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HYDROLOGIC CHARACTERIZATION OF TWO KARST RECHARGE AREAS IN BOONE COUNTY, MISSOURI

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The Bonne Femme watershed, located in central Missouri, is a karst watershed in a rapidly urbanizing area. This study was undertaken to characterize the hydrology of two karst aquifers within this watershed before significant increases in impervious surfaces take place. The specific objectives of this study were to: 1) use dye tracing to delineate the recharge area for Hunters Cave (HC); 2) quantify and summarize annual and monthly stream discharge at the resurgence of HC and Devils Icebox (DI) caves; and 3) characterize the chemical and physical status of the cave streams relative to temperature, pH, specific conductance, dissolved oxygen, and turbidity. The quantity and quality of the water at the resurgence of both cave streams was monitored from April 1999 to March 2002. Both recharge areas were determined to be of similar size (33.3 km^2 for HC and 34.0 km^2 for DI) and were formed in the same geologic strata. Average annual discharge was 55,900 $m^3\ km^{-2}$ at DI and 35,200 $m^3\ km^{-2}$ at HC. Relative discharge, as a percent of annual precipitation, averaged 6.1% at DI and 3.8% at HC. Average monthly discharge was 2,930 $m^3\ km^{-2}$ at HC and 4,650 $m^3\ km^{-2}$ at DI; however, median instantaneous discharge over the three years was about 18% higher at HC (74 $m^3\ h^{-1}$) compared to DI (63 $m^3\ h^{-1}$). Turbidity and pH showed the largest differences between sites over the three years. The higher turbidity and lower pH at DI reflected the greater magnitude and duration of runoff events for this system. The physical characteristics of the two recharge areas explained the observed differences in discharge. The HC recharge area is characterized by limited sub-surface conduit development, small conduits, short flow paths from surface to resurgence, and predominantly allogenic recharge. The DI recharge area is characterized by extensive subsurface-conduit development, large conduits, long flow paths to the resurgence, and autogenic and allogenic recharge.

INTRODUCTION

The nature of ground-water recharge in karst aquifers controls speleogenesis over geologic time, and it directly impacts the quantity and quality of water in the aquifer in current time. There are two basic ground-water recharge types in karst terranes: autogenic and allogenic (Shuster and White, 1971). Autogenic recharge can be further separated into diffuse and discrete recharge. Allogenic and discrete recharge modes are especially vulnerable settings for contaminant transport to ground-water. Allogenic recharge to karst aquifers occurs where surface runoff draining large areas of insoluble rock or low permeability soils flows directly to adjacent soluble carbonate bedrock (Palmer, 2000). Recharge to the karst aquifer occurs along sinking or losing stream channels via infiltration of surface water through porous streambed sediments or through fractures in the streambed (White, 1988). In this setting, the karst aquifer displays flow characteristics that are typical of surface streams, with relatively rapid response to precipitation and variations in resurgence discharge over several orders of magnitude. In mature karst aquifers formed by allogenic recharge, the subsurface conduits will be well developed, resulting in relatively short residence time of water in the subsurface. Under such conditions, thermal and chemical equilibrium of the water will not be attained (Wicks, 1997). Cave formation is enhanced by allogenic recharge due to the concentration of surface runoff from large catchments into a few relatively small subsurface conduits and because the surface runoff is typically under-saturated with respect to calcite or dolomite in these settings (Groves, 1992; Wicks and Engeln, 1997).

Discrete recharge to a karst aquifer occurs through openings, such as sinkholes, that drain a small land area. Karst aquifers recharged in this manner typically have numerous inputs of surface water to the subsurface, with water draining along cracks, fissures, and zones of weakness in soluble bedrock. As enlargement progresses by solution and/or corrosion along these flow paths, conduits capable of rapidly transmitting water from the surface to the subsurface are created. However, discrete recharge will typically have longer subsur-

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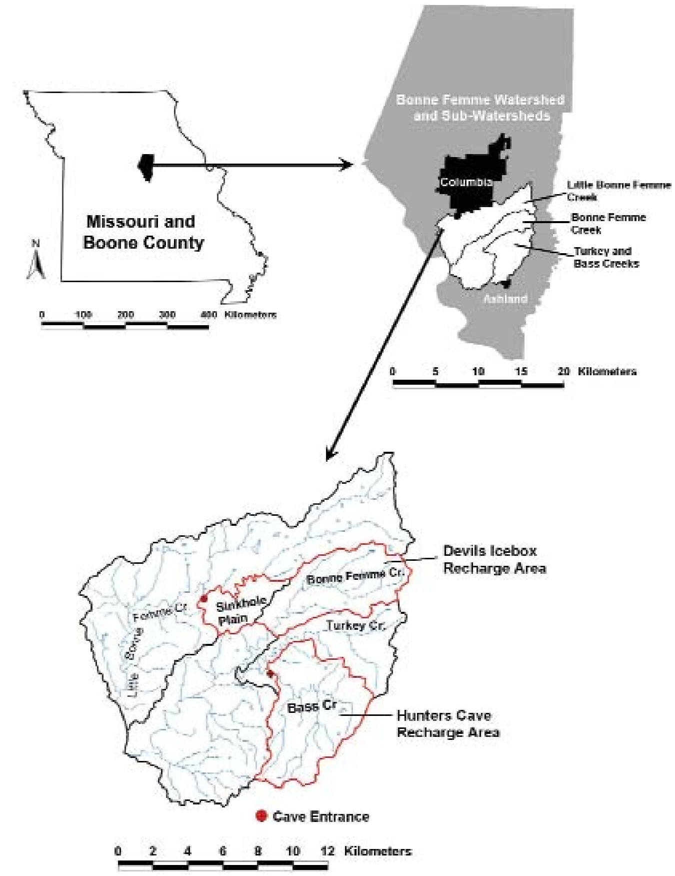

Figure 1. Location and hydrologic setting of the two karst aquifers. For Devils Icebox, the allogenic (upper Bonne Femme Creek) and the autogenic (sinkhole plain) portions of its recharge area are distinguished by the black boundary line shown within the recharge area. Hunters Cave recharge area encompasses allogenic recharge from Bass Creek and two tributaries of Turkey Creek.

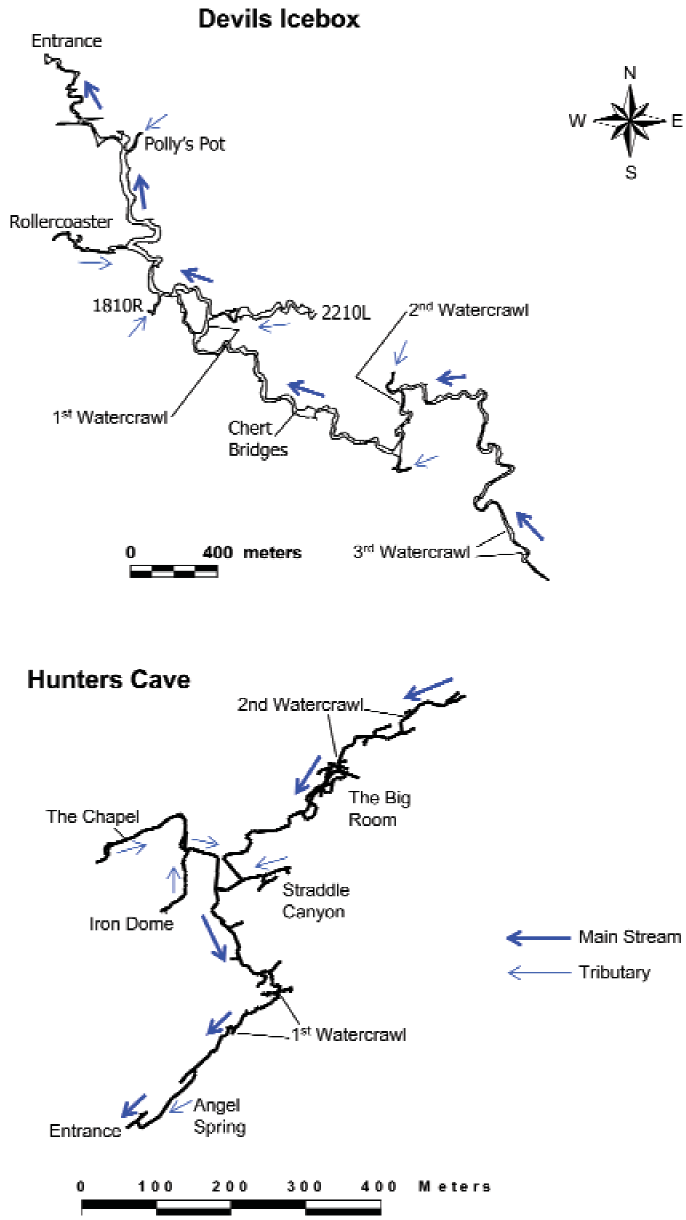

Figure 2. Line plot diagrams of the two cave systems. (Note the difference in scale for the two caves.)

face residence time than water transmitted by allogenic recharge, and therefore, thermal and chemical equilibrium of the water are more closely attained in this situation (Wicks, 1997).

Overall, allogenic and discrete recharge modes represent the most vulnerable setting for ground-water contamination because surface water rapidly enters the subsurface with little or no opportunity for contaminant attenuation by surface soils. Contaminant inputs derived from surface land-use activities within the recharge area will have a profound impact on water quality in these karst aquifers. In the Midwestern USA, common land uses or land covers that are a potential threat to karst ground-water quality include urban development, agricultural practices, private septic systems, industrial production, and military activities. These land uses can impact karst aquifers through a myriad of contaminant inputs, such as oil, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, pesticides, fertilizer, sediment, and fecal coliform bacteria (Ruhe *et al.*, 1980; Boyer and Pasquarell, 1999; Mahler *et al.*, 1999; Lerch *et al.*, 2001).

An additional threat to karst ground-water is the increased impervious surface resulting from urbanization. Impervious surfaces, such as roads, building rooftops, sidewalks, driveways, and parking lots, will negatively impact stream hydrology, biology, and channel geomorphology. In surface stream watersheds, impervious surfaces increase discharge velocity and volume of storm water runoff, leading to degraded aquatic habitat and biological health of streams, increased stream bank erosion, and decreased baseflow discharge (Burges *et al.*, 1998; Booth *et al.*, 2002). These hydrologic impacts have also been shown to occur in allogenic recharge karst aquifers (Betson, 1977; Ruhe *et al.*, 1980). Karst systems further complicate the impact of impervious surfaces because inter-basin transfer of water routes storm runoff from one watershed to another. The altered hydrologic conditions caused by impervious surfaces will most profoundly impact allogenic recharge to karst aquifers and their ecosystems, but localized increases to impervious surface could negatively impact the water quality and quantity of discrete recharge to karst aquifers as well. Because of the analogous impacts of impervious surfaces on karst aquifers and surface streams, Veni (1999) recommended the adoption of impervious surface limits designed for protection of surface streams (Schueler, 1994) as a reasonable guideline for karst areas. Limiting impervious surfaces within a recharge area to 15% of the land area should minimize adverse impacts to karst ground-water resources (Veni, 1999). However, implementation of best management practices (BMPs), local geological factors, and restoration of older impervious areas may sufficiently mitigate water resource degradation and allow for more than 15% impervious area (Veni, 1999).

The present study was undertaken to characterize the hydrology of two predominantly allogenic recharge karst aquifers in the Bonne Femme watershed of southern Boone County, Missouri (USA) (Fig. 1). The Bonne Femme watershed is rapidly urbanizing due to growth in the cities of Columbia and Ashland, and this study was initiated before significant increases in impervious surface had occurred in either of the karst-recharge areas. Thus, the hydrologic impact of increasing imperviousness and the effectiveness of BMPs that may be implemented as urban growth occurs can be documented. The specific objectives of this study were to: 1) use dye tracing techniques to delineate the recharge area for Hunters Cave (HC); 2) quantify and summarize annual and monthly stream discharge at the resurgence of HC and Devils Icebox (DI) caves; and 3) characterize the chemical and physical status of the cave streams relative to temperature, pH, specific conductance, dissolved oxygen, and turbidity.

Materials and methods

Site Descriptions

The recharge area of the DI and HC are both located within the Bonne Femme Creek watershed located due south of Columbia, Missouri, USA (Fig. 1). The caves were formed in the Burlington Limestone (Osagean Series, Mississippian System) (Wicks, 1997). The total thickness of the Burlington Limestone is approximately 50 m. The Chouteau Group (Kinderhookian Series, Mississippian System) underlies the Burlington Limestone, and is composed of limestone, dolomite, and silty dolomite with a total thickness of approximately 30 m. The Chouteau Group is not conducive to cave development (Unklesbay, 1952); this unit serves as the base of the local flow system in the DI cave. The upper (eastern) portions of both cave recharge areas are covered by clay-rich Pleistocene age glacial and loess deposits (St. Ivany, 1988). These low permeability, fertile soils are generally in the Mexico-Putnam or Mexico-Leonard soil associations (USDA-NRCS, 2001). Lower (western) portions of each recharge area are characterized by residual soils of the Weller-Bardley-Clinkenbeard association (USDA-NRCS, 2001) and correspond to the areas with karst features, such as sinkholes, caves, and springs, including the two cave entrances.

The DI cave length is currently listed as Missouri's seventh longest cave at 10.76 km (6.69 miles) (Gulden, 2005) and includes the primary trunk passage and several smaller side passages (Fig. 2). The main trunk passage is the primary stream conduit, and was surveyed to a length of approximately 6.4 km (4 miles) (Fig. 2) before reaching a sump. The cave system's downstream terminus is a spring located in Rock Bridge Memorial State Park (Missouri Department of Natural Resources, Division of Parks), and water travels along the surface for a short distance before discharging into Little Bonne Femme Creek. This flow path creates an inter-basin transfer of water from the upper Bonne Femme watershed to the Little Bonne Femme watershed (Fig. 1).

As part of this project, HC was re-surveyed to an extent of 2.54 km (1.58 miles) which currently makes it the 34th longest cave in Missouri (Fig. 2). The main passage is also the primary stream conduit, and its flow path extends for approximately 1.25 km, accounting for slightly less than half the surveyed distance of the cave. The largest tributary to the main cave stream is Angel Spring (Fig. 2), located about 70 m into the cave (see additional discussion below). Very small tributaries to the main stream also enter through The Chapel, Iron Dome, and Straddle Canyon side passages. Four other intermittently flowing tributaries have also been observed at various points in the cave, with two of these sources entering through the largest domes in the cave. HC terminates at a spring resurgence discharging directly into Bass Creek located within the Three Creeks Conservation Area (Missouri Department of Conservation).

Delineation of Hunters Cave Recharge Area

The HC recharge area was determined using standard dye tracing techniques (Aley, 1999), involving the introduction of fluorescent dyes into stream channels and their subsequent sorption from the water by activated carbon samplers. These samplers contained 4.25 g of activated carbon, derived from coconut shell charcoal, placed in a fiberglass screening with openings of 1.3 to 1.5 mm (Aley, 1999). The samplers were placed at two locations in the cave stream, and they were also placed downstream from all dye introduction points and in adjacent basins in order to assess the possibility of inter-basin transfer. Before dye injection, two separate sets of samplers were deployed, each for one week, to determine if detectable background levels of any of the dyes were present. Raw water samples were also collected once during the time the background sets were deployed. No dyes were detected in raw water or in the charcoal samplers from these background sample sets. Following dye injection, samplers were typically replaced at weekly intervals for up to 3 months. Dyes used included fluorescein ([sodium fluorescein] Acid Yellow 73;

CAS No. 518-47-8), eosin (Acid Red 87; CAS No. 17372-87-1), and Rhodamine WT (Acid Red 388; CAS No. 37299-86-8). The specific location for dye injections, dye amounts and type, and locations of activated carbon samplers are given in Tables 1 and 2. Dye analysis of the activated carbon samplers entailed elution of the dyes from the charcoal with a mixture of isopropanol in a strongly basic solution (Aley, 1999). Raw-water samples were also collected at each sampler location for direct dye analysis. Dye concentrations were determined by fluorescence spectroscopy using a Shimadzu RF-5301 spectrofluorophotometer. Limits of detection for the charcoal eluants were (in µg L^{-1}): fluorescein, 0.010; Rhodamine WT, 0.275; and eosin, 0.035. Limits of detection for the raw water samples were (in µg L^{-1}): fluorescein, 0.0005; Rhodamine WT, 0.05; and eosin, 0.008.

MONITORING PROCEDURES

Hydrologic, chemical, and physical monitoring of the water was conducted near the resurgence of each cave from April 1999 to March 2002. Discharge and water quality were only monitored for the cave streams; no monitoring of the surface streams was conducted. For the three-year study period, the years reported and discussed below extended from April through March. All instrumentation was placed in stilling wells at both locations for protection against turbulent flow and to reduce data variability caused by very short-term fluctuations in the height of the water column. Hydrologic monitoring consisted of measuring the height of the water column (*i.e.*, stage height) at five-minute intervals with a submerged pressure transducer probe (Hach Co., Loveland, CO). Stage height was then used to compute stream discharge, as detailed below. Pressure transducers were checked for accuracy at least twice per month because thermal drift was a known source of error for these instruments. The pressure transducers were calibrated in the field any time that the known stage height and that recorded by the transducer were more than 5% different. In addition, the transducers were routinely calibrated in the field every three months. Chemical and physical water monitoring included temperature, pH, dissolved O_2, specific conductance, and turbidity measured at 15-minute intervals using a YSI 6920 Sonde (YSI, Inc., Yellow Springs, OH). The Sondes were brought into the laboratory every two months for cleaning and calibration of all probes. In addition, the dissolved oxygen probes were cleaned, the membranes replaced, and the probes calibrated in the field every two weeks. The chemical and physical monitoring allowed for detailed documentation of the response of these systems under both runoff event and prolonged low flow conditions on a year-round basis.

At DI, the monitoring station is located within a large karst window approximately 30 m downstream from the resurgence (Halihan *et al.*, 1998). The stage height was correlated to stream discharge using two independently developed rating curves. In both cases, standard protocols for measuring velocity with wade sticks and current meters were employed (Rantz, 1982). One rating curve was developed by Vandike (1983) under lower flow conditions. A second rating curve was developed by Halihan *et al.* (1998) under consistently higher flow conditions in the spring of 1994, following the record high rainfalls of 1993. Thus, two different equations were used depending upon stage height:

For a stage height < 0.36 m (1.2 ft),

$$Q = 10^{\left[(2.15 S_H) - 1.40\right]} \qquad r^2 = 0.99 \tag{1}$$

and for a stage height > 0.36 m (1.2 ft),

$$Q = (124.1 S_H) - 131.8 \qquad r^2 = 0.97 \tag{2}$$

where S_H is stage height (ft) and Q is discharge ($ft^3\ s^{-1}$). Because the field measurements for developing the rating curves were recorded in English units, the initially developed rating curve equations computed discharge in $ft^3\ s^{-1}$, which was then converted to $m^3\ h^{-1}$. The need for two equations arises from the log relationship in Equation (1) which accurately predicts discharge at low stage heights, but severely over-estimated discharge above stage heights of 0.36 m. Equation (2) showed that a linear relationship existed between stage height and discharge for stage heights > 0.36 m. Errors associated with stage-height rating curve relationships developed using current meters have been estimated to range from 5–25% (Tillery *et al.*, 2001).

At HC, the monitoring station was located approximately 15 meters into the cave (*i.e.* upstream from the resurgence). A rating curve could not be developed for HC because high-flow conditions in Bass Creek prevented access to the cave. Therefore, flow-velocity measurements at the resurgence could not be acquired for high-flow conditions, a necessity for the development of an accurate rating curve. As an alternative, the stage height data were used in conjunction with Manning's Equation (Manning, 1890) to compute flow velocity. The cave passage immediately upstream from the resurgence is a very uniform width stream channel with extensive amounts of small to medium-sized breakdown in the streambed. The channel slope over the initial 15 meters and a reference cross-section of the stream channel were surveyed to provide needed data for computation of flow velocity. In addition, a relationship was established to relate stage height at the reference cross-section to the roughness coefficient, *n*. This relationship was developed by measuring flow velocity with a wade stick and pygmy meter placed at 40% of the water depth at stage heights ranging from 0.06 to 0.19 m. Manning's Equation and the area of the reference cross section were then used to estimate discharge and these estimates were compared against the field measured discharge. By choosing roughness coefficients that minimized the error between predicted and measured discharge, a series of roughness coefficients for known stage heights could be generated and graphed. This graph showed a log relationship between these two variables, and linear regression of the log transformed stage height data was then used to determine the following equation:

$$n = [-0.53 \log(S_H)] - 0.02 \quad (3)$$

Equation (3) was valid only for stage heights < 0.19 m (0.62 ft). For stage heights > 0.19 m, the roughness coefficient was assigned a value of 0.10. The inverse relationship between stage height and roughness coefficient suggested that the high degree of streambed non-uniformity caused by the breakdown in the stream channel created a significant impediment to flow under low stage height conditions. To make direct comparisons between the two sites, summaries of annual and monthly discharge from the cave streams were normalized to the size of each recharge area and expressed in $m^3\ km^{-2}$.

Precipitation and other climate data were obtained from two weather stations. The National Weather Service maintains a weather station at the Columbia Regional Airport, located within the HC recharge area, with data available on a daily basis (National Weather Service, 2005). The University of Missouri maintains a weather station at their South Farms research facility, located less than a kilometer north of the DI recharge area. Data at this site are available on both a daily and hourly basis (University of Missouri Extension, 2005).

RESULTS AND DISCUSSION

RECHARGE AREAS AND LAND USES

Previous studies established the hydrologic links between the DI cave stream and upper Bonne Femme Creek (Crunkilton and Whitley, 1983; St. Ivany, 1988) and the Pierpont sinkhole plain (Deike *et al.*, 1960). The initial recharge area delineation was based on these studies in combination with surface water drainage patterns and topography (St. Ivany, 1988; Wicks, 1997). An additional dye trace using 1.4 kg of fluorescein dye injected into the upper Bonne Femme Creek channel immediately south of Missouri Highway 163 (UTM 563,295 east, 4,302,392 north; Zone 15; NAD83 datum) was conducted on December 9, 2003. This dye trace confirmed speculation by St. Ivany (1988) that the losing reach of upper Bonne Femme Creek extends to approximately 213 m above sea level, establishing the southernmost extent of the recharge area (Fig. 1). The DI recharge area is approximately 34.0 km^2, and is comprised of two distinctive hydrologic recharge areas: 1) an allogenic recharge area corresponding to upper Bonne Femme Creek; and 2) a discrete recharge area encompassing the Pierpont sinkhole plain (Fig. 1).

The initial step in the delineation of the HC recharge area was to overlay the survey line plot on the topographic map to determine locations for dye injections and establish the network of charcoal samplers. From this overlay, it could be seen that Bass Creek comes in very close proximity to the cave passage (Fig. 3 and Fig. 4; inset). The estimated distance of this near intersection corresponded to the location of Angel Spring (Fig. 2). In addition, the cave stream beyond the Big Room was shown to be in close proximity to Turkey Creek, located to the north and east of the cave. Therefore, all dye injections were conducted within the Bass and Turkey Creek watersheds (Table 1 and Fig. 3).

Results of the first and second dye injections confirmed the hydrologic connection between Bass Creek and the HC stream (Table 2; Fig. 3). Rhodamine WT injected into Bass Creek on February 25, 2002 resulted in very high concentrations detected in charcoal samplers and raw water samples collected from Angel Spring (Station #3) (Table 2). Visual observation of Rhodamine WT at the HC resurgence was also confirmed within 2 hours of this injection. In addition, a much lower concentration of Rhodamine WT was detected in the cave stream at Station #4. This same result also occurred for the second dye injection in Bass Creek (upstream) in which eosin was detected within the cave at Stations #3 and #4, with higher concentrations at Station #3. These results established that Angel Spring is the discharge point for the major conduit connecting Bass Creek and the HC stream, and this connection establishes a meander cutoff of the large horseshoe bend in the surface stream channel of Bass Creek (Fig 4.; inset). An additional minor flow path from Bass Creek to the cave stream also exists, with an apparently small proportion of Bass Creek discharge entering upstream from Station #4.

Hydrologic connections between the HC stream and two small tributaries of Turkey Creek were also established (Table 2; Fig. 3). Fluorescein dye injected into a small pool of water in the Log Providence tributary to Turkey Creek resulted in

Table 1. Dates, locations, amounts, and type of fluorescent dyes injected to delineate the Hunters Cave recharge area.

Injection Date	Fluorescent Dye	Amount Injected (kg)	Injection Location (UTM Coordinates; Zone 15; NAD83 Datum)	Injection Location Name
2/25/2002	Fluorescein	0.91	563,170 m east; 4,299,020 m north	Log Providence tributary to Turkey Creek
2/25/2002	Rhodamine WT	0.91	562,390 m east; 4,298,412 m north	Bass Creek (downstream)
2/25/2002	Eosin	0.91	562,483 m east; 4,299,331 m north	Turkey Creek (immediately downstream of Log Providence tributary)
5/20/2002	Fluorescein	0.23	564,236 m east; 4,299,462 m north	Equine Center tributary to Turkey Creek
5/20/2002	Rhodamine WT	0.45	562,413 m east; 4,299,686 m north	Turkey Creek (upstream from losing reach)
5/20/2002	Eosin	1.80	564,814 m east; 4,297,259 m north	Bass Creek (upstream)
4/9/2003	Rhodamine WT	0.91	565,533 m east; 4,299,521 m north	Bass Lake tributary to Turkey Creek
4/10/2003	Fluorescein	0.45	568,307 m east; 4,298,434 m north	South Fork Turkey Creek
4/10/2003	Eosin	2.30	568,332 m east; 4,300,763 m north	North Fork Turkey Creek

very high concentrations detected in charcoal samplers and raw water samples at Station #4. There was no flow in the Log Providence stream channel at the time of injection. Furthermore, no fluorescein was detected in charcoal samplers placed downstream from this injection point (Stations #7 and #10), despite a runoff event following 15 mm of rainfall on March 1 and 2, 2002 that occurred after dye injection but before charcoal sampler collection. Thus, all the dye flowed through solution conduits to the cave stream and then traversed nearly the entire length of the cave stream to reach Station #4. The other Turkey-Creek tributary, designated as the Equine-Center tributary (Table 1), showed low-level fluorescein detections at Station #4 following injection into this tributary under high-flow conditions (Table 2). In the 14 days preceding injection, 209 mm of rainfall was recorded. Despite the high-flow conditions and small injection mass (0.23 kg), a 1.6-fold increase in the raw water fluorescein concentration was measured at Station #4. Dye injection at four separate locations in the main Turkey Creek channel failed to establish a hydrologic connection with HC (Tables 1 and 2). Additional injections outside the Bass- and Turkey-Creek watersheds were not conducted. The established hydrologic connections to Bass-Creek and the Turkey-Creek tributaries accounted for the observed discharge at the HC resurgence. In addition, adjacent areas to the west of the Bass-Creek watershed likely drain to the Spring-Cave recharge area, but additional dye-tracing studies are needed to more accurately determine the extent of this recharge area. Creeks to the east and south of Bass and Turkey Creeks (within the Cedar-Creek watershed) are not losing streams, and they drain to the south and east towards Cedar Creek and away from the HC recharge area.

These results established that only the small area drained by the two Turkey-Creek tributaries (2.2 km²) was connected to HC. With the additional drainage area from these two tribu-

Table 2. Sampler locations and detection of injected dyes.

Station Number, Site Description, and Sampler Location (UTM Coordinates; Zone 15; NAD83 Datum)	Dye Injection – 2/25/2002 Fluorescent Dye Detected[a]			Dye Injection – 5/20/2002 Fluorescent Dye Detected			Dye Injection – 4/9 and 4/10/2003 Fluorescent Dye Detected		
	Fluorescein	Rhodamine WT	Eosin	Fluorescein	Rhodamine WT	Eosin	Fluorescein	Rhodamine WT	Eosin
#1, Devils Icebox Resurgence 558,414 m east; 4,302,688 m north	ND	ND	ND	ND	ND	ND	NS	NS	NS
#2, Bonne Femme Creek, upstream from confluence with Turkey Creek 560,595 m east; 4,298,915 m north	ND	ND	ND	ND	ND	ND	NS	NS	NS
#3, Angel Spring in Hunters Cave 562,285 m east; 4,298,393 m north	ND	w, ++++	ND	ND	ND	w, ++	NS	NS	NS
#4, Upstream from Angel Spring in Hunters Cave 562,296 m east; 4,298,404 m north	w, ++++	++	ND	w, +	ND	+	+	ND	ND
#5, Bass Creek upstream from Hunters Cave resurgence 562,188 m east; 4,298,208 m north	ND	+	ND	ND	ND	++	NS	NS	NS
#6, Bass Creek upstream from Station 5 562,454 m east; 4,298,386 m north	ND	ND	ND	ND	ND	++	ND	ND	ND
#7, Turkey Creek upstream from confluence with Bass Creek 561,610 m east; 4,298,678 m north	ND	ND	w, ++	+	w, +++	ND	NS	NS	NS
#8, Turkey Creek upstream from Station 7 562,517 m east; 4,299,533 m north	ND	ND	ND	++	+++	ND	NS	NS	NS
#9, Spring Cave resurgence 560,878 m east; 4,298,346 m north	ND	ND	ND	ND	ND	ND	NS	NS	NS
#10, Log Providence tributary to Turkey Creek 562,634 m east; 4,299,411 m north	ND	ND	ND	NS	NS	NS	NS	NS	NS
#11, Turkey Creek upstream from Station 8 563,002 m east; 4,300,024 m north	NS	NS	NS	++	ND	ND	+	w, +++	ND
#12, Turkey Creek upstream from Station 11 565,073 m east; 4,300,820 m north	NS	NS	NS	NS	NS	NS	+	ND	+
#13, Bass Lake tributary to Turkey Creek 565,258 m east; 4,300,011 m north	NS	NS	NS	NS	NS	NS	ND	w, ++++	ND

[a] w = detected in raw water; maximum concentration detected in eluant from an activated carbon sampler: + < 10 $\mu g\ L^{-1}$; ++ = >10 and <100 $\mu g\ L^{-1}$; +++ = >100 and <1000 $\mu g\ L^{-1}$; and ++++ = >1000 $\mu g\ L^{-1}$. ND = not detected; NS = not sampled.

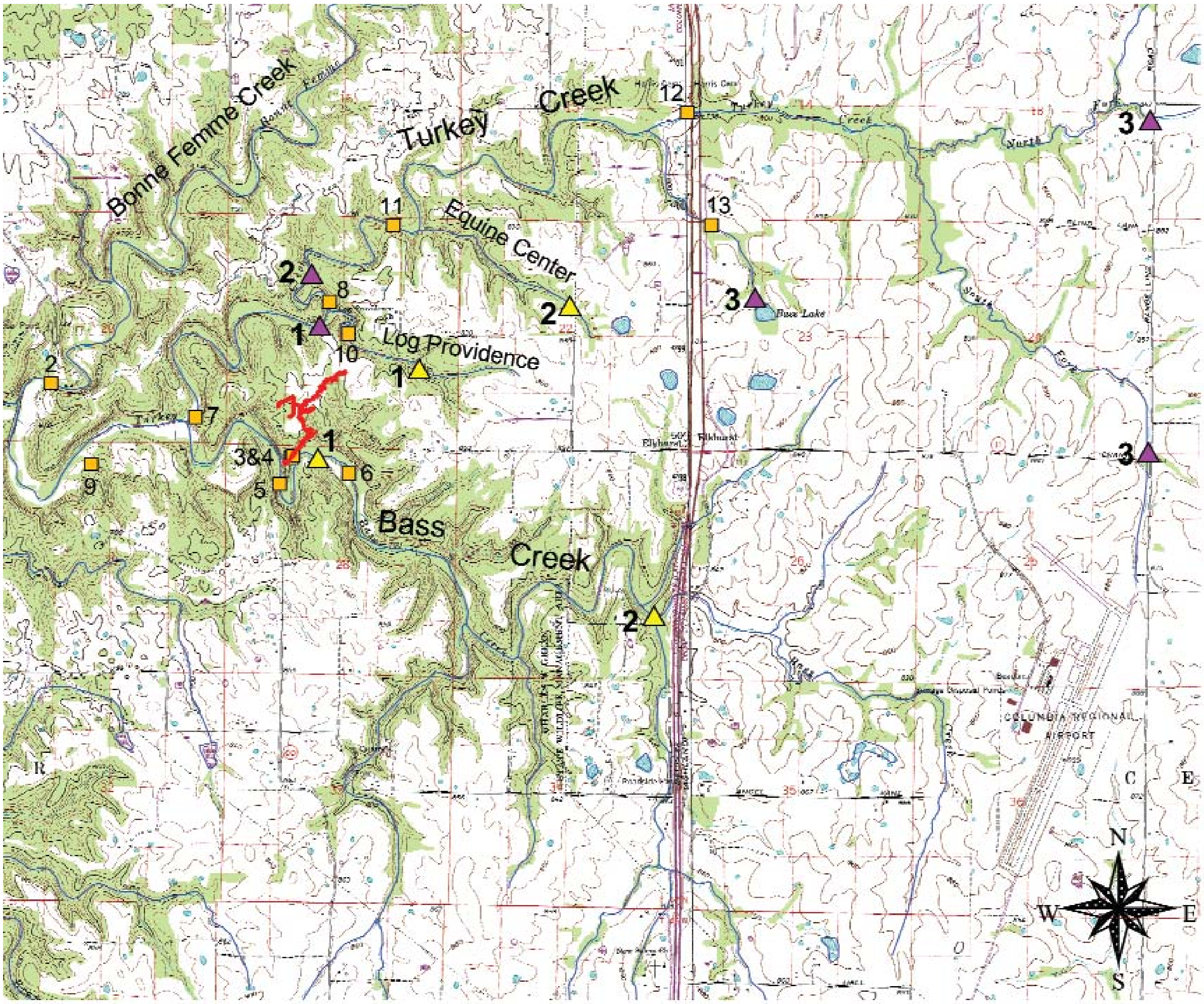

Figure 3. Dye-tracing studies used to delineate the Hunters Cave recharge area. Hydrologic connections were based on dye detection within the cave at charcoal sampler stations 3 and 4 (see Table 2). Large numbers adjacent to triangles represent the round of dye injections and correspond to dates listed in Table 1; 1 = February 25, 2002; 2 = May 20, 2002; and 3 = April 9–10, 2003. Small numbers adjacent to squares represent charcoal sampler stations corresponding to Table 2 (note: station 1 was not located within the view of this figure).

taries, the total recharge area was determined to be 33.3 km² (Fig. 4). The hydrologic connection of the Turkey-Creek tributaries to HC coincides with a fault documented by St. Ivany (1988). The fault intersects perpendicular to the tributaries, upstream from their confluence with the Turkey-Creek stream channel, running along a line from northeast to southwest towards the upper reaches of the cave near the Log-Providence tributary (Fig. 4). This fault is probably responsible for the occurrence of solution conduits connecting these tributaries to the cave stream. The hydrologic connection of the Turkey-Creek tributaries also established that inter-basin transfer occurs between Turkey and Bass Creeks via HC. The importance of these tributaries to the aquatic cave stream ecology is significant because Bass Creek only influences the lower 60–100 m of the stream reach. Thus, these two tributaries are the primary sources of water for the vast majority of the HC stream reach, and the water quality derived from this small area directly impacts stygobites and their habitat. Collectively, the HC and DI recharge areas account for 28% of the area within the Bonne Femme watershed.

Land-use/land-cover data were determined using ArcView GIS (version 3.3) and 1991-93 LANDSAT data with 30 m resolution (Fig. 5). The LANDSAT data were classified by the Missouri Resource Assessment Partnership (Missouri Spatial Data Information Service, 2005). These land-use data are a major improvement over past data in resolution and in the dis-

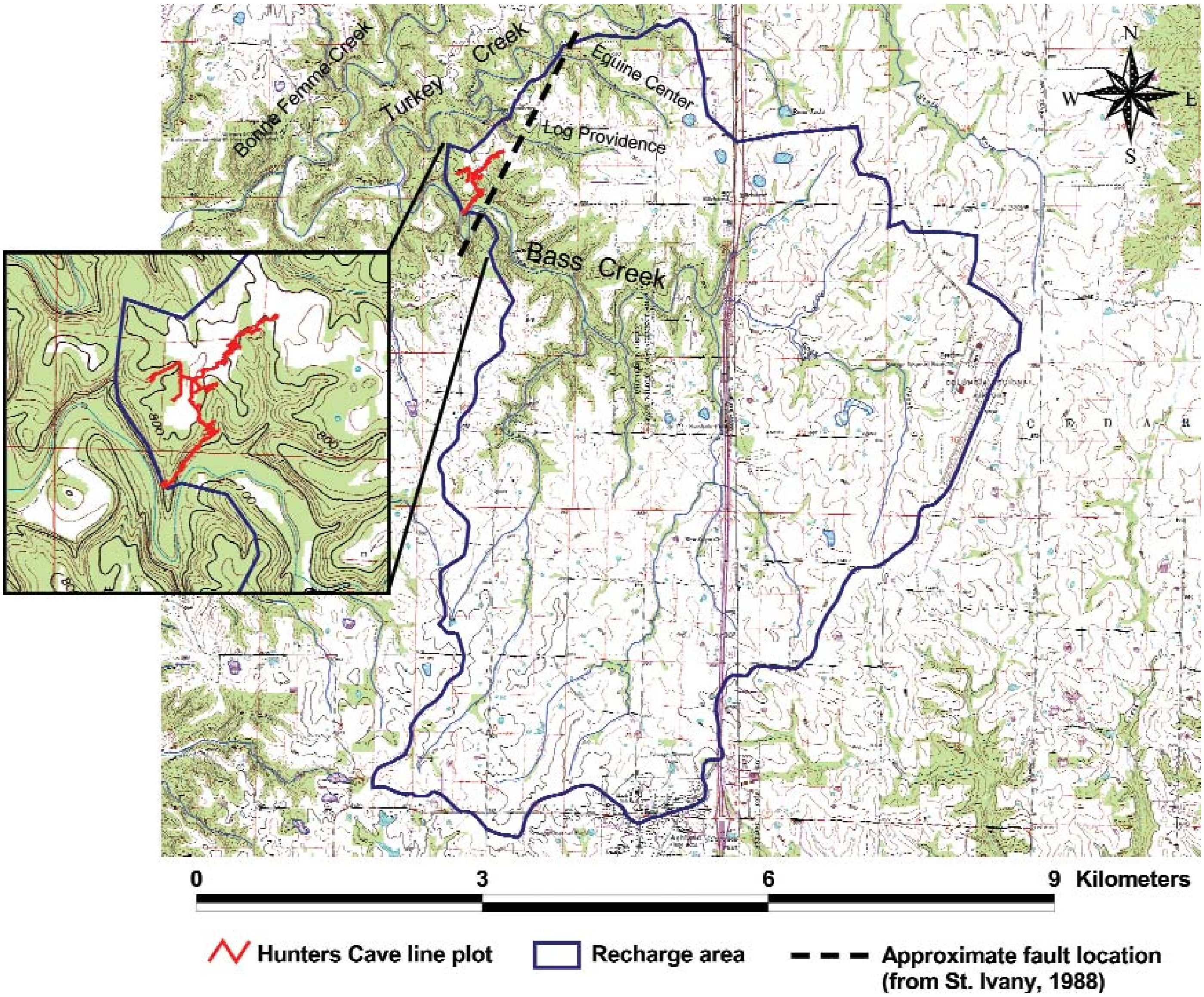

Figure 4. Hunters Cave recharge area delineation. Inset shows the meander cut-off created by the flow path from Bass Creek to the cave stream via Angel Spring. The location of the fault (based on St. Ivany, 1988) creating a likely conduit from the Turkey-Creek tributaries to the upper cave stream is also shown.

tinction between different land-use categories. Most notable is the division between row crop and grassland areas. Because of their close proximity and similarities in geology and soils, both recharge areas had very similar land use/land cover (Fig. 5). About 80% of both recharge areas was comprised of grasslands or row crops. However, the HC recharge area has a higher proportion of grasslands and a lower proportion of row crops than DI. In addition, row crop areas within the DI recharge area were concentrated within the upper Bonne Femme watershed (Figs. 1 and 5). In both recharge areas, row crops were predominantly corn and soybeans, and approximately 40% of the grasslands were range land, with cattle and horses the predominant livestock. The remainder of the grasslands represents forage production for hay. Forested areas lie mostly within public lands (Rock Bridge Memorial State Park and the Three Creeks Conservation Area) and along stream corridors, and these areas were mainly oak-hickory forests typical of the Ozarks region. In addition, the HC recharge area has a small amount of urban impervious area. Urban areas are comprised of commercial and residential development in Ashland, Missouri, and the Columbia Regional Airport in the eastern portion of the recharge area. The DI recharge area currently has no significant amounts of either urban impervious or urban vegetation land cover.

STREAM DISCHARGE

On an annual basis, the area normalized discharge from the DI cave-stream resurgence was consistently greater than the

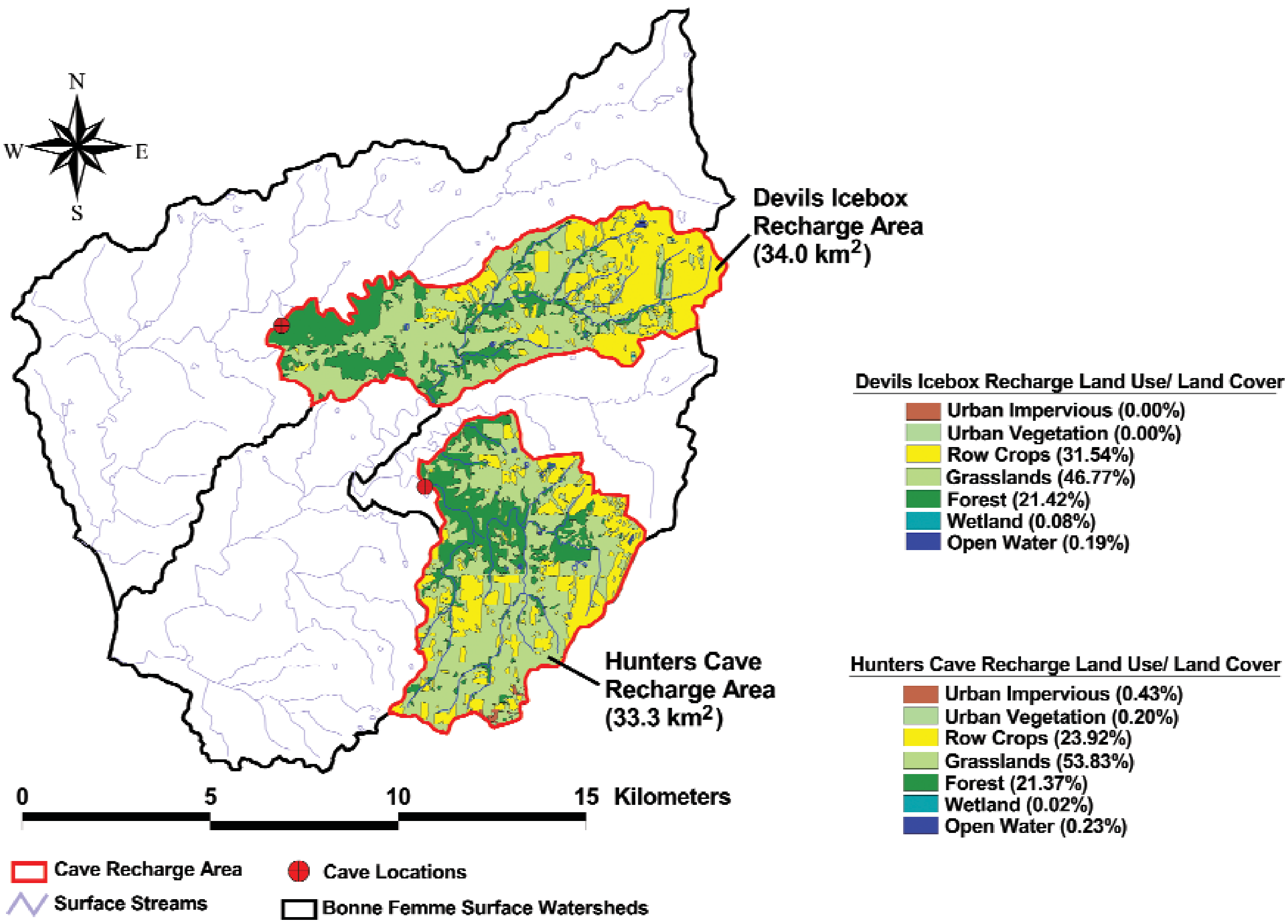

Figure 5. Land use/land cover for Devils Icebox and Hunters Cave recharge areas.

HC resurgence during the three years of monitoring (Table 3). Despite similarities in the amount of precipitation received, DI had an average of 59% more annual discharge than HC. The disparity between sites was greatest in Year 1 when annual discharge at DI was 2.2 times greater than that of HC. Annual discharge was most similar in Year 3. Average annual precipitation over the three years of monitoring was below the 30-year running average of 1,024 mm in both recharge areas (Table 3). Year 1 was among the driest 12-month periods on record for this area, with 30–31% below normal precipitation.

Relative discharge was 5.2 to 6.9% of the annual precipitation at DI and 2.8 to 4.6% of the annual precipitation at HC (Table 3). Comparison of these relative discharges to a nearby non-karst watershed, Goodwater Creek, showed that about 33% of annual precipitation could be accounted for as stream discharge in this surface watershed. Thus, relative discharge from the karst-recharge areas accounted for only about one-tenth to one-fifth that of the nearby non-karst surface watershed. Since Goodwater Creek is a lower gradient stream than upper Bonne Femme or Bass Creeks, its relative discharge likely represents a lower limit of the relative discharge for the two losing streams. Hence, the volume of allogenic recharge to the karst aquifers was much more constrained than it was for their corresponding losing streams. The volume of the sub-surface conduits imposes a physical constraint on the discharge conveyed to the cave streams. As stage height increases during a runoff event, there is a decreasing proportion of the surface water conveyed to the subsurface conduits, causing the increased discharge to remain in the surface channel.

DI had greater monthly discharge than HC in 24 of the 36 months monitored (Fig. 6). At HC, average monthly discharge over the three years was 2,930 $m^3\ km^{-2}$, with a range of 11 to 6,890 $m^3\ km^{-2}$. At DI, the average monthly discharge was 4,650 $m^3\ km^{-2}$, with a range of 599 to 16,100 $m^3\ km^{-2}$ (Fig. 6). In general, monthly discharge at both sites followed seasonal rainfall and ground-water recharge patterns for the region. However, these trends were often punctuated by weather extremes that caused widely varying discharge conditions. In Year 1, an extended dry period from July-November 1999 resulted in extremely low discharge at both sites, but especial-

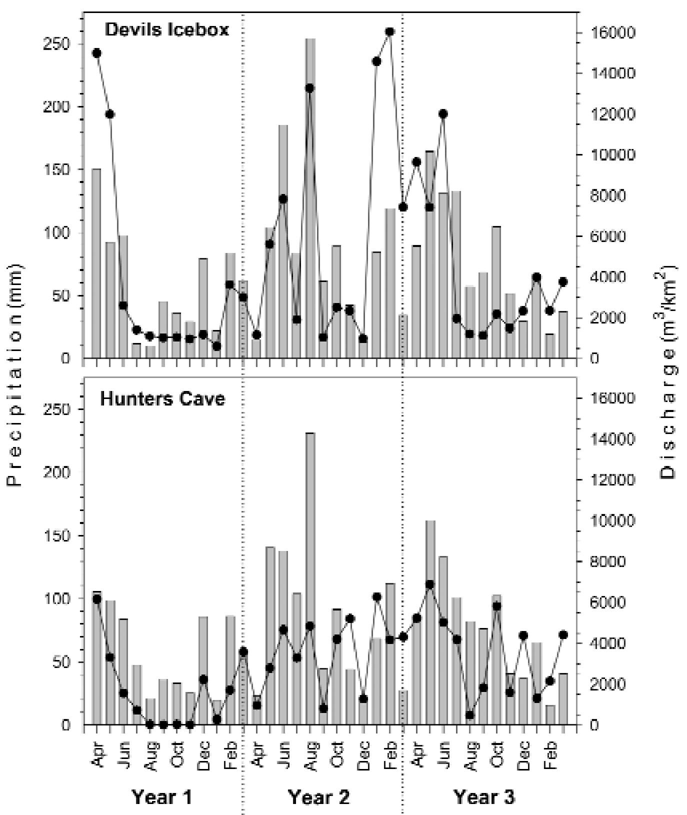

Figure 6. Monthly precipitation (bar graphs) within both recharge areas and monthly discharge (line graphs) for each cave stream at their resurgences.

ly at HC where discharge was <30 m³ km⁻² month⁻¹ from August to November 1999 (Fig. 6). During this dry period, discharge at DI was consistently about 1,000 $m^3\ km^{-2}\ month^{-1}$. In Year 2, greater than normal precipitation from June through August 2000 resulted in much higher discharge than observed for this same time period in Year 1. Monthly discharge and precipitation were significantly correlated ($p < 0.01$) for both recharge areas, based on regression analysis for all 36 months (coefficients of determination, r^2, were 0.32 for HC and 0.41 for DI). However, regression analyses within a given year showed that only in Year 1 did precipitation explain more than 50% of the variability in monthly discharge at either site. Thus, factors such as rainfall intensity, duration, antecedent soil moisture, air temperature, and evapotranspiration were also important factors determining the monthly discharge in both systems.

Comparisons between sites for high- and low-precipitation months revealed general trends about the two recharge areas. There were 10 high precipitation months (>100 mm) within the HC recharge area and nine within the DI recharge area (Fig. 6). Monthly average discharge for these high precipitation months was 4,770 $m^3\ km^{-2}$ for HC and 9,030 $m^3\ km^{-2}$ for DI. HC had greater discharge in only one of these months (October 2001). Relative discharge, as a percent of precipitation, for the high precipitation months was essentially the same as the mean annual relative discharge reported for both recharge areas in Table 3. Because the high precipitation months account for one-third to one-half of the annual discharge, they were representative of the overall trend in which the DI recharge area had greater relative and absolute discharge compared to the HC recharge area. Low precipitation months in summer and fall, particularly July–November 1999, showed that discharge from the HC recharge area could reach very low levels, and even approach zero flow (Fig. 6). The combination of low precipitation, high air temperatures, and high evapotranspiration rates apparently was sufficient to almost completely halt ground-water recharge at the HC resurgence in 1999. In contrast, discharge at the DI resurgence during the same period remained very consistent and much high-

Table 3. Area normalized annual stream discharge and precipitation.

Cave	Year 1[a]	Year 2	Year 3	Mean
Devils Icebox				
Discharge ($m^3\ km^{-2}$)	43,500	74,700	49,400	55,900
Relative Discharge (%)[b]	6.1	6.9	5.2	6.1
Precipitation (mm)	719	1085	954	919
Relative Precipitation (%)[c]	–30	6.0	–6.8	–10
Hunters Cave				
Discharge ($m^3\ km^{-2}$)	19,600	42,800	43,300	35,200
Relative Discharge (%)	2.8	4.1	4.6	3.8
Precipitation (mm)	702	1047	943	897
Relative Precipitation (%)	–31	2.2	–7.9	–12

[a] Year 1 = April 1999 to March 2000; Year 2 = April 2000 to March 2001; Year 3 = April 2001 to March 2002.

[b] Annual discharge as a percentage of precipitation.

[c] Percent deviation from 30-year running average annual precipitation of 1,024 mm (based on National Weather Service data from the Columbia Regional Airport).

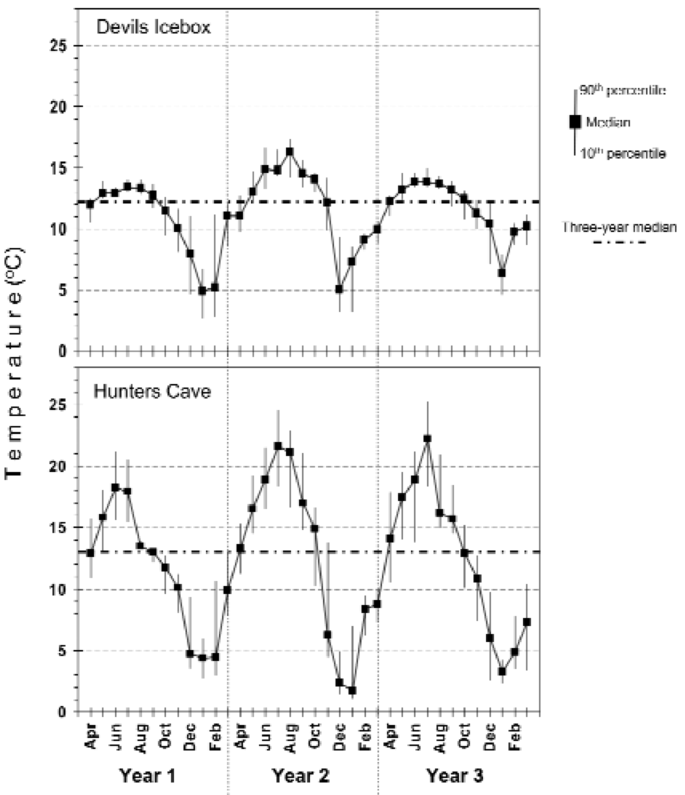

Figure 7. Monthly water temperature at the resurgences to Devils Icebox and Hunters Cave.

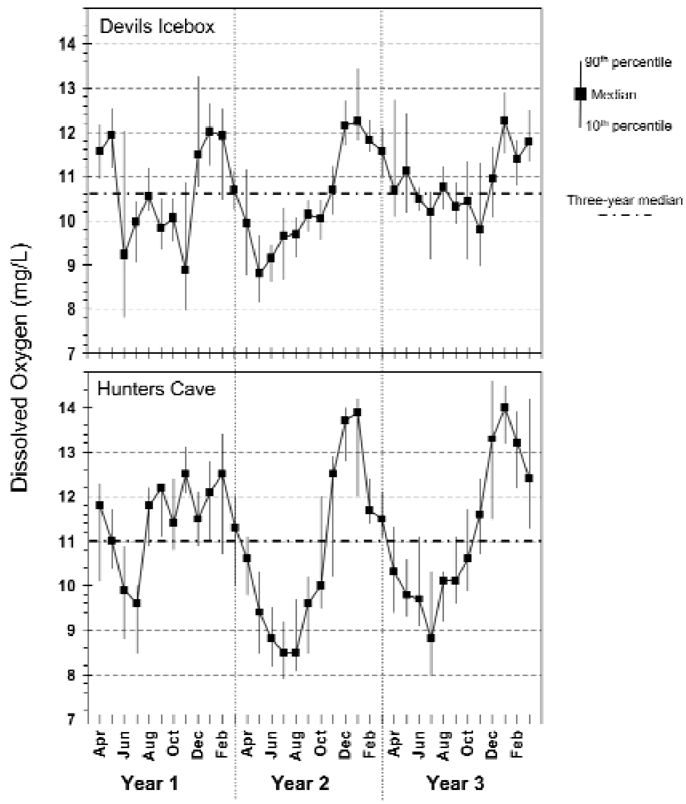

Figure 8. Monthly dissolved oxygen at the resurgences to Devils Icebox and Hunters Cave.

er than at HC. In the six months with precipitation <25 mm, average monthly discharge was 781 m³ km⁻² at HC and 1,260 m³ km⁻² at DI. For these same months, total precipitation within the DI recharge area was 33 mm lower than in the HC recharge area.

Monthly and annual summaries of instantaneous stream discharge reflected the strong influence of seasonal precipitation patterns (Table 4) over the three years of the study. For instance, in Year 1 low precipitation resulted in the overall lowest discharges at both sites. Increased precipitation in Years 2 and 3 substantially increased discharges at both sites, but the increase was much greater at HC. In Years 2 and 3, median discharge at HC increased by about eight-fold compared to Year 1 whereas median discharge at DI in Years 2 and 3 increased by only 20–30% over Year 1. Comparison of discharge data between recharge areas, summarized over all years, showed that HC had 18% higher median discharge, 13% higher 90th percentile discharge, but 96% lower 10th percentile discharge compared to DI. On a monthly basis, all discharge statistics were highest from February through June at both stream resurgences, reflecting the generally high precipitation during these months (Fig. 6). In addition, the seasonally high rates of ground-water recharge that occur during February and March resulted in high discharge for these months, even when precipitation was low.

Chemical and Physical Characterization of the Cave Streams

The chemical and physical parameters monitored were mainly affected by the magnitude of discharge and seasonal differences in climate (Figs. 7–11). Changes in median monthly temperature (Fig. 7), for instance, were strongly related to seasonal changes in air temperature. The long-term median temperature recorded at DI for this study was only 0.7º C lower than that documented over a two-year monitoring period from 1982-84 by Wicks (1997). The minimum and maximum monthly median temperatures were, however, more extreme than values reported by Wicks (1997). Although the seasonal pattern and three-year median values were similar between systems, HC showed much greater variation in water temperature than DI.

Because of the significant inverse relationship between temperature and dissolved oxygen (DO) (Table 5), the seasonal changes in DO responded oppositely to that of water temperature (Fig. 8). Because of the greater variation in water temperature at HC, a similarly greater variation about the three-year median DO level was observed, with generally higher DO in winter and lower DO in summer compared to Devils Icebox (spelled out in this section to avoid confusing syntax). However, the three-year median DO levels were very similar between the two sites. In general, DO levels were always near

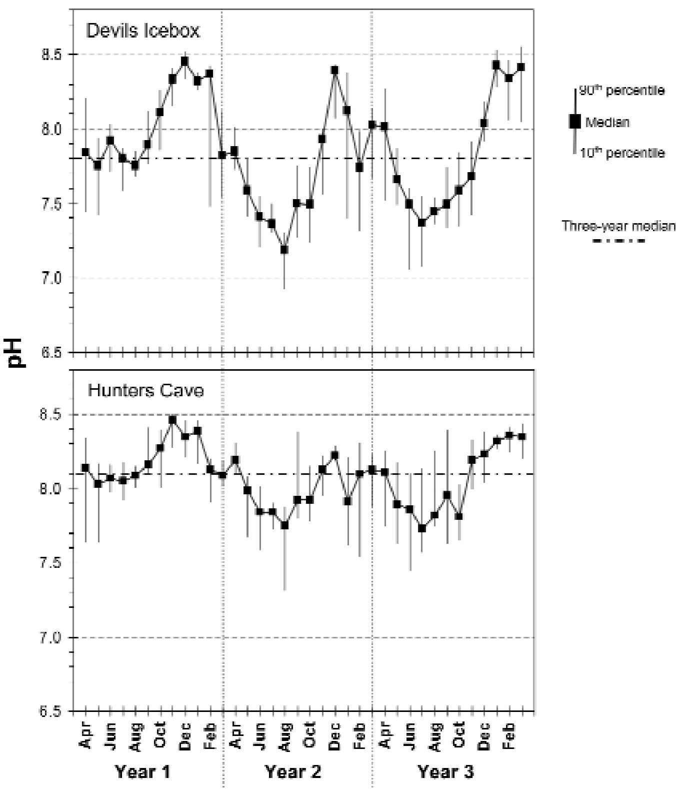

Figure 9. Monthly pH at the resurgences to Devils Icebox and Hunters Cave.

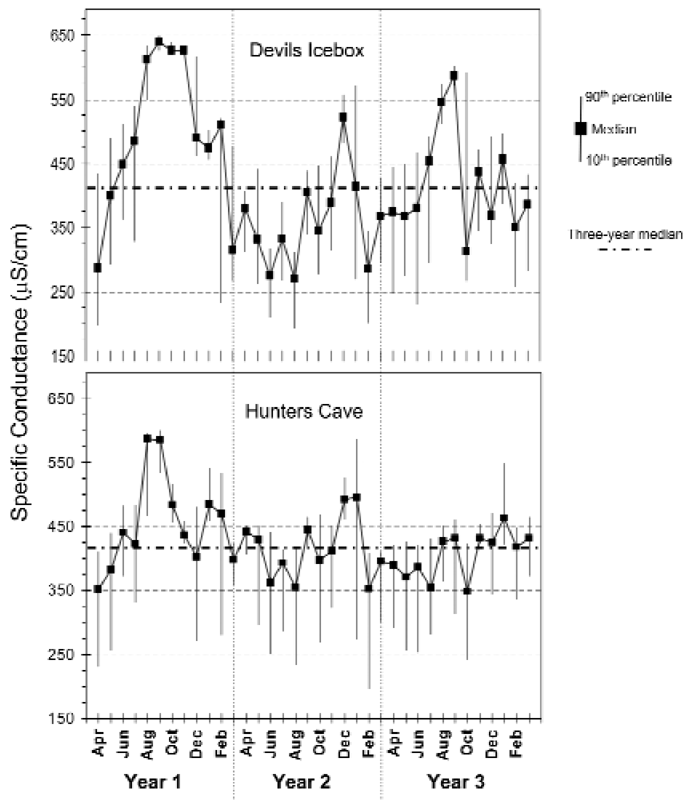

Figure 10. Monthly specific conductance at the resurgences to Devils Icebox and Hunters Cave.

Table 4. Summary of instantaneous stream discharge by month and year.

	Devils Icebox			Hunters Cave		
Month or Year	Median (m^3h^{-1})	90th Percentile (m^3h^{-1})	10th Percentile (m^3h^{-1})	Median (m^3h^{-1})	90th Percentile (m^3h^{-1})	10th Percentile (m^3h^{-1})
January[a]	53	230	24	40	420	11
February	93	570	27	100	210	22
March	140	450	50	180	250	89
April	160	760	43	180	320	29
May	150	790	50	120	480	29
June	110	590	63	120	440	16
July	60	110	41	46	460	6.2
August	53	110	40	15	180	0.59
September	48	55	20	18	70	0.28
October	59	150	42	43	560	0.80
November	59	110	42	27	410	0.41
December	49	120	30	60	450	12
Year 1	54	280	28	13	220	0.41
Year 2	64	430	32	100	450	26
Year 3	72	290	53	110	450	15
All Years	63	320	35	74	360	1.3

[a] Monthly data are summarized across all three years.

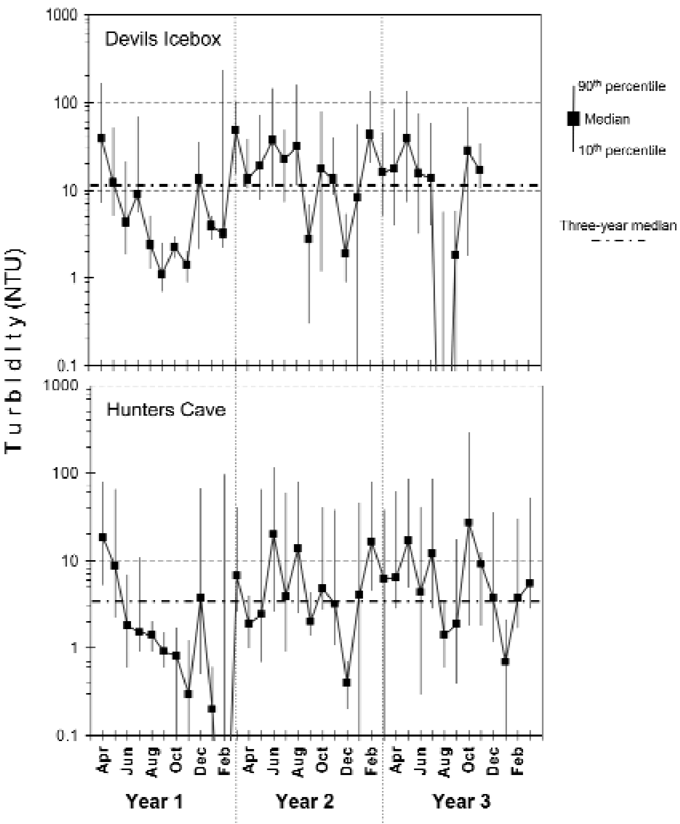

Figure 11. Monthly turbidity at the resurgences to Devils Icebox and Hunters Cave.

or slightly above saturation at both sites. At Devils Icebox, the variation in DO was not as closely related to temperature as HC (Table 5). In Years 1 and 3, Devils Icebox showed changes in median DO levels during the summer and fall months that did not vary inversely with median monthly temperature (Figs. 7 and 8). Typically, increases in DO occurred over the summer months, from July through September, despite increased water temperature. Apparently, the increased DO was associated with photosynthetic activity of algae at the resurgence. The monitoring station at Devils Icebox lies within a karst window, and diurnal fluctuations in DO were observed during these months. Thus, the location of the monitoring station at Devils Icebox resulted in greater variation in the relationship between DO and temperature than at HC, where the monitoring station was underground.

Monthly pH was more closely correlated to water temperature than discharge (Table 5). In general, the winter months had the highest pH, and the summer months had the lowest pH at both sites (Fig. 9). The three-year median pH was slightly lower at DI than at HC. The strong influence of temperature on pH most likely occurred due to the effect that water temperature has on the respiration of aquatic organisms within the surface and subsurface reaches of the recharge areas. The respiration rate of aerobic organisms will be higher when the water temperature is warmer, and this leads to greater evolution of CO_2 and subsequent formation of H_2CO_3, leading to the lower median pH values observed from spring through fall. The poor correlation between pH and discharge was not expected. At shorter time-scales, pH consistently showed an inverse relationship to discharge, and this relationship was especially obvious during runoff events. At the monthly time-scale, the influence of discharge was still apparent, and there was a statistically significant correlation between discharge and pH at HC (Table 5). For instance, one of the lowest monthly median pH values at both sites was observed during August 2000 when monthly discharge was quite high. In addition, the lower three-year median pH at DI most likely reflected the influence of larger and longer duration runoff events, which convey more acidic water, on the long-term pH in this system.

Specific conductance (SpC) was inversely related to discharge and turbidity at both sites (Table 5). Therefore, SpC was greatest during low flow months and lowest during high flow months (Fig. 10). The extended dry period from July-November 1999 resulted in the highest SpC at both sites. The three-year median SpC was nearly identical between sites, but variation about the three-year median was much greater at DI (Fig. 10). The inverse relationship between discharge and SpC has been documented at DI and in other allogenic recharge karst aquifers, but these studies either considered much shorter time scales or less intensive monitoring than reported here (Hess and White, 1988; Ryan and Meiman, 1996; Wicks, 1997). The strong inverse relationship between SpC and turbidity reflected their covariance with respect to discharge. It also reflected that low SpC water from a runoff event more strongly coincided with high turbidity water than high discharge.

Turbidity was directly related to stream discharge and inversely related to SpC at both sites and inversely related to pH at HC (Table 5). Monthly median turbidity at both sites generally varied directly with monthly discharge (Figs. 6 and 11), resulting in high turbidity for the spring and summer months. However, months with one or two very large events, such as March 2000 and February 2001, also resulted in high median turbidity despite modest monthly discharges. The three-year median turbidity at DI was 3.4 times higher than HC (Fig. 11). Median turbidity exceeded 10 NTU for 7 months at HC and for 19 months at DI. Furthermore, DI had 8 months in which median turbidity exceeded 20 NTU compared to only one month at HC (October 2001). Overall, turbidity was greater at DI compared to HC for 30 of the 32 months in which both sites were monitored. Although maximum turbidity levels during runoff events, as reflected by the 90th percentile levels (Fig. 11), were similar between sites, HC consistently returned to very low turbidity levels more quickly following runoff events. As previously noted, DI had greater peak discharge and longer duration runoff events than HC, and this, in part, contributed to its higher turbidity. Another factor that likely contributed to the greater turbidity at DI was the higher relative and absolute amount of row crop acreage within its recharge area (Fig. 5). The rather low correlation of monthly median

Table 5. Correlation coefficients (*r*) between discharge and chemical and physical parameters[a].

	Discharge	Temperature	Dissolved Oxygen	pH	Specific Conductance
			Devils Icebox		
Temperature	0.08	—	—	—	—
Dissolved Oxygen	0.28	–0.70[b]	—	—	—
pH	–0.20	–0.85[b]	0.55[b]	—	—
Specific Conductance	–0.56[b]	–0.23	–0.05	0.34	—
Turbidity	0.54[c]	0.23	0.02	–0.36	–0.82[b]
			Hunters Cave		
Temperature	0.10	—	—	—	—
Dissolved Oxygen	–0.15	–0.93[b]	—	—	—
pH	–0.44[c]	–0.72[b]	0.72[b]	—	—
Specific Conductance	–0.66[b]	–0.37	0.48[c]	0.40	—
Turbidity	0.69[b]	0.29	0.31	-0.46[c]	–0.69[b]

[a] Correlation coefficients determined by correlation analysis of monthly median values for all parameters (n = 36, except turbidity for the Devils Icebox, n = 32).
[b] $p \leq 0.001$ level of significance.
[c] $p \leq 0.01$ level of significance.

turbidity to monthly discharge (Table 5) was related to the observed dynamics between turbidity and discharge during runoff events. Inspection of hydrographs along with the turbidity data showed that their poor correlation resulted from very short-term fluctuations in turbidity during the rising and peak portions of the hydrograph, and the rate at which the two parameters approached pre-event levels during the receding portion of the hydrograph.

RECHARGE AREA CHARACTERISTICS

Despite similarities in geology, size of the recharge areas, land use/land cover, and climate, there were often major differences in annual, monthly, and instantaneous discharge between DI and HC. Two important characteristics distinguish these recharge areas and explain the observed differences: 1) size of the losing stream drainage areas; and 2) size and spatial extent of the sub-surface conduit systems.

Within the HC recharge area, the Bass Creek watershed encompasses 31.1 km², which represents 93% of the HC recharge area. Within the DI recharge area, the upper Bonne Femme Creek watershed represents only 74% of the recharge area, encompassing 25.3 km². Thus, on a relative basis, Bass Creek supplies a greater amount of water to the HC resurgence than does upper Bonne Femme to the DI resurgence. At the annual time scale, this difference explains the large change between Year 1 discharge and that of Years 2 and 3 for HC. On a monthly time scale, the strong influence of Bass Creek on HC discharge can be seen by the much greater seasonal changes in discharge and the wider range in 10th to 90th percentile discharge for most months as compared to DI. For instance, the relative increase in discharge between summer and fall months was much greater at HC compared to DI (Table 4). This reflected the proportionately greater influence that seasonal increases in ground-water recharge had at HC due to the larger drainage area of Bass Creek and its dominating influence on discharge at the HC resurgence. The ratio of 90th to 10th percentile flows was also much greater for HC in every month except February, March, and April. This ratio has been shown to be a measure of runoff propensity in larger surface basins (Blanchard and Lerch, 2000). Indeed, HC had more runoff events than DI in every year, with an average of four more runoff events per year. Therefore, because of the greater drainage area of Bass Creek, the HC recharge area was, overall, more runoff prone than DI.

The other key feature explaining the differences in discharge between the two recharge areas was the size and extent of their subsurface-conduit systems. The DI recharge area has a more extensively developed subsurface-conduit system than the HC recharge area based on the following: 1) consistently higher relative discharge at DI on an annual basis (Table 3); 2) greater 90th percentile discharges at DI from February through June (Table 4), reflecting the much greater discharge during major runoff events; 3) greater 10th percentile discharges at DI, especially during low precipitation months (Table 4), indicating greater water storing capacity in the DI recharge area; 4) the DI recharge area encompasses the autogenic 8.7-km² Pierpont sinkhole plain, indicating the existence of more numerous conduits and greater spatial extent of the conduit system; and 5) the DI cave system is considerably larger, in length and volume, than the HC system, and it has more numerous tributaries with higher discharge.

The greater relative discharge at DI on an annual basis suggests that a larger and more extensive conduit system exists that is capable of capturing and conveying a greater proportion of precipitation to the cave stream. The higher relative and absolute discharge at DI also resulted in its greater 90th percentile and peak instantaneous discharges during most runoff events. For the nine months in which >100 mm of precipitation occurred in both recharge areas, DI had greater peak discharge for every runoff event in these months. At the other end of the discharge spectrum, DI had greater 10th percentile discharges in 11 of 12 months, and the differences in 10th percentile discharges between DI and HC were most pronounced during low precipitation months in summer and fall (Table 4). The most notable differences in discharge, as mentioned above, were during the July-November drought of 1999 when DI maintained consistently higher discharge than HC despite receiving lower precipitation (Fig. 6). This data showed that the DI recharge area must store more water between rainfall events. Apparently, a portion of the water stored within the DI recharge area can have residence times of weeks to months. Given that discharge ceases in upper Bonne Femme Creek during periods of low precipitation, the greater storage of the DI recharge area was, therefore, associated with the autogenic portion of the recharge area. The high SpC observed during prolonged dry periods (Fig. 10) indicated that water storage occurred within the bedrock matrix or within the epikarst of the autogenic portion of the recharge area. Storage within the bedrock matrix and within epikarst would result in water with the observed high SpC, and differentiation between bedrock matrix storage and epikarst storage is not possible based on values of SpC. A consideration that would undermine this explanation was the possibility of significant anthropogenic inputs, such as irrigation, industrial, or wastewater discharges, to the DI recharge area that only became evident under very dry conditions. However, there are no significant agricultural or industrial inputs, and the quality of the water did not indicate significant inputs of domestic wastewater under these conditions.

The drainage characteristics of the two recharge areas represent another important distinction between these two systems. Unlike the DI recharge area, the HC recharge area has only a few sinkholes (<10 based on topographic map inspection) and minimal internal drainage. Within the HC recharge area, ground-water recharge occurs by allogenic recharge through two main subsurface-conduits: the fault conduit connecting the Turkey-Creek tributaries to the uppermost part of the cave stream; and the conduit connecting Bass Creek to Angel Spring (Figs. 3 and 4). The Bass Creek to Angel-Spring conduit accounted for the overwhelming majority of discharge at the resurgence, especially under runoff conditions. The length of this flow path may be as short as 100 m. The much greater water-temperature fluctuations at HC also provided support for the existence of short flow paths within the HC recharge area (Fig. 7). Overall, the HC recharge area lacks significant autogenic recharge, has only two main surface drained conduits, and the primary conduit to the cave stream extends over a very short distance. Hence, this recharge area is characterized by much more limited subsurface-conduit development than DI, leading to attenuated discharge under runoff conditions and lower discharge during dry periods.

SUMMARY AND CONCLUSIONS

Dye-tracing studies were successfully applied to the delineation of the HC recharge area and for improving the accuracy of the delineated recharge area for DI. These studies facilitated determination of existing land uses and land cover for both recharge areas. The recharge areas were shown to be of similar size, have similar land uses, formed in the same geologic strata, and formed primarily by allogenic and discrete recharge. However, intensive hydrologic and water-quality monitoring revealed distinct differences in the characteristics of these recharge areas. For instance, DI was shown to have greater absolute and relative annual discharge, much greater peak discharge during runoff events, and greater water-storing capacity than the HC recharge area. HC had more frequent runoff events, greater median instantaneous discharge, and more pronounced seasonal changes in discharge, water temperature, and dissolved oxygen than DI. Discharge at the HC resurgence was predominantly allogenic, and the areal extent and size of subsurface-conduits are apparently very limited in this recharge area. In contrast, discharge at the DI resurgence represents both allogenic and autogenic (discrete) recharge, and its recharge area is characterized by a subsurface-conduit system that is both greater in volume and areal extent than HC. Currently, land use within both recharge areas is mainly row-crops, grasslands, and forests. As land use changes from rural to urban in these watersheds, the cave streams will be vulnerable to the hydrologic impact caused by increases in impervious land surface, as well as to water-quality contaminants associated with urban land use *(e.g.*, turf chemicals and oil). As a result of this and other studies, the Boone County (MO) Commission was awarded an EPA 319 Nonpoint Source Pollution Control grant to guide future development in the Bonne Femme watershed. Project objectives include: creation of a watershed land-use plan; recommendation of policies and procedures to local governments for the review and approval of new developments that will provide special protection for the watershed; and implementation of BMPs through allocation of cost-share funds. With documentation of the existing land uses and hydrologic conditions, the impact of urban growth and the effectiveness of new policies and implemented BMPs can be assessed.

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