most of the fauna than are sites lacking epikarstic zones. Sket et al. (2003) discuss the role of the epikarstic zone in dispersion of biota and the vulnerability of this zone to pollution, although most of the focus in their paper is on epikarst located beneath features other than valleys.

Size of Recharge Areas

Table 1 summarizes the size of delineated recharge areas for federally listed species in our study region. As noted earlier, two of the three Hine's emerald dragonfly sites represent potential habitat rather than known habitat. One site provides habitat for both the Ozark Cavefish and the Benton Cave Crayfish.

We have also delineated one Missouri site for the Spring cavefish (*Forbesichthys agassizi*). The size of this recharge area is 60.3 ha (0.23 mi.^{2}). We are currently delineating the recharge areas for five populations of the Grotto Sculpin.

Interestingly, the mean size of recharge areas for listed, aquatic cave species is typically in the range of 15.5 to 25.9 km^2 (6 to 10 mi.^{2}). With only two exceptions these recharge areas are within Mississippian age limestones where springs with mean annual discharge rates of more than 0.11 m^3/sec. (4 ft^3/sec.) are uncommon. One should not presume that recharge areas of such size are typical for all aquatic cave species in the study region. For example, there are several known populations of the Southern cavefish (*Typhlichthys subterraneus*) found in the recharge area for Big Spring, Carter County, Missouri. The recharge area for this spring is approximately 2,505 km^2 (967 mi.^{2})(Aley and Creath 1989), and this is the largest spring in Missouri.

Sinkholes and Losing Streams

Except for Fantastic Caverns, Greene County, Missouri, all of the delineated recharge areas for populations of Ozark cavefish contain very few sinkholes and a number of the recharge areas have no sinkholes large enough to appear on 7.5-minute topographic quadrangles published by the U.S. Geological Survey. Sinkholes also are absent or minor in recharge areas for the Tumbling Creek cavesnail, Benton Cave crayfish, and Hell Creek Cave crayfish. None of the delineated recharge areas for fens providing likely habitat for Hine's emerald dragonfly contained sinkholes. Much of the discrete groundwater recharge in these areas occurs in losing-stream segments of the surface stream valleys. In contrast, recharge areas for populations of the Illinois Cave amphipod and the Grotto sculpin are sinkhole plains where losing streams are limited and often rare.

Table 1 Size of delineated recharge areas for listed species.

Species	Number of Sites	Max. Size m^2 (mi.^{2})	Min. Size km^2 (mi.^{2})	Mean Size km^2 (mi.^{2})
Ozark Cavefish	24	103.86 (40.10)	0.31 (0.12)	22.87 (8.83)
Tumbling Creek Cavesnail	1			23.36 (9.02)
Benton Cave Crayfish	4	49.25 (19.17)	8.96 (3.46)	24.48 (9.45)
Hell Creek Cave Crayfish	1			12.10 (4.67)
Illinois Cave Amphipod	7	19.97 (7.71)	5.41 (2.09)	15.57 (6.01)
Hine's Emerald Dragonfly	3	1.27 (0.49)	0.08 (0.03)	0.49 (0.19)

Protecting water quality entering karst groundwater systems through sinkholes and losing streams poses very different challenges. While sinkholes are notorious sites for trash dumps and dead animal disposal, these problems are typically confined to very localized areas with relatively few landowners associated with each sinkhole (except when sinkhole areas are urbanized). In contrast, some of the losing-stream segments contributing flow to important cave faunas drain hundreds to thousands of hectares and water quality is impacted by numerous property owners who may be located several kilometers away from the habitats that their land use activities are affecting. For example, sewage effluent from the town of Jay, Oklahoma and its local industries is discharged to a losing-stream tributary to Muskrat Creek where it sinks and ultimately flows through Star Cave and associated springs and epikarstic features 4.58 km (15,000 ft.) or more from the sinking point.

Shared Recharge Areas

A shared recharge area is one that, under at least some conditions, contributes recharge water to two or more springs. Fifty-eight percent of the Ozark cavefish sites share some (but seldom all) of their recharge areas with at least one other spring. In the case of Fantastic Caverns there are eight springs that share recharge areas with the stream that flows through this cave. All of the known population sites for the Tumbling Creek cavesnail and the Benton Cave crayfish have shared recharge areas; there are no known shared recharge areas for the Hell Creek Cave crayfish. Seventy-one percent of the Illinois Cave amphipod sites share some of their recharge areas with at least one other spring. Springs feeding the three fens providing known or potential habitat for Hine's emerald dragonfly also have portions of their recharge areas shared with other springs.

In many cases the springs that share recharge areas with listed-species sites are not known to provide habitat for these species. They are clearly springs that warrant detailed investigation to determine if they may provide previously unknown habitat for the listed species. In our delineation work we have focused substantial effort on identifying springs and caves that share recharge areas with sites that are the focus of our investigations.

Discharge to Multiple Springs

Some of the caves for which we have delineated recharge areas are located hundreds to thousands of meters from their associated springs. The most spectacular example of discharge to multiple springs is Tumbling Creek Cave, which discharges from a single spring under extreme low-flow conditions, but discharges from 15 to 20 separate springs under high-flow conditions. These springs are located along a 730-m (2,400-ft.) segment of Big Creek and an 855-m (2,800-ft.) segment of Bear Cave Hollow, a surface tributary to Big Creek. All but one of these springs (the highest elevation spring) discharges from an epikarstic zone capped by a massive chert unit typically 0.9 to 1.5 m (3 to 5 ft.) thick. Most of the springs are about a 1.6 km (1.0 mi.) from portions of the cave where cavesnails are routinely found.

Where a cave discharges to multiple springs it often occurs that some or all of those springs are located in the channel of a surface stream where the springs are concealed by the overlying waters, alluvium or both. In this situation it is difficult to determine exactly how many springs may be involved and in some cases whether or not multiple springs are involved. Our data indicate that at least 10% of the caves providing habitat for listed species discharge waters to multiple springs.

Groundwater Travel Rates and Distances

Travel rates for waters moving into and through the groundwater systems providing "likely habitat" are routinely in the range of hundreds to thousands of meters per day. Travel rates are typically greatest under storm-flow conditions and slowest under low-flow conditions when there has not been significant precipitation for a week or longer.

One of the most rapid, documented, groundwater travel rates was a trace conducted under storm-flow conditions from a losing-stream segment on Pelham Creek to the bridge in Tumbling Creek Cave. The straight-line travel distance for this trace was 3.81 km (12,500 ft.), and first dye arrival in the cave occurred within 14.5 hours of the time of dye introduction. This represented a travel rate for the first arrival of dye in the cave of at least 6.3 km/day (3.9 mi./day).

Hine's emerald dragonfly habitats that we studied are calcareous fens, which are a unique type of wetland. The water supplies for the three studied fens and four others investigated less intensively are small springs (rather than seeps) with flow rates typically in the range of less than 3.8 to 38 L/min. (1 to 10 gal./min.). There commonly are multiple springs in a particular fen and flow rates plus water quality parameters such as specific conductance typically vary substantially among the springs and through time. The data for the studied fens shows that water quality and source areas for the springs in a fen are generally different from one another. Dye-tracing work has shown that some of the springs in a particular fen share portions of their recharge areas with other springs.

One of the groundwater traces conducted to a fen in Madison County, Missouri, was from a losing-stream segment in a topographic basin separate from, but adjacent to, the fen. The dye was detected in two of the five springs in the fen. The straight-line travel distances from the losing-stream segment to the springs were 506 and 541 m (1,660 and 1,775 ft.) respectively, and groundwater travel times for the first arrival of the dyes were between 12 and 19 days for the trace to the nearer spring and 5 to 12 days for the trace to the more distant spring. Mean travel velocities under these flow conditions were thus > 27.4 m/day (90 ft./day) for the trace to the nearer spring and > 43.3 m/day (142 ft./day) for the trace to the more distant spring.

The recovery plan for Hine's Emerald Dragonfly (U.S. Fish and Wildlife Service 2001) recognizes the importance of groundwater quality to the species, but is silent on the nature of the groundwater flow systems. Some aquifers are reasonably homogeneous and isotropic and can credibly be modeled with conventional groundwater-modeling approaches. In such aquifers flow rates are commonly in the general range of 1 to 10 m/yr. (3.3 to 33 ft./yr.). Epikarstic aquifers are neither homogeneous nor isotropic. In a group of studied epikarstic aquifers mean groundwater flow rates for first arrival of tracer dyes varied from 6.7 m/day (22 ft./day) for perennially saturated epikarstic zones to 60 m/day (197 ft./day) for seasonally saturated zones (Aley 1997). The data from Aley (1997) are based upon 70 traces in epikarstic zones. The Madison County, Missouri, trace from a sinking stream to two springs in a fen clearly demonstrates that an epikarstic aquifer is feeding these springs. While our experience with fens providing known or potential habitat for Hine's Emerald Dragonfly is limited, it indicates that epikarstic aquifers are sometimes (and perhaps commonly) the aquifers supplying water to fens. The role of epikarstic aquifers in supplying water to fens cannot be properly assessed without using groundwater tracing methods.

The distinction between epikarstic aquifers and reasonably homogeneous and isotropic aquifers has important management implications beyond the dramatic differences in groundwater travel rates. Epikarstic aquifers provide far less natural cleansing of waters passing through them than is the case for reasonably homogeneous and isotropic aquifers. As a result, water quality in a fen supplied by an epikarstic aquifer is far more vulnerable to the introduction and transport of contaminants than is a reasonably homogeneous and isotropic aquifer. If one presumes that the aquifer supplying a fen is reasonably homogeneous and isotropic when it is actually an epikarstic aquifer, then strategies for water quality protection are likely to be grossly inadequate, and the area capable of directly impacting water quality in the fen is likely to be substantially under-estimated.

Unlike the Missouri sites, many of the fens providing habitat for Hine's Emerald Dragonfly are in areas glaciated during the Pleistocene. It is sometimes presumed that epikarstic development in glaciated areas is insignificant. While epikarstic zones in recently glaciated areas may be thinner than in unglaciated regions, preferential solution of the bedrock and the development of integrated groundwater flow routes can still provide for hydrologically significant lateral water transport. Much of the data in Aley (1997) is from glaciated limestone and dolomite areas.

Vulnerability Mapping

We have conducted vulnerability mapping for most of the recharge areas delineated during the last 25 years. Vulnerability mapping is designed as an aid for land management decisions and is based on hydrogeologic settings with attention to current and likely near-term land uses. Vulnerability mapping is a qualitative assessment of how vulnerable particular portions of a recharge area are to the introduction and transport of pollutants that could impact known habitats for listed species. Areas where inputs of water into the groundwater system are highly localized (such as losing-stream segments and sinkholes) have greater vulnerability than lands where the water inputs are more dispersed (such as uplands and hillslopes). Areas closer to the habitat sites have greater vulnerability than lands that are more remote. Losing-stream valley segments downstream of major highways or railroads where catastrophic spills could occur have higher vulnerability rankings than lands that would not be affected by such disasters. Urbanizing areas have higher vulnerability rankings than lands that are maintaining their rural characteristics.

We have typically used three, occasionally four, vulnerability classes. They are routinely High, Moderate, and Low Vulnerability lands. In a few cases we have expanded the classes to include an Extremely High Vulnerability category. The nature of the landscapes and the existing and near-future land uses are such that not all recharge areas have all vulnerability classes. Many recharge areas have no identified Low or Extremely High Vulnerability lands. The standard descriptions we have used for the four vulnerability classes are as follows:

1. Low Vulnerability Lands. These are lands where the hydrogeological setting and existing and anticipated land uses pose low risks of groundwater impacts likely to adversely affect species of conservation concern or associated biological communities. These are often upland areas remote from sinkholes or losing streams where land use does not include hazards such as urban or suburban development or confined animal feeding operations (known as CAFOs, which include commercial poultry operations).

2. Moderate Vulnerability Lands. As above, but land uses pose moderate risks of groundwater impacts.

3. High Vulnerability Lands. There are high risks of groundwater impacts. Examples of high risks are losing-stream segments downstream of a major highway, waste-disposal facilities, and losing-stream valleys in which land application of animal wastes from CAFOs is, or might become, common.

4. Extremely High Vulnerability Lands. As above, but these lands appear to have extremely high risks of groundwater impacts. Land uses and very close proximity to critical habitat areas are factors.

Table 2 summarizes vulnerability mapping of recharge areas for sites providing habitat for one or more of the listed species. The table makes it clear that most of the recharge areas for the species studied currently pose significant threats to water quality at the habitat sites. Seventy five percent or more of the lands in the recharge areas for the Tumbling Creek Cavesnail, Illinois Cave Amphipod, Hell Creek Cave Crayfish, and Grotto Sculpin are ranked as having High or Extremely High Vulnerability. Only the Ozark Cavefish and fens providing known or potential habitat for Hine's Emerald Dragonfly had less than 50% of their recharge areas in High or Extremely High Vulnerability classes. Vulnerability mapping was not conducted for the Spring Cavefish site.

Table 2 *Results of vulnerability mapping of recharge areas for sites providing habitat for federally listed threatened and endangered species and one other species of conservation concern. See text for descriptions of vulnerability classes.*

Species	High or Extremely High	Moderate	Low	Number of Studied Sites
Ozark Cavefish	46	46	8	24
Tumbling Creek Cavesnail	83	17	0	1
Benton Cave Crayfish	57	42	1	4
Hell Creek Cave Crayfish	75	25	0	1
Illinois Cave Amphipod	93	7	0	7
Grotto Sculpin	91*	9*	0	5
Hine's Emerald Dragonfly	13	87	0	3

* Estimated; delineation and mapping in progress.

Localized Land Use Impacts

Localized land use activities likely to create significant, adverse impacts in delineated recharge areas were located by field reconnaissance and aerial photography. Activities mapped include: (a) agricultural and forestry, (b) sewage disposal facilities or concentrated housing served by on-site sewage systems, (c) landfills, dumps, and salvage yards, (d) industrial sites, (e) transportation routes, including pipelines, (f) petroleum storage sites, (g) other chemical storage sites, (h) other types of sites or facilities.

The extent and diversity of land uses that can impact aquatic fauna is frankly amazing and will be summarized for six species.

Ozark Cavefish Sites

The 24 delineated recharge areas for the Ozark Cavefish in Missouri, Arkansas, and Oklahoma incorporate a total of 548.8 km^2 (211.9 mi.^{2}). Numerous federal, state, and county highways cross these lands, including a segment of Interstate 540 in Arkansas and 16.5 km (10.25 mi.) of Interstate 44 west of Springfield, Missouri. This segment of Interstate 44 crosses the recharge area for four known cavefish populations. About 18.2 km (11.3 mi.) of heavily-used rail lines and 9.0 km (5.6 mi.) of petroleum pipelines also cross Ozark Cavefish recharge areas. A pipeline transporting ammonium nitrate and urea fertilizer crossed recharge areas for Ozark Cavefish populations in Oklahoma and Missouri, but is no longer used for liquid transport. While the pipeline was being used for liquid fertilizer transport a major break occurred in 1981 (Vandike 1985). This break resulted in a massive kill of aquatic life at Maramec Spring 20.6 km (12.8 mi.) from the spill site. The dead aquatic life discharged from the spring included Southern Cavefish, Salem cave crayfish (*Cambarus hubrichti*), and Grotto salamander (*Eurycea spelaea*).

Urbanization has been identified as a water quality hazard in 14 of the 24 Ozark Cavefish recharge areas. Urbanization is a very major issue at Cave Springs, Arkansas, which has the largest known population of the Ozark Cavefish. Domestic sewage disposal practices for communities are a problem affecting 42% of the cavefish sites. Sewage treatment plants (both public and private) and their associated discharges are within the recharge areas for six Ozark Cavefish sites, and six sites have communities depending upon septic systems within their recharge areas. Two sites have both treatment plants and communities served by septic systems within their recharge areas. One site is located beneath a community that has public wastewater treatment but where leaky public and private sewers undoubtedly impact groundwater quality.

Both the Northwest Regional Airport and the Springfield-Branson National Airport are located within the recharge areas for Ozark Cavefish populations. An airport at Neosho is also within the recharge area for a cavefish population. Both the Northwest Regional and Springfield-Branson Airport have given substantial attention to minimizing groundwater impacts that could adversely impact cave fauna. Both airports have substantial amounts of green space where development is not planned. These areas can serve to introduce good-quality runoff water into the karst groundwater systems. On September 20, 2001 a fuel truck overturned at the Springfield-Branson airport and spilled 6,098 L (1,611 gal.) of jet aircraft fuel into a sinkhole. Good weather, rapid response, and the removal of 483,600 kg (532 tons) of contaminated soil prevented any detectable offsite migration of the fuel. Also in 2001 a smaller spill occurred at the Northwest Arkansas Regional Airport; it was all captured in a spill control structure installed in recognition of the fact that the airport was in the recharge area for an Ozark Cavefish population.

There are numerous CAFOs in the Ozarks. At the time that recharge areas were being delineated there were 169 commercial poultry houses plus 42 CAFOs for dairy, beef, or hogs in the recharge areas for Ozark Cavefish populations. The current number is undoubtedly larger than this. Land disposal of wastes from these operations is the common approach, and much of this disposal is within delineated recharge areas for populations of Ozark Cavefish. Land application followed by precipitation producing surface runoff into losing streams is a major problem especially during cold weather conditions when wastes are not rapidly trapped in the soil and vegetation.

At least 65 dumps, salvage yards, and one closed municipal landfill lie within delineated recharge areas for Ozark Cavefish populations. This number is undoubtedly an underestimate since many dumps are not readily visible from public roads. As will be discussed below, dump density was about 1.2/km^2 (3/mi.^{2}) in a recharge area where a thorough search was made for these features. Using this value and the total size of delineated recharge areas for Ozark Cavefish populations (548.8 km^2, 211.9 mi.^{2}) the total number of dumps in recharge areas for Ozark Cavefish could be about 660. While some caving organizations have conducted dump cleanup projects in sinkholes and losing-stream valleys, most of the dumps have received no cleanup efforts. Dumps commonly include small amounts of petroleum products, asphalt roofing shingles, some pesticides and inadequately cleaned pesticide containers, and a wide range of undesirable materials. Dumps are commonly located in or near drainageways upstream of losing-stream segments. The one closed municipal landfill pre-dated requirements for reasonably effective liners and leachate collection systems and thus will be a long-term source of groundwater contamination.

Tumbling Creek Cavesnail Site

Figure 1 is a map showing the delineated recharge area for Tumbling Creek Cave. The recharge area encompasses 23.36 km^2 (9.02 mi.^{2}) and lies

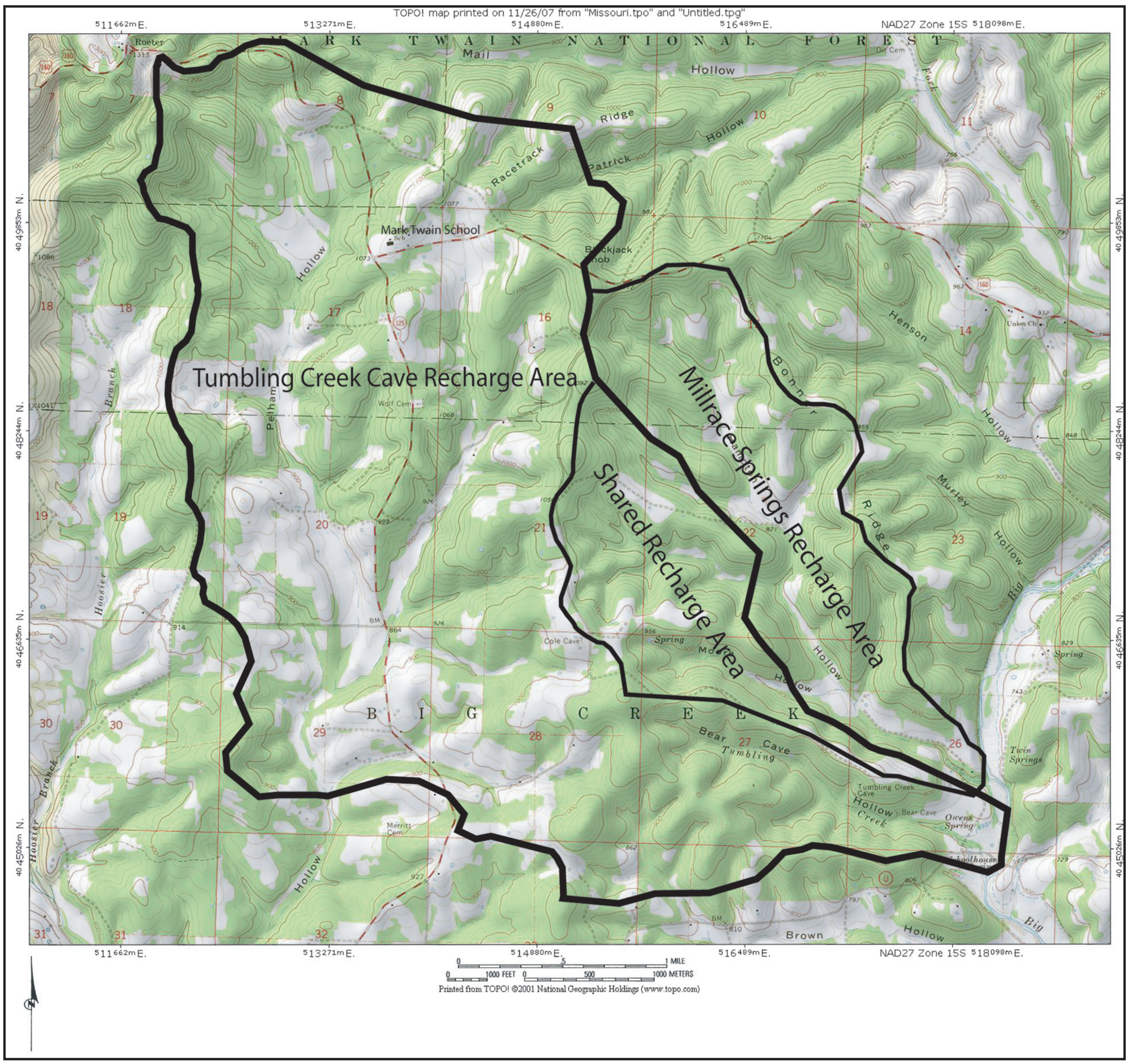

Figure 1 *Delineated recharge area for Tumbling Creek Cave. Note that the recharge area lies in several topographic basins. A portion of the recharge area is shared with another system of springs. The data are based on 62 groundwater traces.*

in several topographic basins. The map illustrates that a portion of the recharge area is shared with another system of springs. A total of 29 dumps (about 1.2/km^2 or 3/mi^2) have been discovered in this recharge area as a result of a cost-share project to discover and assess the dumps. Major funded efforts have been made to cleanup these dumps and dispose of all materials outside of the recharge area for Tumbling Creek Cave. This work should be completed by December 2008.

About 4.57 km (15,000 feet) of U.S. Highway 160 and 4.51 km (14,800 feet) of Missouri 125 cross the recharge area for the Tumbling Creek Cavesnail population. These roads are lightly traveled and are not major trucking routes. However, over the last 40 years there have been several accidents where fuels were spilled. A large tanker load of road oil wrecked in a ditch on Missouri 125 about 2002 but did not lose any appreciable amount of cargo. A beer truck rolled over on U.S. 160 in 1970 and a substantial amount of liquid was spilled. Local residents rapidly responded and removed much of the cargo, thereby protecting groundwater quality.

A rural school using a badly leaking sewage lagoon system was a major problem source in the Tumbling Creek Cave recharge area. A number of entities and individuals contributed funds to design and construct an advanced wastewater treatment plant that now serves the school and protects groundwater quality (Elliott et al. 2007). Several sewage system upgrades have been made at privately owned critical sites in the recharge area and a major effort is underway to expand this program. There are no communities or urbanizing areas in this recharge area.

There is one, small, beef–cattle CAFO in the Tumbling Creek Cave recharge area. It is about 122 m (400 ft.) from a major losing stream that rapidly contributes much of its flow to the cave. Owners of the land between the stream and the CAFO are maintaining an ungrazed and uncut vegetative cover on this land to function as a filter strip, and thereby reduce impacts from this facility.

Sediment from eroding pastureland has been identified as the most likely factor causing a drastic decline in the Tumbling Cavesnail population in Tumbling Creek Cave (McKenzie 2003, Elliott et al 2007, 2008). New owners of the involved properties assisted by funding from U.S. Fish and Wildlife Service and U.S. Department of Agriculture have corrected this problem, yet the cavesnail population has not shown an appreciable increase as of November 2007.

Benton Cave Crayfish Sites

The four known sites for the Benton Cave Crayfish are all in Benton County, Arkansas. One of the sites extends a few feet into Missouri and a cave crayfish reportedly discharged from an estavelle on the Missouri side of the border during a storm period. The combined recharge areas for the four sites encompass 97.9 km^2 (37.8 mi.^{2}). One of these sites, with a recharge area of 30.0 km^2 (11.6 mi.^{2}), also provides habitat for the Ozark Cavefish.

A total of 21.3 km (13.2 mi.) of Arkansas state highways and 6.1 km (3.8 mi.) of U.S. highways cross delineated recharge areas for the Benton Cave Crayfish. All four of the recharge areas are experiencing urbanization and all have communities dependent upon on-site sewage disposal. There are a total of at least 73 commercial poultry houses or CAFOs for other animals in one of the two recharge areas that still contain an appreciable amount of rural land. There are about 15 poultry houses and one hog CAFO in the other recharge area with appreciable rural land. Land application of animal wastes from these operations is the common approach, and much of this land application occurs in delineated recharge areas for listed species.

Hell Creek Cave Crayfish Site

Hell Creek Cave is one of two known sites for this species and is the only site for this species that we have delineated. Our work here was conducted in 1984-85, and land use conditions have changed somewhat since that investigation. Additional tracing work in the region is envisioned, and may add substantially to our knowledge of the hydrogeology of this system. The delineated recharge area encompasses 12.2 km^2 (4.7 mi.^{2}).

The recharge area for this site is crossed by 2.5 km (1.6 mi.) of an Arkansas state highway. There is an industrial site that yields sediments and potentially other materials located in the upper end of the major losing stream, which supplies much of the water to the cave system. In 1985 there were five petroleum storage sites, one chemical storage location, and three dumps and salvage yards in the delineated recharge area. Urbanization is occurring in parts of the recharge area and these developments rely upon on-site sewage systems.

Illinois Cave Amphipod Sites

We have delineated the recharge areas for seven sites for this southwestern Illinois species. The total size of delineated recharge areas for this species is 108.8 km^2 (42.0 mi.^{2}). There are 6.0 km (3.7 mi.) of state highways crossing recharge areas for this species.

Urban expansion is the major water quality threat in the region since it is within commuting distance of the greater St. Louis area. Expanding suburbs exist on 9.8% of the lands in the delineated recharge areas, and many of the new homes rely upon on-site sewage systems. Soils in the area are largely derived from loess, and row crop agriculture now occurs on 58.1% of the lands in the seven recharge areas. Most of the expanding suburbs are located on lands that were formerly used for row-crop agriculture. Pesticides are a concern with row-crop agriculture, but in our opinion suburban development presents more water quality problems to karst groundwater systems than are presented by the agriculture of this region.

Hine's Emerald Dragonfly Sites

The total size of the three delineated recharge areas for this species is 1.6 km^2 (0.6 mi.^{2}). All of these sites were studied because of planned highway improvements that would cross the recharge areas for the sites. The total length of highway corridors in these three recharge areas is 1.42 km (0.88 mi.). None of these recharge areas had other land uses likely to adversely impact water quality and habitat conditions for the dragonfly.

Sites for Other Species

We are currently delineating the recharge areas for five sites in Perry County, Missouri that provide habitat for the Grotto Sculpin, and at this time we do not have sufficient information to warrant a detailed discussion. We have also delineated the recharge-area for one cluster of springs that provide habitat for the Spring Cavefish. Vulnerability mapping was not conducted in this recharge area. Finally, we have conducted recharge-area delineation work for populations of cavefish and cave crayfish that are not federally listed. This work is mentioned here to illustrate that there are other aquatic species dependent upon springs and cave waters that have recharge areas warranting delineation and vulnerability mapping.

Defensibility of the Delineated Sites

The delineated recharge areas for Ozark Cavefish, Tumbling Creek Cavesnail, Hell Creek Cave and Benton Cave Crayfish, Illinois Amphipod, and Hine's Emerald Dragonfly encompass a total area of 764 km^2 (295 mi.^{2}). About 95% of this land is in private ownership. It is estimated that the lands encumbered by right-of-ways for county, state, and federal roads in the delineated recharge areas almost equal the acreage owned by conservation agencies, not-for-profit conservation entities, or that are included in conservation easements. Good resource management practices on private lands are clearly essential to the continued existence of these species and the number of habitat sites that presently exist.

Under present conditions and anticipated near-term changes in land use, many of the habitat sites cannot be effectively defended against land use activities or accidents that could seriously damage or destroy some of the populations discussed in this report. Based upon conditions in the studied recharge areas we have qualitatively ranked the defensibility of the sites over the next thirty years. Poorly defensible sites are those where land use and hydrologic conditions are such that it is more likely than not that the population of the species of concern will be seriously damaged or destroyed within the next 30 years. Moderately defensible sites are those where some damage to the population of the species of concern is likely within the next 30 years, but where the population is likely to continue to exist. Highly defensible sites are those where little or no damage to the population of the species of concern is likely within the next 30 years. These sites are generally remote from most disturbances and have landowners or some conservation entity that is capable of providing some protection for the sites and for water quality in the recharge areas. While the credibility of our assessments can be questioned, they represent the best estimates of people familiar with the sites. Table 3 summarizes our assessment of site defensibilities for habitats for the listed species. We have not made an assessment

Table 3 Defensibility of federally threatened and endangered cave and spring species. See text for a description of the categories. Values are number of sites.

Species	Poorly Defensible	Moderately Defensible	Highly Defensible	Total Studied Sites
Ozark Cavefish	10	8	6	24
Tumbling Creek Cavesnail	0	0	1	1
Benton Cave Crayfish	0	4	0	4
Hell Creek Cave Crayfish	0	1	0	1
Illinois Cave Amphipod	7	0	0	7

for Hine's Emerald Dragonfly since our sample is only a small portion of total known sites and the sites investigated were not reflective of typical sites for this species.

Summary

Perennially saturated epikarstic zones with "likely habitat" are associated with 79% of the delineated cavefish sites, all of the Benton Cave Crayfish sites, and at the only known site for the Tumbling Creek Cavesnail. Five hand-dug wells bottom in the epikarst support populations of Ozark Cavefish, and attest to the significance of epikarstic habitat beneath valley floors.

Fens underlain by limestone and dolomite units are usually associated with populations of Hine's Emerald Dragonfly. All three of the delineated fen recharge areas receive groundwater supplies from the epikarstic zone. It is likely that other fens, both in glaciated and unglaciated areas, are dependent upon epikarstic groundwater flow.

Protecting water quality entering karst groundwater systems through sinkholes and losing streams poses substantial challenges. Problems associated with sinkholes are typically confined to very localized areas with relatively few landowners. In contrast, some of the losing-stream segments contributing flow to important cave faunas drain hundreds to thousands of hectares and water quality is impacted by numerous property owners who may be located far from the habitats that they are affecting.

With the exception of fens, travel rates for waters moving into and through the groundwater systems providing "likely habitat" are in the range of hundreds to thousands of meters per day. Travel rates are greatest under storm-flow conditions and slowest under low-flow conditions when there has not been significant precipitation for a week or longer. Travel rates through epikarstic aquifers to the studied fens are in the range of 3 to 30 m/day (10 to 100 ft./day) or more.

Vulnerability mapping is a qualitative assessment of how vulnerable particular portions of recharge areas are to the introduction and transport of pollutants that could impact sensitive habitats. Most of the recharge areas for the species studied currently have significant threats to water quality in the habitat sites. Seventy-five percent or more of the lands in the recharge areas for the Tumbling Creek cavesnail, the Benton Cave crayfish, the Hell Creek Cave crayfish and the Grotto sculpin are ranked as having High or Extremely High Vulnerability. Only the Ozark Cavefish and fens providing "likely habitat" for Hine's Emerald Dragonfly had less than 50% of their recharge areas in High or Extremely High Vulnerability classes.

The 24 delineated recharge areas for the Ozark Cavefish are crossed by numerous federal, state, and county highways; five of the recharge areas are crossed by interstate highways. Significant segments of heavily used rail lines and petroleum pipelines cross some of the recharge areas. Sewage treatment plants and communities with on-site sewage systems are found in many of the Ozark Cavefish recharge areas. Fuel spills have occurred at two of the three airports located in recharge areas for the Ozark Cavefish; both of these spills were rapidly contained and recovered.

Disposal of CAFO wastes is a major concern in many of the Ozark Cavefish recharge areas since there are at least 211 CAFOs in the delineated recharge areas. Land disposal of wastes from these operations is the common approach, and much of this disposal is within delineated recharge areas for populations of Ozark Cavefish. A major problem is land application followed by precipitation yielding surface runoff into losing streams, is especially during cold weather conditions when wastes are not rapidly trapped in the soil and vegetation.

The recharge area for the Tumbling Creek Cavesnail encompasses 29 dumps, but all of these should be cleaned up and the trash exported out of the recharge area by December 2008. The recharge area for the cavesnail population is crossed by U.S. Highway 160 and Missouri 125. These roads are lightly traveled and are not major trucking routes, but some spills have occurred. Several sewage system upgrades have been made at a school and privately owned sites in the recharge areas and this program is being expanded. There are no communities or urbanizing areas in this recharge area. Sediment from eroding pastureland was identified as the most likely factor causing a drastic decline in the Tumbling Cavesnail population in Tumbling Creek Cave. New land owners have corrected this problem, but the cavesnail has not increased.

There are four known sites for the Benton Cave Crayfish in Benton County, Arkansas. One site also provides habitat for the Ozark Cavefish. A total of 21.3 km (13.2 mi.) of Arkansas state highways and this species. Urbanization is increasing in along with all four of the recharge areas on-site sewage disposal. At least 89 CAFOs, and associated waste-disposal problems are a major concern.

Hell Creek Cave is one of two known sites for *C. zophonastes* and is its only site that we have delineated. The delineated recharge area is crossed by 2.6 km (1.6 mi.) of an Arkansas state highway. An industrial site that yields sediments and potentially other materials located in the upper end of the major losing stream supplies much of the water to the cave system. Urbanization increases in parts of the recharge area, and these developments have on-site sewage systems.

We have delineated the recharge areas for seven Illinois Cave Amphipod sites in southwestern Illinois. Urban expansion is the major threat to water quality in these recharge areas. Expanding suburbs exist on 9.8% of the lands in the delineated recharge areas, and many new homes have on-site sewage systems. Row-crop agriculture now occurs on 58.1% of the lands in the seven recharge areas, and most of the expanding suburbs are located on former farm lands. Pesticides are a concern with row-crop agriculture, but in our opinion suburban development presents more water-quality problems to karst groundwater in this case.

The total size of the three delineated recharge areas for Hines Emerald Dragonfly is only 1.6 km^2 (0.6 mi.^{2}). All of these sites were studied because of planned highway improvements that would cross the recharge areas for the sites. The total length of highway corridors in these three recharge areas is 1.42 km (0.88 mi.). No other land uses are likely to adversely impact water quality and habitat conditions for the dragonfly.

We are currently delineating the recharge areas for five sites in Perry County, Missouri that provide habitat for the Grotto Sculpin, so that is a work in progress.

The delineated recharge areas for Ozark Cavefish, Tumbling Creek Cavesnail, Hell Creek Cave and Benton Cave Crayfish, Illinois Amphipod, and Hine's Emerald Dragonfly encompass a total area of 764 km^2 (295 mi.^{2}). About 95% of this land is in private ownership. Lands encumbered by right-of-ways for county, state, and federal roads in the delineated recharge areas are estimated to almost equal the size of the area owned by conservation agencies, nonprofit conservation entities, or that are included in conservation easements. We qualitatively ranked the defensibility of the sites over the next thirty years. All seven of the delineated sites for the Illinois Cave Amphipod are poorly defensible. There are no highly defensible sites for either the Benton Cave Crayfish or the Hell Creek Cave Crayfish. Seventy-five percent of the Ozark Cavefish sites are poorly or moderately defensible. The only known site for the Tumbling Creek Cavesnail is ranked as highly defensible because of restoration actions during the past seven years. In the absence of such aggressive efforts in other recharge areas it is our conclusion that many population sites and perhaps some species will be lost within the next 30 years or sooner.

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