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MACA

National Park Service
U.S. Department of the Interior

# MAMMOTH CAVE NATIONAL PARK

## KENTUCKY

## WATER RESOURCES MANAGEMENT PLAN

The National Park Service Water Resources Division is responsible for providing water resources management policy and guidelines, planning, technical assistance, training, and operational support to units of the National Park System. Program areas include water rights, water resources planning, regulatory guidance and review, hydrology, water quality, watershed management, watershed studies, marine resource management, and aquatic ecology.

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# WATER RESOURCES MANAGEMENT PLAN

## MAMMOTH CAVE NATIONAL PARK

KENTUCKY

April 2006

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United States Department of the Interior
National Park Service

Approved by: ______________________ 4/27/06
Superintendent, Mammoth Cave National Park Date

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## Figures

Note: Unless otherwise cited, all figures are previously unpublished and created by the author for this document.

## Tables



## Plates

the pennyrile
lies upon her carbon back
dissolves under an acid sun.
like me
or the elk
or the bull-bat,
she had an alpha.
and too, and until,
our final note and measure
are washed into
a common sea.

*-- an excerpt from "la fin du monde", joe meiman*

**Commonly Used Abbreviations**

| | |
|---|---|
| AQRV | Air Quality Related Values |
| BMI | Benthic Macroinvertebrates |
| BMP | Best Management Practice (USDA) |
| CWA | Clean Water Act (USEPA) |
| CREP | Conservation Reserve Enhancement Program (USDA) |
| DAT | Depositional Analysis Thresholds |
| FLM | Federal Land Managers |
| DO | Director's Order (NPS) |
| DO | Dissolved Oxygen |
| GMP | General Management Plan (NPS). |
| HpCDD | Heptachlorodibenzo-p-dioxin |
| KDFWR | Kentucky Department of Fish and Wildlife Resources |
| IBI | Indices of Biological Integrity |
| LTEM | Long-Term Ecological Monitoring (NPS) |
| KDOW | Kentucky Division of Water |
| MACA | Mammoth Cave National Park (NPS) |
| NEPA | National Environmental Protection Act (USEPA) |
| NPS | National Park Service |
| NWQA | National Water Quality Assessment (USGS) |
| OCCD | Octachlorodibenzo-p-dioxin |
| SP | Strategic Plan (MACA) |
| TCDD | Tetrachlorodibenzo-p-dioxin |
| USACE | United States Army Corps of Engineers |
| USDA | United States Department of Agriculture |
| USEPA | United States Environmental Protection Agency |
| USFWS | United States Fish and Wildlife Service |
| USGS | United States Geological Survey |
| WRD | Water Resources Division (NPS) |
| WQMP | Water Quality Monitoring Program (MACA) |
| WRMP | Water Resources Management Plan (NPS) |

*Thanks to:*

*Several individuals made valuable contributions to drafting and completing this document. General inspiration flowed from the Buffalo River, via someone who had run this section of white before, Dave Mott. The river, in the case of this document, heads up in Lakewood Colorado, home of the Planning and Evaluation Branch of the NPS Water Resource Division. Thanks to Mark Flora, David Vana-Miller, and especially Donnie Weeks for their guide service.*

*For those who think writing a Water Resources Management Plan might be a fun and entertaining endeavor. I can say it is akin to operating a jack-hammer, in that it looks a good time until you're a few hours into it.*

# Executive Summary

Mammoth Cave National Park's 1983 General Management Plan (GMP) provided limited direction relative to management of the park's natural resources. In 2000, the "Mammoth Cave National Park Strategic Plan 2000-2005" was completed. This document presented the following Mission Statement for the park, "*The mission of Mammoth Cave National Park is to protect and preserve for the future the extensive limestone caverns and associated karst topography, scenic riverways, original forests, and other biological resources, evidence of past and contemporary lifeways; to provide for public education and enrichment through scientific study, and to provide for development and sustainable use of recreational resources and opportunities.*"

Adjacent to the great karst plain of Southcentral Kentucky lies Mammoth Cave. The hydraulic ties of the karst make transparent the boundary of the surface and subsurface, and back to the surface – as precipitation recharges the cave streams and they in turn discharge into the Green River.

Designated by the Commonwealth of Kentucky as an "Outstanding Resource Water" and a state "Wild River", the 42 km of the Green River within the park is home to one of the most diverse fish and mussel communities in the state. The conservation status and subsequent management of a national park has allowed the cave and the Green River to become a refugium of many Federally-listed endangered species and other rare forms of aquatic life. With 226 native species, Kentucky supports about one quarter of the nation's freshwater fish fauna; two thirds of which (151 species) are found in the Green River (Cicerello and Hannan, 1991). The Green's mussel diversity also ranks among the highest in the nation. Of the 104 taxa comprising the Kentucky fauna, 71 are known to the Green River (Cicerello, and Hannan, 1990). Seven species are listed by the United States Fish and Wildlife Service (USFWS) under the Endangered Species Act of 1973, as amended, ten are candidates or have been proposed for listing by the USFWS, and six additional taxa have been assigned conservation statuses by the Kentucky Academy of Science-Kentucky State Nature Preserves Commission. The lower 11 km of the Nolin River winds through the western portion of the park under 100 m sandstone and conglomerate bluffs. The Nolin meets the Green about 3.5 km from the western park boundary. These streams of Mammoth Cave support one of the most diverse cave aquatic communities in the world, including the Category 2 Northern Cavefish and the federally endangered Kentucky Cave Shrimp.

The objectives of this report include identifying the specific fundamental water resources at Mammoth Cave National Park, including laws and policies that relate to Mammoth Cave's water resources, developing goals for those fundamental water resources, and identifying issues preventing the achievement of the water resource goals, with strategies that work through those issues and towards the goals.

The primary water resource goals for Mammoth Cave National Park are:

> Water Resource Goal #1: *Chemical (water quality) integrity of park water is improved and/or maintained to support all native life and to meet or exceed designated use standards.*

The primary concern driving the majority of water-related issues at the park is water quality. Like many other highly threatened aquatic resources, Mammoth Cave is located downstream from a myriad of pollution sources. The Green River drainage basin (5260 $km^2$) upstream of the park drains a wide range of ever-changing land-uses; including agricultural, silvicultural, urban, industrial, petroleum exploration, and transportation. The Kentucky State Nature Preserves Commission states that human alterations of the land and water have led to 34% of the state's mussel taxa to be considered rare or endangered at the state and federal level (Cicerello, 1990).

Likewise, the cave aquatic ecosystem experiences similar threats, as the majority (75%) of the park's groundwater recharge basins, 319 $km^2$, lie beyond park boundaries. The most striking geomorphic feature associated with mature karst terrains is the lack of surface drainage. Any pollutant found on the surface within the recharge area, both in the sinking streams and the Sinkhole Plain, directly enters the cave streams in the form of unfiltered runoff during rainfall events. Flow through the aquifer can be quite rapid, on the order of 20 kilometers per day. Contaminants entering the karst aquifer can thus be rapidly transported, unaltered, through the cave streams and impact their dependent aquatic fauna. Threats to this ecosystem are real and have been documented with data from the water quality and biological inventory.

Factors preventing or impeding the achievement of this Water Resource Goal include:

- Domestic sewage
- Agricultural non-point source runoff
- Airborne contaminants
- Urban and transportation corridor impacts
- Lock and Dam #6 impacts
- Endocrine disruptors
- Lack of "cause and effect" relationships between water quality and aquatic life
- Public education and environmental enforcement

Comprehensive strategies that begin to address these issues include:

- Water quality monitoring
- Watershed land use monitoring
- Air quality monitoring
- Aquatic biological monitoring
- Public outreach

<u>Water Resource Goal #2</u>: *Hydrologic (water quantity) integrity of park waters (surface and ground waters) is improved and/or maintained to support natural geomorphic processes of fluvial and aquifer systems and to support native life.*

The most pressing, direct, and proximal alteration to the hydrology of the Green and Nolin Rivers and cave streams is Lock and Dam Number Six. Several key park species (including six mussels and a freshwater cave shrimp, all federally listed) are directly and immediately affected by this decommissioned, low-head dam. The Green (15 km) and Nolin (11 km) rivers are impounded by Lock and Dam Number Six. Each listed mussel species is reliant on shallow, free-flowing condition, and, like many other mussel species, are not found in the pooled section. The cave shrimp's habitat, found within the major slow-flowing base-levels of the cave, is altered by this decommissioned structure. Landuse practices within the rivers' riparian corridors can alter the sediment flux into the stream by bank destabilization, altering stream morphology, thus changing habitat for aquatic wildlife. Twenty-six km of endangered species habitat has been severely altered.

Current development trends within the park's watershed will increase the use of water for domestic water supply, agriculture, and recreational use. Water quantity, in terms of minimum flow requirements to support a functional aquatic ecosystem, as well as flow modifications that alter the intensity, periodicity, and sediment erosion and deposition, can greatly impact aquatic fauna. During drought conditions in the region, water demand remains relatively constant, with little or no water conservation measures employed. This is a critical time when minimum flow requirements become important in maintaining healthy aquatic habitats.

Factors preventing or impeding the achievement of this Water Resource Goal include:

- Lack of knowledge on fluvial geomorphology of the Green River
- Ecological flow requirements for threatened and endangered species and habitat quality
- Impacts from dams
- Recharge boundary definition
- Restoration of flow at Haney Springs

Comprehensive strategies that begin to address these issues include:

- River morphologic inventory and monitoring
- Removal of Lock and Dam #6
- Refinement of karst watershed maps
- Removal of historic flow structures from Haney Springs

Water Resource Goal #3: *Exotic species are removed from the park and future introduction of exotics is prevented.*

In many respects, the Green and Nolin rivers have not seen the ecologically crippling effects brought by the invasion of aquatic exotic species. That is not to say that several exotics do not exist within these streams, they do, with favorable conditions existing for new exotics entering Mammoth Cave National Park's aquatic environments.

The Asian Clam (*Corbicula fluminea*) is very widespread, overly abundant, and present throughout the Green River, including waters within the park. The Zebra Mussel (*Dreisenna polymorpha*) is present in the Green near confluence with the Ohio River. Many experts agree that a zebra mussel infestation of the Green within the park will occur, it's just a matter of when, while other experts believe the spread of zebra mussels to the park to be unlikely.

There are several exotic fish species found within the park. Rainbow trout *(Onchorhynchus mykiss)* are currently stocked by the Kentucky Department of Fish and Wildlife Resources (KDFWR) in the tailwaters of the Nolin Dam (only three km from the park boundary). To give an order of scale, 16,600 were stocked into this put-and-take fishery in 2000. The KDFWR also stocks rainbows within the Green River at Roundstone Creek, upstream of the park. These fish, native to the far western portions of the United States, have been introduced throughout the east, especially in the cold-water lake releases as a sport fish.

Common Carp (*Cyprinus carpio*), native to Eurasia, were introduced at least 100 years ago and are common in the Green and Nolin rivers within the park. Its cousin, the goldfish (*Carassius auratus*) is also found within the park's two surface rivers.

Mosquito fish (*Gambusia affinis*) were recently found in the park, possibly due to bait bucket introductions or habitat modifications that favor it. Its native range is somewhat speculative, but experts suspect that it was not native to the Green River basin.

Factor preventing or impeding the achievement of this Water Resource Goal include:

- Deliberate introduction of exotics
- Accidental introduction of exotics

Comprehensive strategies that begin to address these issues include:

- Complete park inventory of extant aquatic species
- Promote multi-agency exotic group for the Green River Basin
- Determine threat level of existing and potential exotics

## Water Resources Management Plan Purpose and Objectives

Water Resources Management Plans (WRMPs) have evolved over the past 15 years, providing a comprehensive review of NPS aquatic resources where the management of these resources is considered complex, numerous, and/or controversial.

Since starting the Mammoth Cave National Park WRMP in 2003, there have been significant changes in the NPS general planning framework (2004 *Park Planning Program Standards*), including resources planning (draft *Director's Order 2.1: Resource Stewardship Planning*), requiring programmatic revision to the existing NPS Water Resources Planning Program to assure that its products support the new NPS planning framework within which planning and decision-making are now accomplished. The Mammoth Cave WRMP is one of the first water resource reports to capture some elements of this new planning design.

## New NPS Planning Overview

Within the new NPS planning framework, six discrete elements of planning are in place that is captured in six planning-related documents (Figure 1).

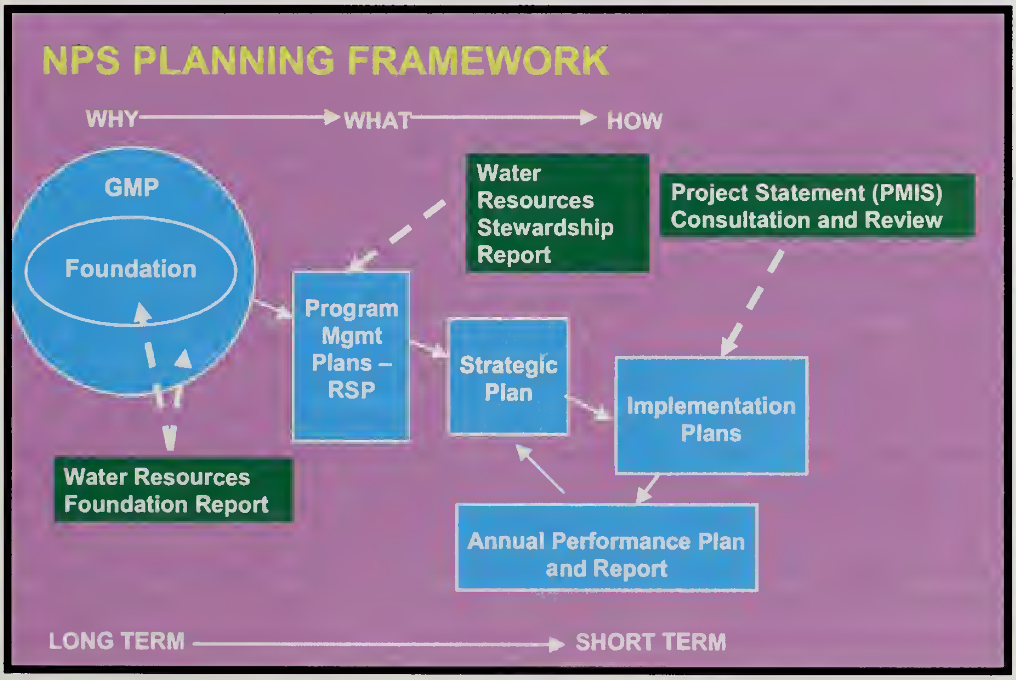


*Figure 1. The "new" NPS framework for planning and decision making (blue boxes). Green boxes represent WRD planning or assistance. RSP = Resource Stewardship Plan. Figure courtesy of the NPS WRD.*

The *Foundation for Planning and Management* defines the legal and policy requirements that mandate the park's basic management responsibilities, and identifies and analyzes the resources and values that are fundamental to achieving the park's purpose or otherwise important to park planning and management.

The *General Management Plan* uses information from the *Foundation for Planning and Management* to define broad direction for resource preservation and visitor use in a park, and serves as the basic foundation for park decision-making, including long-term direction for d*esired conditions* of park resources and visitor experiences.

The *Program Management Plan* tiers off the *General Management Plan* identifying and recommending the best strategies for achieving the desired resource conditions and visitor experiences presented in the *General Management Plan.* Program planning serves as a bridge to translate the qualitative statements of *desired conditions* established in the *General Management Plan* into measurable or objective indicators that can be monitored to assess the degree to which the *desired conditions* are being achieved. Based on information obtained through this analysis, comprehensive strategies are developed to achieve the *desired conditions*. The *Program Management Plan* component for natural and cultural resources is the *Resource Stewardship Plan* (Figure 1).

The *Strategic Plan* tiers off the *Program Management Plan* identifying the highest-priority strategies for the park, including measurable goals that work toward maintaining and/or restoring the park's *desired conditions* over the next 3 to 5 years.

*Implementation Plans* tier off the *Strategic Plan* describing in detail (including methods, cost estimates, and schedules) the high-priority actions that will be taken over the next several years to help achieve the *desired conditions* for the park.

The *Annual Performance Plan and Report* measures the progress of projects from the *Implementation Plan* with objectives from the *Strategic Plan.*

## New Water Resources Planning Products

New water resources planning products that support this latest planning framework for parks, now include; 1) the *Water Resources Foundation Report* and 2) the *Water Resources Stewardship Report*. The *Water Resources Foundation Report* (Figure 1) addresses the needs of either the park's *Foundation for Planning and Management* document or phase one of the *General Management Plan*, including descriptions of the "fundamental water resources" and water-related laws, policies and mandates specific to the park. The *Water Resources Stewardship Report* (Figure 1) is designed specifically to address the water resource needs in a park's *Resources Stewardship Plan (*recently changed to *Resource Stewarship Strategies).* This includes strategies that work toward achieving or maintaining the GMP's "desired conditions" with measurable or objective indicators to assess the degree to which the "desired conditions" are being achieved.

## Mammoth Cave National Park's Water Resources Management Plan Objectives and Structure

Mammoth Cave's Water Resources Management Plan is caught in the transition between the earlier design of a *Water Resources Management Plan* and the new design of the *Water Resources Foundation Report* and *Water Resources Stewardship Report*. As such, elements from both the old and new planning design are captured in this WRMP. An example is the development of strategies (new design), instead of project statements (old design). Water resource goals are identified in this plan for future consideration since Mammoth Cave's GMP is dated with no desired conditions (new design) for natural resources established yet for the park. It is recommended that these goals be considered for inclusion in Mammoth Cave's next GMP.

The objectives of this report include identifying the fundamental water resources at the park, including laws and policies that related to Mammoth Cave's water resources, developing goals for those fundamental water resources, identifying issues preventing the achievement of the water resource goals, with strategies that work through those issues and towards the goals.

The report is divided into eleven major parts. The first part, *Introduction*, includes a general overview of the park and visitor use. The second, third and fourth sections, *Description of Water Resources, Hydrology, and Water Quality*, includes identification and detailed descriptions of the fundamental water resources, and brief discussion on the influential environments (i.e., climate, physiology, geomorphology, geology, soils, vegetation, etc.). The fifth section, *Sediment Quality*, provides a similar account of sediment quality investigations. The sixth section, *Land Use*, describes in detail the documented land uses for each watershed affecting the park, as well as a land use comparison between the early and late 1990s. The seventh section, *Aquatic Biology*, is a general description of surface and subsurface biology found in the park. The eighth section, *Management Authority*, is a listing and brief description of the applicable park-specific, Federal and State legislation that provide the mandates and foundation for management decisions related to water resources. The ninth section, *Management Objectives*, outlines general management objectives of the park as well as a host of non-park land management or cooperative agencies. The tenth section, *Water Resource Goals*, introduces several qualitative goals for Mammoth Cave's water resources to be considered during development of the park's next GMP, since desired conditions have not been identified for the park's water resources. Issues that influence these goals are summarized, with strategies presented that address the issue(s) and work toward restoring or maintaining each water resource goal. Finally, the eleventh section, *Summary*, provides a condensed summary of the state of water resources of Mammoth Cave National Park.

# The Water Resources Management Plan and NEPA

The National Environmental Policy Act (NEPA) requires that federal agencies prepare a study of the impacts of major federal actions that may produce a significant effect on the human environment and alternatives to those actions. The adoption of formal planning documents can be considered an action requiring NEPA analysis providing those plans recommend decisions that affect resource use, submit options, commit resources of preclude future decisions. Lacking these elements, this Water Resources Management Plan (WRMP) has no measurable impacts on the human environment and thus is categorically excluded from further NEPA analysis.

According to Director's Order (DO) #12 Handbook (section 3.4), the Mammoth Cave National Park WRMP is covered this Categorical Exclusion:

- 3.4B (4) Plans, including priorities, justifications, and strategies for non-manipulative research, monitoring, inventorying, and information gathering.

Furthermore, suggested actions or potential issue resolutions that discussed within this document are covered by the following Categorical Exclusions:

- 3.4B (1) Changes or amendments to an approved plan when such changes have no potential for environmental impact.
- 3.4B (7) Adoption or approval of academic or research surveys, studies, reports and similar documents that do not contain and shall not result in NPS recommendations.
- 3.4E (2) Restoration of non-controversial native species into suitable habitats within their historical ranges.
- 3.4E (4) Removal of non-historic materials and structures in order to restore natural conditions when the removal has no potential for environmental impacts, including impacts to cultural landscapes or archeological resources.
- 3.4E (6) Non-destructive data collection, inventory, study, research, and monitoring activities.
- 3.4E (7) Designation of environmental study areas and research of natural areas, including those closed temporarily or permanently to the public, unless the potential for environmental (including socioeconomic) impact exists.

These Categorical Exclusions require that formal records be completed (Section 3.2, DO-12 Handbook) and placed in park files. It is the responsibility of the park to complete the documentation for the applicable Categorical Exclusion(s).

# Introduction

## Park Location

Mammoth Cave National Park is located within the Interior Low Plateau on the southeastern edge of the Illinois Sedimentary Basin in Southcentral Kentucky, approximately midway (150 km) between Louisville Kentucky and Nashville Tennessee (Figure 2). This 21,198 hectare park, cloaked beneath an eastern deciduous forest, is primarily situated upon the Chester Cuesta, dissected by broad and deep karst valleys underlain by Mississippian strata adjacent to the Sinkhole Plain of the Pennyroyal Plateau to the south. The park is divided into two nearly equal halves by the deep gorge (100 m) of the Green River, about mid-way in the river's course to the Ohio.


*Figure 2. Location map of Mammoth Cave National Park, from Palmer, 1981.*

## Land Ownership

The National Park Service owns all lands within the actual boundaries of the park with exception of three small graveyards (Personal Communication, 2004, Robert Ward, Cultural Resources Management Specialist, Mammoth Cave National Park). The authorized boundary of the park extends around most of the park with an additional 7,200 hectares. At present, there is no action or intention to acquire these lands.

## Land Cover and Land Use

### *Prehistoric and Historic Land Use*

One can only speculate, based on general climates associated with great continental glacial advances and retreats within broad topographic and geographic zones, on the pre-human land cover in the Mammoth Cave area. Current thought is that vegetative communities have been relatively stable since the Hypsithermal, approximately 5,000 years ago (Watson and Carstens 1982, and Delcourt and Delcourt 1981). Prentice (1993) summarized the general sequence for environmental change in the Kentucky region shortly before and during times of human occupation. During the peak of the Late Wisconsin Glacial period (16,000 B.C.), Kentucky was dominated by jack pine (*Pinus banksiana*) forests with spruce and fir as subordinate species (Delcourt and Delcourt 1981). Some 12,000 B.C., a general warming trend retreated the continental glaciers causing a general migration of forest communities northward, as spruce-Jack Pine forests dominated the region. The global warming continued and about 8,000 B.C. Kentucky was dominated by mixed hardwood forests with relict spruce and fir at higher elevations. Between 7,000 and 3,000 B.C. (the Hypsithermal Interval) warming continued as the mixed hardwoods changed to Oak-Hickory forests as the region's climate became drier. Following the Hypsithermal, the climate has become somewhat wetter, but the general forest community has changed little.

Man, at least as far as can be documented by cultural deposits (projectile points), has had a presence in the Mammoth Cave area since 9,500 B.C., the Paleoindian Period (9,500-8,000 B.C.) (Tankersley 1996). Paleoindians are not thought to have occupied the Mammoth Cave area (perhaps only passing through as hunting parties). There is ample evidence of human occupation in the Archaic Period (8,000-1,000 B.C.). By the Late Archaic, humans began setting up trading networks, domesticating plants and began using the caves (Prentice 1993). By the Woodland Period (1,000 B.C. – A.D. 900) natives, still occupying the park area, began to change from egalitarian hunter-gatherer culture to one based in horticultural activities (Prentice 1993). Human occupation continued throughout the Mississippian Period (A.D. 900-1,500), but there is little archeological evidence of occupation during the Proto-Historic Period (A.D. 1,500-1,700).

Although it is uncertain of their impacts or influences to regional land use, inhabitants ultimately left behind what was found by explorers and settlers in the mid 1750's. The

Pennyroyal Plateau swung crescent-like from the northeast to the southwest, tracing the vast karst belt in a tall-grass prairie of over 7,300 $km^2$ (Ray, 1997). The uplands of the Chester Cuesta, graded from these grasslands to an oak savanna. This natural system changed during early settlement, as land use began a conversion to agriculture. In general, early agricultural practices, as the prairie was cut by plow and harrow, and the uplands cut and cleared, were severe enough to leave landscape changes – deep gullies and sediment-choked streams. Crocker (1976) estimates that over 80 million board feet of timber was cut from the Green River valley in 1895 alone. Little agricultural or silvicultural conservation was practiced, especially in terms of soil-loss.

With exception of isolated ravines, the Big Woods (125 hectares), and much of the 925 hectare Mammoth Cave estate, the remaining mosaic of croplands and woodlots began conversion of what is now the park with the 1924 establishment of the Mammoth Cave National Park Association. This group led to the creation of the park through public involvement (including a visit by the Southern Appalachian National Park Commission (H.R. 11980) and Congressional legislation (S. 4209, and H.R. 12020) which authorized the creation of Mammoth Cave Park in April 1926 (Goode, 1986). The Kentucky National Park Commission was authorized by the state in 1928, with the authority of eminent domain, to acquire park lands. Bills and Resolutions were passed (S. 1491 and H.R. 4676) signifying that the Commonwealth of Kentucky would cede to "the United States exclusive jurisdiction over, within and under the territory in the Commonwealth as may be acquired for the Mammoth Cave National Park, are hereby accepted." The Secretary of Interior formally accepted the lands for administration and protection as a national park in May, 1936, and the National Park Service took full ownership of the lands on July 1, 1941 (Goode, 1986).

Gradually, the montage of the 1920s, inhabited by about 600 families and 30 documented communities, mostly small farms with an average farm size of about 30 hectares, merged into what we see today. These farms, similar to those currently surrounding the park, scratched out a living on the ridges, slopes and valleys of the Chester Cuesta, relying on nominal row crops (to provide winter stock feeds), tobacco, haylands, pastures, and small woodlots. The imprint of their land uses remains prominent. Even after being abandoned for well over 60 years, one is constantly moving across obvious boundaries of old fields and forests while hiking through the park, although these traces will meld into obscurity as the years pass. Natural reforesting of the park lands has now reached the stage where there is seed dispersal from adjacent woodlands, at least with respect to eastern red cedar, red maple, and American beech (McDaniel, 2000). McDaniel (2000) found that flood dispersal of seeds plays an important role in the reforestation of lowland old fields, as the Green's floodplains were fully or partially inundated 22 times between 1940 and 1960 alone.

Land use within the Green and Nolin watersheds experienced a similar transition from natural systems into small farming operations from the times of initial Euro-American settlement in the late 18$^{th}$ century. Hillslopes were stripped of trees – many used in railroad ties – and level-lands were cleared for agrarian practices. These were days that preceded the Soil Conservation Service and much erosion occurred.

### *Specific Park Land Use*

The park has been managed as a natural ecosystem since its creation in 1941. In 1960 and 1961, the two remaining in-holdings (the 106-hectare Floyd Collins Crystal Cave, and the 98-hectare Great Onyx Cave) were sold to the Department of Interior. Just prior to the federal government taking full possession of the park – the National Park Service began establishing oversight in 1936 – the Civilian Conservation Corps was busy with infrastructural improvements (roads and cave trails), as well as natural resource conservation, restoration and stabilization projects (stream-bank stabilization, tree plantings) (Goode, 1986).

Over the years there has been much debate on how the park should be managed, primarily following the release of the preliminary Mammoth Cave Master Plan (1972), and the management of the park as a Wilderness (as per the Wilderness Act of 1964) (Goode, 1986). Great conflicts arose, pitting conservationists and local tourism promoters. A compromise was struck in the General Management Plan (1983) that deemed the lands unsuitable for Wilderness designation, but led to specific conservation steps, notably the relocation of the Department of Labor Great Onyx Job Corps (Goode, 1986).

Currently the park is managed as a natural area with basic infrastructure (roads, lawns, residential, maintenance, administration, campgrounds and visitor services) to serve park visitors. Detailed descriptions of park land cover and watershed land use are addressed in later sections.

## Visitor Use

### *Ranger-lead Activities*

Ranger lead tours comprise the majority of visitor use activities, aside from normal through-park road traffic (commutes). Since 1816, Mammoth Cave has been a tourist attraction, shortly after the nitrate-mining production ceased following the War of 1812. Cave guiding traditions, starting with slaves in the early to mid 1800's, continue today as thousands of visitors are lead through the cave. Cave tour numbers peaked in the 1970's, but remain strong today – in order to provide a higher-quality visitor experience and to better protect cave resources, tour sizes are smaller than three decades ago. In 2005, some 347,357 visitors took a ranger-led cave tour.

Aside from cave tours, ranger lead activities also includes nature walks and other surface tours. Primarily in the summer months, beginning with spring wild flower walks and ending with fall color viewing, thousands of park visitors are lead about the surface of the park.

### *Backcountry*

The park contains over 110 km of backcountry surface trails, mostly among the hilly country north of the Green River. South of the Green River are over five kilometers of well-paved (crushed limestone) trails and over 700 meters of handicap-accessible trails leading to various points of interest. A short (3 km) bike trail, leading from the main park campground, was established in the mid 1990's. The park is currently extending the bike trail an additional 13 km to Park City.

While thousands of visitors use these south side trails each year, trails on the north side of the Green are considered backcountry and attract thousands of visitors wishing to hike and camp. The park saw an estimated 9,900 backcountry hikers in 2003. Horse-back riding is permitted on most of the north-side trails (a practice prohibited on the south side). An estimated 2,500 horse-back excursions take place each year (2002 and 2003 for example). Mountain biking is permitted (beginning in 2000) on the Sal Hollow loop trail (approximately 18 km). Bike use is difficult to gauge, but estimated at over a thousand users per year.

The park operates two vehicle ferries, Green River Ferry (located proximal to the Visitor Center) and Houchins Ferry (located near Brownsville). The former conveys the majority of vehicle traffic, and their combined 2003 total was 179,462 individuals.

### *Concessions*

Like many parks, Mammoth Cave relies on concessions to serve the visiting public. Concession contracts currently held with Forever Resorts, Inc. include hotel, gift shop, restaurant, camp store, and cave tour transportation. Contracts are also made for canoe, scenic boat tour, and horse-back riding activities.

Horse-back concessions are held by Double J stables (incidental business permit), located on the park's northern boundary where 1,564 rides into the park were conducted in 2003. Miss Green River Boat Concessions (concessions contract) has long operated a scenic boat tour of the Green River. In 2003, 24,083 visitors boarded the Miss Green River II for this 14 km tour from Green River Ferry to the head of Sand Cave Island and back.

Recent years have seen a dramatic increase in canoe concession activities. There are currently two incidental business permits for canoe concessions. Mammoth Cave Canoe and Kayak, and Green River Canoes launched 2,858 and 1,866 craft, respectively, in 2003. An increasing trend in concession canoe launches is expected to continue in the future.

### *Aquatic Recreation*

Aside from the many canoe concession launches, private canoe/kayak use has also increased in recent years. Although the majority of canoe use occurs in the section between Dennison and Green River Ferries (13 km), several visitors float the pooled section between Green River and Houchins Ferries (20 km), as well as floating into the park from upstream. Scenic, although somewhat remote, several visitors float the Nolin River from the Nolin Dam and then upstream on the Green to Houchins Ferry. Regardless of the section of river floated, most canoeists engage in wading and swimming (primary contact recreation) during their trips. Many make overnight trips and camp along the banks and islands.

Many people use power boats on the Green and Nolin. Boat use has remained steady in recent years, and restricted primarily to the pooled sections, although during moderate to high river stages, boaters will venture into the free-flowing sections of the Green above Cave Island. The primary recreational activity of boaters is fishing. A total of 15,566 boaters, canoeists, and kayakers (both concession and private) floated the park's rivers in 2003.

# Description of Water Resources

Building from the park's Mission Statement and park significance statements found in the Mammoth Cave National Park Strategic Plan 2000-2005 (see Management Objectives section), water is easily defined as a fundamental resource at the park.

The streams of Mammoth Cave support one of the most diverse cave aquatic communities in the world. The hydrogeology and geomorphology of the Mammoth Cave region is and has been controlled by the Green River, producing the world-class cave system we see today. The Green River is designated by the Commonwealth of Kentucky as an "Outstanding Resource Water" and a state "Wild River", supporting several rare and endangered species.

The fundamental water resources at Mammoth Cave National Park include surface water streams, ponds, wetlands, springs and subsurface aquifers and cave streams. This section and the following two sections, *Hydrogeology* and *Water Quality*, describe these various water resources in detail, along with the influential environments (i.e., climate, geology, vegetation, etc.)

## Climate

The Kentucky Climate Center at Western Kentucky University described Kentucky's climate as follows (Western Kentucky University, 2004):

> The climate of Kentucky reflects the interplay of several locational influences. Kentucky's inland location contributes to a continental influence, which acting alone, tends to produce a large seasonal temperature range between summer and winter. Meanwhile, its position north of the Gulf of Mexico contributes to a tropical marine influence that moderates temperatures and yields ample precipitation. Kentucky's mid-latitude position places it in a region where weather can be highly variable. While prevailing surface winds are southerly and light, upper level westerly winds steer frontal systems across the state. These systems bring warm, moist air from the south, followed by cooler, drier air from the north. At a broader scale, Kentucky's climate is influenced by interactions involving the oceans and atmosphere. While these influences originate thousands of miles away, they may contribute to significant variations in Kentucky's climate on a seasonal or annual time scale.

Weather records from the Mammoth Cave Air Quality Station reflect a sub-tropical climate (Figure 3, Tables 1, 2, and 3). Temperature extremes of –29.4°C (-20.9°F) on Friday February 2$^{nd}$, 1951 to 42.2°C (108.0°F) on Sunday, July 27$^{th}$, 1952 were recorded. The park has an annual mean temperature of 13.7°C (56.7°F), and an annual maximum mean of 20.4°C (68.7°F) and an annual minimum mean of 7.1°C (44.8°F). Maximum temperatures occur in July and August, with the coldest month being January.

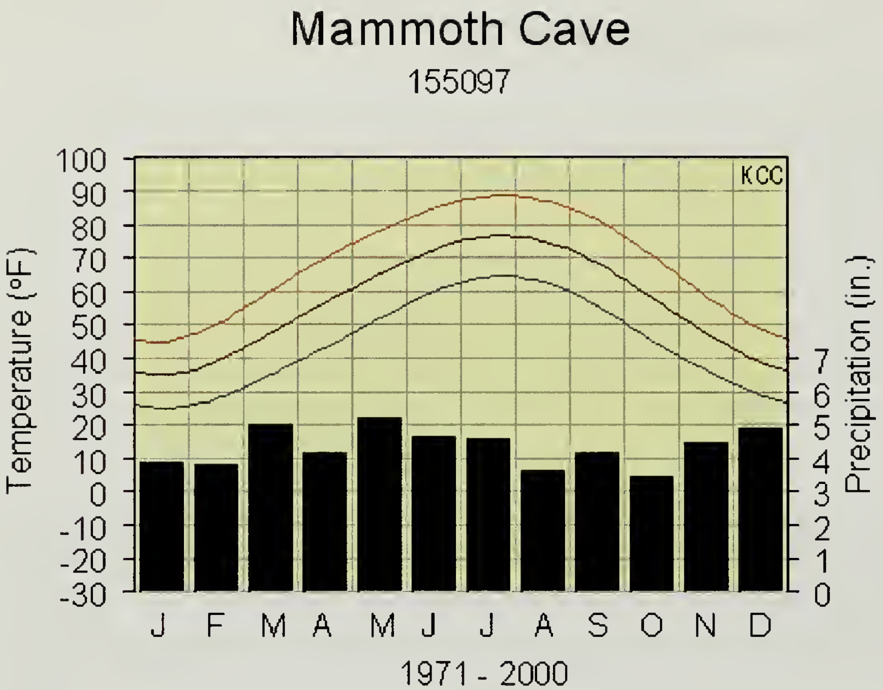


*Figure 3. General weather at Mammoth Cave National Park, showing mean daily (center line), mean daily maximum (upper line), mean daily minimum (lower line) temperatures, and mean monthly precipitation (bars), from Kentucky Climate Center, Western Kentucky University (2004).*

*Table 1. Historical climate data, temperature summary, Station 155097, Mammoth Cave National Park, period of record 1971-2000.*

| Element | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Anl |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max °C | 6.7 | 10.2 | 15.8 | 21.4 | 25.6 | 29.4 | 31.4 | 30.8 | 27.6 | 21.7 | 14.8 | 9.1 | 20.4 |
| Min °C | -4.2 | -2.3 | 2.1 | 6.2 | 10.9 | 15.7 | 18.1 | 17.2 | 13.4 | 7.2 | 2.7 | -1.9 | 7.1 |
| Mean °C | 1.3 | 3.9 | 8.9 | 13.8 | 18.3 | 22.6 | 24.8 | 24.0 | 20.5 | 14.4 | 8.8 | 3.6 | 13.7 |

*Table 2. Historical climate data, temperature extremes, Station 155097, Mammoth Cave National Park, period of record 1935-2001.*

| Month | High Mean°C | Year | Low Mean°C | Year | 1-Day Max°C | Date | 1-Day Min°C | Date |
|---|---|---|---|---|---|---|---|---|
| JAN | 8.1 | 1950 | -7.5 | 1940 | 26.7 | 1/24/1943 | -28.9 | 1/24/1963 |
| FEB | 8.3 | 1976 | -3.5 | 1978 | 27.8 | 2/13/1962 | -29.4 | 2/2/1951 |
| MAR | 13.4 | 1946 | 0.5 | 1960 | 30.0 | 3/31/1963 | -21.1 | 3/5/1960 |
| APR | 17.4 | 1981 | 11.2 | 1983 | 33.9 | 4/10/1995 | -7.8 | 4/14/1950 |
| MAY | 22.4 | 1962 | 15.7 | 1940 | 35.6 | 5/17/1991 | -2.8 | 5/1/1963 |
| JUN | 26.7 | 1952 | 19.6 | 1955 | 40.6 | 6/29/1936 | 0.0 | 6/5/1950 |
| JUL | 27.6 | 1999 | 21.2 | 1947 | 42.2 | 7/27/1952 | 4.4 | 7/7/1950 |
| AUG | 27.0 | 1983 | 20.4 | 1950 | 40.0 | 8/27/1936 | 2.8 | 8/4/1950 |
| SEP | 23.9 | 1936 | 17.8 | 1950 | 41.1 | 9/5/1954 | -1.7 | 9/29/1942 |
| OCT | 18.7 | 1963 | 10.5 | 1988 | 34.4 | 10/2/1953 | -7.8 | 10/28/1976 |
| NOV | 12.8 | 1985 | 3.7 | 1976 | 33.9 | 11/1/2000 | -22.2 | 11/25/1950 |
| DEC | 8.7 | 1971 | -3.1 | 1989 | 26.7 | 12/7/1951 | -27.8 | 12/22/1989 |
| | | | | | | | | |
| Annual | 15.9 | 1935 | 12.0 | 1940 | 42.2 | 7/27/1952 | -29.4 | 2/2/1951 |
| Winter | 6.3 | 1950 | -2.9 | 1940 | 27.8 | 2/13/1962 | -29.4 | 2/2/1951 |
| Spring | 16.1 | 1977 | 11.3 | 1947 | 35.6 | 5/17/1991 | -21.1 | 3/5/1960 |
| Summer | 26.3 | 1952 | 20.8 | 1950 | 42.2 | 7/27/1952 | 0.0 | 6/5/1950 |
| Fall | 16.8 | 1999 | 11.3 | 1976 | 41.1 | 9/5/1954 | -22.2 | 11/25/1950 |

*Table 3. Historical Climate data, temperature threshold climatology derived from 1971-2000 averages, Station 155097, Mammoth Cave National Park. *Annual/seasonal totals may differ from the sum of the monthly totals due to rounding.*

| Month | # Days Max ≥ 32.2°C | # Days Max ≤ 0°C | # Days Min ≤ 0°C | # Days Min ≤ -17.8°C |
|---|---|---|---|---|
| JAN | 0.0 | 5.9 | 23.0 | 1.5 |
| FEB | 0.0 | 2.9 | 17.8 | 0.6 |
| MAR | 0.0 | 0.3 | 12.6 | 0.0 |
| APR | 0.1 | 0.0 | 4.6 | 0.0 |
| MAY | 0.5 | 0.0 | 0.3 | 0.0 |
| JUN | 5.9 | 0.0 | 0.0 | 0.0 |
| JUL | 12.8 | 0.0 | 0.0 | 0.0 |
| AUG | 10.7 | 0.0 | 0.0 | 0.0 |
| SEP | 4.0 | 0.0 | 0.0 | 0.0 |
| OCT | 0.0 | 0.0 | 3.8 | 0.0 |
| NOV | 0.0 | 0.1 | 11.0 | 0.0 |
| DEC | 0.0 | 2.8 | 19.2 | 0.5 |
| | | | | |
| Annual | 34.4 | 12.0 | 92.6 | 2.7 |
| Winter | 0.0 | 11.5 | 60.0 | 2.6 |
| Spring | 0.6 | 0.3 | 17.4 | 0.0 |
| Summer | 29.4 | 0.0 | 0.0 | 0.0 |
| Fall | 3.9 | 0.1 | 15.0 | 0.0 |

Precipitation occurs throughout the year (Tables 4, 5, and 6). With an annual mean precipitation of 1320 mm, the spring months of March, April, and May bring an average of 127 mm or rain – dominated by broad cold-frontal systems. The highest one-day rainfall total recorded in the park was 173 mm (05-07-1984), while the driest month on record was zero precipitation in October 1975. The bulk of precipitation occurs as rain, the mean annual snowfall from 1961 through 1990 in Bowling Green (40 kilometers to the southwest) is 380 mm. Although mean annual evapotranspiration rates have not been calculated for Mammoth Cave, it can be expected to be within the range calculated for the state, about 13 cm per month (Western Kentucky University, 2004). This assumptive calculation does cause concern, as at this rate, annual evapotranspiration (13 cm/month * 12 months = 156 cm (or 1560 mm) exceeds the annual precipitation total of 1320 mm. Certainly this would be a matter of worry, if true.

*Table 4. Historical climate data, precipitation summary, Station: 155097 Mammoth Cave National Park, period of record 1971-2000.*

| Element | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ann |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Precip (mm) | 98 | 97 | 128 | 106 | 133 | 118 | 116 | 92 | 106 | 88 | 114 | 125 | 1321 |

*Table 5. Precipitation extremes, Station: 155097 Mammoth Cave National Park, period of record 1935-2001.*

| Month | High (mm) | Year | Low (in) | Year | 1-Day Max (mm) | Date |
|---|---|---|---|---|---|---|
| JAN | 534 | 1937 | 18 | 1984 | 79 | 1/10/1974 |
| FEB | 307 | 1989 | 3 | 1947 | 98 | 2/14/1949 |
| MAR | 382 | 1997 | 36 | 1966 | 114 | 3/1/1997 |
| APR | 248 | 1979 | 13 | 1976 | 90 | 4/4/1968 |
| MAY | 358 | 1995 | 34 | 1939 | 173 | 5/7/1984 |
| JUN | 231 | 1935 | 16 | 1936 | 85 | 6/27/1973 |
| JUL | 259 | 1967 | 21 | 1944 | 124 | 7/19/1941 |
| AUG | 236 | 1944 | 15 | 1973 | 101 | 8/23/1942 |
| SEP | 233 | 1979 | 2 | 1956 | 112 | 9/14/1979 |
| OCT | 194 | 1975 | 0 | 1963 | 82 | 10/2/1962 |
| NOV | 333 | 1957 | 23 | 1976 | 169 | 11/18/1957 |
| DEC | 311 | 1978 | 19 | 1965 | 102 | 12/8/1978 |
| | | | | | | |
| Annual | 1827 | 1950 | 667 | 1999 | 173 | 5/7/1984 |
| Winter | 838 | 1950 | 138 | 1963 | 102 | 12/8/1978 |
| Spring | 640 | 1983 | 149 | 1999 | 173 | 5/7/1984 |
| Summer | 497 | 1967 | 112 | 1999 | 124 | 7/19/1941 |
| Fall | 536 | 1957 | 77 | 1963 | 169 | 11/18/1957 |

*Table 6. Precipitation threshold climatology, Station: 155097 Mammoth Cave National Park, derived from 1971-2000 averages. *Annual/seasonal totals may differ from the sum of the monthly totals due to rounding.*

| Month | # Days Total ≥ 0.254 mm | # Days Total ≥ 2.54 | # Days Total ≥ 12.7 mm | # Days Total ≥ 25.4 mm |
|---|---|---|---|---|
| JAN | 9.8 | 7.2 | 2.8 | 0.9 |
| FEB | 9.1 | 6.3 | 2.6 | 1.1 |
| MAR | 12.1 | 8.4 | 3.5 | 1.4 |
| APR | 11.2 | 7.8 | 2.7 | 1.2 |
| MAY | 10.5 | 7.7 | 3.9 | 1.5 |
| JUN | 9.3 | 7.3 | 3.2 | 1.3 |
| JUL | 9.1 | 6.9 | 3.2 | 1.5 |
| AUG | 8.4 | 5.5 | 2.6 | 1.1 |
| SEP | 8.4 | 5.9 | 2.9 | 1.3 |
| OCT | 8.1 | 5.2 | 2.4 | 1.1 |
| NOV | 9.8 | 6.9 | 3.2 | 1.5 |
| DEC | 10.3 | 7.6 | 3.5 | 1.8 |
| | | | | |
| Annual | 115.8 | 82.5 | 36.5 | 15.8 |
| Winter | 29.1 | 21.1 | 8.9 | 3.9 |
| Spring | 33.8 | 23.9 | 10.1 | 4.1 |
| Summer | 26.8 | 19.7 | 9.1 | 3.9 |
| Fall | 26.4 | 18.1 | 8.5 | 3.9 |

As all water flowing though the park originates as atmospheric precipitation, rainfall chemistry is worth noting (Table 7). Mammoth Cave National Park participates in the National Atmospheric Deposition Program in which weekly composite precipitation samples are collected and analyzed for several ionic constituents. The following table represents samples collected between September 2002 and October 2003. Precipitation is typified by low pH values, high nitrate and sulfate concentrations originating from mobile emission sources and regional coal-fired electrical generation plants.

*Table 7. Typical precipitation water quality from the National Atmospheric Deposition Program station (KY10) operated by Mammoth Cave National Park. All constituents are reported as dissolved.*

| Parameter | Minimum (mg/l) | Maximum (mg/l) | Mean (mg/l) |
|---|---|---|---|
| Ca | 0.0100 | 1.3500 | 0.1738 |
| Mg | 0.0030 | 0.0880 | 0.0209 |
| K | 0.0030 | 0.2600 | 0.0264 |
| $NH_4$ | 0.0030 | 0.2750 | 0.3385 |
| $NO_3$ | 0.1500 | 5.4400 | 1.3126 |
| Cl | 0.0200 | 0.4300 | 0.1160 |
| $SO_4$ | 0.4100 | 6.0500 | 1.6294 |
| pH | 4.28 (SU) | 5.49 (SU) | 4.67 (SU) |
| SpC | 4.8 (μS) | 61.0 (μS) | 16.6 (μS) |

## Physiography and Geomorphology

Mammoth Cave National Park is situated on the southeastern edge of the Illinois Sedimentary Basin on the edge of the Western Kentucky Coalfield. It lies almost entirely upon the Chester Cuesta (such named for the age group of strata comprising the ridgetops of this upland). The park is dissected by the Green River and each half is characteristically different, from the nearly flat-topped ridges and intervening broad limestone valleys on the south side, to the rugged hills and ravines of the north side. Approximately 15 kilometers northeast of the park lays the Pottsville Escarpment and the great coalfields beyond. Directly south of the park, the cuesta falls down the steep face of the Dripping Springs Escarpment and onto the Pennyroyal Plateau.

Since the early 19$^{th}$ century, scientists and visitors alike have wondered how this extensive cave system was formed, and why it is located in Southcentral Kentucky. The author, (in Kuehn, et al., 1996) summarizes four basic elements that interplay to create this celebrated surface and subsurface landscape.

1. ***Existence of a suitable body of rock.*** Although minor karst features can develop in a variety of rock types (all rocks are soluble to different extents), clearly carbonate rocks are the primary soluble rock types forming karst landscapes. Due to both its relatively high solubility in carbonic acid, as well as its kinetic properties, pure limestone is an excellent medium for karst development. In the Mammoth Cave region the Girkin, Ste. Genevieve, and St. Louis limestones (100 m thick) provide an ideal framework for karst development. Although there is some heterogeneity, with minor amounts of dolostone, clay, and other silisiclastic impurities, this carbonate sequence is relatively pure. From about the middle of the St. Louis downwards (the St. Louis is the lowest of this carbonate sequence), the rocks contain many shales that inhibit dissolution, and thus karst development. The geometry of the rocks, the structure, is also important. Because of the gentle geologic dip, these limestones are exposed at the surface over a vast area (the Pennyroyal Plateau) supporting hundreds of kilometers of cave passage development within a thickness of only 100 meters.

2. ***Existence of a suitable solvent for dissolution.*** Limestones are only slightly soluble in water. In solutions of carbonic acid the solubility increases dramatically. Carbon dioxide is dissolved into rainwater in minor amounts in the atmosphere, but most is derived from contact with soil gas where microbial decay of organic material can drive carbon dioxide partial pressures to over 100 times atmospheric levels (White 1988, Atkinson 1977). Karst development is thus favored in areas of; a) abundant rainfall, b) thick soils, and c) relatively warm temperatures supporting both vegetative and microbial communities that enhance soil $CO_2$. Note that although limestone is more soluble in colder waters, the increased $CO_2$ production by microbial in warmer climes greatly overshadows $CaCO_3$ temperature kinetics. White (1988) measured $CO_2$ partial pressures of 0.1 atmospheres in the thick soils of the region.

3. ***Hydrogeologic relations resulting in a sufficient hydraulic gradient.*** The nature of the carbonic acid/limestone interaction is such that the time scales over which the solvent becomes saturated are on the order of a few days (Rauch and White 1977, Hess and White 1988). For this reason if groundwaters cannot move into, through, and out of an incipient carbonate aquifer at a sufficient rate, the groundwaters will so closely reach saturation while still within the rock that karst development will not occur (Groves and Howard 1994). In order to provide the energy needed to move solvents through the rock with sufficient rapidity, a hydraulic gradient must exist. At Mammoth Cave, the Green River has cut downward into the Mammoth Cave (Chester) Cuesta, carving through the Big Clifty Sandstone caprock, and exposing the underlying carbonate sequence. A gradient was therefore created between the recharge areas of the Pennyroyal Plateau and the river. This gradient, along with the vast exposures of the carbonate rock mass of the Pennyroyal surface, has created the extensive drainage basins which collect water from hundreds of square kilometers and drain to a series of large springs along the Green. Between the recharge and discharge points, lays the most extensive cave system known.

4. ***Time.*** Think of where we are, at our place in time with respect to this karst area. Over the course of the world's geologic history many great landscapes, rivaling or surpassing any of those seen today, have been formed and eroded away. Where are we in the geologic history of Southcentral Kentucky? Although modern geomorphologists tend to shy from the Davisian concept of clearly defined stages of landscape development, there is without doubt an evolutionary sequence of events that create the karst of Southcentral Kentucky. There was an exact moment in time when rainwaters first touched the Girkin Limestone. At some point in the future, there will be a moment when the last mole of that formation is carried away. We are today within these temporal landmarks.

   Karst landscape forming processes, as stated by White (1988) is one of decay. Several lines of evidence suggests that the Southcentral Kentucky karst and Mammoth Cave have been under development for less than 10 Ma., and that much of that work within the past few million (Palmer 1981, White and White 1989). These include a paleomagnetic dating of cave sediments (by Schimdt 1982 and confirmed by Granger, et al. 2001), radioisotope dating of speleothems (Harmon, et al. 1978), and consideration of time scales bound by dissolution kinetics of limestone (Dreybrodt 1990, and Palmer 1991). Granger (et al. 2001), by cosmogenic radionuclide dating of cave sediments, found that the oldest passages of Mammoth Cave to be at least three million years old.

The most dominant geomorphic agent in the region is channelized flowing water, and the most striking surface expression of this agent is the deep canyons of the Green and Nolin Rivers. These rivers are ancient channels, far predating the earliest cave sediment dates (3.5 Ma) reported by Granger, et, al., 2001. Their courses form well-incised meanders through the entire stratagraphic sequence. All caves have drained to the Green throughout their formation. All regional landscapes are tied directly to the rivers. To know the geomorphic history of the Green, and subsequently its tributary, the Nolin, is to understand the processes and timing of the surface and subsurface landscapes of the Mammoth Cave Region.

Granger, et al. (2001) conducted an extensive study of burial dates of quartzite gravels in the main levels of Mammoth Cave to unravel the incision history of the Green River. By carefully collecting quartzite pebbles (weather material from the Caseyville Formation) from various levels throughout the cave system, Grainger, with the aid of a linear accelerator, was able to very precisely determine the concentrations of radio-isotopes of $^{26}Al$ and $^{10}Be$ in the pebbles. These isotopes, products of cosmogenic energy bombardment and alteration of the silicon and oxygen of the quartz prior to being washed into the cave, decay at known rates. Once buried in the cave – cosmogenic energy effects only materials within the upper meter of the earth's surface – no new nuclides are produced. Thus by comparing the ratios of $^{26}Al$ and $^{10}Be$ in the collected pebbles, burial dates can be determined, and thus extrapolated to when a particular cave passage was actively flowing and transporting sediments. Granger, et al. (2001) was able, with dates and elevations of cave passages to unravel the past 3.5 Ma history of the Green River's incision. Their research has shown that the Green has a complex history of rapid (~30 m/m.y.) and slow downcutting (~2-7 m/m.y.), interspersed with periods of aggradation (some as great as 15 m). Granger concluded that the river and subsequent landscape of the Mammoth Cave area is therefore in a state of climatically induced erosional disequilibrium, a product of the advance and retreat of continental glaciers.

### *North of the Green River*

In what is locally known as the "Hilly Country", the physiography of the North Side is dominated by deeply incised, carbonated-floored valleys alternating with silisiclastic-capped ridges. Due to the limited surface exposure of the thick basal carbonate sequence, in addition to the geologic dip being away from the river, extensive karst development is localized, for the most part, within topographic watersheds. The result is an example of ravine karst, where streams flowing over the silisiclastic uplands sink into the underlying limestones. The limited aerial exposure of limestone allows little doline (sinkhole) development. The ridges are not composed entirely of clastic strata, as the geologic section alternates between sandstones and limestones – ranging from 10 to 15 meters thick. The resulting geomorphology is a series of surface stream runs over the sandstones, sinking into the underlying limestones, and reappearing as a spring at the next sandstone contact (Figure 4). The stair-stepping alternation of surface and subsurface flow is found throughout the North Side. This geologic sequence has produced a pronounced bench-slope morphology as the chemically-resistant sandstones form steep slopes and the limestones tend to produce topographic benches.

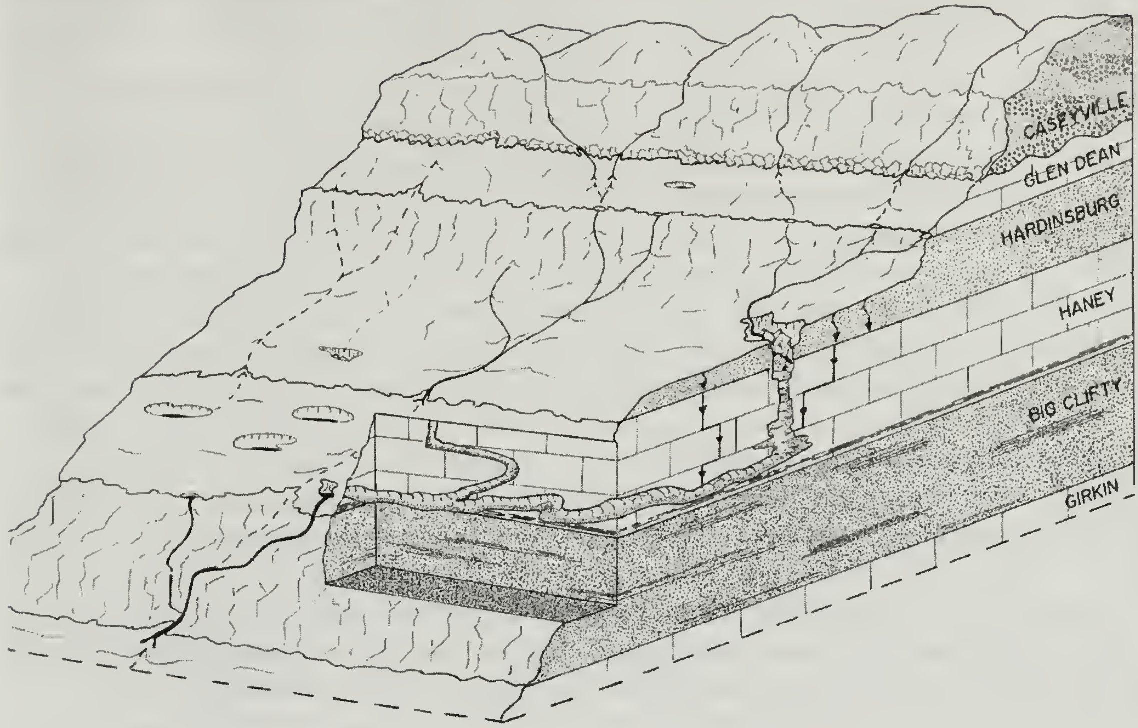


*Figure 4. Typical hydrogeology north of the Green River, where streams flow over the silisiclatics and through the limestones in a stair-step fashion.*

Cutting northeast to southwest in the northwestern portion of the park lays the Brownsville Channel of the Caseyville Formation. This Pennsylvanian sandstone conglomerate lies unconformably over the Mississippian strata, and cuts as much as 100 m into the underlying sequence along the Brownsville Channel. The resulting geomorphology is dominated by sheer cliff faces and rock shelters. The best examples of the Brownsville Channel are along the Nolin River, and its tributaries of First, Second, and Bylew Creeks.

### *South of the Green River*

The groundwatersheds of the park south of the Green have been intensively studied for decades and are considered one of the classic karst landscapes in the world. This region – extending beyond the park boundary – can be divided into two distinct physiographic provenances: the intervening valleys and ridges of the Mammoth Cave Cuesta and the Pennyroyal Plateau. The Cuesta (defined as a sloping plateau, terminated on one side by a steep slope) is interrupted by a series of southeast-northwest trending karst valleys – remnants of a time of earlier fluvial processes – and bound on its southern edge by the Dripping Springs Escarpment. The ridgetops of the Cuesta are largely underlain by the Big Clifty Sandstone while the karst valleys are cut into the underlying Girkin and Ste.

Genevieve Limestones. Precipitation falling upon the ridges is channeled into seasonal streams and sinks at discrete points upon encountering the limestone units.

South of the Dripping Springs Escarpment lies the Pennyroyal Plateau where the Mississippian carbonates of the Girkin, Ste. Genevieve, and St. Louis Limestones are exposed. The Pennyroyal is laterally extensive and is a prominent feature rimming the western, southern and eastern margin of the Illinois Basin. The Pennyroyal Plateau is comprised of two distinct physiographic regions: The Glasgow Uplands and the Sinkhole Plain. The former, ranging from three to six kilometers wide at an elevation ranging from 170 to 230 meters, is underlain by the argillaceous limestones of the lower portions of the St. Louis Limestone and is characterized by numerous sinking streams. These streams flow northward until they reach the more soluble beds of the upper portion of the St. Louis where they sink at discrete ponors (swallets). Note that although the regional dip is a gentle one to one and a half degrees to the northwest, the hydraulic gradient within the watershed (which is also generally towards the northwest) is even more inconspicuous, thus as water flows downstream it is also flowing up-section.

Thus begins the Sinkhole Plain. Bounded by the Dripping Springs Escarpment to the north and the Glasgow Uplands to the south, the Sinkhole Plain (typically about five to eight kilometers wide at an elevation of ranging from 170 to 210 meters) is entirely internally drained. The sinking streams of the Glasgow Uplands form the main trunk conduits carrying water through the karst aquifer and are fed by countless dolines of the Sinkhole Plain. In general, the "water table" (if such a thing exists in this aquifer) is approximately 50 meters beneath the surface of the Sinkhole Plain. The many doline ponds that dot the Plain are not the "water table", but are dolines that have been either naturally or artificially plugged and are perched above the aquifer. An extremely important groundwater recharge and storage mechanism is the epikarst that underlies the soils throughout this region. These solutionally-enhanced fractures and bedding plains, usually extending 5 to 10 meters into the bedrock, provide a tremendous amount of readily-accessible stores that keep the cave streams flowing during times of extreme drought.

## Geology

Kentucky was the first state of the Union to be entirely geologically mapped at the 1:24,000 scale. The United States Geological Survey (USGS) sent field mappers to the Mammoth Cave region in the early 1960s. Geologic quadrangle maps that cover the park are as follows:

| *Quadrangle* | *Mapper* | *Year* | *Map #* |
|---|---|---|---|
| Bee Springs | B. Gildersleeve | 1968 | GQ-757 |
| Cub Run | C.A. Sandberg, C.G. Bowles | 1965 | GQ-386 |
| Mammoth Cave | D.D. Haynes | 1964 | GQ-351 |
| Nolin Reservoir | B. Gildersleeve | 1971 | GQ-895 |
| Park City | D.D. Haynes | 1962 | GQ-183 |
| Rhoda | H. Klemic | 1963 | GQ-219 |
| Smiths Grove | P.W. Richards | 1964 | GQ-357 |

The 1:24,000 geology maps of the state are now being converted into GIS coverages by the Kentucky Geological Survey. The geology of the park quadrangles were digitized early in this program and is displayed, clipped to the park boundary in Plate 1.

In many respects, the geology of Mammoth Cave has been studied for over 200 years. If one were able to understand the geology of the cave, one could answer the fundamental questions of why the longest known cave is here, and the geologic constraints that bound the cave and its watersheds. There is a set of geologic parameters that define why Mammoth Cave exists. They are, as mentioned earlier, the existence of a suitable body of rock, the existence of a suitable solvent for dissolution, a hydraulic gradient, and time.

The landscape of the Mammoth Cave area is carved into and through a nearly flat-lying sequence of Mississippian strata, devoid of major structure. The regional geologic dip is one to one and a half degrees to the northwest, thus if one were to move along a particular elevation, one would move down-section to the southeast. Before this narrative launches into a meld of geology and hydrology – it is impossible to remove one from the other when discussing the geologic framework of the park – let us first examine the geologic section, with their roles in the park's hydrogeology, from top-down (youngest to oldest), of the park and contributing area (Figure 5). Stratagraphic descriptions are from the aforementioned geologic quadrangles.

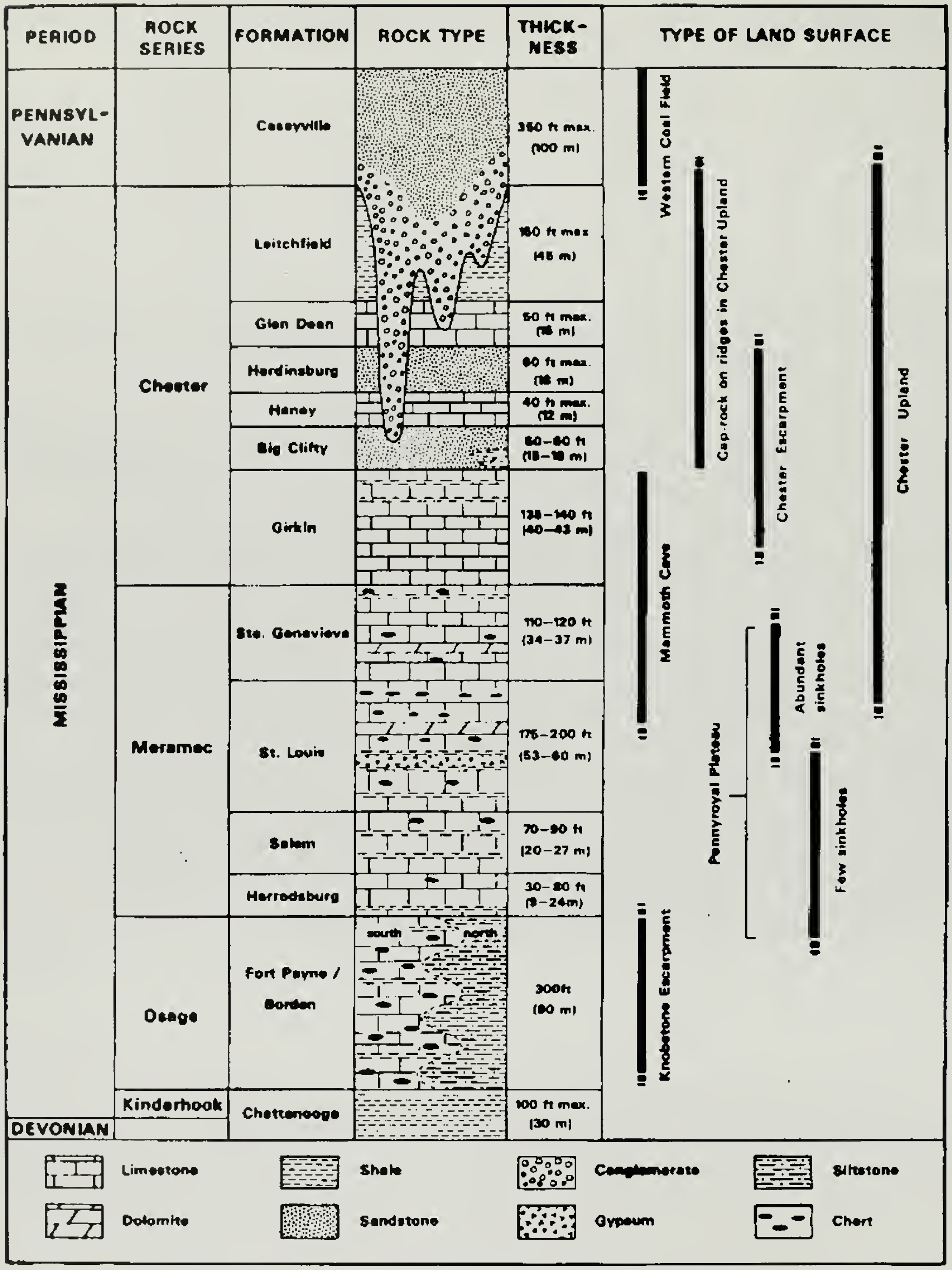


*Figure 5. Stratagraphic column of the rocks of Mammoth Cave National Park, from Palmer, 1981.*

**Caseyville Formation,** *Pennsylvanian:* Blending into the Tradewater Formation to the North, the Caseyville is the only Pennsylvanian rock within the park. It lies unconformably upon the lower strata – cutting as deep as 100 m into the Girkin Limestone along the ancient Brownsville Channel in the northwestern portion of the park. This sandstone-conglomerate is typified by thick lenses -- some several meters thick – of well-rounded quartz pebbles within thickly bedded and cross-bedded sandstone. Many of the landforms on the north side are dominated by the Caseyville, which produces most of the large rock shelters found in the park. There is little groundwater flow though the Caseyville – nearly all flow is overland – however, a few acid seeps are found, which in some cases, head boglands. Some remnants of the Caseyville can be found on the south side, and many ridges are draped with residual pebbles weathered from this rock.

**Glen Dean Limestone,** *Mississippian:* This light to blueish gray limestone ranges from 0-20 m thick and contains several thin shale layers. The Glen Dean, the uppermost of the Chesterian series of rock, forms a perched karst aquifer, sandwiched between silisiclastic strata. Dolines are commonly found where the Glen Dean is exposed, routing water into the subsurface, and reappearing at small springs at its base. There are a few small caves developed in the Glen Dean.

**Hardinsburg Sandstone,** *Mississippian:* A yellowish to dark brown when weathered, this sandstone ranges from 0-15 m thick. The Hardinsburg has several thin shale layers, and is characterized by many vertical fractures. Water flow is overland across the Hardinsburg, but may sink into these strata via these fractures. Collapse dolines, into the underlying Haney Limestone Member, are common.

**Haney Limestone Member, Golconda Formation,** *Mississippian:* Ranging from 0-12 meters thick, this fossiliferous limestone is predominantly thick-bedded and found throughout the park where not removed by the Caseyville unconformity. The Haney functions in a role similar to the Glen Dean Limestone, as surface waters are routed into this perched karst aquifer via dolines and ponors. Several small caves are developed in the Haney Limestone Member and springs, located at the contact with the underlying Big Clifty Sandstone, are common.

**Big Clifty Sandstone Member, Golconda Formation,** *Mississippian:* This cross-bedded sandstone, commonly referred to as the "cap-rock" over Mammoth Cave (actually part of a sequence of strata, each playing a significant role in "preserving" the underlying cave) ranges from 0-20 m thick and forms many prominent cliff lines within the park. The Big Clifty is commonly bracketed by shale layers (one meter thick) and is typically white to grayish-orange in color. Water flows overland across the Big Clifty Sandstone.

**Girkin Formation,** *Mississippian:* The limestone of the Girkin Formation marks the uppermost strata of the cave-bearing rock of the vast karst aquifer. It ranges from 30-60 m thick and contains many fossil fragments in the upper portion and is interbedded with thin greenish shales. Chert is abundant near the base of this thick-bedded formation.

There is no overland flow across the Girkin Formation. All water sinks into its many dolines and ponors. Haney Limestone springs feed into Big Clifty surface streams and immediately sink into the Girkin.

**Ste. Genevieve Limestone,** *Mississippian:* The bulk of Mammoth Cave is developed in this thick bedded, oolitic limestone. Typically 55 m thick, this limestone is nearly indistinguishable from the overlying Girkin and underlying St. Louis Limestones, as there is no lithologic break or unconformity between them. Functioning as a continuous hydrostratagraphic unit, stratagraphic discrimination is based upon fossil content.

**St. Louis Limestone,** *Mississippian:* The lower portion of the karst aquifer, the St. Louis can be as thick as 90 m, but it is not exposed on the surface in the park. It is, however, found throughout the lower levels of Mammoth Cave. Near the top of its section is the Horse Cave Member, ten meters of thickly-bedded limestone braced top and bottom by the bedded cherts of the Lost River and Corydon, respectively. About half way through the St. Louis, the soluble, thick-bedded limestones suddenly grade into thinly-bedded limestones with interbedded shales. Although the transition from the cavernous and highly soluble beds of the upper St. Louis are not distinguished by stratigraphers from the argillaceous beds of the lower, they behave, hydrogeologically, in very different manners. There is no overland flow across the beds of the upper St. Louis, as all waters are directed underground by the ubiquitous dolines and epikarst. Nearly all flow is across the surface of the lower St. Louis, as the thin, shaley beds do not promote karst development. One can easily map this "contact" based upon the ponors of the sinking streams, sinking upon encountering the soluble, massive beds of the upper St. Louis.

### *Hydrostratigraphy*

Each stratagraphic unit plays a role in the hydrogeology of the park. In general, water flows overland across silisiclastics and relatively insoluble, argillaceous limestones and sinks into underlying soluble limestone layers. The park has two perched karst aquifers developed in the Glen Dean and Haney Limestones – each receiving concentrated allogenic recharge from overlying sandstones and discharging along springs at the contact of the next underlying sandstone unit. There is a limited amount of groundwater recharge through the silisiclastics, mostly via fractures and bedding plain partings. These groundwaters do emerge as small seeps and acid-springs along favorable fracture traces. As nearly all perched karst aquifers and the limited input to the sandstones are locally recharged within park bounds, they are typically of high water quality. It is worth noting that in times of heavy precipitation (high runoff), the suspended solid content and fecal coliform bacteria of the perched aquifer can become elevated, reflecting natural conditions. This reminds us that even in natural, undisturbed karst systems, a certain amount of soil erosion and bacterial runoff occurs. In other words, the bear, or in this case, other wildlife, does, indeed, defecate in the woods.

The limestone package, from the upper beds of the Girkin Formation to the lower beds of the upper St. Louis Limestone, comprise a continuous sequence of highly soluble, massively bedded strata that comprise the Mammoth Cave Karst Aquifer. Although cave passage formation and groundwater flow routes are influenced by the presence of local shale and chert horizons, cave development is not controlled by or preferred from one formation to the next. They act as one hydrostratagraphic unit, although lithologic heterogeneity, particularly in the bedded cherts of the upper St. Louis Limestone has profound influence on both the movement of groundwater and surface geomorphology (Howard 1968 and Woodson 1981). The most prominent of these is the Lost River Chert. Where exposed on the surface, the Lost River creates the Bristow Plain, a broad plain of shallow dolines located southwest of the park. Within the cave, flowing water may encounter these chert horizons. All concentrated allogenic recharge of the Glasgow uplands enter the geologic section below the cherts and discharge at springs along the Green River above the cherts. As the regional geologic dip is greater than the hydraulic gradient, cave streams cut up-section as they flow to the river. Thus, at some point they must cut through the bedded cherts of the Horse Cave Member of the St. Louis Limestone. These streams are “pinned” down by the overlying cherts and sump (where the cave passage ceiling is at or below the stream surface). Streams may be forced into phreatic loops (below the water table) until a fracture route through the chert can be exploited.

### *Structure*

There is little structural modification to the rock units of the park. Regional dip is a gentle one to one and a half degrees to the northwest, thus striking from southwest to northeast. Major fractures are typically aligned in orthographic sets, but play a very limited role in the horizontal movement of groundwaters – although they may heavily influence specific geomorphic features and certainly the vertical movement of groundwater.

The park is on the outer fringes of the Rough Creek Fault Zone, but few faults extend from this western Kentucky feature into the park (Palmer 1981). There is only one mapped fault in the park, the Cub Run Fault located along the extreme northeastern edge of the park. This normal fault with 30 m of displacement serves as the eastern boundary of the Big Spring groundwatershed, and movement of dissolved anhydrite and gypsum along the fault surface from the lower beds of the St. Louis Limestone are thought to be the source of elevated sulfur and strontium levels in Big Spring. There are a few smaller faults with minimum displacement exposed in the cave. Geophysical surveys recently discovered series of faults immediately adjacent to the southwestern edge of the park near Arthur. Shallow (<500 m) oil wells were quickly drilled along the park boundary in the early 1990’s. Their production has waned in recent years. Within the park’s Turnhole Spring groundwatershed is a long monocline crossing the basin from the northwest to the southeast. Deep groundwater movement along this structure may be the source of brine-laden waters of Sulfur Springs, Sulfur River (in Parker Cave within the basin), and Sulfur Well. The former and latter locations are outside the park’s groundwatersheds and were once the location of health spas during the turn of the 19$^{th}$ century.

This subtle structural framework can be considered a fifth element in why the longest known cave in the world, as well its associated karst features, is located here in Southcentral Kentucky. It is the gentle structural dip to the northwest – allowing bedding plains to be aligned with the regional groundwater gradient to the Green River – that has permitted the development of an extensive karst system. The mellow dip of the strata, combined with gentle topographic features, allow a vast surface exposure of the massive and soluble beds of limestone. This exposure, the Pennyroyal Plateau, reveals millions of recharge avenues into the bedrock in the form of bedding plain partings and fractures. A geomorphic antonym is found on the north side where the only difference is that the dip is away from the river, thus cave formation is at a much smaller and localized scale. The subtle warps and distortions of this seemingly structureless geology also play an important role in cave passage morphology. Local flexures, mapped in detail by leveling along bedding plains, influence the exact positioning of conduits (Palmer and Palmer 1993).

## Soils

The Soil Conservation Service (now the Natural Resource Conservation Service) conducted a soil survey of Mammoth Cave National Park in the early 1990's and published its findings in 1994. Mitchell, et al. (1994) summarize the park soils and the factors in their occurrence and creation as a product of climate, parent material, plant and animal life, relief, and time:

Although climate plays an important role in soil creation, there is not enough climatic variability over the park to dictate or favor the development of any particular soil. Climate influences the rate and degree of weathering and soil formation. If in a climate of significant rainfall, such as Southcentral Kentucky, water percolating through the soil leaches soluble bases from the soil and translocates clay minerals to lower layers in the soil profile – if not entirely out of the soil. The moderate climate of the park, with its ample and well distributed rains has permitted a process of continuous soil formation. This process has also leached many of the soluble bases and clay minerals, resulting in acid soils. Most soils in the park are acid, with a loamy surface layer, and a subsoil that has accumulated clays washed down from upper horizons. Examples are the Rosine, Wellston, and Gilpin soils.

Parent material plays an important role in soil characteristics like degree of consolidation, texture, and mineralogy. The influence of parent material is most evident in younger soils. Most soils within the park have been derived from the residuum of sedimentary rocks. Some soils, like the Clarkrange and Rosine, are comprised of loess (wind deposited fine silt) and residuum. Loess soils are common on the uplands and thickest on the gentle slopes. Other soils are comprised entirely of residuum. They are found on steeper slopes where loess was not deposited or eroded prior to soil development. The Wallen and Lily soils are formed in sandstone residuum, while the clayey Lenberg is formed in residuum of shales. Soils on floodplains and stream terraces are formed in alluvium, and reflect present or former hydrologic controls. The silty Newark, Nolin, and Melvin soils are found along the rivers. Older, inactive stream terraces (no longer receiving input from the streams) contain Elk and Otwell soils. Colluvium is common at the base of steep slopes found throughout the park. Bledsoe and Jefferson soils are examples formed in the clayey or loamy colluvium.

Biological processes play an important role in soil development. They add to and decompose organic matter, cycle nitrates and other nutrients, control soil gases through respiration, and physically mix and aerate the soil. The vegetation of the park is predominately hardwood forests, and soils reflect the biological impacts as they are acidic and typically have a thin dark surface layer. Man's impact to the soils is evident as well. In places, accelerated erosion has removed most of the original surface layer, exposing the subsoil. A carryover from land use practices predating the creation of the park.

Slope also influences soils. Those formed on nearly level surfaces, have poor internal drainage, and are not as well developed as those formed on moderate slopes where internal drainage networks are well organized. Soils formed upon steep slopes are not as deep and are less developed than those in gently sloping areas, as the former erodes into the latter. Lily and Wallen soils are found on the steeper slopes of the park.

Like all geological processes, the dimension of time must be considered in the development of soils. Generally, the longer soil forming processes occur, the older and more well developed the soil profile will be. Ultimately, the amount of profile development determines the maturity of a soil rather than its age. The soils of the park range from the young alluvial soils of the Chagrin, Melvin, Newark, and Nolin (where there are no distinct soil horizons and show little profile development) to the older soils of the Bledsoe, Pembroke, Rosine, and Wellston. These older, deeply weathered soils with well-developed argillic horizons, formed in stable landscape position in a variety of residual materials.

## Vegetation

The park has been the focus of numerous studies of vegetation mapping and inventories over the decades. As the park lands began their succession from human occupation, Ellsworth (1936) began classifying the park's forests, and defined the floodplain forests along the Green as a river birch-sycamore association, documenting sycamores in excess of 30 meters tall and 2 meters in diameter. In 1997, Badger reclassified the forests of the park. He defined the floodplain as an association of sycamore-box elder-silver maple.

The river floodplains also contain various species of herbaceous plants, including *Verbesia virginica, Verbesia alternifolia, Urtica dioica*, and *Eupatorium coelestinum* (M. Webber, unpublished report, 2004). Webber also reports the presence of invasive exotic species along the floodplain, including the tree of heaven (*Ailanthus altissima*), gill-over-the-ground (*Glecoma hederaceae*) and garlic mustard (*Alliaria officinalis*). The author estimates that garlic mustard (an infestation that began near the Historic Entrance to Mammoth Cave in the early 1990's and went unchecked until recently) may cover well over 100 hectares of the Green River floodplain. Webber documents grasses along the floodplain, including the native river cane (*Arundinaria gigantea*), river oats (*Chasmanthium latifolium*) and the exotic Johnson grass (*Sorghum halapense*).

Park wetlands are rich in vegetative diversity. Webber reports gravel bars along the Green to contain button bush (*Cephalanthus occidentalis), Hibiscus moscheutos, Asclepias incarnata, Lysmachia ciliata, Phyla lanceolata*, and *Rorippa sylvestris*. Upland ponds can contain the rare sedge *Carex decomposita*, as well as *C. crintia, C. tirbuloides, Janus acuminatus, Eleocharis quadrangulata, Scirpus cyperinus, Rhynchospora corniculata, Dulichium arundinaceum, Urticulata gibba, Viola lanceolata,* and *Sagittaria rigida*.

# Hydrogeology

Precipitation, mostly rain, falls through the atmosphere, through the forest canopy and over farm fields and towns, and seeps through soils. It flows down infrequent perennial streams or is channeled within ubiquitous ephemeral streams and dolines (sinkholes) and recharges the great underlying karst aquifer. It flows through uncharted cave passages as countless tributaries feeding larger cave streams, and reemerges ultimately as springs – tributaries to the master surface stream, the Green River. Throughout its course, water contacts every living organism within the park.

## Green River

The Green is an old river. It predates the Ohio, which formed along a recent (about 1.5 Ma) ice sheet boundary (Granger, et al. 2001). Its 100 m deep canyon is the physical and chemical erosional product of over 10 Ma in the making. The river, at least over the 3.5 Ma range of cosmogenic radionuclide dating, has undergone periods of rapid and slow down-cutting (30 m/m.y. and 2-7 m/m.y., respectively), and times of dramatic aggradation of its channel – one such event filled its channel, and that of caves draining into it, with gravels at least 15 m in depth some 2.3-2.4 Ma (Granger, et al. 2001). These rates are in large part governed by continental ice sheet movement across eastern North America. Surely these fluvial geomorphic processes have responded to similar glacial activity pre-dating 3.5 Ma, each charting its course, and tributary system.

The Green, a tributary to and entering the Ohio at Hendersonville Kentucky, drains 23,093 $km^2$ of Southern Kentucky, heading in Lincoln County some 460 km distant along its main stem. The Green's gradient averages about one meter per kilometer. The mean annual discharge of the Green at Brownsville (immediately downstream of the park) is 123.7 $m^3/s$, including the 26.6 $m^3/s$ from the Nolin River. An annual flood stage of 8 meters can be expected, while a ten-year flood will raise the stage of the Green some 15 meters. The Green's major surface tributaries include Russell Creek, the Little Barren River, the Nolin River both upstream of the park, and the Barren and Rough Rivers downstream. The Green, for most state planners, is divided into the Upper and Lower Watersheds; the former includes all that drains to the confluence of the Green and Barren over 40 km downstream of the park. The focus of this section will be the watershed of the Green contributing to the park, not including the park's karst watersheds to the Green, which are addressed in another section.

From its headwaters to the confluence of the Nolin, the Green drains 5085 $km^2$. It is considered to be one of the most biologically diverse rivers in the United States – and the bulk of that within the free-flowing sections of the Green, basically from the park, upstream to the Green River Lake (160 km). In considering mussels alone, the Green is home to 71 of Kentucky's 103 species – Kentucky's being the third richest in the country and 59 of the 71 are found in this reach (Cicerello, et al. 1991). Seven of these mussel species are listed as Endangered by the USFWS. Kentucky is again third in freshwater fish diversity, following Tennessee and Alabama, with 230 taxa (Burr and Warren 1986). Of the 151 fish species known to the Green, 109 are found in this stretch (The Nature

Conservancy 1998). This section of the Green is also abundant in benthic macroinvertebrates, supporting over 170 taxa.

The Green River within the park has been divided into three zones depending on the degree of, or lack of, influence from Lock and Dam Number Six, located directly adjacent to the park's downstream boundary. The Impounded Zone, with its deep pools, reaches for about 15 km from this low-head obstruction to Sand Cave Island. The Transition Zone continues from Sand Cave Island to Cave Island, 8 km upstream. The remaining 17 km is the Free-flowing Zone comprised of alternating riffles and pools (Figure 6).

Grubbs and Taylor (2004), rather than separating the Green into the free-flowing, transitional, and impounded zones, demonstrated a clear lotic-lentic break at Cave Island – the beginning of what was once considered the transitional zone – and divided the river into the "erosional" (free-flowing) and the "impounded" (impounded and transitional) reaches (Figure 6). They note that the transitional and impounded zones were taxonomically indistinguishable.

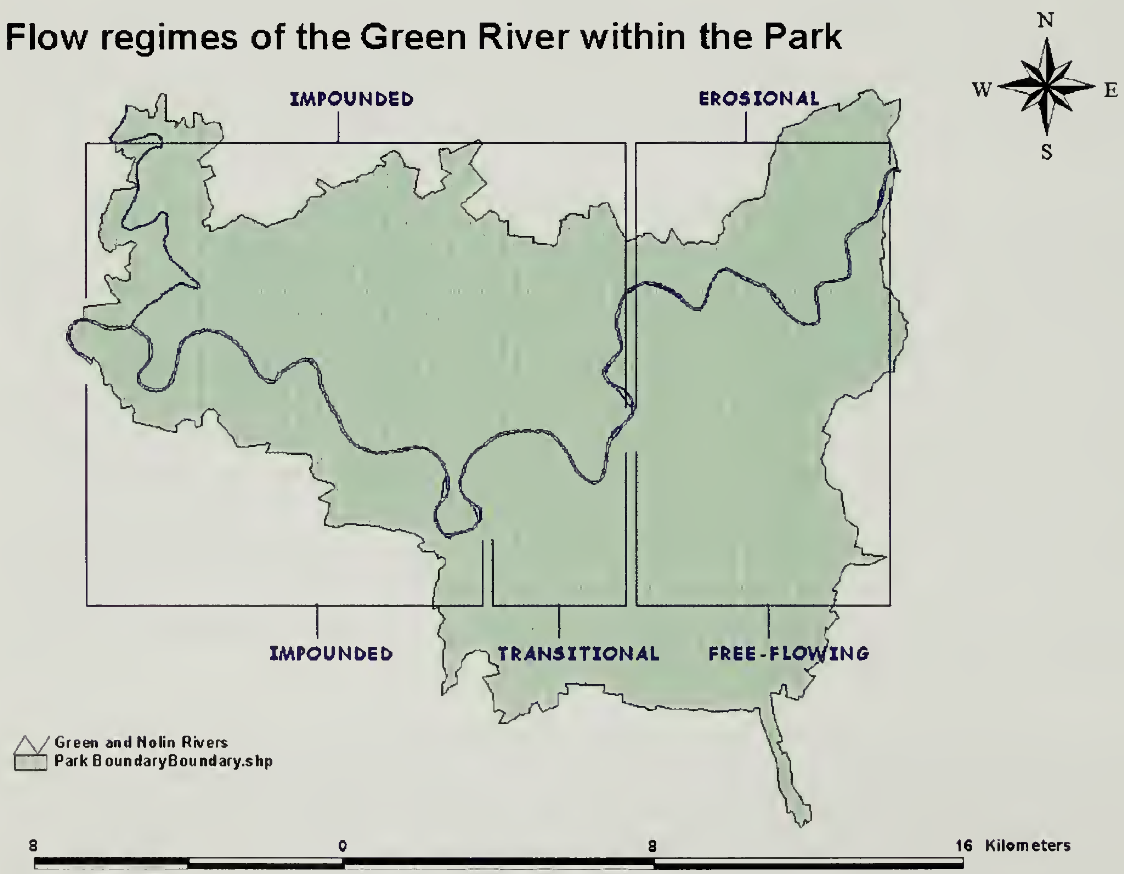


*Figure 6. Flow regimes of the Green River. Divisions into the Impounded (lentic) and Erosional (lotic) regimes by Grubbs and Taylor.*

## Nolin River

As old as the Green is its tributary the Nolin. Draining 1879 $km^2$, the Nolin winds under the high bluffs of the Caseyville Formation and into the Green near the western park boundary. There is extremely limited karst development along the Nolin and its tributaries (within the park) as the Caseyville cuts a deep unconformity (the Brownsville Channel) into the Girkin Limestone. The 11 km of the Nolin within that park is characterized by sheer bluffs of up to 75 meters high and is fully impounded by Lock and Dam Number Six up to the base of the Nolin Reservoir Dam, three kilometers upstream of the park. The hydrology of the Nolin within the park is fully under the influence of these two dams. Not only is this entire stretch impounded, all its flow (save a few small creeks) is regulated by the US Army Corps of Engineers through the Nolin Dam. The Nolin Reservoir project began in January 1959 and was completed in March 1963. The earth and rock dam impounds a minimum of 1170 hectares under low winter pool and as much as 2343 hectares during summer pool.

In the early 1900's, natural asphalt deposits were mined near the present-day site of the Nolin Dam. In the spring of 2004, permits were granted by the state to re-open these strip mines.

## Surface Hydrology of the Park

The hydrogeology and geomorphology of the Mammoth Cave region is and has been controlled by the Green River. The Green serves as the master stream for Southcentral Kentucky. The Green, flowing generally from east to west, has entrenched its meander pattern over 100 m deep. Its present course was established long ago, predating the earliest cave sediment dates of 3.5 Ma found by Granger, et al., 2001, and bisects the park into nearly equal halves, north and south.

### *North of the Green River*

#### *Streams*

The hydrology north of the Green is characterized by ravine karst. Headwater stretches are typified by streams – with base flows on the order of one to ten liters per second – flowing over and through alternating silisiclastic (quartz-pebble conglomerates, sandstones, and shales) and carbonate units, respectively. Each stream sinks at a discrete swallet (ponor) into the top of the Girkin Formation (limestone), the basal carbonate unit exposed along major valley axes. Downstream of the ponors, the streambeds are normally dry as all base flow and most moderate flow is pirated into the Girkin Limestone, reappearing only as springs along the Green, leaving isolated segments of surface streams.

The main recharge driver supplying water to these streams are springs issuing from the base of the Haney Limestone (10-15 m thick). Early settlers, both historic and pre-historic, as evidenced by the numerous cultural artifacts located near many of them, knew the perennial reliability of Haney Limestone springs. Haney Springs are the primary sources of perennial surface and subsurface flow in every major drainage north of the Green River and south of Nolin Reservoir from Cub Run to the Nolin River.

It is worth noting that above the Haney Limestone is the Hardinsburg Sandstone (8-14 m thick), which is overlain by the Glen Dean Limestone (15-20 m thick). The Glen Dean, where present, functions in much the same manner as the Haney – pirating overland flow from the overlying Caseyville Formation at its upper contact and discharging at its basal contact with the Hardinsburg. The Caseyville Formation is a very resistant iron-cemented sandstone conglomerate that caps nearly every major drainage divide in the Hilly Country north of the Green River.

The Haney Limestone is a prominent component of the complex Hilly Country drainage, which is typified by repeating surface and subsurface flow along a single stream course, from drainage divide to regional base level. A typical stream course can be observed in the Dry Prong of Buffalo Creek. Discharge from the Haney Limestone, Lulu Mart Spring, forms the ultimate headwaters of the Dry Prong of Buffalo Creek's perennial surface stream. This surface stream, which runs atop the insoluble Big Clifty Sandstone (as well as upon the shales of the upper Girkin), is supplemented by water from numerous other Haney springs as it flows towards its baseflow terminal sinkpoint, about 3 kilometers downstream from Lulu Mart Spring. At the terminal ponor, surface flow is lost entirely into the subsurface conduit network formed within the underlying soluble limestone of the Girkin. Under baseflow conditions, this water does not reappear at the surface until it reaches Buffalo Spring near the Green River, 5 kilometers downstream from the terminal sinkpoint. Dye traces have revealed that the same water flows through Buffalo Creek Cave and Fort's Funnel Cave in route to the Green River (Ryan and Meiman, 1992; Ryan, 1992; and Harmon, 1992). Under baseflow conditions Haney springs, like Lulu Mart Spring, play a critical role in providing perennial recharge to the subjacent aquatic cave habitat in the Girkin/Ste. Genevieve karst conduit system beneath the Dry Prong.

The stair-stepping of overland and subsurface flow is common in every ravine and valley north of the Green within the park (Figure 4). Park staff has identified, through dye-tracer studies, 17 groundwater basins within the park on the north side. Although groundwater resources will be addressed later, it is worth noting that each basin contains isolated surface stream segments. Also, each basin has a spring along the Green (with the exception of the First Creek basin, which discharges to the Nolin River) with spring runs ranging from 10 to 250 m in length.

### *Springs*

A full range of seasonal seeps to perennial springs can be found on the North Side. Acid seeps and small springs of the Caseyville Formation are found recharging bogs within the Lulu Mart drainage (Buffalo Spring groundwater basin) and within the headwaters of the Big Spring groundwater basin in the Big Woods. Where present – the overlying Pennsylvanian Caseyville Formation cuts an unconformity as deep as the Girkin Formation in places – the Glen Dean Limestone produces many small (<1 l/sec) springs at its contact with the underlying Hardinsburg Sandstone. These small springs are collected by surface streams and again sink into the Haney Limestone, where they reappear again as Haney springs at the base of its host unit. The numerous Haney springs, as stated above, are typically perennial and each supply one to ten liters per second to surface streams flowing over the underlying Big Clifty Sandstone. These streams are intercepted by the basal carbonate unit, the Girkin Formation, and flow through caves until ultimately discharged into the Green or Nolin Rivers. One can view the ravine karst of the North Side as a typical convergent and dendritic drainage pattern found in non-karst settings with long (100m to 5 km) dry stretches as limestone units are encountered.

### *Ponds*

There are very few impoundments on the North Side. While many small farm ponds may have existed historically, a small (20m across) and shallow (< 1m deep) pond near the Maple Springs Group Campground is all that is known today. Along the floodplain of the Nolin River, at the mouth of First Creek is First Creek Lake. This broad (150m across) and shallow (< 2m deep) pond is greatly augmented by a beaver dam at its outfall run to the Nolin. It receives flow from two Girkin springs, recharged by First Creek groundwater basin, and occasionally (about every 5 years) by flood flow from the Nolin. In recent drought years (1998-2000), combined by the failure of the beaver dam, First Creek Lake was reduced to a mere puddle (50-75m across and < 1m deep).

### *Wetlands*

The geology and topography of the Hilly Country, although not devoid of wetlands, are not well suited for extensive wetland development. Those that do exist are small scale (on the order of a few hundred square meters) and controlled, in large part, by the underlying hydrogeology. Mammoth Cave, like parks throughout the country, was mapped by the USFWS as part of the National Wetlands Inventory (NWI). Unfortunately, as most wetlands at the park are very small, the rather course scale and remote sensing methods used in compiling the NWI – using 1:58,000 aerial photography with very limited ground-truthing – gave a very incomplete picture. The resulting product overlooked all but the largest wetlands, especially if under a dense forest canopy like that found in the park. A recent pilot inventory (two months) found a great disparity between the NWI map and what actually exists on the ground. Many NWI delineated wetlands simply do not exist. Conversely, scores of wetlands were found (over 5 hectares combined area) that were not inventoried by the NWI. In short, not much is known of the park's wetland resources.

There are two wetlands that deserve special mention. Covering approximately one hectare (in two distinct portions) is a bog within the headwaters of the Dry Prong of Buffalo and is fed by low-pH seeps from the Caseyville Formation. These seeps, not uncommon in the Hilly Country, may produce wetlands with thick organic mats, specialized vegetation, and very low pH (some are recorded around 3.3 standard units). Similarly, there is a smaller (a couple hundred meters square) bog located in the Big Woods of the Big Spring groundwater basin.

### *South of the Green River*

South of the Green lie a succession of silisiclastic-capped ridges and limestone flanked and floored valleys roughly aligned southeast to northwest. These broad karst valleys represent an earlier history of surface fluvial processes as evident by convergent and dendritic abandoned flow networks. Wide spread karst processes began as each valley being sequentially (east to west) pirated underground as the downcutting Green exposed the limestone proximal to the valley mouths. Surface waters ceased to flow in these valleys long ago, ranging from approximately 3.5 to 1.2 Ma based upon burial dating of abandoned cave stream sediments (Grainger, et al. 2001). Today we see a landscape dominated by the imprint of an earlier fluvial history beneath later-stage karst processes in which all surface flow is intercepted at or near the lithologic contact at the top of the 100 m thick karst aquifer.

#### *Streams*

There are only a few, small perennial surface stream segments on the South Side. Most common are contact springs (at the base of a perched carbonate unit overlying silisiclastic strata) flowing from the Haney Limestone, over the underlying Big Clifty Sandstone, and sinking into the underlying Girkin Formation. Each of these short (30-150 m) segments sink into the underlying Girkin at or near the contact.

#### *Springs*

Park researchers also delineated groundwatersheds on the South Side (Plates 2 and 3). Twelve basins discharge through springs along the southern bank of the Green, with spring runs of zero (for those discharging directly into the river) to approximately 300 m. These range from the third largest spring (as a measure of base flow discharge) in the state, Turnhole Spring, which drains 345 km$^2$ into the Green, down to local seasonal springs of the Glen Dean Limestone in the southwest corner of the park.

The larger, basal springs, drain extensive areas, and for the most part, flow into the Green. At times when the Green is at a high stage relative to spring discharge (either by a flood event up-basin or by releases from the Green River Reservoir 150 kilometers upstream of the park) the springs may become hydraulically dammed temporarily by the high-stage river. While the karst groundwater continues to flow towards the river, it must contend with a temporarily elevated discharge elevation. At these times river water may be pushed a short distance into the conduit feeding the spring.

A unique (at least to Southcentral Kentucky) hydrologic condition exists between the Green, River Styx and Echo River Springs, and their interconnecting conduit system. When the stage of the Green is between one and a half and three meters above base, and the springs are discharging near base flow, River Styx Spring reverses its flow. Water from the Green enters River Styx's spring run, into the cave for perhaps one kilometer (uncharted), mixes with the karst groundwater, and exits the cave (flowing for an additional kilometer) via Echo River Spring. While this relationship has no doubt occurred historically, it is believed that Lock and Dam Number Six (its pool extending to the Echo River Spring elevation) and the Green River Reservoir (with sudden and long-duration increases in releases) have caused an increase in duration and frequency of these flow reversals.

***Ponds***

The ridge tops, especially those underlain by silisiclastic rock, are dotted with many small, abandoned farm ponds. Old farm ponds developed upon the limestone-floored valleys have long since failed into the karst aquifer. Untended for over 60 years, many of the ridge-top ponds are in advanced stages of eutrophication. Several ponds have been the foci of amphibian studies in the mid to late 1990s (Dr. Floyd Scott, Austin Peay University). The largest pond on the south side is the Beaver Pond at Sloan's Crossing. Located upon the Big Clifty Sandstone, this pond – archeological evidence suggests a prehistorical presence of a pond at this location – has been modified over the past 80 years by rimming the down-gradient side with a low berm and spillway. The pond is now a popular visitor stop as it is encircled with a boardwalk trail.

***Wetlands***

The karst terrain of the park, especially on the South Side, is noted for its lack of surface waters – as the vast majority of surface waters quickly sink into the underlying karst aquifer. Their importance is thus magnified where they do exist, as they provide a rare oasis for aquatic and terrestrial life. Wetlands of the park are known habitats for the Double-ringed Pennant dragonfly, (*Celithemis verna*) State listed specie of Special Concern, and the expatriated Showy Lady Slipper orchid (*Cypripedium reginae*) – the latter currently being re-introduced to the park.

Wetlands at Mammoth Cave National Park are confined to the nearly flat-lying portions of silisiclastic-capped ridgetops and within the riparian corridors along the Green and Nolin Rivers. The floors and flanks of the broad, intervening valleys are underlain by limestone, where any surface water quickly sinks into the karst aquifer. The relative lack of surface waters magnifies the importance of each entity. We estimate that the NWI wetland map displays less than 50% of actual wetlands at the park.

## Subsurface Hydrology

Throughout the park groundwater exists in all strata and soils. For the purpose of this document, subsurface hydrology will focus on karst. Soils, which were addressed in an earlier section, are intimately reflective of associated bedrock geology. Thicknesses range from greater than ten meters to absent. The thickest soils are draped over dolines where debris washed in over the years. Soil waters are, for the most part, non-existent over limestones as it is rapidly transferred to the underlying karst. The silisiclastic-capped ridges are characterized by thick soils (two to five meters deep), which can retain substantial amounts of water. Early settlers typically dug wells into these sandy soils for perennial water supplies. Such waters are slowly (laminar flow) drained to the ridge edges where it may appear as small seeps. Thick, water-rich soils are also found along the flood plains of the Green and Nolin Rivers and act as typical bank-stores – recharged and discharged with each flood cycle.

### *North of the Green River*

Topography of the North Side is dominated by deeply incised valleys draining southward to the Green (and westward to the Nolin in the extreme western portion of the park). The surface exposure of the basal carbonate sequence on the North Side is limited to valley floors where fluvial erosion has cut through the alternating layers of sandstones and perched limestones. Although very limited in aerial extent, nearly all water draining the North Side is ultimately through the basal carbonate karst aquifer, typically the Girkin and Ste. Genevieve Limestones. A typical course of water on the North Side is described in the earlier section on Surface Hydrology: Overland flow across the silisiclastics (Caseyville, Hardinsburg, and Big Clifty) and subsurface flow through alternating carbonates (Glen Dean and Haney Limestones).

#### *Groundwatersheds*

There are 17 karst groundwatersheds on the North Side, ranging from 0.1 $km^2$ Sycamore Spring basin to the 32.9 $km^2$ Buffalo Spring basin (Figure 7, Table 8). Groundwater flow tends to be aligned along geologic strike as the dip is away from the Green River. Strike-oriented flow makes the most efficient use of lithologic bedding plains, along which the vast majority of conduits are formed. Most of these groundwatersheds mimic the drainage pattern of the surface topography – owed to a great extent by the somewhat limited surface exposure of the thick basal carbonates. However there are exceptions as groundwater flow uses the steepest gradient to the river. For example, a through-ridge piracy of flow within the Buffalo Spring topographic watershed takes surface tributaries under a ridge and discharges at McCoy Hollow Spring, the adjacent basin to the west (and along strike), a one kilometer distance. Another through-ridge piracy can be observed in the headwaters of Dry Prong of Buffalo. Surface waters in the Dry Prong sink near Raymond Hollow, flow under Collie Ridge, and discharge at Big Spring, 1.7 km away within the headwaters of the Wet Prong of Buffalo. A more detailed and regional-scaled view of the karst groundwatersheds of the park and Southcentral Kentucky can be found in Plates 2 and 3.

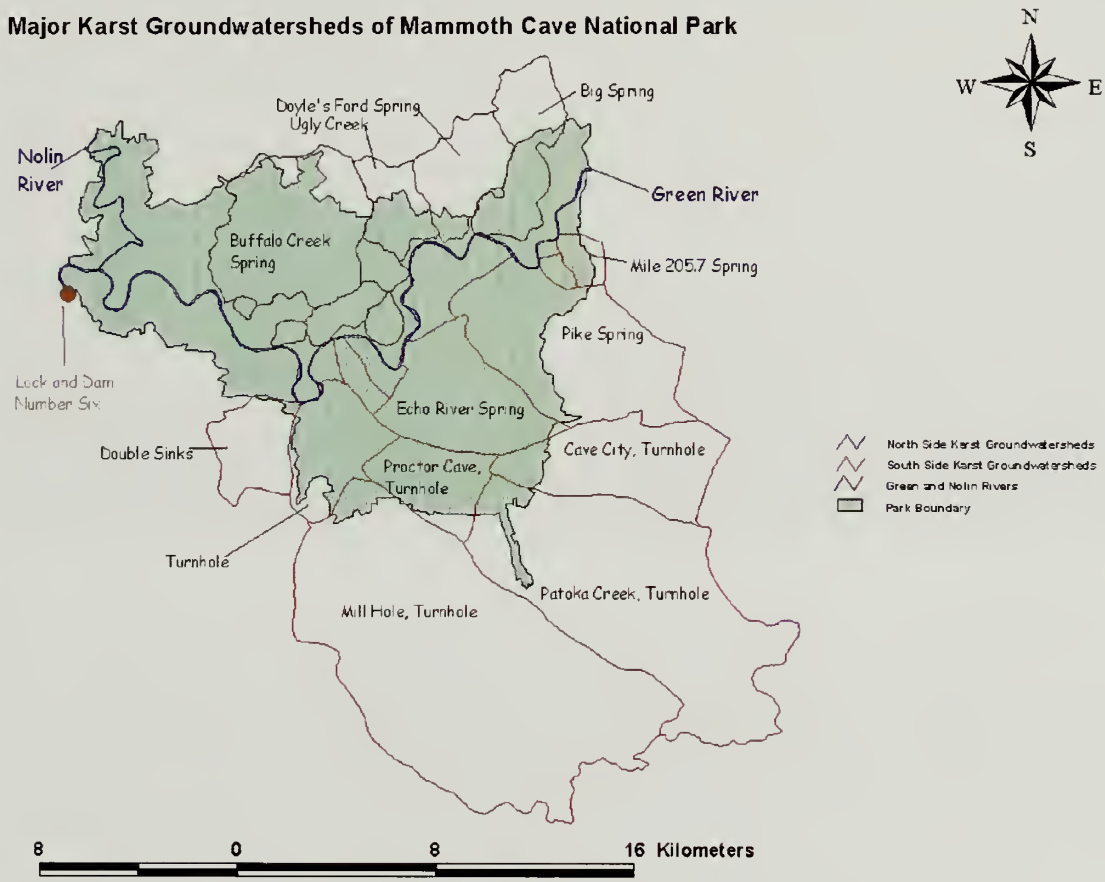


*Figure 7. Major karst groundwatersheds of Mammoth Cave National Park.*

*Table 8. Surficial geology of the major groundwatersheds of the North Side. Each unit is calculated as hectares within a particular basin. Blue font represents carbonate strata.*

| *Basin* | *Alluvium* | *Casey ville* | *Glen Dean* | *Hardi nsburg* | *Haney* | *Big Clifty* | *Girkin* | *Ste. Gen.* | *St. Louis* |
|---|---|---|---|---|---|---|---|---|---|
| **Big Spring** | 24 | 423 | 115 | 382 | 179 | 170 | 198 | 11 | 0 |
| **Doyle's Ford** | 0 | 513 | 103 | 279 | 131 | 142 | 98 | 0 | 0 |
| **Ugly Creek** | 2 | 180 | 128 | 151 | 120 | 139 | 106 | 2 | 0 |
| **Big Hollow** | 0 | 15 | 22 | 49 | 72 | 60 | 59 | 1 | 0 |
| **Running Branch** | 1 | 7 | 11 | 64 | 40 | 70 | 33 | 2 | 0 |
| **Mary Parker** | 0 | 5 | 51 | 107 | 99 | 101 | 33 | 2 | 0 |
| **Stillhouse** | 0 | 11 | 23 | 29 | 20 | 13 | 14 | 1 | 0 |
| **Buffalo Creek** | 59 | 1182 | 701 | 551 | 299 | 266 | 227 | 0 | 0 |

***Cave Streams***

The current park cave inventory notes 121 caves on the North Side. The majority of these caves are relatively small and do not contain streams. The best examples of North Side cave streams are found beneath the Dry Prong of Buffalo (so named for the lack of surface water). Near the headwaters of the basin is the largest known Haney Limestone cave, LuluMart Cave, with over 500 meters of surveyed passage, all along stream courses. Further downstream, the Dry Prong Buffalo Creek Cave is found. With 2,900 meters of surveyed passage, this cave traces the route of the Dry Prong with a slight down-dip offset. The majority of this cave follows the stream, which terminates in a downstream sump. A few hundred meters downstream of Buffalo Creek Cave, the same stream emerges from an upstream sump in Fort's Funnel Cave. There the stream is followed for less than 100 meters to its downstream sump. Its flow is joined with that of the Wet Prong and emerges at Buffalo Spring on the Green River floodplain, a one km distance.

Another North Side cave stream of note is that of Running Branch Cave, a 1,775 meter long cave in the heart of the 2.3 $km^2$ Running Branch Spring groundwatershed. Its stream represents the main trunk conduit draining the basin and terminates in short order in a downstream sump. Although one kilometer (straight line) from the Green River, it's base level elevation is only a few centimeters above the river. This extremely low gradient is typical of most, if not all, trunk drains in the Mammoth Cave region. Groundwater recharging the aquifer moves rapidly through the carbonates via vertical fractures, perhaps perching on local shale or chert layers for short distances, as it seeks base level. It is also important to note that the bed of the Green River was at one time some ten meters lower in elevation than presently. The Green is now flowing over ten meters of fill as the river channel has aggraded to its present elevation (Palmer, 1981).

### *South of the Green River*

The karst of the Mammoth Cave region is among the most recognized landscapes in the world. Geologic textbooks across the globe contain photographs, not only of the celebrated cave, but its surrounding and overlying geomorphology. To many, it typifies a mature karst landscape developed on and through dense crystalline carbonates. It also serves as a microcosm of global karst, as water quality and dependent aquatic life contend with daily stresses of human activities.

The most striking geomorphic feature associated with mature karst terranes is the dearth of or total absence of surface drainage features. The numerous surface streams in the southern portion of the watershed (Glasgow Uplands) flow northward atop relatively insoluble strata and sink into the karst aquifer where the soluble strata is encountered. These streams provide the Mammoth Cave karst aquifer with large volumes of water, which immediately flow into cave streams (these surface streams can be thought of as the headwaters of the cave streams) and continue their northwestward flow towards the Green River, the regional master stream. The second major recharge area is the Sinkhole Plain, which lies upon the soluble limestones roughly between the sinking streams and the Mammoth Cave Cuesta. In this area, where no surface streams are present, water directly enters the karst aquifer through dolines and the epikarst. Any pollutant found on the surface within the recharge area, both in the sinking streams and the Sinkhole Plain, directly enters the cave streams in the form of unfiltered runoff during rainfall events.

### *Groundwatersheds*

The groundwatersheds of Mammoth Cave extend far beyond park boundaries. South of the Green, eleven karst watersheds drain into the park (Figure 7, Table 9). As an artifact of the constant evolution of the karst aquifer, many of these basins are inter-related by high-stage overflows or piracy routes. Unlike the evolution of a surface drainage system, where tributaries of the master stream simply entrench their channels in step with the downcutting of the master, water flowing through karst is not held to a particular course. That is, it continues to take advantage of the most efficient route to the master stream – or from one cave stream to another adjacent down-gradient stream – that may or may not be along its present course. When this occurs – and the cave system preserves scores of examples of ancient interactions – a piracy route develops, as water is "stolen" or "captured" from one cave stream to another stream or spring. Given time to develop, this piracy route may become the main conduit of flow. Given more time, the original route becomes less used until only the largest floods are necessary to spill over into the original flow route. Imagine an erosional nick-point migrating upstream on the Green. As it slowly migrates it creates a very steep hydraulic gradient at and immediately downstream of the nick-point. Groundwater becomes focused on this new, steep-gradient pathway to the master stream – or within the cave, from one stream to an adjacent stream already tied into the newly lowered base level. This scenario has played out many times during the development of the karst aquifer, as groundwater basin boundaries are constantly rearranged over time.

*Table 9. Surficial geology of the major groundwatersheds of the south side. Each unit is calculated as hectares within a particular basin. * Denotes subbasins within the Turnhole Spring karst groundwatershed. Blue font corresponds to carbonate strata.*

| *Basin* | *Alluvium* | *Caseyville* | *Glen Dean* | *Hardinsburg* | *Haney* | *Big Clifty* | *Girkin* | *Ste. Gen.* | *St. Louis* |
|---|---|---|---|---|---|---|---|---|---|
| **Mile 205.7** | 1 | 0 | 0 | 43 | 60 | 120 | 84 | 4 | 0 |
| **Grinstead Mill** | 2 | 0 | 0 | 7 | 7 | 21 | 75 | 16 | 0 |
| **Pike Spring** | 1 | 25 | 68 | 319 | 424 | 1241 | 1564 | 338 | 0 |
| **Echo Spring** | 18 | 1 | 4 | 39 | 175 | 899 | 970 | 214 | 0 |
| **Cotton Gin** | 4 | 0 | 0 | 19 | 123 | 65 | 60 | 3 | 0 |
| **Sand Cave** | 1 | 0 | 0 | 15 | 110 | 117 | 52 | 2 | 0 |
| **Double Sink*** | 0 | 29 | 82 | 541 | 240 | 128 | 120 | 2 | 0 |
| **Turnhole*** | 1 | 0 | 0 | 33 | 198 | 384 | 556 | 14 | 0 |
| **Mill Hole*** | 172 | 0 | 0 | 107 | 87 | 691 | 904 | 1546 | 7701 |
| **Proctor*** | 0 | 0 | 0 | 0 | 26 | 466 | 627 | 156 | 0 |
| **Patoka*** | 0 | 0 | 0 | 6 | 54 | 514 | 886 | 2478 | 3306 |
| **Cave City*** | 0 | 0 | 0 | 28 | 146 | 762 | 496 | 1056 | 12 |
| **Turnhole total** | 173 | 29 | 82 | 715 | 751 | 2945 | 3589 | 5252 | 11019 |

## *Recharge Mechanisms*

Unlike common consolidated or unconsolidated granular aquifers, karst aquifers are characterized by an intimate and immediate connection to surface waters. Recharge enters the karst aquifer of Southcentral Kentucky in four forms: *diffuse allogenic* (very slow seepage through non-carbonate strata*), diffuse autogenic* (relatively slow seepage through carbonate strata (epikarst)), *concentrated allogenic* (rapid recharge through sinking streams perched upon non-carbonate strata (or non-cave forming strata), and *concentrated autogenic* (rapid recharge via dolines). The former category represents a very small volume of karst recharge in the Mammoth Cave area, while the latter three contribute the majority of the water entering the aquifer. While the diffuse autogenic recharge via the epikarst – the highly solutionally-eroded soil-bedrock interface (typically 10m thick) underlying all sub aerial exposed carbonates – is ubiquitous throughout our karst watersheds and drives the base-flow component of aquifer discharge, the two concentrated mechanisms comprise the vast majority of rapid runoff, or quick-flow into the aquifer. The very nature of both sinking streams and dolines act to augment runoff to points of recharge, either the ponor of a sinking stream or the bottom of a doline.

### *Diffuse Allogenic Recharge*

Limited by very low hydraulic conductivities, diffuse recharge through non-carbonate strata is the lesser of all recharge mechanisms. Precipitation is easily shed off the non-carbonates (typically sandstones) and recharges the aquifer via concentrated means. Some water may make its way through these sandstones, either via interstitial porosity, or more commonly through fractures and enter the karst aquifer. In any case, this is not a very effective method of recharge.

### *Diffuse Autogenic Recharge*

By far the most ubiquitous and ironically, the least understood recharge and storage mechanism is the epikarst. Wherever the thickly bedded carbonates that comprise the aquifer are exposed at the surface there is epikarst. Epikarst can be defined as the well integrated, solutionally-enhanced network of fractures and bedding plains just below the soil-bedrock interface. The epikarst is best viewed along roadcuts and outcroppings of the limestone and is characterized by deep (one to ten meters) enlarged fractures (from a few centimeters to several meters in diameter) that diminish at depth. These vertical features are interconnected by solutionally-enlarged bedding plains and are typically wholly or partially soil-filled. It exists throughout the Pennyroyal Plateau. Precipitation sinks into the overlying soils and slowly percolates (or is transferred rapidly via soil macropores) into the epikarst, where it is slowly released into the underlying bedrock through discrete conduits.

### *Concentrated Allogenic Recharge*

The most dominant mechanism for quick-flow recharge is from streams flowing over non-carbonate strata and sinking upon reaching the limestones. Concentrated allogenic recharge occurs in two physiographic regions; the Glasgow Uplands and the Chester Cuesta. The Glasgow Uplands, the extreme headwaters of the large karst watersheds of Mammoth Cave, contain 14 sinking streams that recharge the aquifer. These surface streams are established primarily upon the lower (thinly-bedded and shaley) section of the St. Louis Limestone. They flow across these relatively insoluble strata until the thickly-bedded, highly soluble beds of the upper St. Louis are encountered where they sink at discrete points (swallets or ponors). Recall that the hydraulic gradient is less steep than the stratagraphic dip, so a traverse downstream is to move upsection. Three of these streams, Little Sinking Creek (the westernmost), Patoka Creek (the easternmost) and Gardner Creek (near the center) are perennial, while the remaining streams are usually dry during the late summer/early autumn months. In total, these streams drain approximately 70 $km^2$ into Mammoth Cave.

Upon the sandstone-capped ridges of the Chester Cuesta is the other portion of concentrated allogenic recharge. Water is augmented into the channels of seasonal streams flowing over the Big Clifty Sandstone and sinks abruptly into the underlying Girkin Limestone. There are easily hundreds, if not thousands of such recharge points. By calculating the exposure of the sandstone-capped ridges of the Cuesta within the watershed, one can estimate – including contributions from perched karst aquifers of the Haney, and to a lesser extent, the Glen Dean Limestone – that 85 $km^2$ are drained into Mammoth Cave in this fashion.

### *Concentrated Autogenic Recharge*

The final recharge mechanism is the sinkhole, or doline. The Sinkhole Plain of the Pennyroyal Plateau and karst valleys that dissect the Cuesta within the watershed are dotted with thousands of dolines, ranging from tens to hundreds of meters wide and from a few to tens of meters deep. In the limited space between the dolines, and under the doline flanks is the epikarst. Runoff that is not intercepted by the epikarst is routed into the bottoms of the dolines and is quickly recharged into the aquifer. The bottoms of the dolines typically do not have open portals (ponors) into the underlying limestone, as they commonly are draped with thick soils. Each doline transfers its water at different rates. Some become ponded following rainfall and slowly drain, while others rapidly drain and seldom, if ever, pond.

## *Groundwater Storage*

Where typical laminar-flow (Darcian) aquifers transmit flow on the order of centimeters to meters per year, karst aquifers transfer water, both vertically and horizontally, on the order of kilometers per hour. The Mammoth Cave karst aquifer conducts convergent flow, much like the convergent flow patterns of a dendritic surface stream. While other aquifers may exhibit diffuse flow, where contaminants slowly disperse, the conduit flow of the Mammoth Cave karst aquifer quickly channels both recharge and pollutants toward a common cave stream or spring. Flow through the aquifer can be quite rapid, on the order of 20 kilometers per day. Contaminants entering the karst aquifer can thus be rapidly transported, unaltered, through the cave streams and impact their dependent aquatic fauna.

Precipitation continually recharges the aquifer stores, which can be thought of as subcutaneous stores and bedrock stores. Little research has been devoted to the former, while at least two Masters Theses have examined a component of bedrock stores.

### *Subcutaneous Storage*

Nearly the entire karst watershed of the park is soil covered to some degree, ranging from a few centimeters to over ten meters deep – there are limited areas (ecologically referred to as barrens) where carbonate bedrock crops to the surface. While the soils are typically wrought with macropores, they are still capable of storing large amounts of groundwater. As mentioned previously, many settlements built upon the sandstone-capped ridges developed water supply wells into the deep saturated soils. Soil water levels are sustained throughout much of the year, dropping to the sandstone-soil contact by late summer or early autumn. Water loss may be attributed to evapotranspiration and gradual discharge through surface seeps or into the aquifer by diffuse allogenic means.

Soils developed upon the wide carbonates of the Sinkhole Plain and the karst valleys within the Chester Cuesta do not retain water for extended periods. Following a precipitation event, soil waters are quickly drained into the underlying epikarst or loss via evapotranspiration.

It is thought that the bulk of the subcutaneous stores are within the epikarst. It may be a matter of argument in that the epikarst is comprised of components of both soils and bedrock. For this discussion, epikarst will remain a separate entity. Above was discussed its role in aquifer recharge. One can estimate, based on the aerial extent of exposed carbonates (both barren and soil covered) within the watershed of 160 $km^2$ (with 90 $km^2$ of that area from the Sinkhole Plain) and assume an epikarst thickness of ten meters (based upon observations at outcrops), that the volume of the epikarst to be about 1.6 $km^3$.

The storage potential of the epikarst can be demonstrated during prolonged droughts. Many weeks after the last rainfall cave streams, even very small tributaries, still flow, long after all sinking streams have dried. Storage, being delivered into the conduit system, from the epikarst is believed responsible. During the nadir of the 1999 drought, four large springs upstream of the park were profiled for discharge, as well as the Green River – which was gauged at River Styx Spring at 5.42 $m^3/s$. These simple measurements demonstrated that more than 25% of the river's drought flow was derived from the 560 $km^2$ of four karst watersheds– which comprise only 11% of the river basin upstream of the measurement site (Personal Communication and Unpublished Data, Joe Ray, Karst Hydrogeologist, Kentucky Division of Water, 2004). The importance of the epikarst on the overall hydrologic behavior of the Southcentral Kentucky karst is hard to overstate.

### *Storage within the Carbonate Bedrock Mass*

Analogous to the bank stores of surface streams, the karst aquifer has conduit adjacent porosity. As a conduit is developed, it intersects a matrix of fractures and bedding plains, which many have undergone solutionally enhancement. Flood waters can be pushed back into and released from this matrix during and following a storm event. Recker (1990) and Johnson (1994) examined the transmissivity of the conduit adjacent system. Recker found that (though tracer dye injections from wells intersecting the conduit adjacent system to the conduit) flow rates were on the order of 100 meters per day. Johnson carefully instrumented a well field within the conduit adjacent system and noted its response to rapid recharge relative to conduit stage. Both researchers concluded that the conduit adjacent system is capable of storing vast amounts of groundwater and contributing flow to or reversing flow from conduits several hundreds of meters away. They also agree that this porosity can temporarily store contaminated flood waters, and release these waters back into the conduit well after the flood event.

### *Groundwater Transfer (Flow)*

The dividing line between storage and transfer is somewhat dynamic, in that the same features may in one moment act as stores, and in the next, a transfer mechanism. In the above discussion, one can envision a scenario in which groundwaters are transferred into the bedding plains and fractures adjacent to a conduit during the rising limb of a flood. There these waters are held in storage until the head in the conduit falls and the same waters are transferred back into the conduit. It is both a matter of physical location of this matrix (adjacent to a conduit) and its place in time relative to a flood.

With that said, the transfer of groundwater through the aquifer is quite simple, in that fractures and bedding plains, and most efficiently by those that are solutionally-enlarged, are the only transfer mechanism. All recharge, with the exception of that intercepted by evapotranspiration and water wells, must be delivered to the river. It is the very transfer of groundwater from one point of the basin to another along with chemical and physical erosion of the rock mass that developed the cave. Transfer of water is both vertical and horizontal, with the former taking advantage of fractures and the latter, bedding plains. One may think of the carbonate strata in the Mammoth Cave region as being "pre-wired" for cave development as vertical fissures are aligned to transfer water down into the aquifer, and bedding plains dipping towards the river. Essentially it is the transfer mechanism, both active and long abandoned, that is the cave we know. These transfer mechanisms, or conduits, both vertical and horizontal, range in size from a few millimeters to tens of meters across – functions of water chemistry, velocity, sediment load, discharge, and time.

Consider this situation - Precipitation falls onto the Glasgow Uplands, where it enters a sinking stream via overland flow. It sinks into the aquifer at a ponor and is carried along an enlarged bedding plain conduit. Along its route it is met with tributaries draining the dolines of the Sinkhole Plain. As it continues northwestward toward the Green River, it is met by scores of tributaries draining the sandstone-capped ridges. Their contribution is through streams that sink upon contact with the underlying limestone forming vertical shafts, born out of fractures. As stage rises within the master conduit, these waters are pushed back into the conduit adjacent system and temporarily stored until the stage begins to fall. Last to arrive are stores from the epikarst as they are transferred through a myriad of fractures and bedding plains and eventually into the main conduits. All waters ultimately resurge at springs along the banks of the Green River.

# Water Quality

Although scientists have journeyed to Mammoth Cave for nearly two hundred years, water quality issues did not receive much attention until the past two decades. This may be due to an overall under appreciation of water quality threats amplified by non-defined watersheds for the park. Beginning in 1973, park hydrologist James Quinlan and his associates began the task of delineating the park's karst watersheds. A final product, a groundwater hydrology map of the Mammoth Cave Region (Quinlan and Ray, 1989) was produced. This map showed, for the first time, that Mammoth Cave is recharged by lands far beyond the park boundary. These lands include some of the most productive farm lands in the state, a major interstate highway, and urban areas – all without runoff and wastewater treatment measures. Finally park managers could view water quality threats in the full light of a defined watershed.

It is the intent of this section to give the reader a rigorous overview of water quality studies, including a general description of monitoring activities, watersheds, and water quality as compared to state standards. As water quality monitoring at Mammoth Cave, at least as a part of a coherent program, began in 1990 (and continues today), the data are not suitable for meaningful trend analysis as they are temporally and spatially limited. Data will be presented and discussed in terms of water quality signatures relative to watershed land use and state limits.

## Water Quality Monitoring Studies

In the late 1950s and early 1960s, the USGS conducted a water quality survey and monitoring relative to the disposal of oil-field brines into the Green River upstream of the park near Greensburg, Kentucky. This study showed brines in the park's section of the Green River, with chloride levels well over 100 mg/l.

Besides this USGS water quality survey related to brine contamination of the Green, there was not any sustained or systematic survey of park water quality until 1990. With groundwatersheds well defined, the park could now concentrate on water quality – prior to such basin delimiting, water quality data of the karst system would be of limited use as park managers would not know the source of the water, let alone what contaminant sources to attack.

Since 1990, park hydrologists have determined the most effective methods for accurately monitoring the quality of park waters, and expanded into more detailed descriptions of hydrogeology, and land uses. Activities and summaries of these studies follow:

*1990-1992 Water Quality Inventory*

Park hydrologists completed 31 consecutive rounds of non-conditional synoptic water samples at ten selected locations. Serves as a detailed inventory of contaminant occurrence, both temporal and spatial, and contaminant type.

Revealed correlation between land-use and water quality. Suggested that majority of non-point source contamination is associated with flood-pulse activities.

*1990-1993 Groundwater Tracing and Karst Watershed Delineation of North Side*

Park hydrologists compiled an inventory of karst features and conducted a dye-tracing program on the north side of the Green River. 17 karst watersheds were identified and basic land-uses were determined.

*1992-1993 Pesticide Survey*

Topical water quality survey for pesticides. Park hydrologists found that pesticides, while only present immediately following peak application periods, can attain very high concentrations – some samples seven times higher than maximum drinking water standards – during flood-pulse activity within cave's headwaters. High pesticide concentrations occur coincidentally with high suspended sediment loads.

*1993-1994 Detailed Land-use Classification*

Park cartographer compiled a detailed land-use classification (Anderson Level III) based upon color-IR (infrared) transparencies for the major karst watersheds draining into Mammoth Cave.

*1994-1995 Flood-Pulse Water Quality Research Program*

Flood-pulse water quality research confirmed that the majority of non-point source contaminants enter and are quickly transferred through the karst aquifer during and immediately following rainfall events. Park hydrologist demonstrated that dye injected into a discrete sink-point could determine the relative pollutant contribution from a specific recharge point.

*1997-1998 Water Quality Monitoring*

Based upon the 1990-1992 Water Quality Inventory, key parameters were monitored on a monthly synoptic basis (24 consecutive monthly samples of 12 locations). Water quality data from the 1990-1992 inventory are being statistically compared to these data to determine water quality trends and relate to changing land use.

*2001-2002 Water Quality relative to Land Use Change*

The USGS re-classifies the Anderson Level III land use scene of the park's groundwatersheds south of the Green River. Analysis of land use change was made relative to the 1990 scene and compared to trends in water quality.

*2001-2003 Sediment Contamination Assay*

A stream sediment sampling and analysis program was initiated for the waters of Mammoth Cave National Park and adjacent karst watersheds with documented metal and pesticide contamination histories. A series of core and bed-load samples were collected and analyzed for total organic carbon, grain size, metals, organochlorides and organophosphates.

*2002-2005 Water Quality Monitoring*

The previous round of water quality monitoring resumes on an annual basis at the same sites as the park's Long-Term Ecological Monitoring Program is funded. Monitoring includes only monthly non-conditional synoptic sampling. Mammoth Cave forms its own water quality laboratory to analyze samples in the summer of 2002. During the summer of 2004 the park laboratory was joined with that of Western Kentucky University, creating the WATERS laboratory.

## Water Quality Threats

To better understand threats to the aquatic ecosystems it is necessary to have a basic understanding of the relationship between Mammoth Cave and its groundwater recharge basins (Figure 7, Tables 10 and 11). Mammoth Cave owes the majority of its recharge to a 24,000-hectare region beyond the park boundary. Many land-uses occur within this watershed, each contributing to the overall water quality. A detailed description of these uses is found in a latter section. Some uses produce contaminants, which can be divided into three main categories:

**Non-Point Source:** Agricultural pollutants (animal waste, suspended sediments, and pesticides) and some urban pollutants (parking lot and road runoff) accumulate on the surface in virtual storage until they are washed into the karst aquifer during rainfall events. Each year thousands of tons of sediments, animal wastes, nutrients, and pesticides are introduced into the streams of Mammoth Cave from these lands.

**Chronic Point Source:** From land-uses such as oil and gas exploration and production (hydrocarbons and brines), urban development (septic waste), and agriculture (wastes deposited directly into sinking streams), these pollutants are released into the karst aquifer at a relatively steady rate, regardless of precipitation.

**Acute Point Source:** Traversing the cave's recharge basin are three major transportation corridors. Interstate 65, the Cumberland Parkway, and the CSX railroad are drained by sinking creeks, dolines, and Class V injection wells. Any contaminant released along these routes is quickly washed into the Mammoth Cave karst aquifer. An average of four spills per year of hazardous materials has occurred along these routes within the park's groundwatersheds.

*Table 10. Major groundwatersheds on the North Side.*

| *Basin* | *Size km²* | *In park km²* | *% in park* | *Out park km²* | *% out park* | *% Basal aquifer* | *% "cap-rock"* |
|---|---|---|---|---|---|---|---|
| **Big Spring** | 15.2 | 8.1 | 53 | 7.1 | 47 | 2 | 98 |
| **Doyle's Ford** | 12.7 | 1.5 | 12 | 11.2 | 88 | 8 | 92 |
| **Ugly Creek** | 8.3 | 4.7 | 57 | 3.6 | 43 | 13 | 87 |
| **Big Hollow** | 2.8 | 2.8 | 100 | 0 | 0 | 21 | 79 |
| **Running Branch** | 2.3 | 2.3 | 100 | 0 | 0 | 17 | 83 |
| **Mary Parker** | 4.0 | 4.0 | 100 | 0 | 0 | 8 | 92 |
| **Stillhouse** | 1.1 | 1.1 | 100 | 0 | 0 | 18 | 82 |
| **Sal Hollow** | | | 100 | 0 | 0 | | |
| **Buffalo Creek** | 32.9 | 27.6 | 84 | 5.3 | 16 | 7 | 93 |

*Table 11. Major groundwatersheds on the South Side. * Denotes subbasins with the Turnhole Spring karst groundwatershed.*

| *Basin* | *Size km²* | *In park km²* | *% in park* | *Out park km²* | *% out park* | *% Basal aquifer* | *% "cap-rock"* |
|---|---|---|---|---|---|---|---|
| **Mile 205.7** | 3.1 | 2.0 | 65 | 1.1 | 35 | 29 | 71 |
| **Grinstead Mill** | 1.3 | 1.3 | 100 | 0 | 0 | 69 | 31 |
| **Pike Spring** | 39.9 | 17.3 | 43 | 22.6 | 57 | 48 | 52 |
| **Echo Spring** | 23.2 | 23.0 | 99 | 0.2 | 1 | 51 | 49 |
| **Cotton Gin** | 2.8 | 2.8 | 100 | 0 | 0 | 21 | 79 |
| **Sand Cave** | 3.0 | 3.0 | 100 | 0 | 0 | 17 | 83 |
| **Double Sink*** | 11.2 | 0.4 | 4 | 10.8 | 96 | 9 | 91 |
| **Turnhole*** | 11.9 | 9.3 | 78 | 2.6 | 22 | 48 | 52 |
| **Mill Hole*** | 112.1 | 3.1 | 3 | 109.0 | 97 | 91 | 9 |
| **Proctor*** | 12.8 | 11.2 | 88 | 1.6 | 12 | 61 | 39 |
| **Patoka*** | 72.4 | 3.5 | 5 | 68.9 | 95 | 47 | 53 |
| **Cave City*** | 25.0 | 2.8 | 11 | 22.2 | 89 | 62 | 38 |
| **Turnhole total** | 245.4 | 30.3 | 12 | 215.1 | 88 | 67 | 33 |

As the majority of the groundwater recharge area for Mammoth Cave lies beyond park boundaries, water quality is and will remain, the most significant resource threat to the park's water resources. Groundwater flow properties combine to create a hydrologic system in which the surface is highly integrated with the subsurface, and the aquatic ecosystem unique to karst of the Mammoth Cave region.

## Impaired Waters

The influence of non-park lands on the park's water quality can be inferred by examining Kentucky's 2002 303(d) list submitted to Congress in January 2003 (KYDOW, 2003). The 303(d) list must be prepared by each state under provisions of the Clean Water Act, and lists state waters that are not meeting water quality goals for a waterbody's designated use. The only park water on the 303(d) list – and it has appeared on this list for the past decade – is the Green River. The citation appears as follows:

Green River of Ohio River — Hart/Edmonson/Green Counties
From River Mile 183.5 to 250.2 — Segment Length: 66.7 miles
Impaired Use: Swimming (Nonsupport)
Pollutant of Concern: Pathogens
Suspected Sources: Agriculture

One also needs to be aware of streams and stream segments upstream of the park on the state's 303(d) list:

South Fork Russell Creek of Russell Creek — Green County
From River Mile 0.0 to 0.6 — Segment Length: 0.6 miles
Impaired Use: Aquatic Life (Nonsupport)
Pollutant of Concern: Salinity/TDS/Chlorides
Suspected Sources: Resource Extraction (Petroleum Activities)

Little Pitman Creek of Big Pitman Creek — Taylor/Green Counties
From River Mile 5.9 to 10.1 — Segment Length: 4.2 miles
Impaired Use: Aquatic Life (Nonsupport)
Pollutant of Concern: Metals (Copper), Nutrients
Suspected Sources: Municipal Point Sources (Major Industrial Point Sources)
This listing is from the 1998 303(d) Report. Metals data indicate that copper values are now being met by the Campbellsville wastewater treatment plant and that instream values for copper meet water quality standards. The state requests that Little Pitman Creek be delisted for copper. Nutrient listing remains. Biological assessment has not been completed.

Bacon Creek of Nolin River — Hart/Larue Counties
From River Mile 0.0 to 31.2 — Segment Length: 21.2
Impaired Use: Swimming (Nonsupport)
Pollutant of Concern: Pathogens
Suspected Sources: Agriculture, Land Disposal (Onsite Wastewater Treatment Systems – Septic Tanks)

Nolin River of Green River — Hart/Hardin/Grayson Counties
From River Mile 44.0 to 93.2 — Segment Length: 49.2
Impaired Use: Swimming (Nonsupport)

Pollutant of Concern: Pathogens
Suspected Sources: Agriculture

## Water Quality Monitoring Program Description

Water enters the karst aquifer, as described earlier, primarily by the relatively slow recharge via the epikarst or the rapid recharge through dolines and ponors of sinking streams. The latter mechanism conducts the vast majority of the quick flow of surface runoff into the groundwater system.

There are two basic ways to examine water quality of this aquifer. At Mammoth Cave, both the USGS National Water Quality Assessment (NWQA) based monthly non-conditional synoptic program provides a long-term data set where trends can be observed, as all flow conditions, base to flood, are sampled without temporal bias. The second method, flood pulse monitoring, samples around the clock at close intervals, beginning just before a flood pulse event and continuing until the pulse subsides. These data reveal the contaminant "maxima" associated with runoff-producing rainfalls. Upon reception of Long-Term Ecological Monitoring Funds, park science administrators decided to suspend the five-year "off" period and commenced monthly non-conditional synoptic sampling.

Since 1990, the Mammoth Cave Water Quality Monitoring Program (WQMP; 1990 – present) has generated monthly non-conditional synoptic water quality data. We have learned that: 1) The water quality of the cave streams and springs is correlative to the landuse of the watershed; 2) the most significant non-point source contamination occurs immediately following precipitation events as surface pollutants are quickly washed into the karst aquifer through numerous sinking streams and countless dolines. Water quality parameters, such as turbidity (0.1 to 400 NTU), atrazine (BDL to 21 ppb), and fecal coliform bacteria (10 to 50,000 colonies/100ml) may suddenly increase (within minutes) several orders of magnitude. These parameters are largely non-point source contaminants. They are entrained into the runoff during or following a storm event and are directly injected, via dolines and ponors, into the aquifer. Quantitative dye-tracer studies have shown that a storm pulse, with its associated contaminants, can traverse the entire watershed – from the sinking stream headwaters to the springs along the Green – within 24 hours, an average groundwater flow velocity of one kilometer per hour.

## Flood Response

There is little attenuation of the flood pulse, in terms of flow dynamics or water quality, as the sudden recharge is swept into the cave system. Unlike a surface stream network, cave streams are confined to a fixed cross-sectional area. Rather than simply rising up and splaying over natural levees onto flood plains, cave streams are highly restricted within their conduits. A cave stream will rise in response to recharge until it becomes pipe-full creating very high hydraulic heads. The only way to move more water through a fixed, pipe-full conduit is to increase velocity. Stage rises in excess of 30 meters over 12 hours, with velocities approaching 10 m/s have been recorded within cave streams during large flood events. Mirroring the physical response to sudden recharge, water quality parameters undergo similar dramatic changes.

Over a decade of water quality monitoring at Mammoth Cave National Park indicates that the non-point source runoff from agricultural lands is the leading cause of chronic contamination of the karst aquifer with respect to nutrients, bacteria, sediment, and pesticides. Following runoff-producing rainfall events, cave streams and springs recharged by agricultural lands of the Pennyroyal Plateau show a dramatic and sudden rise in these contaminants. Our studies have shown this relationship, in which, for example, fecal coliform levels at Turnhole Spring (draining a 245 $km^2$ watershed) rose from a background of less than 200 colonies/100ml to 22,250 colonies/100ml following a rainfall event. This, unfortunately, is a typical response. A Master's thesis study (Hall 1996) within cave streams located near the center of the watershed documented peak concentrations of fecal coliform in excess of 20,000 colonies/100ml associated with runoff into dolines and sinking streams (Figure 8). In addition, as recent as October 2002 (during a large rainfall event), detailed DNA fingerprinting of *E. coli* bacteria was performed on a sample from the discharge of the Turnhole Spring watershed. Of the five colonies isolated for this test, four were of animal origin, and one human. Again, the quick-flow component of the recharge event is associated with this bacteria signature when compared to provenance and groundwater flow velocities.

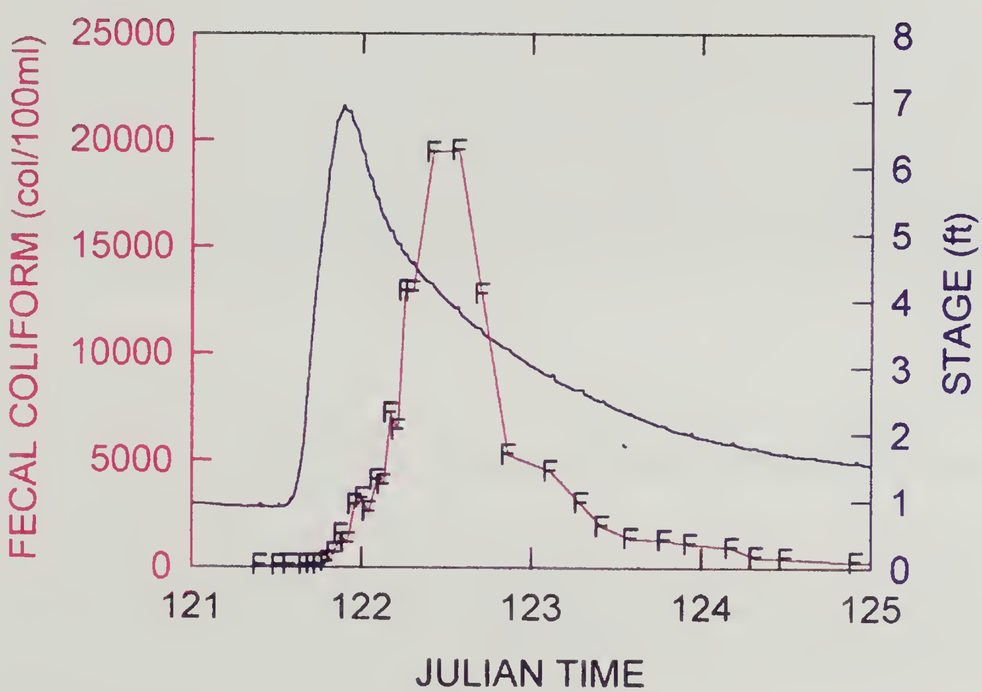


*Figure 8. Fecal coliform bacteria response at the Logsdon River monitoring site to moderate recharge event, from Hall (1996).*

## Monthly Non-Conditional Synoptic Sampling Results

A data set of 56 samples, collected at 12 locations within the park from March 1990 - September 1992, October 1997 – September 1999 were prepared for the discussion below. Monthly sampling of these same sites also occurred between July 2002 and September 2005. Sampling locations are considered to be "Integrator Sites", and are located at the downstream end of a watershed, and thus reflective of land use within their contributing basins (Figure 9, Table 12, Plates 2 and 3).

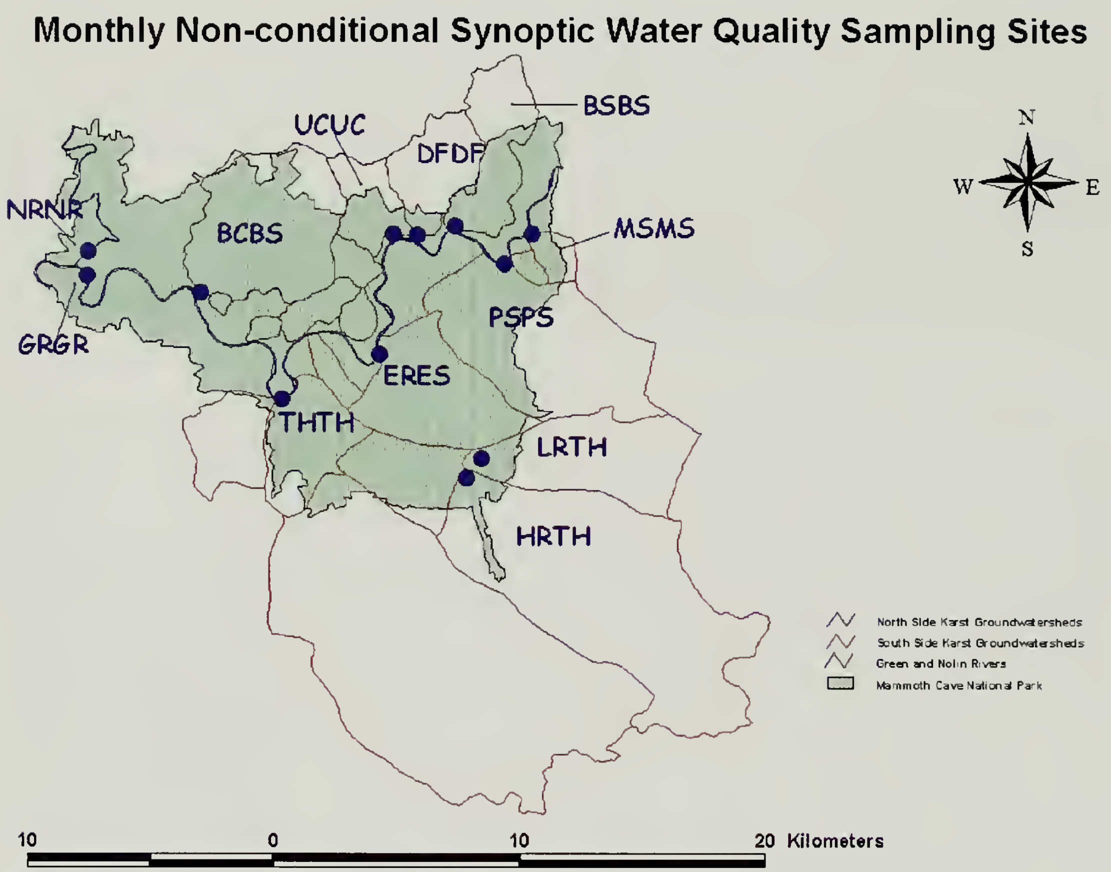


*Figure 9. Site locations for monthly non-conditional synoptic water quality sampling. LRTH and HRTH are the cave streams, Logsdon River and Hawkins River. GRGR and NRNR are sample locations upstream of the confluence of the Green and Nolin Rivers. All other sites are springs.*

*Table 12. Listing of monthly non-conditional synoptic sampling locations.*

| SAMPLE LOCATION | SAMPLE ID | DRAINAGE AREA ($km^2$) | NORTHING (NAD27) | EASTING (NAD27) | PRIMARY LAND-USE |
|---|---|---|---|---|---|
| **Mile 205.7 Spring** | MSMS | 3.1 | 4120120 | 585070 | F,P |
| **Pike Spring** | PSPS | 39.9 | 4118920 | 583720 | A,F,P |
| **Big Spring** | BSBS | 15.2 | 4120350 | 581930 | F,P,A |
| **Doyle's Ford Spring** | DFDF | 12.7 | 4119920 | 580590 | F,P,O,A |
| **Ugly Creek Spring** | UCUC | 8.3 | 4120090 | 580140 | F,P,O,A |
| **Echo River Spring** | ERES | 23.2 | 4114970 | 579080 | P,F,a,u,t* |
| **Turnhole Spring** | THTH | 245.4 | 4113440 | 575490 | A,F,T,O,U, P |
| **Hawkins River** | HRTH | 72.4 | 4110600 | 582490 | A,F,U,P,T |
| **Logsdon River** | LRTH | 25.0 | 4110700 | 582570 | F,A,U,P,T |
| **Buffalo Spring** | BCBS | 32.9 | 4117490 | 571480 | P |
| **Green River** | GRGR | 5260 | 4118750 | 566690 | A,F,O,T,U, P |
| **Nolin River** | NRGR | 1883 | 4118890 | 566620 | A,F,O,U,P |

- A = Agriculture
- O = Oil and gas
- U = Urban development
- P = Park lands
- T = Transportation corridor
- F = Forest

* Echo River receives a large portion of flow from Hawkins River, downstream of the confluence of Hawkins and Logsdon Rivers during periods of high flow (greater than 3 meters above base level). This common occurrence (some 15-20 times each year) brings an additional 100 $km^2$ of mostly non-park lands.

### *Description of Synoptic Sampling Locations*

The **Mile 205.7 Spring** (MSMS) groundwater basin (3.1 $km^2$) is relatively small and much of it is contained within the park boundary (2.0 $km^2$). The recharge area, which lies outside the park boundary, is sparsely populated with minimal human impact. Water quality data indicate relatively unaltered conditions.

The recharge area of the **Pike Spring** (PSPS) groundwater basin (39.9 $km^2$) contains both park (17.3 $km^2$) and non-park lands (22.6 $km^2$). Unlike the Turnhole Spring groundwater basin where there are significant numbers of feedlots, homes, and petroleum wells, the Pike Spring groundwater basin contains less agricultural, domestic, and urban development. This basin, whose main underground flow conduit has not been discovered by explorers, supports populations of endangered Kentucky Cave Shrimp.

The **Big Spring** (BSBS) groundwater basin (15.2 $km^2$), roughly bisected by the park boundary, is comprised of park, forest and light agricultural land-uses. It has been the focus of topical water quality studies including flood pulse and sulfate monitoring. Topical water quality data have reflected both park and private land-uses in time-resolved series.

The **Doyle's Ford** (DFDF) groundwater basin (12.7 $km^2$) has more active silviculture than Ugly Creek. The 11.2 $km^2$of private lands of this watershed undergo a constant cycle of timber harvesting.

**Ugly Creek** (UCUC) groundwater basin (8.3 $km^2$) contains both park lands (4.7 $km^2$) and mostly forested private lands (3.6 $km^2$). Water quality, in general, reflect the overall low disturbance and light land uses in this watershed. Like the neighboring Doyle's Ford basin, the major cave streams draining this watershed have not been discovered.

The **Echo River** (ERES) groundwater basin, the type locality of the Kentucky Cave Shrimp, is almost entirely contained within park boundaries – 22.2 $km^2$ of its 23.2 $km^2$ are within the park. However, it does receive a large portion of its recharge from the adjacent Turnhole Spring basin (primarily agricultural lands) during periods of high flow. Research has allowed us to determine when, relative to stage condition, this overflow route is activated (Meiman and Ryan 1993). Water quality from this station is excellent during periods of low flow, but water quality is severely degraded during and immediately following high flow when the overflow route is active. There also exists a condition where if the stage of the Green is within 1.5-3 meters above base level and the karst aquifer is in a stage of low discharge, a flow-reversal occurs. River water enters (at rates of over one cubic meter per second) River Styx Spring, flows into Mammoth Cave, and out Echo River Spring (total distance underground of about two kilometers). During these conditions, which occur for several weeks during the winter months, the recharge area of Echo River Spring is the entire Green River watershed upstream of River Styx Spring. Water quality signatures are obvious in low flow, overflow, and flow reversal states.

The drainage area of the **Turnhole Spring** (THTH) groundwater basin is clearly much smaller than that of the Green River, but the potential for acute pollution of the cave aquatic ecosystem is much greater. The Turnhole basin will be sampled at its resurgence on the Green River. The vast majority of this 245.4 $km^2$ karst basin lies on private lands (215.1 $km^2$), including some of the most intensely farmed land in the state. Sub-basins of the Turnhole are sampled at Hawkins and Logsdon Rivers (below).

**Hawkins River** (HRTH), drains the 72.4 $km^2$ Patoka Creek karst watershed, 68.9 $km^2$ beyond park boundaries. The basin's recharge is dominated by the Sinkhole Plain and one of the larger perennial surface streams (Patoka Creek, in the watershed's headwaters on the Glasgow Uplands). Land uses include the town of Park City and agricultural production.

**Logsdon River** (LRTH), as is Hawkins, is sampled under any flow condition through a well and sample pump. Logsdon drains the Cave City Sub-basin (25.0 $km^2$), including both park (2.8 $km^2$) and non-park lands (22.2 $km^2$). The land-use of this basin includes a moderate amount of agriculture and a corridor of expanding tourism-based businesses.

**Buffalo Spring** (BSBC) groundwater basin (32.9 $km^2$) is the only large perennial watershed that is virtually contained within park boundaries (27.6 $km^2$). This basin and Mile 205.7 Spring serve as natural controls against which to compare more impacted sites. Although the Buffalo Creek drainage basin has been devoid of gross human-derived impacts for nearly fifty years, and water quality trends at this site should reflect near pristine conditions, an increase in the amount of back-country use may impact water quality.

The **Green River** (GRGR) is the regional base-level stream and is sampled just upstream from its confluence with the Nolin. Aquatic fauna of the Green, just within the park, ranks among the most diverse in North America. Six species of freshwater mussels are listed as Endangered, and four more are classed as Category 2, as are two species of fish. The Green River, with more than 80 species of fish (including five endemics), and 170 species of benthic macroinvertebrates, including 53 species of freshwater mussels, has been designated an Outstanding Resource Water by the Kentucky Environmental Protection Cabinet. The flow at this site originates primarily as surface water from the upper Green River, and its chemistry reflects those land-uses rather than local influences.

The **Nolin River** (NRNR), roughly parallel to the western park boundary, is sampled upstream from its confluence with the Green River. Discharge from the entire Nolin River basin will be sampled at this station. Land-use in the Nolin River basin primarily consists of forest, agriculture, and hydrocarbon extraction. This site is 14 kilometers downstream from the Nolin River dam. Data have demonstrated a correlation between water release patterns and water quality.

### *Parameters*

Established protocols require that the discharge for each location be measured upon sample collection. We have found that an increase in flow may be accompanied with an increase in contaminant concentration instead of dilution, because surface contaminant stores are released in runoff. In order to closely assess the quality of the park's groundwater, the following parameters were monitored:

| **PARAMETER** | **ANALYSIS** |
|---|---|
| Discharge | Field |
| Specific conductance | Field |
| Water temperature | Field |
| Dissolved oxygen | Field |
| pH | Field |
| Alkalinity | Field |
| Turbidity | Park lab |
| Fecal coliform | Park lab |
| Triazine-class herbicides (assay screening) | Park lab |
| Nitrate-Nitrogen | Park lab |
| Chloride | Contract lab |
| Bromide | Contract lab |
| Sulfate | Contract lab |
| Inorganic Metals | Contract lab |

The park's current water quality monitoring program relies on its own laboratory, but still maintains USGS sampling protocols, and USEPA and Standard Methods laboratory procedures. With the exception of calcium, magnesium and alkalinity, each parameter or a combination of two or more may indicate the presence of contaminants in the water. An explanation of each parameter can be found in Appendix B.

The Commonwealth of Kentucky, as every state in the Union, must, under guidance of the USEPA, promulgate law to set both designated uses for streams, and set water quality standards. The sampling sites at Mammoth Cave National Park fall into these basic designated uses categories, from highest to lowest standards (401 KAR 5:031, Section 2):

**Outstanding Resource Waters:** Waters designated by the Natural Resources and Environmental Protection Cabinet as an outstanding resource water pursuant to 401 KAR 5:031. This list includes all underground streams and the main stem of the Green within Mammoth Cave National Park. This designated use category, as it is the most restrictive and the highest quality in the state, will be used as a minimum standard for these waters.

**Cold Water Aquatic Habitat:** Waters and associated substrate that will support indigenous cold water aquatic life or self-sustaining trout populations on a year-round basis. All cave streams within the park meet the Cold Water Aquatic Habitat criteria. Although the state stocks rainbow trout in the tailwaters of the Nolin dam just upstream of the park's boundary, the population is not self-sustaining.

**Warm Water Aquatic Habitat:** Waters and associated substrate that will support indigenous warm water aquatic life. The Green and Nolin Rivers can be considered under this category, although the Outstanding Resource Waters designation of the Green supersedes this category.

**Primary Contact Recreation:** Those waters suitable for full body contact recreation during the recreation season of May 1 through October 31. Both the Green and Nolin fall under this category.

**Secondary Contact Recreation:** Those waters that are suitable for partial body contact with minimal threat to public health to water quality. All park waters would fall into this minimum category.

### *Water Quality Criteria*

Since the National Park Service administers the park under exclusive federal jurisdiction, water quality criteria under these categories can be used as a minimum level, and can be set at higher standards. For the following discussion of park water quality, the highest standards will be applied as per its highest-ranking designated use. If a parameter is not addressed by the designated use category, Human Health limits are used. If the parameter is still not assigned a value, Domestic Water Supply Use standards are used. Several parameters monitored do not have state standards, and some are newly proposed, but at the time of this writing not passed by the state legislature. The only monitored constituent that will change under the Proposed 401 KAR 5:031 is barium, from 2.0 mg/l to 1.0 mg/l. The highest barium concentration to date at Mammoth Cave was 0.054 mg/l. There are many parameters that are not covered by any existing or proposed standard. It is important to note that the state sets all metal standards for total recoverable metals from an unfiltered sample. Metal analysis for the park's water quality program is dissolved ions (filtered and acidified), and in most cases should be considered as a minimum concentration if compared to total values (unfiltered) from the same water.

Water Quality Criteria (mg/l unless specified)

| | |
|---|---|
| Aluminum | no standard |
| Acid Neutralizing Capacity* | see below |
| Ammonia[w] | less than 0.05 |
| Barium[d] | less than 2.0 |
| Boron | no standard |
| Calcium | no standard |
| Chloride[c] | less than 600 |
| Chromium[o] | less than 0.011 |
| Cobalt | no standard |
| Copper[o] | less than e(.8545 (in Hard) – 1.702) |
| Dissolved Oxygen[c] | greater than 5.0 |
| Fecal Coliform[r] | less than 200 col/100ml** |
| Fluoride[d] | less than 2.0 |
| Iron[o] | less than 1.0 |
| Lead[o] | less than e(1.273 (in Hard) – 4.705) |
| Lithium | no standard |
| Magnesium | no standard |
| Manganese[d] | less than 0.05 |
| Nitrate-Nitrogen | less than 10.0 |
| pH | between 6.0 and 9.0 SU |
| Phosphorous | no standard |
| Potassium | no standard |
| Silicon | no standard |
| Sodium | no standard |
| Specific Conductance | no standard |
| Strontium | no standard |
| Sulfate[d] | less than 250 |
| Sulfur | no standard |
| Turbidity | no standard |
| Temperature*** | see below |
| Zinc[o] | less than e(0.8473 (in Hard) + 0.884) |

* If expressed as alkalinity (as $CaCO_3$) it cannot be reduced by 25% of what is considered "natural" to that water body.
[w] Warm Water aquatic standard
[d] Domestic Water Supply Use
[c] Cold Water aquatic standard
[o] Chronic Warm Water aquatic standard
[r] Primary Contact Recreation standard
** Based on a monthly geometric mean of not less than 5 samples per month, nor exceed 400 col/100 ml in more than 20% of all samples taken during the month
*** Temperature means and instantaneous standards are addressed in 401 KAR 5:031, and are too cumbersome to display here. All park waters meet their temperature requirements as per these period based standards.

In this section, each monitored parameter will be examined and compared to the above water quality criteria. General interpretation, including contaminant source and transport will be discussed. Graphics of each parameter can be found in Appendix B.

## ***Results***

### Field Measures

#### *Acid Neutralizing Capacity*

Acid neutralizing capacity (ANC, the same test as bicarbonate alkalinity, except that the sample is not filtered prior to analysis) is, as expected, quite high in these limestone-dominated watersheds. There seems to be a correlation between the amount of ANC and the amount of surfacially-exposed limestone within individual watersheds, and transport time (contact time) with the limestone. In any case, the high ANC values bode well in the system's ability to counter the effects of acid precipitation, prevalent throughout Southcentral Kentucky

#### *Discharge*

As it is logistically impossible to measure discharge at every site on every visit (high water conditions typically interfere), these data – with exception of GRGR and NRNR, which are continually monitored by the USGS – are a combination of actual measurements and extrapolations. Through years of measurements we have calculated "unit base flow" for each watershed. If a few sites are measured on a given high flow day, their actual measurements are compared to their base flow values and the percentage over base flow is determined. This "percent above base flow" is entered to the unmeasured sites, and combined with their unit base flow values, discharge is extrapolated. QA/QC checks indicate that these estimates are within 5-10% of actual. General assumptions are that the rainfall was equally distributed over all watersheds, and that each basin is generally synchronized in their response to the event.

#### *Dissolved Oxygen*

Dissolved oxygen levels, for the most part are near or at saturation for all park waters. Values at all current sampling locations show very robust DO levels, reflecting relatively low biological oxygen demand and aerated flow, both in the surface rivers and cave streams. The state DO limits are reported in concentration values (mg/l), and thus do not reflect saturation levels which are governed by temperature – the higher the temperature, the less oxygen is required to maintain saturation. In any case, DO values of park waters are well over the lower limit of 5.0 mg/l.

*Fecal Coliform*

Fecal coliform, although not pathogenic to humans, is derived from the digestive tract of warm-blooded animals, and can be considered an indicator of pathogens. The state's primary recreational contact limit is 200 colonies/100 ml, based on a geometric mean of not less than 5 samples per month, nor exceed 400 colonies/100 ml in more than 20% of all samples taken during the month. Park waters are sampled only once per month, but if sampled more often, results would be very similar to those of the monthly samples. Fecal coliform contamination is very high for nearly all park waters – the lowest values are found in watersheds primarily drained by park lands (MSMS, BSBC) and the Nolin River, where sampling is about 14 km downstream of the dam with little contribution from developed lands within that stretch. High fecal coliform levels are always associated with flood events as the recharge areas flush animal waste into the waterways, and fecal levels are in the 10,000 to 20,000 range. Background levels, when the systems are recharged by stored waters, are low.

*pH*

As one would expect in waters with high bicarbonate alkalinity that drain large expanses of carbonates, pH remains well within the state standards of 6.0 to 9.0 SU. The lower values typically accompany storm events as the higher readings with base flow, paralleling calcium, magnesium, and bicarbonate ions, which is in large part dictated by residence time of the water in contact with limestone. The one outlier is from a January 10, 1991 sample at NRNR. All other parameters with this sample are within normal ranges, however the very low bacterial count with this sample may indicate it is associated with releases from the Nolin Reservoir.

*Specific Conductance*

Specific conductance (SpC), a measure of the ability of water to conduct an electrical current, has no set standards at either the state or federal level. THTH, with its large expanse of carbonates and oil field brines has the highest values, while the limited carbonate exposure and rapid through-put times of BSBC has the lowest readings. During times of flood, when recharge has little residence time with the rock, SpC values are low, and conversely, base-flow times yield the highest values.

*Turbidity*

Turbidity is roughly correlative to suspended solids. No state or federal standard exists for turbidity. All sites experience very high turbidity during times of flood flow, as soil particles are washed into streams with the runoff. A pattern is obvious, especially when the means and 75$^{th}$ percentiles are examined, between turbidity and land use (addressed in a later section). Watersheds, such as THTH, GRGR, and HRTH, with the highest percentage of agricultural land use have the highest turbidity values. For background comparison, look at the range of BSBC (with nearly the entire watershed within the park) when compared to other watersheds. It is worth noting, similar to fecal coliform that a substantial background of turbidity exists even within relatively pristine karst watersheds.

*Water Temperature*

All park waters meet state requirements for water temperature as per their designated uses (all springs and cave streams are Cold Water Aquatic Habitat, while the rivers are classified as Warm Water Aquatic Habitat). The few outliers on the spring sites are due to a sampling event occurring while the Green River was backed up into the spring orifice. The somewhat wider ranges at DFDF and UCUC are caused by the sampling site being located more than 100 m from the spring (within the spring run), while the wider ranges for BSBS and BSBC are influenced by rapid through-flow.

Anions

*Ammonia*

The state warm water aquatic standard for ammonia is 0.05 mg/l. The 95$^{th}$ percentile for most park waters approaches this limit, and on occasion – mostly during drought flow conditions, exceed this standard. It is worth noting the number of samples in the accompanying data, which are lower than most parameters as ammonia, was not always included in laboratory testing. Highest ammonia levels are found in the Green and Nolin rivers and in springs on the north side of the park (BSBS, DFDF, UCUC, and BSBC). Ammonia sources include sewage, but it is unlikely the source for these north side sites as there is little development within their watersheds.

*Chloride*

The state's strictest standard, Cold Water Aquatic habitat, places the upper limit on chloride at 600 mg/l. The highest levels reported in this database range in the 30 mg/l range at THTH. Generally chloride levels are low and are derived from wet atmospheric precipitation. This chemically conservative ion readily passes though soils and bedrock and acts as a natural "tracer". The Green River, which had historic high levels of chloride of over 100 mg/l from oil field brine pollution in the late 1950's has returned to background levels. Brines are likely the source of elevated chloride levels in THTH, and are known to be high in the Mill Hole portion (western) of the watershed and joins the conduit system above THTH but below HRTH and LRTH. A documented brine source is found in Sulfur River of Parker Cave, 4 km upstream of Mill Hole. Other brine-related ions, sodium, sulfate and barium, are also higher in THTH than elsewhere.

*Fluoride*

The only state standard for fluoride is for Domestic Water Supply Use, and is set at 2.0 mg/l. Fluoride levels in monitored park waters are usually below detection limits (BDL). A few outliers, with seemingly random occurrence, have been reported, but all below

1.0 mg/l. These minute levels may be derived from weather rock or leaching from soils. In any case, levels are very low.

*Nitrogen-Nitrate*

State standards for nitrogen-nitrate are set at 10.0 mg/l and are based on human health issues associated with methemoglobinemia, "blue-baby syndrome". Nitrate levels of monitored park waters have low concentrations of nitrogen-nitrate and rarely exceed 3.0 mg/l. Watersheds of HRTH, LRTH, and THTH have the highest levels and have the highest amounts of agricultural and urban development. It is worth noting that atmospheric precipitation of nitrogen-nitrate has a mean of 1.3 mg/l. The highest precipitation nitrate value between September 2002 and October 2003 (the first year the park became a National Precipitation Deposition Program site) was 5.4 mg/l. It is interesting that atmospheric precipitation concentrations of this ion are found near or above that found in park waters.

*Phosphorous*

Phosphorous is generally considered the limiting nutrient for eutrophication. There are no state or USPEA standards for phosphorous. Overall, phosphorous levels are fairly low, commonly under 1.0 mg/l in monitored waters.

*Sulfate*

The state standard for sulfate is 250 mg/l (Domestic water supply use). Even the highest outlier (BSBS) is about 70 mg/l. It is interesting that sulfate levels among the different watersheds parallel strontium values, with the exceptions of HRTH-LRTH and NRNR-GRGR in comparison (the formers higher than latters in strontium but lower in sulfate). These ratios may be of interest to those wishing to further explore the hydrogeochemistry of the watersheds.

Cations

*Aluminum*

No state standard exists for aluminum. In general, aluminum concentrations are low, with the exception of a few outliers. The highest value was taken in Owl Cave (just upstream of Turnhole Spring, and is sampled when Turnhole's flow does not reach the surface of its rise-pool, typical for summer, low flow conditions) on August 10, 1992. Other data from this sample collection are within normal ranges, and do not match other outliers at the Nolin River and Echo River Spring. There is no evidence that these outliers represent a significant threat to park water quality as they are isolated occurrences and not associated with a particular flow condition. Potential sources of aluminum include weathered bedrock.

*Barium*

The Domestic Drinking Water Source standard for barium is 0.2 mg/l. All samples taken are well below this limit (mean values are nearly one order of magnitude below this threshold). Again, Turnhole had the highest values. Potential sources of barium include erosion of bedrock. As the Turnhole basin is the largest groundwatershed monitored, with a wide variety of different rock types, this may explain the slightly higher levels, although it may be derived from oil field brines leaking into the aquifer. In any case, barium remains low, even when compared to Buffalo Spring (BSBC), which can be considered a background reference site.

*Boron*

No water quality standard exists for boron, and levels are very low. It is curious that boron, along with most other "trace" elements is typically higher at Turnhole Spring than other sites. No obvious source of boron is known.

*Calcium*

No standard exists for calcium, and as obvious, calcium levels are very high in the karst waters of the park. Like ANC, there seems to be a correlation between the amount of exposed limestone and contact within the watersheds and calcium levels. Buffalo Creek, where there is little exposed limestone and transfer rates are very high, has a tight range of low values when compared to Turnhole (THTH). The wide range of values of THTH reflect flood and drought flow, which has strikingly different chemistries over these flow conditions (drought flow = high ionic strength waters, flood flow = low ionic strength waters). This pattern is also seen in SpC.

*Cobalt*

No water quality standard exists for cobalt, and the Florida Geological survey states that aquatic life tolerates cobalt concentrations over a wide range (3-10 mg/l), and that mineral weathering is a common source. Cobalt levels in the park's waters are very low and all sites range from 0.0 mg/l to about 0.04 mg/l, well below what is considered detrimental to aquatic life.

*Copper*

Copper limits, as with many metals, are governed by the accompanying hardness values; the greater the hardness, the less likely copper exists in a dissolved phase. Copper values in park waters are very low and generally below detection limits. There is no correlation between copper values and watersheds, as all are low.

*Chromium*

With the exception of two outliers (THTH and NRNR) of 0.190 mg/l, chromium values were bordering on the range of detection (0.01 mg/l), and below the state standards for chronic exposure for warm water aquatic life. One would not expect chromium to be in a dissolved phase in waters with high bicarbonate alkalinities and relatively high pH values that are common throughout park waters. Metals, such as chromium, are only mobile under very low pH ranges and tend to form relatively insoluble carbonate-complexes in highly alkaline waters.

*Lead*

Lead occurs with a mean concentration of approximated 0.02 mg/l, with outliers generally between 0.10 and 0.15 mg/l. There is no obvious explanation of the distribution of lead levels and land use, however there seems to be a slight increase at sites being drained from outside the park.

*Lithium*

The state sets no standards for lithium, and the USEPA Water Quality Criteria (1994) reports that, with respect to human health, it is beneficial in concentrations less than 1.25 mg/l. Lithium values remain very low in all monitored sites, generally not rising above 0.005 mg/l, however THTH consistently had values higher, with a mean of 0.011 mg/l.

*Iron*

Iron levels, set by the state for chronic exposure of warm water aquatic life is 1.0 mg/l. Iron, like most metals, does not exist in large concentrations in high-alkaline waters common to limestone terranes – one reason why Kentucky produces the best whiskies in the world by using limestone spring waters, which are largely devoid of iron that imparts a bitter taste to the distillate. With the exception of one outlier at THTH (1.35 mg/l) iron concentrations are very low, generally less than 0.10 mg/l. Likely iron sources are from the weathered silisiclastic bedrock which contains minor amounts of pyrite.

*Magnesium*

Limits are not set for magnesium at state or federal agencies. Magnesium sources are weathering of bedrock, like the ubiquitous dolostone found throughout the basal carbonate aquifer. Magnesium, like calcium, tells us something about the hydrogeology of the watershed. THTH has the widest range, bracketed by lower concentrations during flood flow, and higher levels during base flow, as reflected in longer residence times of the water in this carbonate-dominated watershed. Conversely, the limited exposure of carbonates in the BSBC watershed, coupled with rapid groundwater transfer, narrow the magnesium range.

*Potassium*

No state standard exists for potassium, and sources include commercial fertilizers and natural weathering from bedrock. Potassium levels range from zero to an overall mean of about 1 mg/l. THTH consistently had the highest levels of this ion, perhaps reflective of the agricultural-dominated land use of its watershed.

*Silicon*

There is no state or federal limits on silicon, and these data were collected as an element in the broad-spectrum of ion analysis. The most likely source of silicon is from weathered silisiclastic grain cement, common throughout all watersheds. Range variations may be caused by the amount of available siliceous strata within a given watershed.

*Sodium*

No state or federal limits are set for sodium. Relative concentrations of sodium parallel those of chloride in every watershed. Sodium sources are natural background from precipitation and oil field brines.

*Strontium*

No state standard exists for strontium, and the USEPA (also with no set limit) claims that strontium (is believed essential for human and animal health) is no more toxic than calcium. Strontium levels are predictable per watershed with the highest found in BSBS. Dye tracing of the Big Spring watershed suggests that strontium is migrating upwards along the Cub Run fault from the evaporite beds of the lower St. Louis Limestone. These beds contain gypsum and anhydrite, and celestite ($SrSO_4$) is commonly found with these calcium-sulfate minerals. Strontium variations in other watersheds may simply be indicative of the amount of celestite being dissolved into their waters.

*Sulfur*

Sulfur, of course, is a component of the sulfate molecule, and produces the same pattern across the watersheds as does sulfate. There is no state or federal standards for sulfur.

*Zinc*

The state sets a low limit for zinc (the highest standard set by Chronic Warm Water Habitat). The USEPA Secondary Maximum Contaminant Level is set at 5.0 mg/l. The highest value found in the data was an outlier of 0.2 mg/l at LRTH. Zinc values are essentially BDL across all monitoring locations, as would be expected as dissolved phase zinc, like most heavy metals, can only exist in waters of very low pH.

## Flood Pulse Water Quality

Research by Ryan and Meiman (1996) and Hall (1996) demonstrate that the full-range of water quality variations are best resolved with circum-storm, or flood pulse sampling. Just as the stage and velocities of flood pulse waters undergo rapid and spectacular change – a ten-year storm will produce 30 meter rises over 12 hours within Logsdon and Hawkins Rivers – water quality constituents change concentrations just as significantly. As mandated by the park's original, NPS Water Resources Division-approved Water Quality Monitoring Program, flood pulse monitoring defines the non-point-source contaminant maxima, as nutrients, bacteria, pesticides, and sediments are washed into and through the karst aquifer (the surface rivers as well) within a matter of hours or days.

When comparing flood pulse sampling results, from one storm to the other at the same site, one must realize the natural and man-created variables, including: antecedent condition, rainfall intensity, distribution within the watershed, and volume, as well as the synoptic state of land use (for example, area of tilled land) and available contaminants. Nonetheless, these contaminants are quickly washed into the caves and created a pulse with a steep ascending limb and a long tailing recession (a chi-squared waveform).

Defining water quality "maxima" serves two purposes. First, it helps define maximum concentrations of runoff-derived contaminants, which cause acute exposure risks for aquatic life. If one were to rely solely upon monthly non-conditional synoptic sampling (samples taken on a fixed calendar date, regardless of flow condition), it would take many years, perhaps decades or more, to sample coincidentally with peak concentrations. Secondly, circumstorm sampling, by design, captures the entire flood event which, when contaminant data are multiplied by flow, yields mass flux [concentration (mg/l) * flow (l/s) = mass flux (mg/s)] and the signature of its curve tells the nature of import and movement of the contaminant through the aquifer.

In his MS Thesis, Hall (1996) conducted circumstorm sampling at the downstream ends of the Cave City subbasin (Logsdon River – LRTH), the Patoka Creek subbasin (Hawkins River – HRTH), and the Mill Hole subbasin (Mill Hole – MHTH) of the Turnhole Spring groundwater basin. Several events were sampled over a two-year period for a variety of parameters. We can examine a single event, for a select group of parameters at a single location to get the general idea of water quality's response to a flood event.

As shown in Figure 10, the moderate rainfall event of May 1, 1995 (Julian day 121) produced an immediate response in stage in Logsdon River, followed directly by a decrease in SpC, followed by a turbidity pulse. The bimodal signature of two peaks in SpC and turbidity are common and thought to be the result of the initial arrival of freshly input storm waters and the subsequent arrival of conduit-adjacent stores, released from storage after the main head wave has passed. Another possibility is that the first pulse is from inputs from the lower reaches of the basin arriving as a distinct pulse prior to that of distal inputs. This signature yields information on the nature of the aquifer in terms of recharge, storage, and flow.

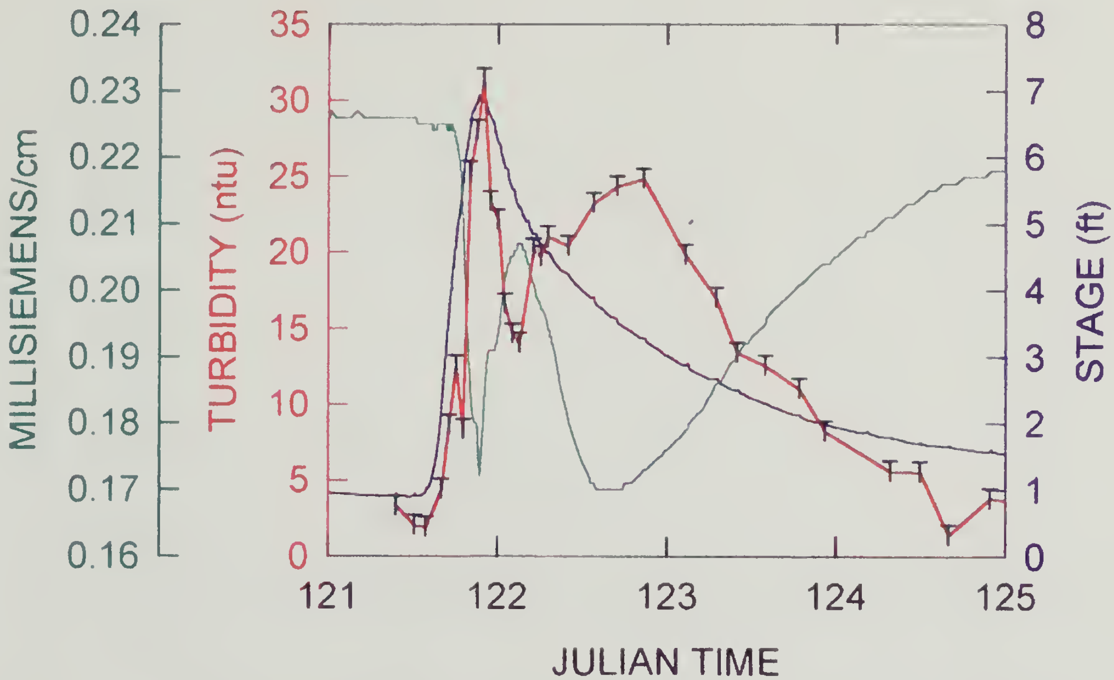


*Figure 10. Specific conductance and turbidity response at the Logsdon River monitoring site to a moderate recharge event, from Hall (1996). Julian days are noted on the X-axis.*

The chemograph of chloride (Figure 11) is typical of contaminants that are being delivered into the aquifer regardless of flow. There is a slight decrease in chloride concentration as the main pulse of water passes the monitoring site. When multiplied by discharge (Figure 12), there is an increase in chloride mass flux, but only as a function of flow. This response means that chloride is not being washed into the aquifer by the runoff event, but being delivered at a constant rate.

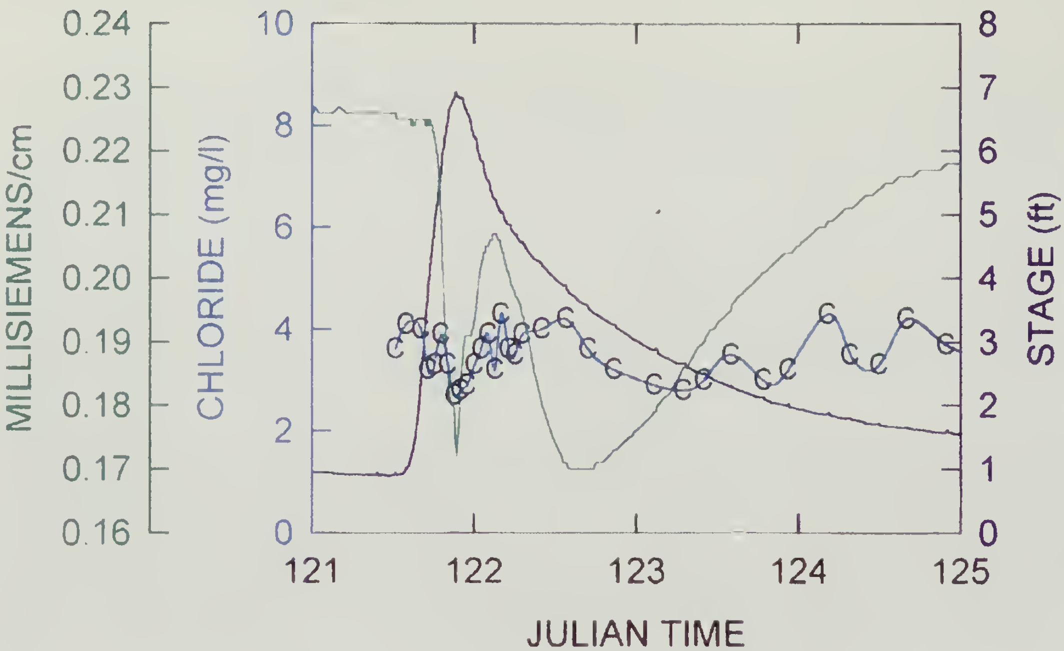


*Figure 11. Specific conductance and chloride response to a moderate recharge event at the Logsdon River monitoring site, from Hall (1996). Julian days are noted on the X-axis.*

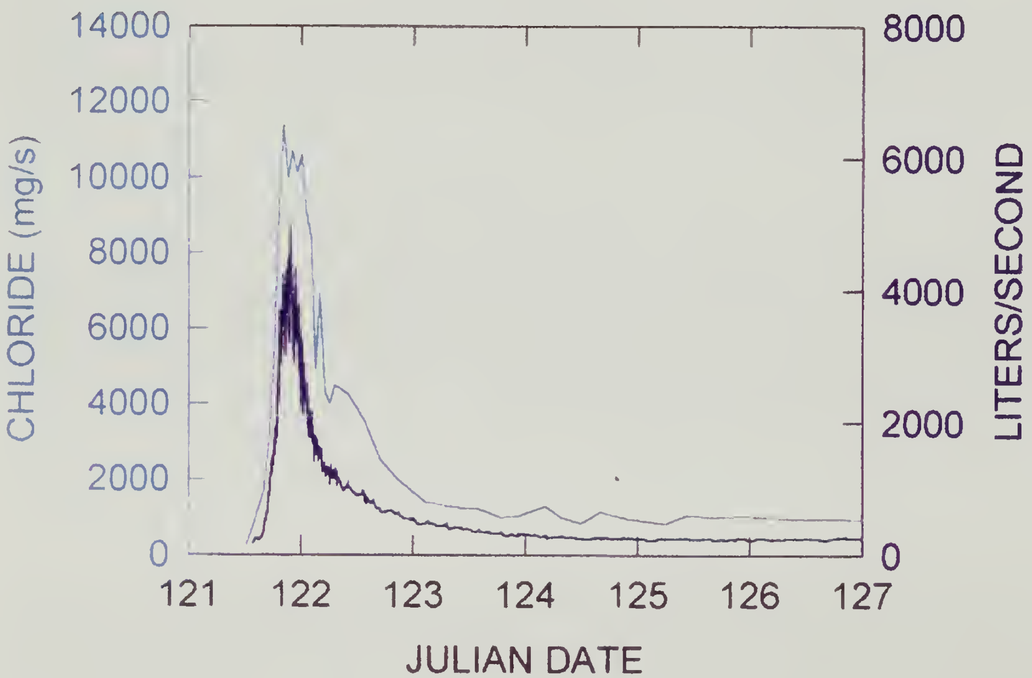


*Figure 12. Chloride mass flux and discharge response to a moderate recharge event at the Logsdon River monitoring site, from Hall (1996). Although chloride mass flux increases in response to flow, its response is concordant with discharge and only varies by five times over base conditions. This "constant" signal is indicative of a contaminant entering the aquifer at a relatively constant rate.*

Conversely, let us examine the response of fecal coliform bacteria (Figure 13). There is not an increase in fecal coliform until some 10 hours after stage, SpC, and turbidity, peaking at 20,000 col/100ml 18 hours after the stage peak. The timing and temporal lags between these components suggests that fecal coliform is being imported into the aquifer with runoff, arriving coincidental with the second SpC pulse – lending credence to the second argument of overall pulse signatures discussed above. In either case, the tremendous rise in fecal coliform mass-flux is obvious as the peak of bacterial concentrations multiply with the tailing discharge curve to produce a huge flux increase in bacteria of over $2 * 10^8$ col/s (200,000,000 col/s from a background of near zero) (Figure 14).

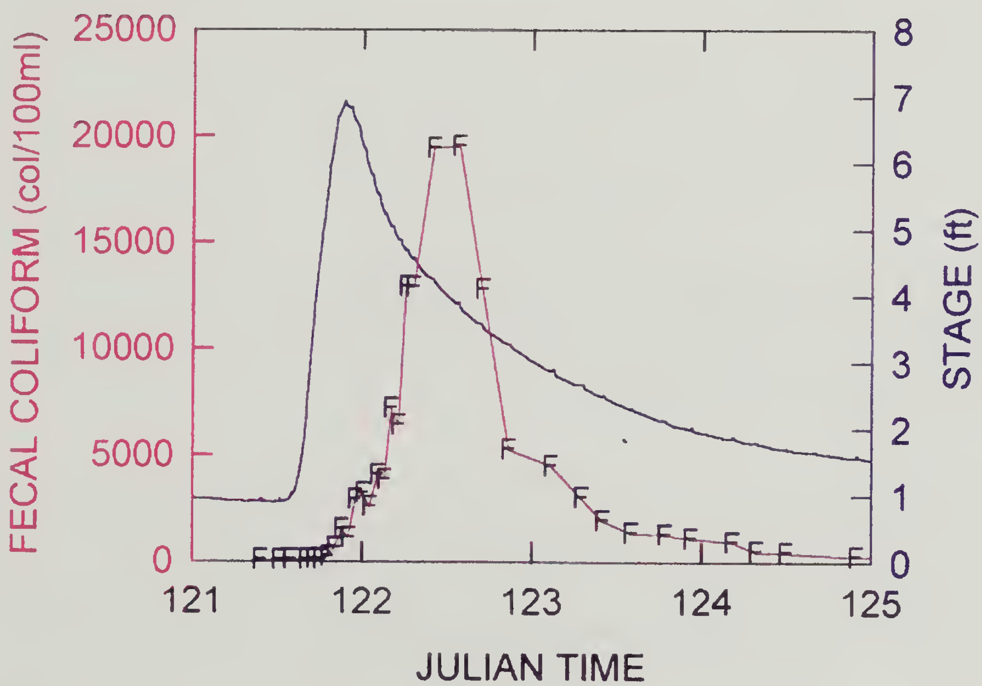


*Figure 13. Fecal coliform bacteria response to a moderate recharge event at the Logsdon River monitoring site, from Hall (1996). Note the out-of-phase relationship between peak stage and peak bacteria levels, indicative of the main bacterial source being in the distal portions of the watershed. Julian days are noted on the X-axis.*

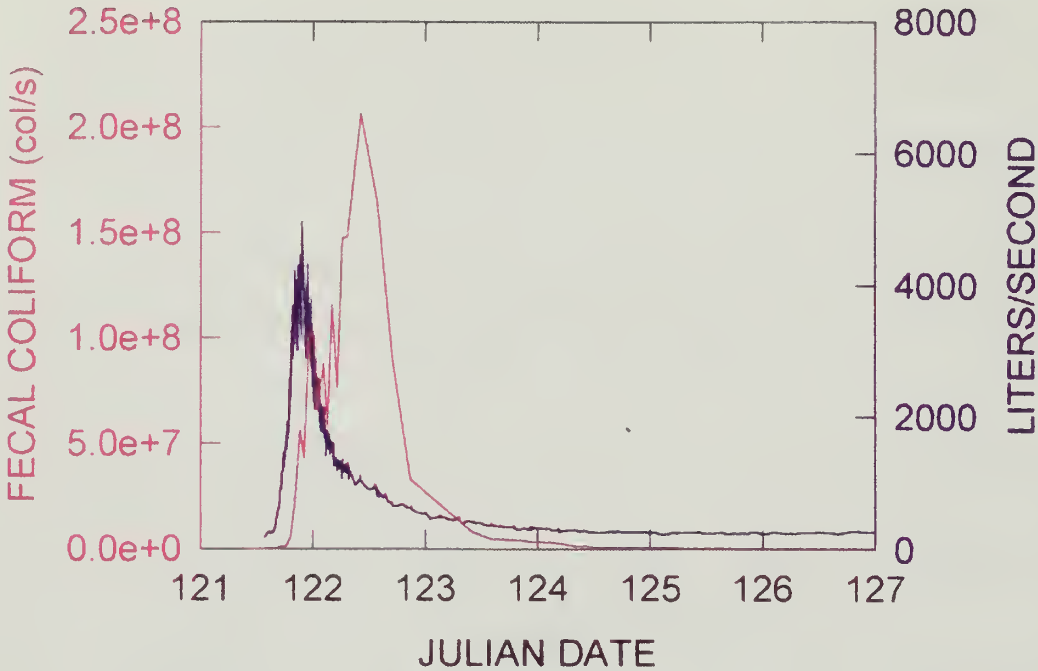


*Figure 14. Fecal coliform mass flux and discharge response to a moderate recharge event at the Logsdon River monitoring site, from Hall (1996). Note that the bacterial pulse is out-of-phase with the discharge peak (occurring on the falling limb of discharge) and that fecal coliform mass flux is many orders of magnitude above antecedent levels, indicative of a run-off induced contaminant.*

It is important that the reader realize that the flood pulses shown here are moderate at best, with stage increases of about two meters – a response of a precipitation event just large enough to produce surface run-off into the many ponors and dolines of the watershed. In general, the larger the event – in terms of rainfall intensity and volume – and the amount of time transpired since the last event, the larger the flux of non-point contaminants.

## Pesticides

Since 1990, there have been several efforts designed to take a closer look at pesticides in the park's waters. As a parameter of the park's monthly non-conditional synoptic sampling program, pesticide analysis has confirmed hypotheses on spatial and temporal occurrence of these compounds. For example, watersheds with a dominance of agricultural activities have the highest amounts of pesticides in their waters. The water quality data set (1990-1992, and 1997-1998) relied on immuno-assay screening for triazine-class herbicides (atrazine, by far the most commonly applied and commonly found, followed by simazine and cyanazine) and if positive, the master sample is sent to a laboratory for full analysis (MS/GC). Monthly samples found atrazine (2-chloro-4-ethylamine-6-isopropylamino-S-triazine) in the largest agricultural watersheds; Turnhole Spring, Pike Spring, Echo River (during periods of overflow from Turnhole), the Green and Nolin Rivers, immediately following peak application periods (April – June).

Atrazine concentrations were commonly found in the 1.0 ppb range. Metolachlor was the second most common pesticide and typically below 0.5 ppb. Sporadic low concentrations of linuron, and alachlor were found as well.

More surprising was the re-occurrence of atrazine in autumn in the Green River, and to a lesser extent, the Nolin. This pattern has been observed each year (Figure 15). Discussions with local NRCS conservationists confirmed that atrazine was only applied prior to and immediately following spring planting. It is interesting that this re-appearance of atrazine is coincidental with draw-down of the Green and Nolin River Lakes. It seems that the lakes, which fill to summer recreation pool while the atrazine is applied in the spring, are acting as atrazine capacitors. These capacitors release their charge (atrazine) when the lakes are lowered to winter pool. This alone would not explain the sudden re-appearance of this chemical, as the lakes discharge water throughout the year. However, shortly after peak application, the lake undergoes a thermal stratification, and just prior to draw-down, the lakes "turn-over" or more accurately, de-stratify. Atrazine, both long-lived and with a high affinity for fine organic particles, may be "stored" within the organic-rich and anoxic "floc-zone" comprising the lower two meters of the lake. When the lake destratifies, the floc is mixed into the lake and released into the river.

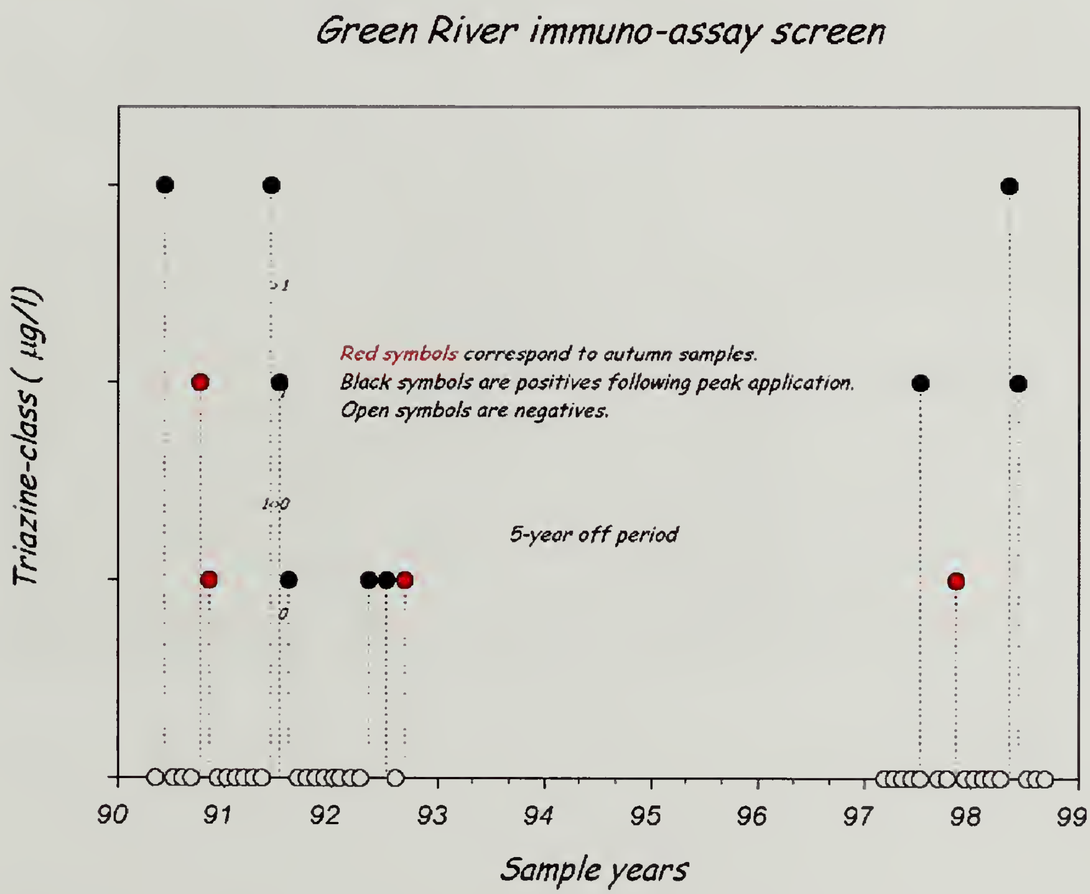


*Figure 15. The annual re-occurrence of atrazine in the Green River.*

Atrazine, due to its environmental persistence – the compound is not easily destroyed by sunlight, water, or organic means and can last for well over one year after application – and its common use throughout Southcentral Kentucky, has been the focus of two other major studies in and around the park. Anderson (2002) sampled Hawkins and Logsdon rivers during runoff-producing rainfall events after spring application. His primary sampling site was the Hawkins River well, a focal point of many studies, which intersects Hawkins River 40 m upstream of its confluence of Logsdon River. This point also marks the downstream terminus of the Patoka Creek subbasin (72.4 $km^2$) of the Turnhole Spring karst groundwatershed (Figure 16). Anderson collected samples during the course of several events, each sample split into filtered and unfiltered aliquots to determine if the pesticide is directly related to fine sediment particles. He found that, at least during his sampling period, nearly all atrazine moving through the cave was adsorbed to the fine sediment and was not dissolved in the water (Figure 17). His results are typical to other studies linking atrazine to sediment. It must be noted, for sake of data comparison, that all atrazine analysis from the park's water quality sampling program are not filtered.

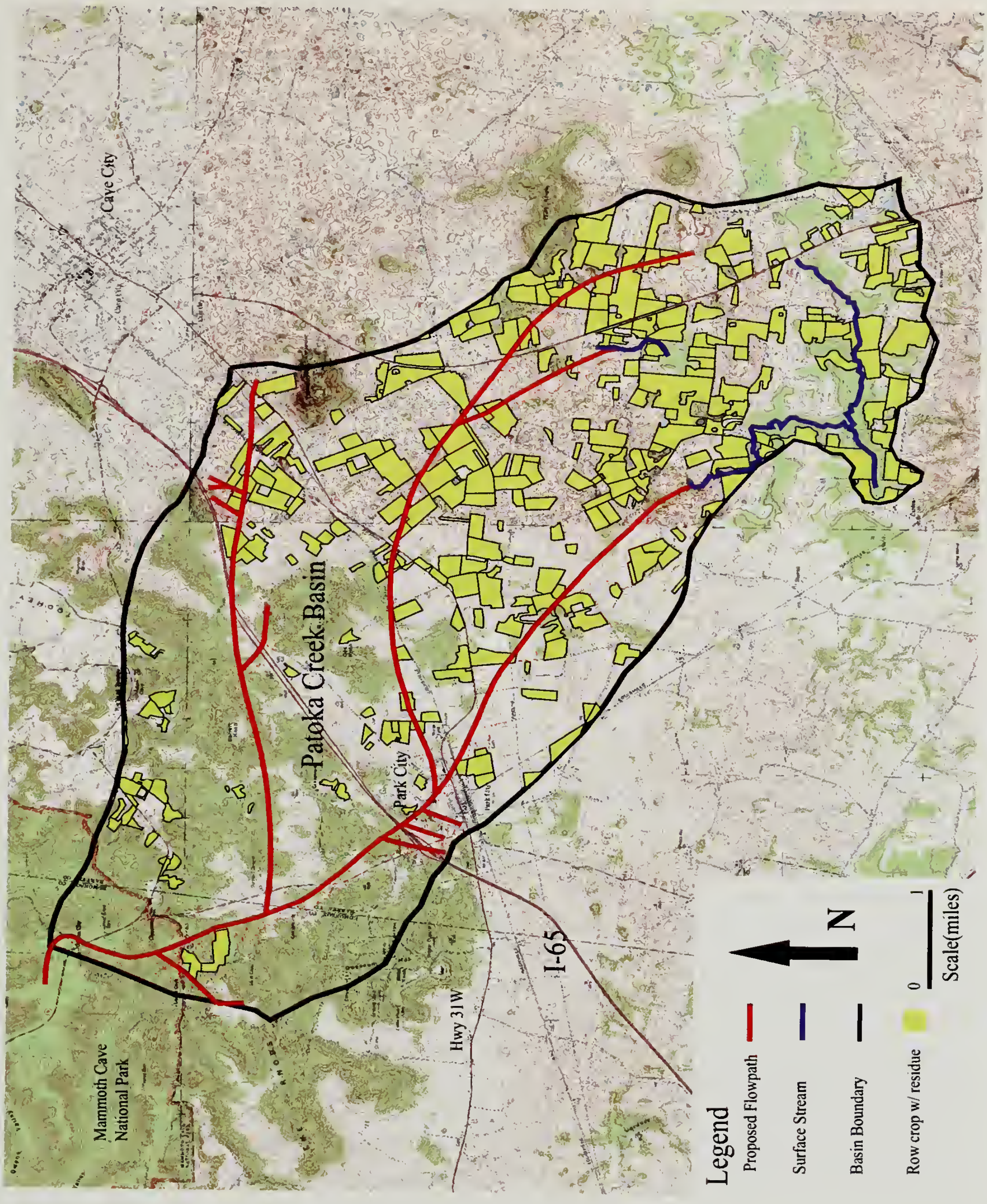


*Figure 16. Row crops within the Patoka Creek subbasin in 1990 (Anderson, 2002).*

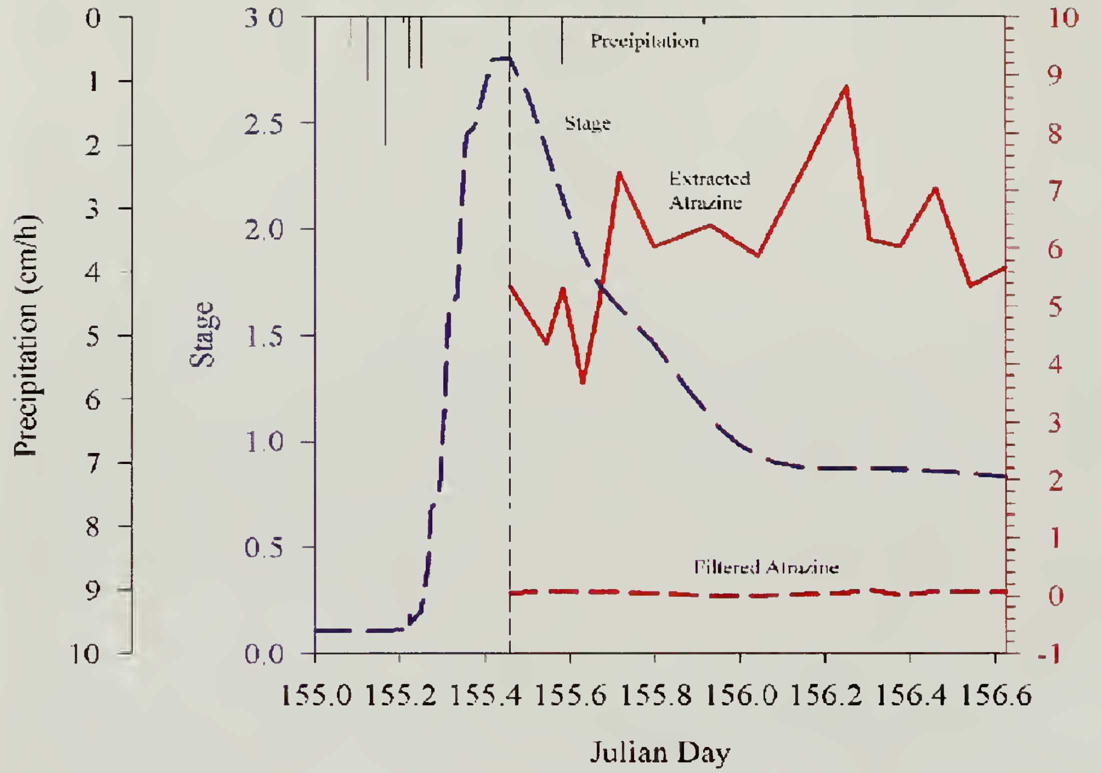


*Figure 17. Atrazine response to a rainfall event at Hawkins River. Note that split samples that were filtered (0.45 µm) also removed the atrazine, indicating the compound's affinity to particles (Anderson, 2002).*

Western Kentucky University conducted atrazine sampling on rainwater samples during the spring and summer of 2003. Rainwater collectors were stationed at sites over Southcentral Kentucky, including the park, and were sampled after every precipitation event. The results were surprising. Of the 199 samples collected between April 17 and August 29, 180 (90%) were greater than 0.05 ppb, 43 exceeded the 1.00 ppb USEPA maximum contaminant level for drinking water, six samples were over 2.00 ppb, and two samples were greater than 3.00 ppb (Kuykendall and Groves, 2003). Four samples taken sequentially during an April storm event showed a scavenging effect as the first sample was 3 ppb, followed by much lower concentrations in subsequent samples. Samples collected during peak herbicide application (ending on May 31) had a mean concentration of 0.70 ppb, almost three times higher than later samples (0.25 ppb). Mechanisms for atrazine dispersion and deposition into the atmosphere are not known at this time.

In a related study, Western Kentucky University in cooperation with Mammoth Cave National Park conducted a synoptic sampling of park waters on June 10, 2003 in conjunction with the park's water monitoring round. Twenty-five samples were taken, and although no atrazine is applied within the park, it was found above the assay detection limit of 0.04 ppb in 22 (88%) of the samples (Groves and Meiman, 2003).

Mean concentrations were found in the following waters: shallow surface depressions (0.29 ppb), surface streams and rivers (1.32 ppb), cave streams (0.92 ppb), perched carbonate (Haney) springs (0.06 ppb), ponds (0.09 ppb), and other small springs and seeps (0.14 ppb).

In 1993, the park conducted a limited pesticide survey, concentrating on headwater streams, cave streams, and springs within the Turnhole Spring watershed. Samples were taken at several sites on daily intervals following peak application periods. Automatic water samplers were deployed to Little Sinking Creek (draining approximately 2,000 hectares of headwaters) and Owl Cave, near the downstream terminus of the basin. The spatial distribution of pesticides is summarized in Figure 18. By far, due to proximity to agricultural activities and little dilution from non-row-crop farming, the highest concentrations were found in the sinking stream headwaters of the basin. Figure 19a and 19b are time series samples taken at Little Sinking Creek and Owl Cave following moderate rainfall events.

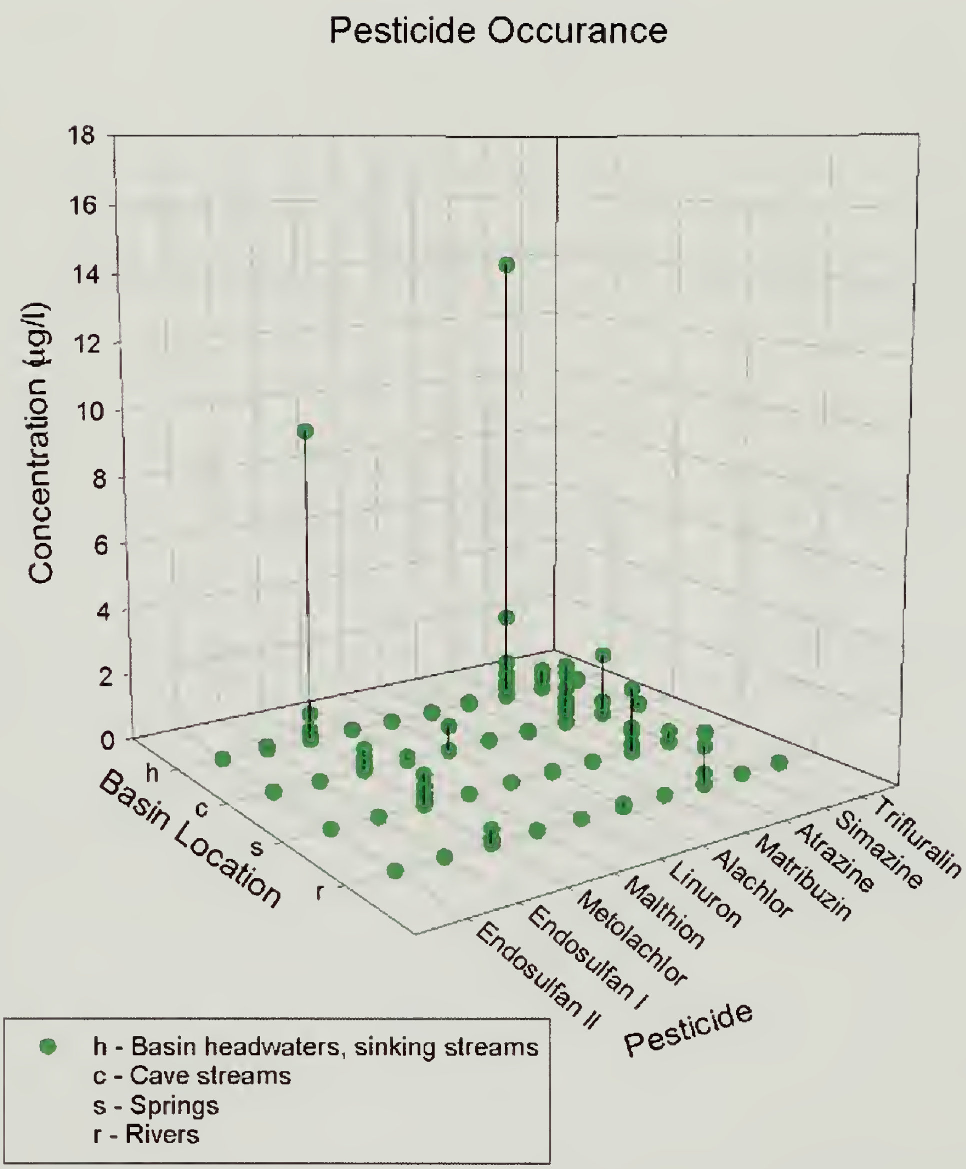


*Figure 18. The highest concentrations were found in the headwater streams, which are directly adjacent to row-cropping practices and receiving flow from the fields. For reference, the drinking water standard for atrazine is 3.0 µ/l.*

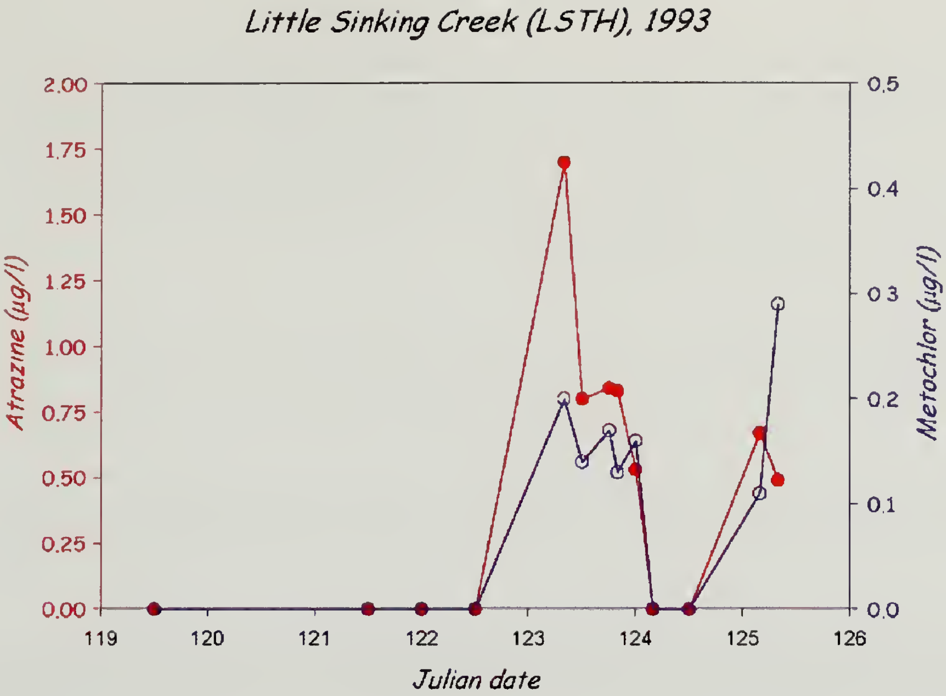


*Figure 19a. Time-series sampling of Little Sinking Creek. The two peaks of pesticides are correlative to two rainfall events, one on day 122 and the second on day 124.*

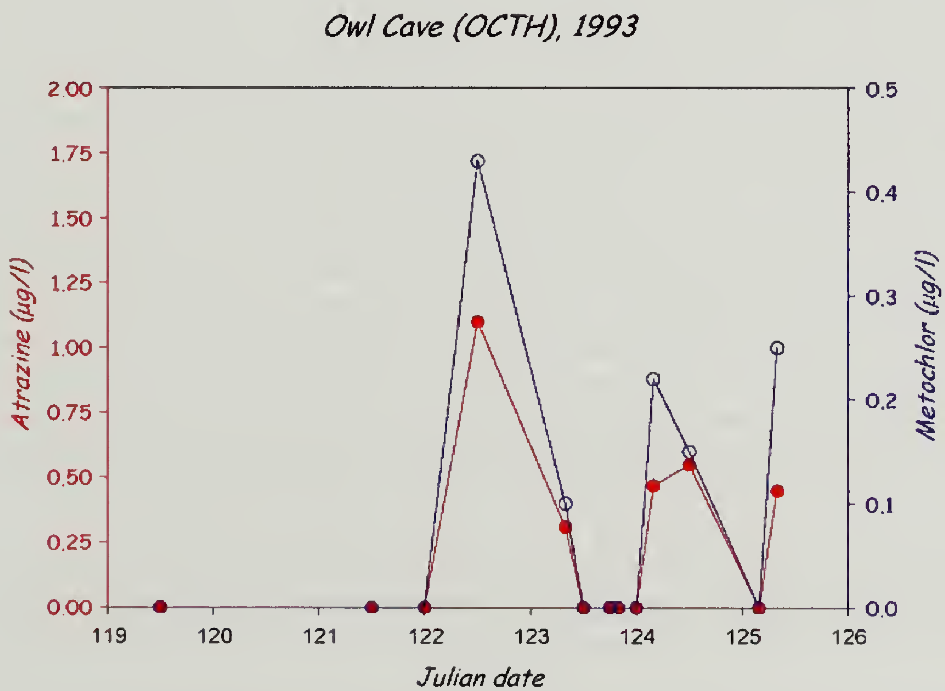


*Figure 19b. Time-series sampling at Owl Cave. Again note the pesticide peaks associated with rainfall events. Temporal differences between this and the distal, upstream Little Sinking Creek site are due to additional tributaries entering the system upstream of Owl Cave.*

## Sediment Quality

Although the past decade has seen quite a bit of water quality monitoring, little attention has been paid to sediment toxins. Many aquatic organisms, including mussels, aquatic insects, and meo- to microscopic fauna live within stream sediments. Pesticides adsorbed to silt and clay particles are flushed into the aquifer; heavy metals such as zinc are introduced from parking lots and roadways; chromium, copper, lead and zinc have been dumped into sinkholes from industrial processes.

The NPS Water Resources Division funded "Chemical Analysis of Toxins in Stream Sediments" (PMIS 47377) during FY01-02. To assess sediment quality a series of bedload and core stream sediment samples were collected and analyzed for total organic carbon, grain size, metals, organochlorines and organophosphates. Core and bedload stream sediment sampling occurred during two late summer synoptic events spanning the park and adjacent watersheds with known or suspected water/sediment quality issues in 2001 and 2002. Sampling locations coincide with biological inventory stations and reflect the spectrum of land-uses of Southcentral Kentucky. The sampling protocols and strategies were adapted from the USGS NAWQA Program (USGS Circular 1112 - Design of the National Water-Quality Assessment Program: Occurrence and Distribution of Water-Quality Conditions).

Site selection intentionally spanned the park as well as adjacent karst watersheds that eventually flow into the park via the Green River and sites that are well downstream from the park in Bowling Green, Kentucky. These sites serve as a means of comparison for the park samples, critical in data interpretation as no federal or state standards exist for sediment quality. The sites in Bowling Green (Lost River Blue Hole and Lost River Rise) for example, indicative to karst watersheds that have received decades of urban and industrial contamination, serve as an example of a severely impacted watershed.

The results of this first examination of sediment quality, specific to occurrence and concentrations of heavy metals, organophosphates, organochlorides, total organic carbon, grain size, total petroleum hydrocarbons, and dioxin congeners were correlative to upstream land uses within groundwatersheds and within expectations of low-temperature aqueous geochemistry. For example, metals such as cadmium, chromium, copper, lead and zinc were found in sediments recharged by urban and industrial areas even though no metals are found in the waters transporting the sediments. The abundance of bicarbonate ions, expressed in part by the high pH values (7.5 to 8.2 SU), quickly buffer acid recharge, even if containing high levels of metals, resulting in the precipitation of low-soluble metal-carbonate compounds ($ZnCO_3$ for example). The most startling result was the occurrence of dioxin congeners within a groundwatershed, which ultimately drains into the Green River immediately upstream of the park.

Four sediment samples were taken in FY02 for dioxin analysis. All four were positive for congeners octachlorodibenzo-p-dioxin (OCDD) and one positive for 1,2,3,4,6,7,8-heptachlorodibenzo-p-dioxin (HpCDD). All four sites are immediately upstream of the park and will enter the park via the Green River entrained in sediments.

In 1967, a train loaded with Agent Orange derailed near Mammoth Cave. Many drums were ruptured and buried in sinkholes on-site. The wreck and burial occurred near the town of Horse Cave Kentucky, within the Gorin Mill groundwatershed, which drains through the Hidden River and Hicks Cave systems and into the Green River at Gorin Mill and Hicks Springs, approximately 20 km upstream of Mammoth Cave National Park. Gorin Mill, the largest spring in the state, is the underflow spring of the basin, while Hicks is only active under high flow or flood conditions. Spring sediment size is representative of this flow distributary as Gorin Mill is characterized by fines where courser sediments dominate Hicks Spring. Sediment samples for dioxin congener analysis were taken at Hidden River Cave (downstream of the spill site), Gorin Mill Spring, Green River downstream from Gorin Mill, and Hicks Springs. All four locations tested positive for dioxin congeners as listed below (Table 13).

*Table 13. Dioxin congeners found in sediments within the Gorin Mill karst watershed and the Green River proximal to its springs. Results expressed as "parts per trillion" (ppt).*

| ***Site*** | ***Dioxin congener: ppt dry weight*** |
|---|---|
| **Hidden River Cave** | OCDD: 233 |
| **Gorin Mill Spring** | OCDD: 470 |
| **Green River below Gorin Mill Spring** | OCDD: 170 |
| **Hicks Spring** | OCDD: 700, 1,2,3,4,7,8-HpCDD: 26 |

At this point we know that dioxin congeners are in the sediments of two springs feeding the Green River and in the Green River upstream of Mammoth Cave National Park. We know that the USEPA considers the toxicity of the OCDD congener to be about 1/1000th less toxic than the fully-chlorinated congener 2,3,7,8-TCDD (tetrachlorodibenzo-p-dionix, the most toxic congener with water quality standards set at 0.01 ppt). No standards are set for the congeners found, however for means of comparison (with OCDD being 1/1000th less toxic than 2,3,7,8-TCDD), OCDD levels were found to be seven times higher than what is considered dangerous. We also know that the USEPA, although not setting a threshold for sediments, consider that dioxin levels in sediments should not be as low as that for water. Dioxin congeners have been studied in various environments upon scores of species. Congeners present in the sediments of this watershed are considered to have real potential to bioaccumulate in both fish and invertebrates (USEPA, 2000).

We have consulted with aquatic toxicologists with the USGS Leestown Science Center. Craig Snyder, Toxicologist, examined these data, and through personal communication in 2004 and stated:

> There are many different forms or congeners of dioxin. All forms tend to be highly persistent in the environment, with USEPA-reported half-lives ranging from months to years in soils and sediments and 3 to 27 years in humans. The toxicity of different congeners varies over several orders of magnitude and is

related to the degree and location of chlorination on the ring structure. Increasing chlorination at the 2nd, 3rd, 7th, and 8th carbon locations on the ring structure is associated with increased toxicity. Thus, 2,3,7,8-TCDD (all 4 locations chlorinated) is the most toxic form of dioxin. By contrast, OCDD, which is not chlorinated at all locations and was most abundant and widespread in the Green River screening study, is only 1/1000th as toxic as 2,3,7,8-TCDD.

Dioxins have the potential to biomagnify within food webs due to an affinity for fat tissue, but again this potential is significantly affected by chemical structure. OCDD has less potential to bioaccumulate – bioaccumulation factor (BCF) of 34-2226, as opposed to a BCF of 37,900 to 128,000 for 2,3,7,8-TCDD. There is considerable variability in the amount of biomagnification among food webs and species. Dioxins also have a high affinity for soil and sediment and the potential for bioaccumulation is lessened in the presence of sediment. However, sediments also serve as a reservoir for dioxin and, therefore, increase their persistence in the environment.

Because of their persistence, dioxins have the ability to move substantial distances. For example, dioxins were measured in fish as far as 11 km downstream of an abandoned source site. Unfortunately, there does not appear to be much detailed information on the toxicity of individual dioxin congeners to different aquatic species, 2,3,7,8-TCDD being the one exception. Recommended safe levels of this form for freshwater aquatic life are 0.01 ppt in water and 34 ppt in tissue. Concentrations of 10-12 ppt have been recommended as the upper limit in food items for birds and other wildlife. EPA's ecological risk assessment methodology for other dioxins appears to be based on estimates of 2,3,7,8-TCDD toxicity equivalents (TEQ) for each dioxin congener. For example, the TEQ for OCDD is calculated by multiplying the environmental concentration by 0.001. So, for the Hick Spring site, which had the highest reported concentration of OCDD, the TEQ would be 700 x 0.001 = 0.7 ppt 2,3,7,8-TCDD.

The park is set to begin a two-year assessment of the dioxin issue (FY06-07). The first year will consist of sediment sampling downstream from the Gorin Mill watershed, defining the extent of the dioxin-containing sediments. The second year will focus on tissue sampling of mussels within the defined reach. Recent (early 2006) examination of stream sediment dioxin data may indicate that these congener concentrations are well within what is considered background levels in North America. A peer review group is being gathered by WRD and the author at the time of this writing to determine if this study is even needed.

The data presented below are metals from total sample digestion and total petroleum hydrocarbons. In comparison with samples taken from the Gorin Mill Spring karst watershed – where years of metal plating waste waters were disposed into the aquifer and the Lost River karst watershed draining Bowling Green, and its many urban and industrial inputs – the sediment quality of the park is good. Of concern would be the slightly elevated levels of lead and chromium in Hawkins River and Mill Hole, both within the Turnhole Spring karst watershed. Sources of these metals are unknown, although both drain large potions of Interstate 65.

## Description of Sampling Locations

As the main objective of the analysis was to determine if, and to what concentration and extent do contaminants exist in the streambed sediments of Mammoth Cave, the sampling net was extended beyond park watershed boundaries, in areas of known pollution in order to gain a sense of comparison (Table 14). As these sites are new to the reader, a brief site description is needed to aid data interpretation.

*Table 14. Locations for sediment quality sampling.*

| Site | Description |
|---|---|
| HRGM | Hidden River Cave; downstream of metal plating waste disposal |
| GOUS | Green River; upstream of Gorin Mill Spring |
| GOGM | Gorin Mill Spring |
| GODS | Green River; downstream of Gorin Mill Spring |
| HSUS | Green River; upstream of Hicks Spring |
| HSGM | Hicks Spring |
| HSDS | Green River; downstream of Hicks Spring |
| LRBH | Lost River Blue Hole; Bowling Green, Kentucky |
| LRLR | Lost River Rise; Bowling Green, Kentucky |
| MHTH | Mill Hole |
| OCTH | Owl Cave; Mammoth Cave National Park |
| HRTH | Hawkins River; Mammoth Cave National Park |
| LRTH | Logsdon River; Mammoth Cave National Park |
| RSER | River Styx; Mammoth Cave National Park |
| GTPS | Golden Triangle; Mammoth Cave National Park |
| CIGR | Green River; at Crump Island, Mammoth Cave National Park |

Seven sites were sampled in association with the Gorin Mill Spring karst watershed, Kentucky's largest, covering 390 $km^2$. This watershed, which drains into the Green River via Gorin Mill and Hicks Springs approximately 20 km upstream of the park, experienced years of improper disposal of metal plating waste in the city of Horse Cave. For over a decade, the Ken-Dec corporation disposed of low-pH plating wastes through the municipal sewage treatment plant of Horse Cave, whose effluent was either disposed in a sinkhole or an adjacent dry well and into the underlying Hidden River Cave, a major tributary of the Gorin Mill Spring watershed. In addition, in 1967 a train derailment in Horse Cave caused an untold number of drums of Agent-Orange to rupture. Leaking drums were buried on site.

The Gorin Mill watershed, like others in Southcentral Kentucky, has a complex developmental history which is manifested in a distributary flow system. Gorin Mill

Spring, the largest spring in the Commonwealth, is the underflow spring of the watershed, discharging large volumes of water at all times. Flood flows do not greatly effect this spring as Hicks Spring, 6 km further downstream on the Green takes all excess discharge. Sediment size at the springs express this flow relationship as only fine sediments are found associated with Gorin Mill, and coarser sediments at Hicks Spring. Four other sampling sites associated with the springs include locations upstream and downstream on the Green River.

Two other distal sites were chosen to examine sediment quality in watersheds drained by urban areas. Lost River Blue Hole (a large spring that emerges and enters Lost River Cave) and Lost River Rise (the ultimate resurgence of the watershed) in Bowling Green were chosen. Both sites have a history of urban and industrial pollution. The Lost River watershed enters the Barren River and does not flow into the park.

Mill Hole, a large karst window draining the 112.2 $km^2$ Mill Hole subbasin of the Turnhole Spring watershed, was sampled. Its watershed has a history of agriculture and oil/gas exploration.

A few sites were chosen coincidental with water quality sampling. These include Owl Cave (a surrogate for Turnhole Spring as it is only 1.5 km upstream from the spring), and Hawkins and Logsdon Rivers. The Golden Triangle, a tributary of Pike Spring, was chosen to represent pristine, or background conditions, as it is recharged solely by park lands and is habitat for the Kentucky Cave Shrimp. Crump Island was sampled to determine if the contaminants from the Gorin Mill basin has made it to the park in appreciable concentrations.

## Results

As there are no state or federal standards for sediment toxins, the following discussion is more a matter of relative comparison from one site to another rather than against a set limit. The impact of sediment toxin levels on their dependent biota is not known. Data are presented for both bedload (a sampling of the upper two centimeters) and core (a composite 0.75 m core) samples. Each site was sampled twice; once each in the late summers of 2000 and 2001. Complete scans for organophosphate and organochloride pesticides were done for the 2000 samples but were not found. Graphics of sediment quality results can be found in Appendix B.

*Aluminum*

Within the park's drainage area, Gorin Mill Spring (GOGM) is a source of aluminum. The springs have elevated concentrations, and for Gorin Mill Spring, it is substantial enough to increase the metal concentration within the river (GODS > GOUS). Lost River Blue Hole (LRBH) had by far the highest aluminum sampled. It is interesting that Lost River Rise (LRLR) is quite a bit lower than its major tributary (LRBH).

*Arsenic*

Arsenic concentrations, perhaps because all were low, showed no particular pattern or signature that might suggest a source.

*Barium*

Barium concentrations were almost exactly the same as those found for aluminum. Gorin Mill Spring (GOGM) seemed to raise the barium levels in river sediments. Again, Lost River Blue Hole (LRBH) had the highest concentrations, higher than the Lost River Rise (LRLR) further downstream. This pattern may be the result of dilution or a slug of contaminated sediments which have yet to arrive at the Rise.

*Beryllium*

Like arsenic, beryllium occurs in very low amounts. The highest levels are found at the Lost River Blue Hole.

*Cadmium*

Hidden River Cave (HRGM) was the recipient of metal plating waste and they may be a source of the elevated cadmium. It is interesting that the highest cadmium found was in the Green River downstream from Gorin Mill Spring (GODS). Higher concentrations in the river (note that no cadmium was found upstream of the spring) than the spring or cave stream may indicate that the cadmium-laden sediments have for the most, been washed through the cave and into the river.

*Chromium*

Seemingly substantial concentrations of chromium still exist in the Gorin Mill watershed, enough to quintuple the amounts in the river downstream of Gorin Mill Spring (GODS). These elevated levels may be remnants of the plating operation. Other high chromium concentrations were found in the urban-industrial watershed of Lost River, and in Hawkins River. The latter is a mystery at this point.

*Copper*

Copper, like other metals, remains high within the Gorin Mill watershed, the greatest in that basin found in Hidden River Cave (HRGM). Like other metals, the impact of this watershed is found in the river as concentrations are higher downstream of Gorin Mill and Hicks Springs than upstream. In a pattern similar to aluminum and barium, copper levels are higher in the Lost River Blue Hole than Lost River Rise.

*Iron*

Iron is common is all sediments, a product of parent sediment material from weathered sandstones.

*Mercury*

Mercury was found at only three sites, Hidden River Cave (HRGM), Gorin Mill Spring (GOGM), and the Green River upstream of Gorin Mill (GOUS). Levels are at the 0.10 mg/kg detection limit and are not considered relevant for alarm or comparison of one site to another.

*Magnesium*

Magnesium is common throughout Southcentral Kentucky as a constituent of dolostone. If one were to consider the concentrations of magnesium to be natural and ubiquitous, relative concentrations may be used to gauge to effects of sample locations on metal concentrations. The fact that magnesium levels of the Green River are "impacted" by Gorin Mill Spring, may be an artifact of the hydraulics, and thus sediment deposition, of a particular sample site. This is an important caveat when discussing the "impacts" or contributions of a spring to the river with other metals.

*Manganese*

Manganese is common in the form of manganese hydroxide coating limestone surfaces in caves throughout the region. It may be possible, during flood flow conditions, that manganese may be abraded from the limestone and enter the sediment flow.

*Nickel*

Aside from the Lost River system, nickel is found within the Gorin Mill watershed, with the highest concentrations downstream from Gorin Mill Spring. It is possible, especially since there are relatively high levels found in Hidden River Cave, that the metal plating wastes are the main sources.

*Lead*

Aside from the Gorin Mill and Lost River watersheds, which are typically higher in all metals than other sites, Mill Hole and Hawkins River have elevated lead levels. These sites are both tributaries of Owl Cave which has low lead concentrations. This may be an artifact of sample location (relative to depositional hydraulics) in that lead-laden sediments were not properly represented at Owl Cave. If not, it is possible that these contaminated sediments have not yet made it to Owl Cave.

*Selenium*

Similar to mercury, selenium concentrations are found in three sites (although not the same sites) and are pushing the 0.5 mg/kg detection limit. In any case, concentrations are quite low.

*Strontium*

Strontium is found in a similar distribution and concentration as many other metals. The most likely source of strontium is from evaporite minerals in the lower St. Louis Limestone.

*Vanadium*

Vanadium concentrations mirror that of strontium. Potential sources of vanadium are not known.

*Zinc*

Again, like most other metals, zinc is found in highest amounts in the Gorin Mill and Lost River watersheds. Potential sources are metal plating for Gorin Mill and urban-industrial runoff in Lost River.

### *Notes Regarding Sediment Analysis*

Note that with exceptions of chromium and lead found in Hawkins River, metal concentrations at in-park sites are very low relative to other sites. Although the sediments found in the Lost River watershed are consistently among the highest for all sites, there is a substantial amount of metals associated with the Gorin Mill watershed. As this watershed enters the Green River upstream of the park, its contaminated sediments are cause for concern for park managers and aquatic organisms, especially those that are in direct contact with the sediments.

One may think of the transport of sediments as a poorly-functioning conveyor belt, moving by the jerks and starts of flood events. The high-velocity waters of flood flow erode sediment from the upstream and re-deposit it at a location downstream. By observations following major flood events, the author has seen sediments scoured to bedrock (at least one meter deep) in Logsdon River. The bedload is quickly re-deposited by smaller subsequent flood events. If there is no new source of contaminated sediments, eventually the system will be cleared of these tainted sediments. Even if the source is eliminated, as was the metal plating wastes of Ken-Dec in the early 1990's by close-loop processing and a regional sewer system, metal-laden sediments are still prevalent downstream over a decade later. It may take several flood events, on the order of ten-year magnitudes, to fully scour these contaminants from the cave system. Then, in the case of the Gorin Mill watershed, they will end up in the Green River upstream of the park.

In addition to bedload samples, composite core samples (0-75 cm) were extracted from many of the sites, for the sake of comparison, and to shed light on sediment source volume. For example, a substantially higher concentration of metals in a core sample may indicate that stores are available for export as each flood event moves new sediment through the system.

For the most part, core and bedload samples are very comparable. Figure 20 shows the relationship between core and bedload chromium concentrations (additional core and bedload graphs can be found in Appendix B). In both Hidden River Cave (HRGM) and Gorin Mill Spring (GOGM), chromium levels are higher in the core than in the bedload sample, suggesting that there are ample chromium stores available to keep this system exporting large amounts of this metal for years to come.

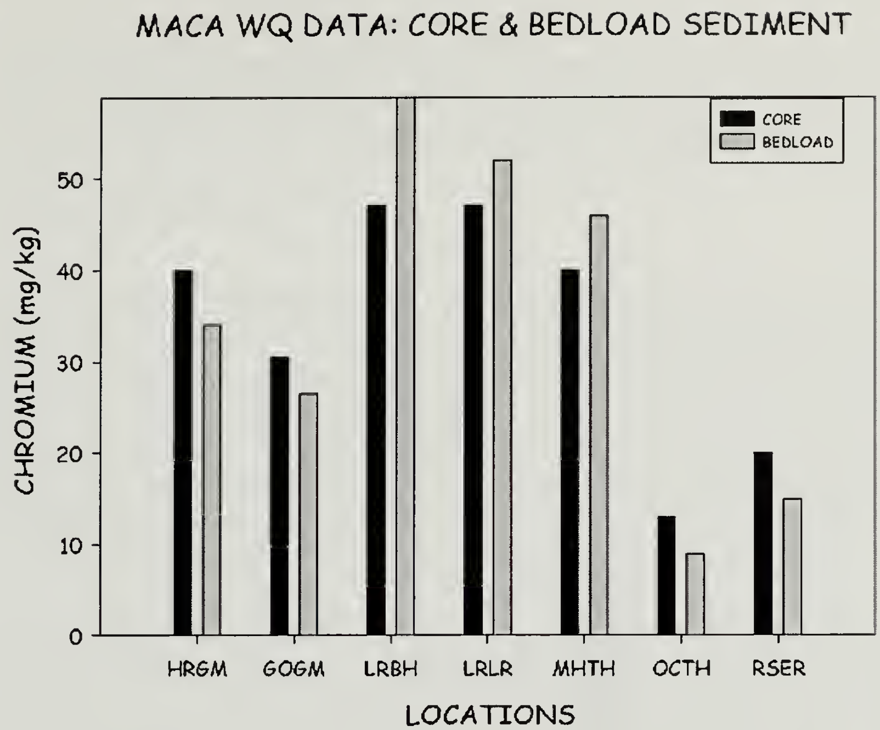


*Figure 20. Core and bedload samples at seven sites. Relative concentrations are indicative of stored metals.*

Petroleum hydrocarbons are no stranger to the waters of Southcentral Kentucky. Automotive (roadway) oil and grease are washed into the system following every rainfall event. Oil and gas exploration are also sources. Core and bedload samples were taken from six sampling sites that either have a history of urban runoff, petroleum exploration activity, or key cave streams in the park. Petroleum hydrocarbons, as they are lighter than water and do not dissolve well in water, have a difficult time transferring through the karst aquifer. As a typical cave stream may flow through several sumps on its way to the river, petroleum hydrocarbons, which generally float atop the stream, are caught upstream of the sump. Only during times of high velocity can individual globules of oils pass through these phreatic conduits. The week after sampling at Mill Hole (MHTH), a tanker overturned on Interstate 65 spilling at least 16,000 liters of diesel fuel. Although only four kilometers upstream of Mill Hole, no trace of the fuel was ever found. Over the course of time, as the oils break down, they can be incorporated into the sediment in a fashion similar to oil-balls washed ashore following a tanker spill – only at a much smaller scale.

Figure 21 shows total petroleum hydrocarbon (TPH) in bedload samples. Values for both wet and dry are shown – the former taking into account sediment weight before drying, and thus less volatilization of the TPH. Hidden River Cave (HRGM) had the highest TPH levels (recall it is partially fed by the runoff of two communities). It does not seem likely that urban runoff is the sole source of the TPH in Hidden River Cave, as the Lost River Blue Hole (LRBH) is in the heart of a city of 50,000 and its TPH values are nearly an order of magnitude lower. Owl Cave (OCTH) is the recipient of interstate runoff as well as scores of oil and gas wells. It is possible that a single unreported spill event can greatly effect TPH concentrations. Remember, these data are based on only two sampling events and any generalizations and interpretations must be made in this light.

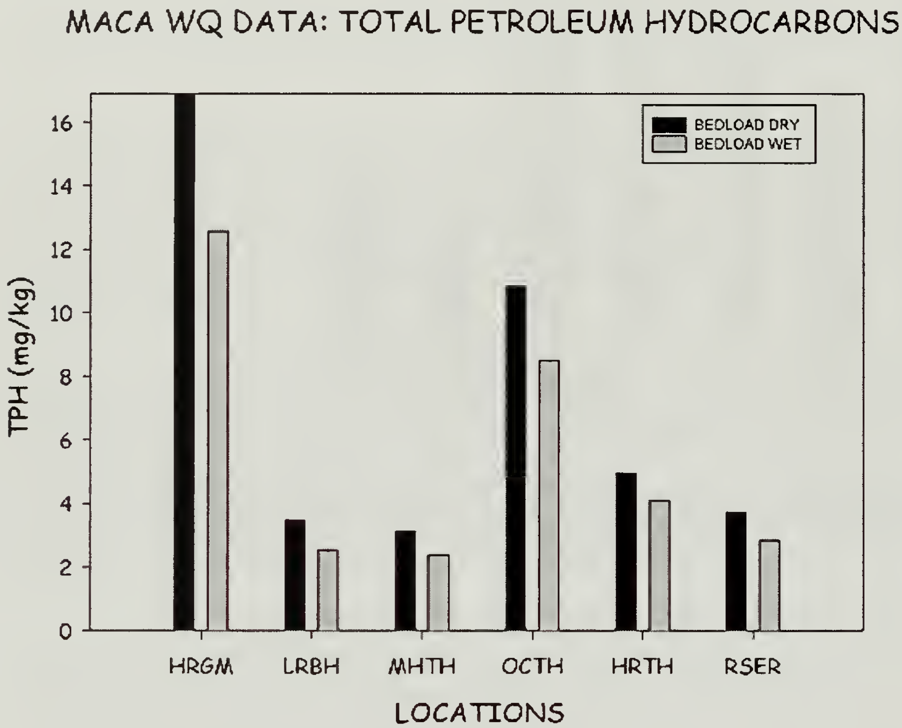


*Figure 21. Total petroleum hydrocarbons at six locations. These data represent two sampling events. Probable sources of the TPH are not known.*

# Land Use

As if keeping pace with the every changing karst aquifer which receives its waters, land cover has swung through natural cycles from moist arboreal climes, to long periods of warmer and drier environments – each bringing its own plant assemblages, covers and densities. Land use is a term based upon human occupation and manipulation of the lands. Human use of the lands can either greatly or marginally alter the natural covers, and all ecosystems linked to that cover.

Original human occupants of Southcentral Kentucky likely found hardwood savannas topping the Mammoth Cave Cuesta and a broad tall grass prairie over the Pennyroyal Plateau. They had marginal impact to the land as a whole as their population and ability to cause whole-sale land use changes were small. The first modern settlers found these lands under a similar cover. Land use at a scope and scale that can alter habitat at a pace and severity far beyond natural limits was about to begin, as the prairies were plowed and the timber cut. This occurred in the late 18th century. Land use change has been occurring ever since.

Water resources at Mammoth Cave are directly tied to land cover and subsequent use of the lands through the ease in which the karst aquifer accepts and transfers water. Precipitation and runoff are on the surface one second, and coursing through the solutional conduits of the limestone the next. The incredible aquatic taxa of the park, both surface and subsurface, are the result of the natural conditions set by the limits of natural land cover for many centuries. Just as the eyeless animals of the cave evolved in the lack of sunlight, the mussels, fish, and aquatic insects evolved within water quality bounds set forth by natural conditions.

Land use will be addressed in two sections; for those lands draining into the park by surface streams and lands that recharge the park through the karst aquifer. As described earlier, the basic hydraulic principles that apply to standard surface stream hydrology apply, with some modifications such as pipe-full flow and conduit arrangement, to karst hydrology. The two sections are created by knowledge base, proximity, interest, and scale. For example, the 319 $km^2$ that drain into the park via caves is well-studied as it has been the focus of many projects and of great interest to park managers over the years, as opposed to the 6960 $km^2$ that enter the park through the Green and Nolin Rivers, which comprise a grand slice of Southcentral Kentucky and has had far less study.

## Groundwatershed Land Use South of the Green River

With the exception of the Green and Nolin River basins, all water that flows into and through Mammoth Cave National Park spends at least part of its journey underground. It is all ultimately derived from meteoric waters, rainfall (to a lesser extent from snowmelt). This water may flow for several kilometers across the surface, as it recharges sinking streams, or disappear into the thousands of dolines within minutes of hitting the ground. In any case, its quality is greatly influenced by the lands it encounters on its way underground.

The following discussion will examine each groundwatershed based upon a series of aerial photographs made in the spring of 1990. These photographs, pairs of 1:24,000 color infrared transparencies with 1:12,000 color prints for visual comparison, were classified into Anderson Level III categories. An additional series of photographs were flown in the spring of 2001 as part of a land use change project by the USGS. These results will be presented in the end of the Land Use section. The watersheds that are presented in this section account for all monitored waters through the park's Water Quality Monitoring Program on the south side of the Green River. Detailed (Anderson Level III) classifications have not been done for park watersheds on the north side of the river. A detailed listing of land use within each karst watershed is found in Appendix C. The following Figure 22 can be used as a legend for all Anderson Level III land use figures (karst groundwatersheds south of the Green River).


*Figure 22. Land use legend for Anderson Level III land use classifications.*

### *Mile 205.7 Spring Karst Watershed*

The 3.1 $km^2$ Mile 205.7 karst watershed is mostly within the park (2.0 $km^2$) and is dominated by forest lands in the lower 2/3 of the basin (Figure 23). The upper 1/3 of the watershed contains a forested land and light agriculture. Over 99% of the watershed was classified as forest, (deciduous, mixed, to evergreen) with 70% well-crowned (61-100%).

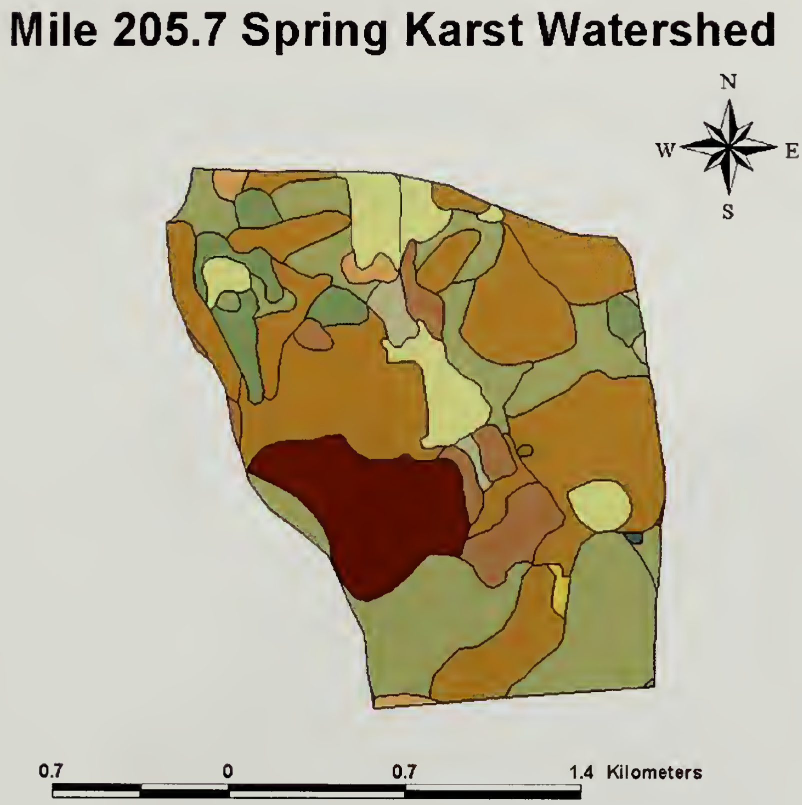


*Figure 23. Land use of the Mile 205.7 Spring karst watershed, Anderson Level III. Classification based upon analysis of 1990 scene.*

### *Pike Spring Karst Watershed*

17.3 of the 39.9 km$^2$ Pike Spring karst watershed are within the park. This portion comprises the lower 43% of the basin and is dominated by forests (Figure 24). The non-park headwaters of the basin are a patch-work of light agriculture (pasture and row-crops), and light residential (farmsteads). There is a moderate amount of silvicultural activity as small areas of forest are clear-cut or select-cut. On the whole, this watershed is well dominated by forests, which cover 90% of the land. Agricultural activities comprise the remaining share, with 7% row crop and about 3% pasture.

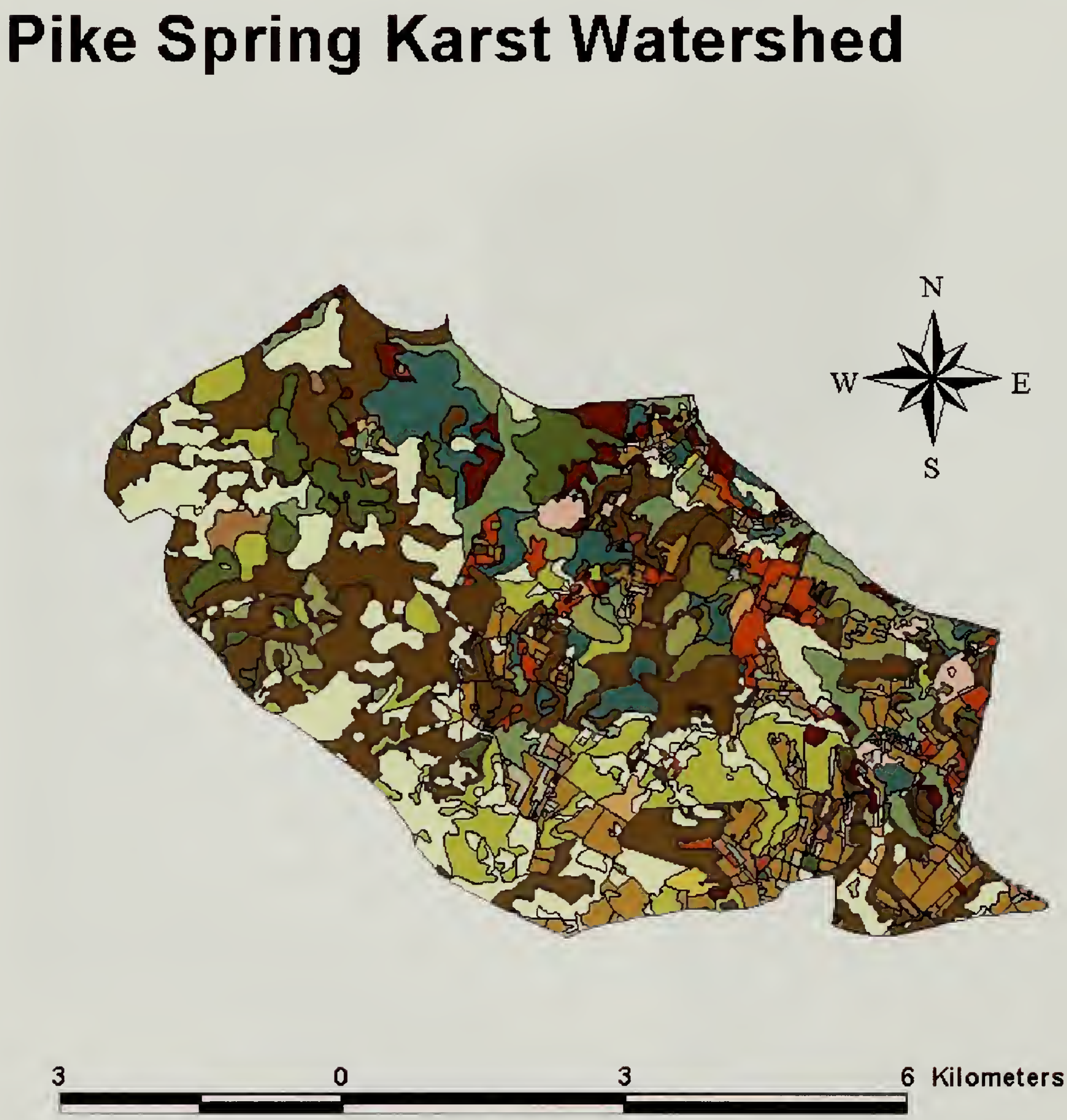


*Figure 24. Land use of the Pike Spring karst watershed, Anderson Level III. Classification based upon analysis of 1990 scene.*

### *Echo River Spring Karst Watershed*

The 23.2 $km^2$ Echo River Spring watershed is almost entirely contained within the park, and its scene is dominated by forest cover (Figure 25). The only development, save from a small pasture or two in the headwater area, is from the park. The park headquarters, visitor center, maintenance, residential, hotel, and campground are located near the downstream end, occupying less than 1% of the basin.

Remember the hydrogeology of the Echo River Spring watershed. It is directly linked to the Cave City (Logsdon River), and Patoka Creek (Hawkins River) subbasins. Anytime the stage of Logsdon River at the monitoring well rises above three meters, the additional 97.4 $km^2$ of these agriculturally dominated watersheds spill over into Echo River. During these spates, which may comprise 4% of the year, the land use of these subbasins must be considered.

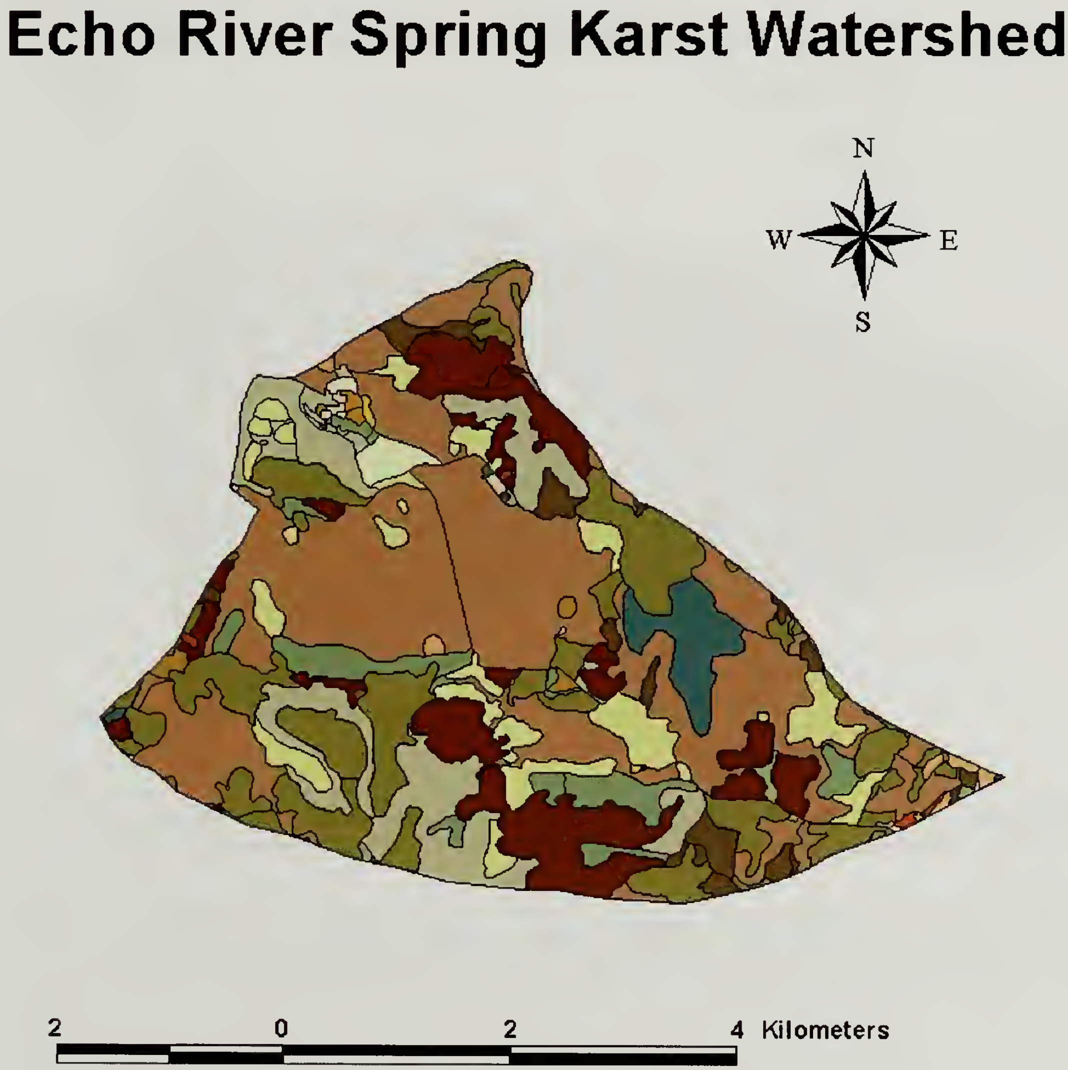


*Figure 25. Land use of the Echo River Spring karst watershed, Anderson Level III. Classification based upon analysis of 1990 scene.*

### *Turnhole Spring Karst Watershed, Cave City Subbasin (Logsdon River)*

The Turnhole Spring karst watershed can be divided into subbasins – a product of finding confluences of portions of the entire watershed (Figure 26). One such subbasin was defined by dye traces to the downstream end of the Cave City subbasin, where Logsdon River flows into Hawkins River. The Cave City subbasin is 25.0 km$^2$, but only 2.8 km$^2$ is within the park boundary. This portion, the lower bit of the basin, is dominated by forest lands, while the private section, comprising nearly 90% of the total area, is a mixture of woodlands (45%), agricultural activity (38%), single family dwellings (2%), and the Interstate 65 right of way (2%).

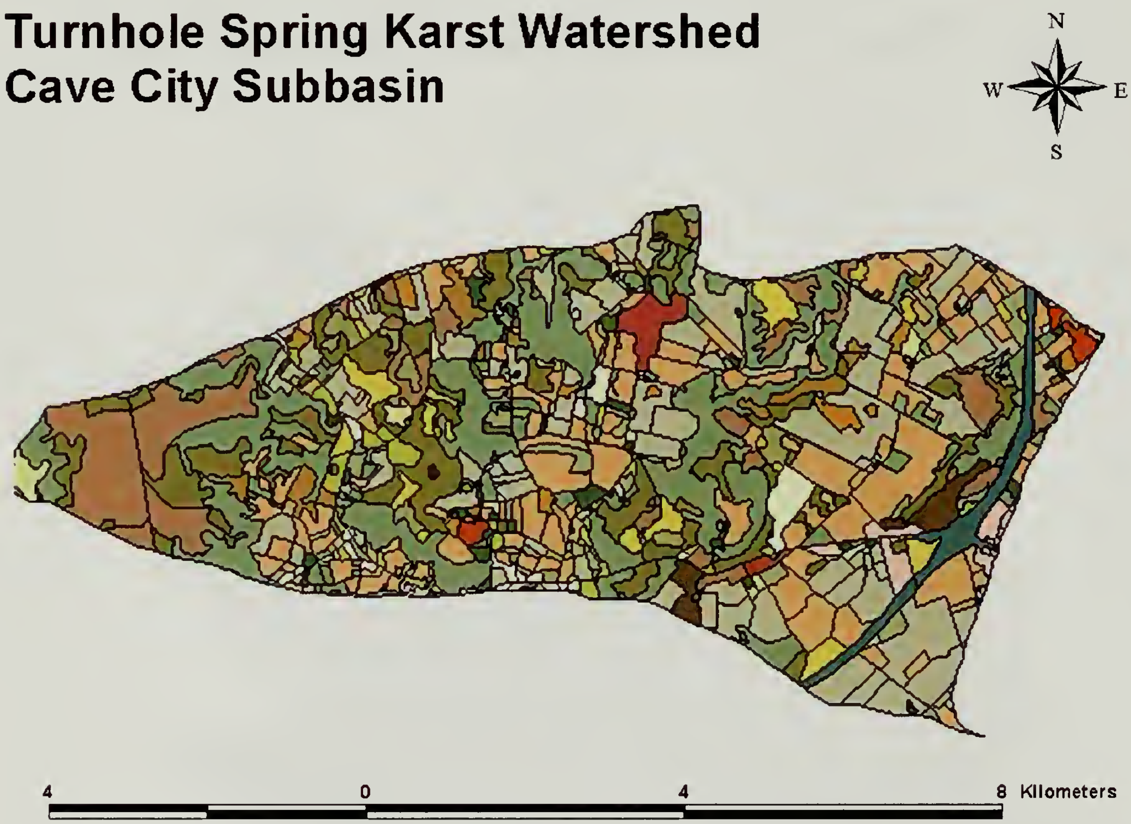


*Figure 26. Land use of the Turnhole Spring karst watershed; Cave City Subbasin, Anderson Level III. Classification based upon analysis of 1990 scene.*

### *Turnhole Spring Karst Watershed, Patoka Creek Subbasin (Hawkins River)*

As the Cave City subbasin was defined by the catchment of Logsdon River, the Patoka Creek subbasin is defined by Hawkins River to its confluence with Logsdon. It drains an area of 72.4 $km^2$ and only the lower 3.5 $km^2$ is within the park. Forests cover 31% of the basin. The remaining land is dominated by agriculture, with a large percentage pasture and hay lands (22%) over the Sinkhole Plain, giving way to row crops (28%) in the Glasgow Uplands to the south (Figure 27). This basin also contains single family dwellings and farmsteads (3%), including the community of Park City (population just over 500) and the right of way of Interstate 65 (2%).

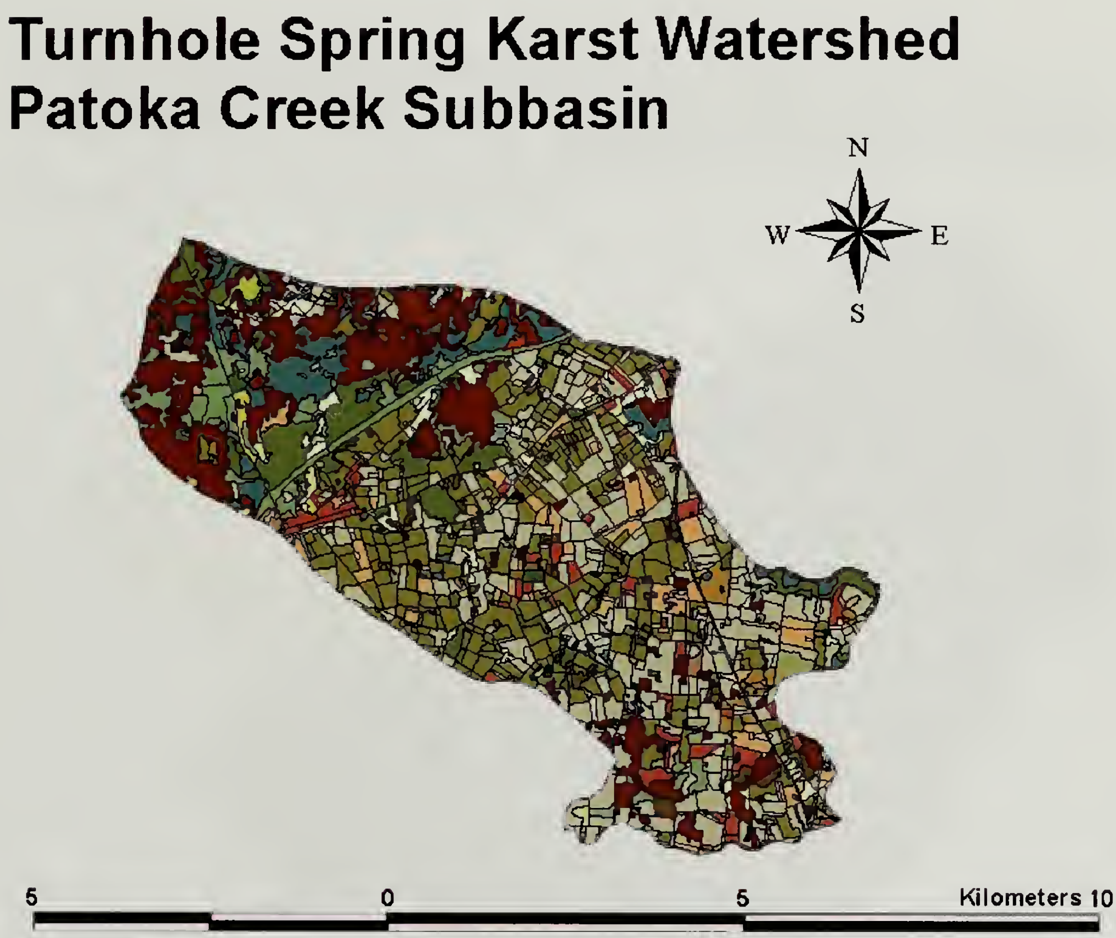


*Figure 27. Land use of the Turnhole Spring karst watershed; Patoka Creek Subbasin, Anderson Level III. Classification based upon analysis of 1990 scene.*

### *Turnhole Spring Karst Watershed, Mill Hole Subbasin*

The 112.1 km$^2$ Mill Hole subbasin is not routinely monitored for water quality at its downstream terminus, the large karst window of Mill Hole. Its entire area lies outside of the park, but its size and land use can greatly impact park waters. Its land use is very similar to its eastern neighbor, Patoka Creek, as 35% of the land is forested. Pasture and hay lands (26%) cover much of the Sinkhole Plain and row crops upon the southern Glasgow Uplands (24%) (Figure 28). There are a few large (> 5 hectare) animal feeding grounds (3%), and most residential use is low-density single family and farmsteads (3%).


*Figure 28. Land use of the Turnhole Spring karst watershed; Mill Hole Subbasin, Anderson Level III. Classification based upon analysis of 1990 scene.*

### *Turnhole Spring Karst Watershed, Proctor Subbasin*

Yet another component of the Turnhole Spring karst watershed is the 12.8 $km^2$ Proctor subbasin. This subbasin is not specifically sampled for water quality (as all samples are taken further downstream at Turnhole Spring or Owl Cave). It lays 88% within the park and its land use is dominated by forests (Figure 29). The Proctor subbasin is mostly upon the Mammoth Cave Cuesta, and the privately owned portion is along the upper fringes of the watershed. Most private land use is forest and campgrounds. About 98% of this watershed is forested, while the remaining 2% is a mixture of light agriculture, recent clear cut, and a campground.

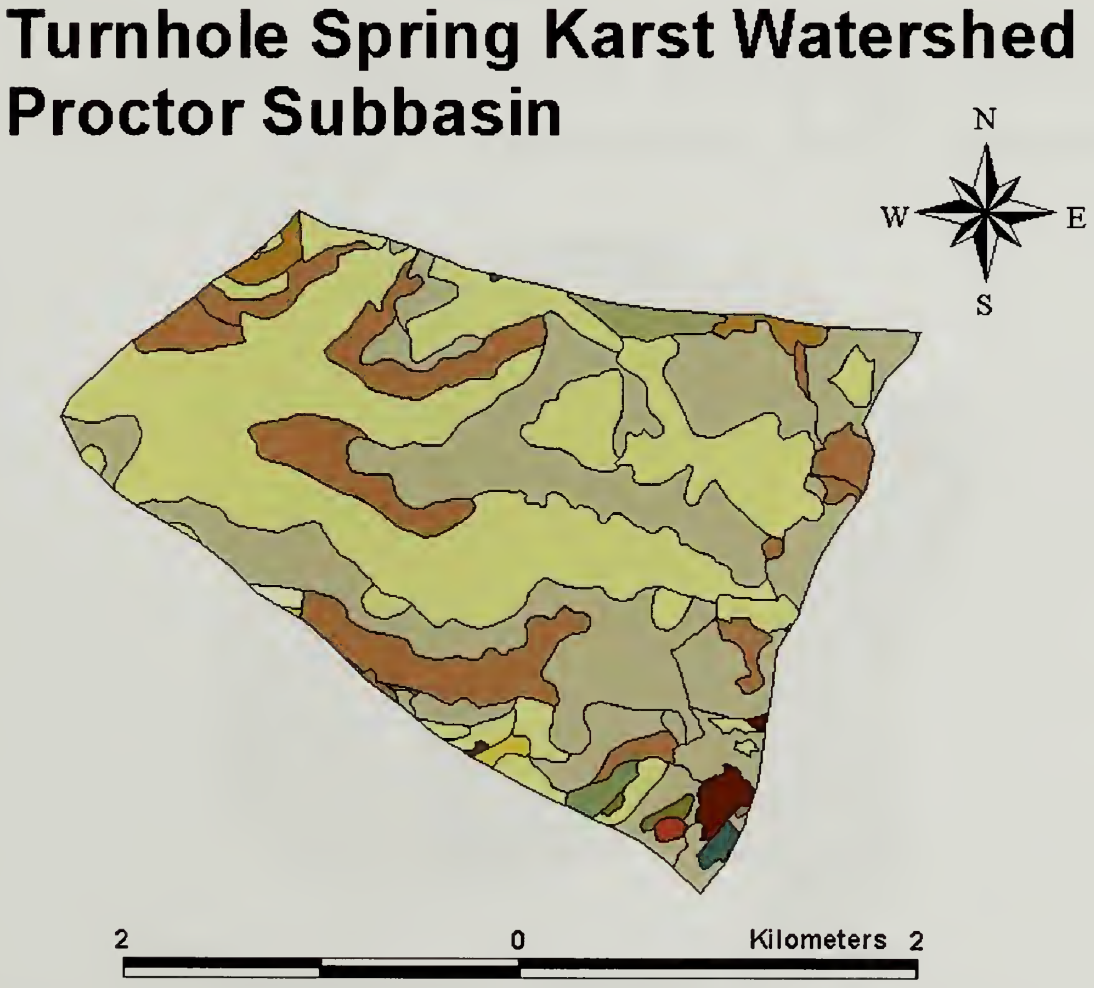


*Figure 29. Land use of the Turnhole Spring karst watershed; Proctor Subbasin, Anderson Level III. Classification based upon analysis of 1990 scene.*

### *Turnhole Spring Karst Watershed, Double Sink Subbasin*

Although not separately sampled for water quality, the 11.2 km$^2$ Double Sink subbasin is located near the downstream end of the Turnhole Spring karst watershed (Figure 30). Only 4% of this subbasin lies within the park, and its dominant privately-held portion is mainly under agriculture production, both animal and row-crop activities. Most of the watershed, 54% withstands various degrees of agricultural activity. While well-maintained pasture and row crops (with residue) comprise the bulk of agricultural activities, over 9% of the watershed was classified as fair to heavily overgrazed pasture. The remaining 46% of the basin is forested.

The Double Sink subbasin has at times discharged into the Green River at Notch Spring, and at times of flood flow, at Sandhouse Cave Spring. At other times, this subbasin joins the flow of the entire watershed and emerges at Turnhole Spring, using Notch and Sandhouse Springs during overflow.

**Turnhole Spring Karst Watershed**
**Double Sink Subbasin**

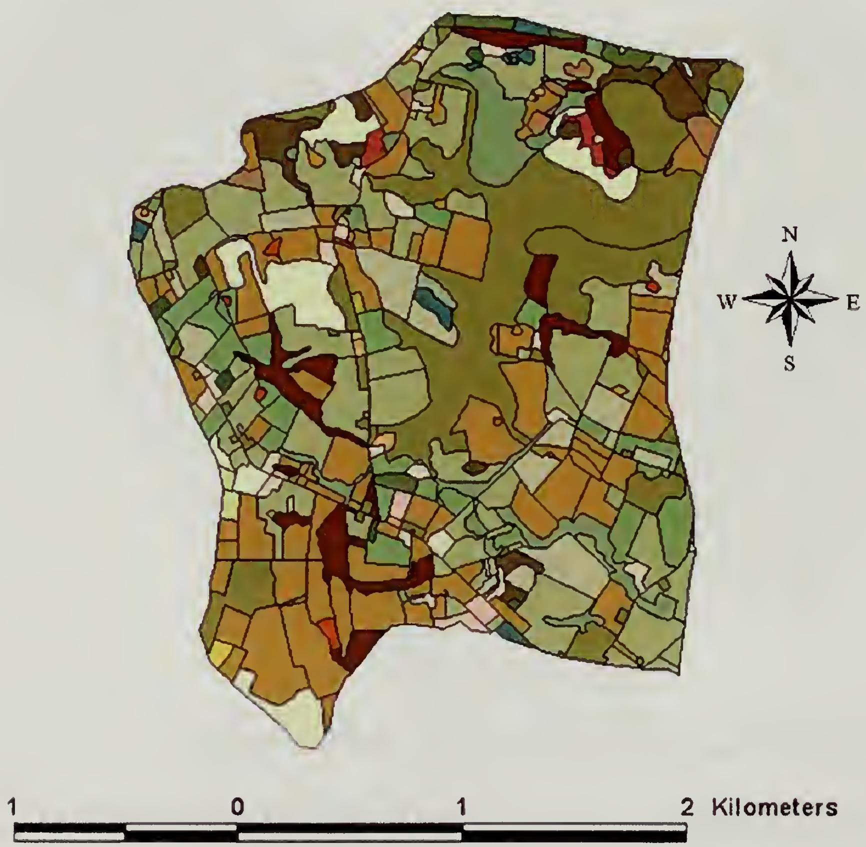


*Figure 30. Land use of the Turnhole Spring karst watershed; Double Sink Subbasin, Anderson Level III. Classification based upon analysis of 1990 scene.*

***Turnhole Spring Karst Watershed, Turnhole Subbasin***

The extreme lower end of the Turnhole Spring karst watershed is divided into the 11.9 $km^2$ Turnhole subbasin (Figure 31). This is the area that was traced to Turnhole Spring – and at times of flood flow to Notch and Sandhouse Springs – that is downstream from Cedar Sink. Although 78% (9.3 $km^2$) of this subbasin is within the park and dominated by forests (78%), the remaining 2.6 $km^2$ of private lands (located in the southern portion of the subbasin) contains agricultural lands (pasture and animal activities) and several farmsteads. Some of the pasture lands are poorly managed to the point of visible (from 1:12,000 photographs) erosion.

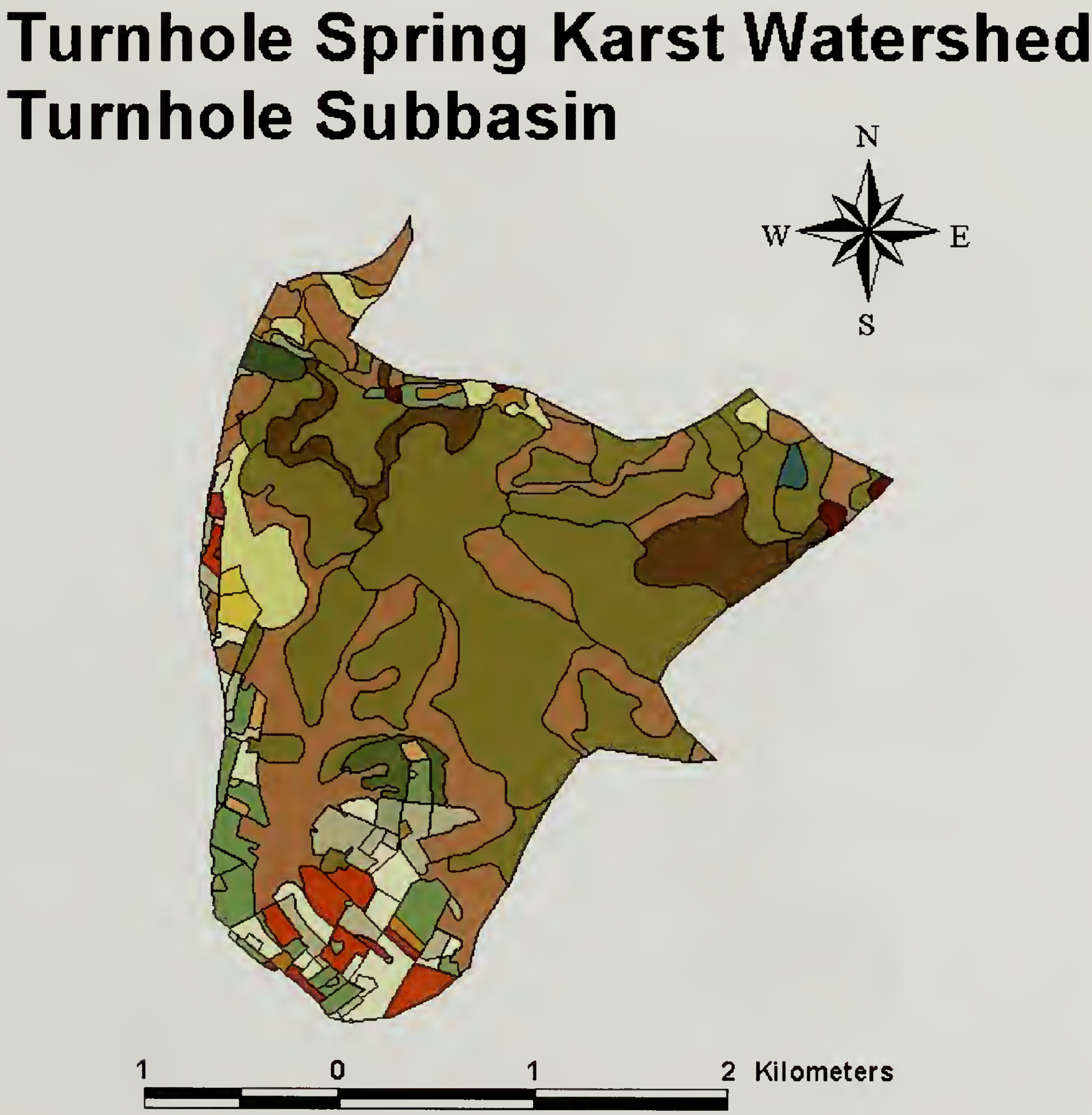


*Figure 31. Land use of the Turnhole Spring karst watershed; Turnhole Subbasin, Anderson Level III. Classification based upon analysis of 1990 scene.*

## Groundwatershed Land Use North of the Green River

Unlike the highly-detailed land use coverage of the groundwatersheds feeding the southern portion of the park – where efforts are concentrated because of the higher-impact land uses located there – the watersheds north of the park (defined by Meiman and Ryan unpublished data, 1993, and Currens and Ray, 2001) are dominated by park and forest lands. The much larger Nolin and Green River basins upstream of the park are too large for detailed land use classification at this time. We rely on a general state wide land use layer published by the Kentucky Geography Network using the Anderson Level II categories of land cover for both the north side and the Green and Nolin drainages.

### *Big Spring Karst Watershed*

The Big Spring karst watershed, a focus of land use/water quality studies by Ryan and Meiman (1996), is divided into two nearly equal halves by the park boundary (Figure 32). The lower portion of the watershed is forested park land and home to the 120 hectare old-growth forest, the Big Woods. The upper portion of the watershed is a mixture of forest lands (81%) and light agriculture (19%), with a small number of rural farmsteads (classified as low intensity residential).

**Big Spring Karst Groundwatershed**

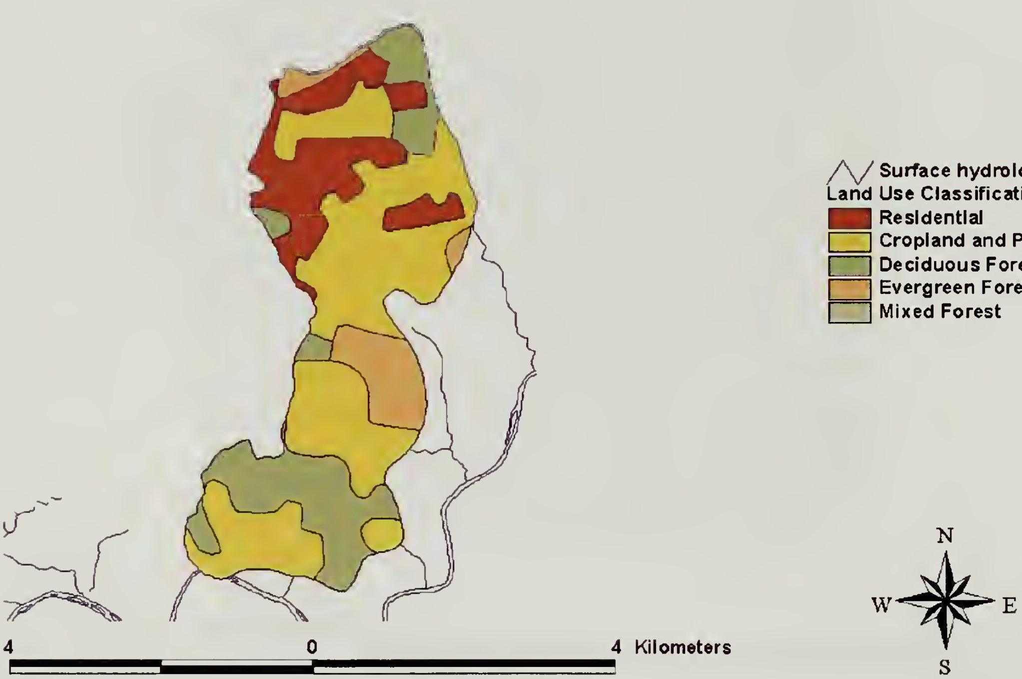


*Figure 32. Anderson Level II land use classification of the Big Spring Karst groundwatershed. Classification based upon analysis of 1992 scene.*

### *Doyle's Ford Spring Karst Watershed*

The Doyle's Ford watershed, typical to those found on the north side of the river, is dominated by forest lands in the lower park-owned portion of the basin, and forest (83%) and light agricultural lands (17%) in the more distal areas (Figure 33).

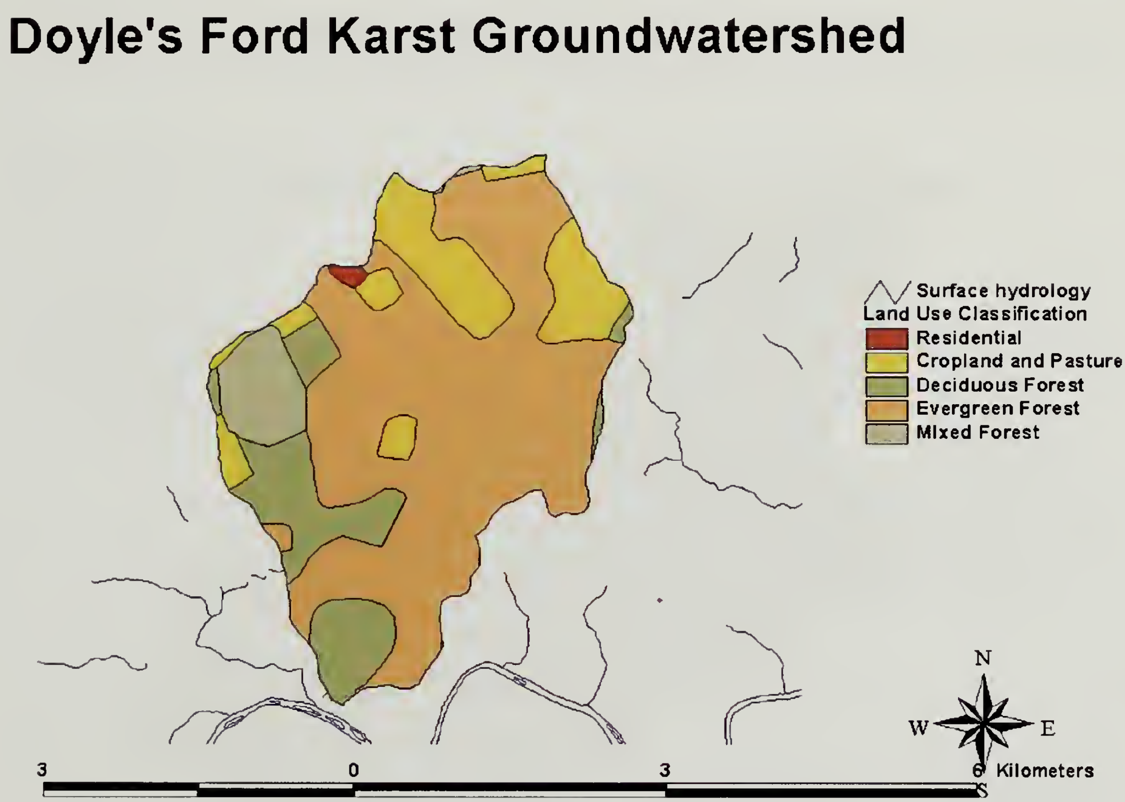


*Figure 33. Anderson Level II land use classification of the Doyle's Ford Karst groundwatershed. Classification based upon analysis of 1992 scene.*

### *Ugly Creek Spring Karst Watershed*

Although only the lower 43% is within the park, the 8.3 km$^2$ Ugly Creek Karst Watershed, is dominated by forest cover (87%) (Figure 34). Recent years (since the early 1990's) several tracts have undergone select and clear cuts and light agricultural activities (13%).

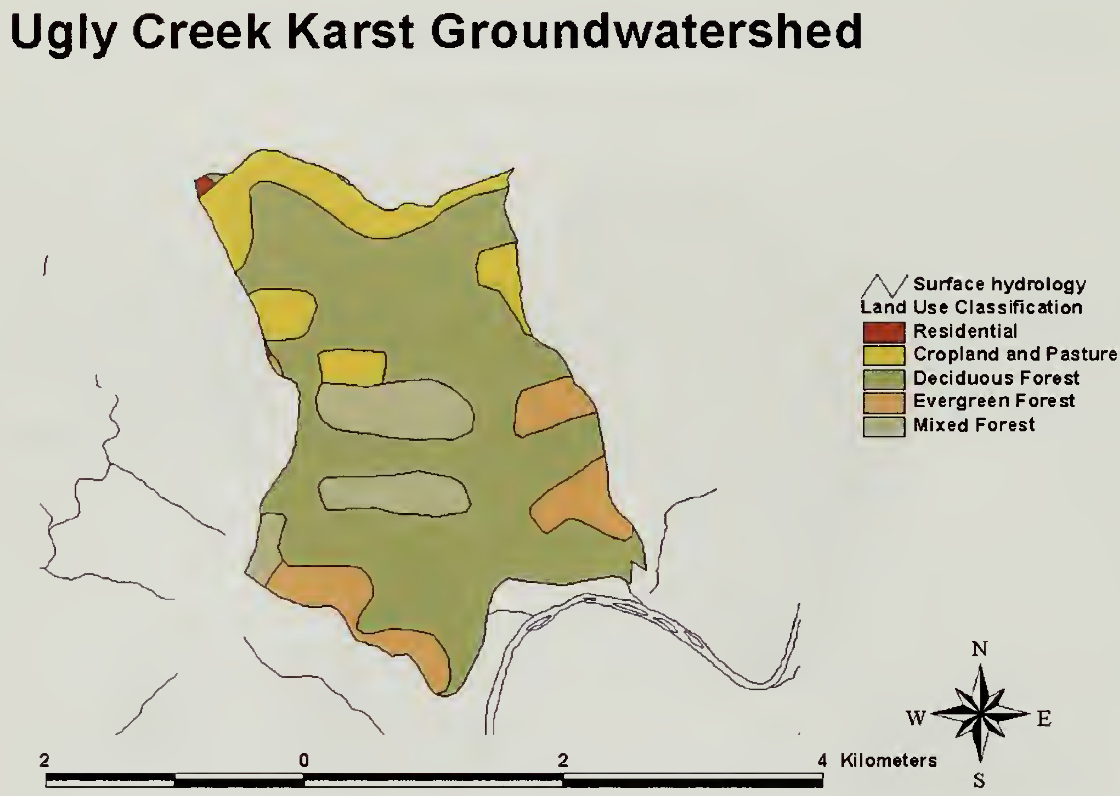


*Figure 34. Anderson Level II land use classification of the Ugly Creek Karst groundwatershed. Classification based upon analysis of 1992 scene.*

### *Buffalo Creek Spring Karst Watershed*

The 32.9 $km^2$ Buffalo Creek karst watershed, displaying the park's best example of the ravine karst common to the north side of the Green, is largely contained within the park, some 27.6 $km^2$, or 84%. It is the largest, least-impacted karst drainage entering the park. Even the portion beyond the park boundary is dominated by forests (92%) (Figure 35). Light agriculture and low intensity residential uses represent about 6% of the area, while nearly 2% is classified as open water. There is no commercial development within the watershed.

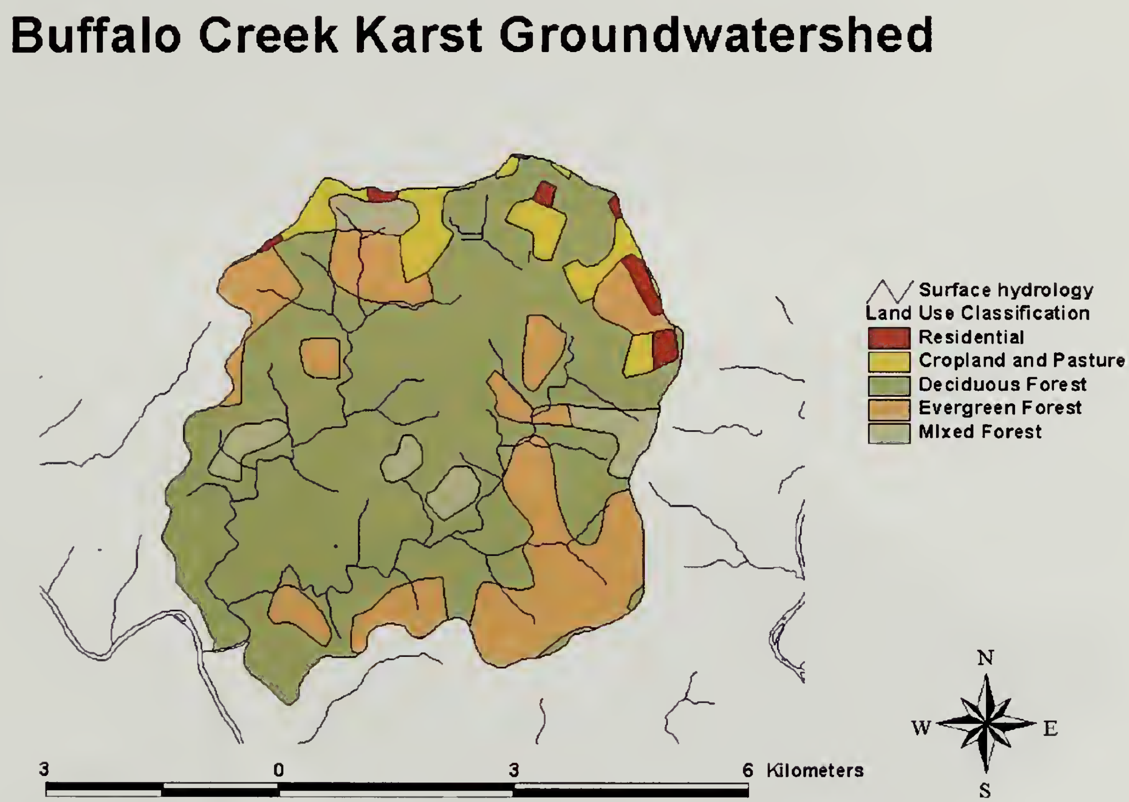


*Figure 35. Anderson Level II land use classification of the Buffalo Creek Karst groundwatershed. Classification based upon analysis of 1992 scene.*

***Surface Stream Watersheds***

***Green River***

The Green River watershed, that portion upstream from the confluence with the mouth of the Nolin, drains 5,085 km$^2$ of southern Kentucky. Its land use, in 1992, shows that agricultural activities dominate the watershed (Figure 36, Table 15). Agrarian land use comprises 61% of the watershed draining into the park, while forests cover 35% of the land. The remaining 4% is classified into a number of uses, including 12,472 hectares of residential lands, 3334 hectares of the Green River Reservoir, and 1782 hectares of transportation corridors (mainly the Cumberland Parkway and Interstate 65). Commercial (1124 hectares) and industrial (168 hectares) are limited and mostly confined to the communities of Horse Cave, Greensburg, and Campbellsville. It is worth noting that the watershed boundaries that spatially define the data presented in the figures and tables of this discussion were extracted from the USGS National Hydrologic Database – a system based on the Hydrologic Unit Code (HUC) that delimits the contributing watershed of each subbasin – known to be flawed when traversing a karst area. Ray, et al. (2000) show that the HUC boundary crosses the Turnhole Spring Karst watershed, assigning some 220 km$^2$ of what we know by dye tracing to the adjacent barren River watershed.

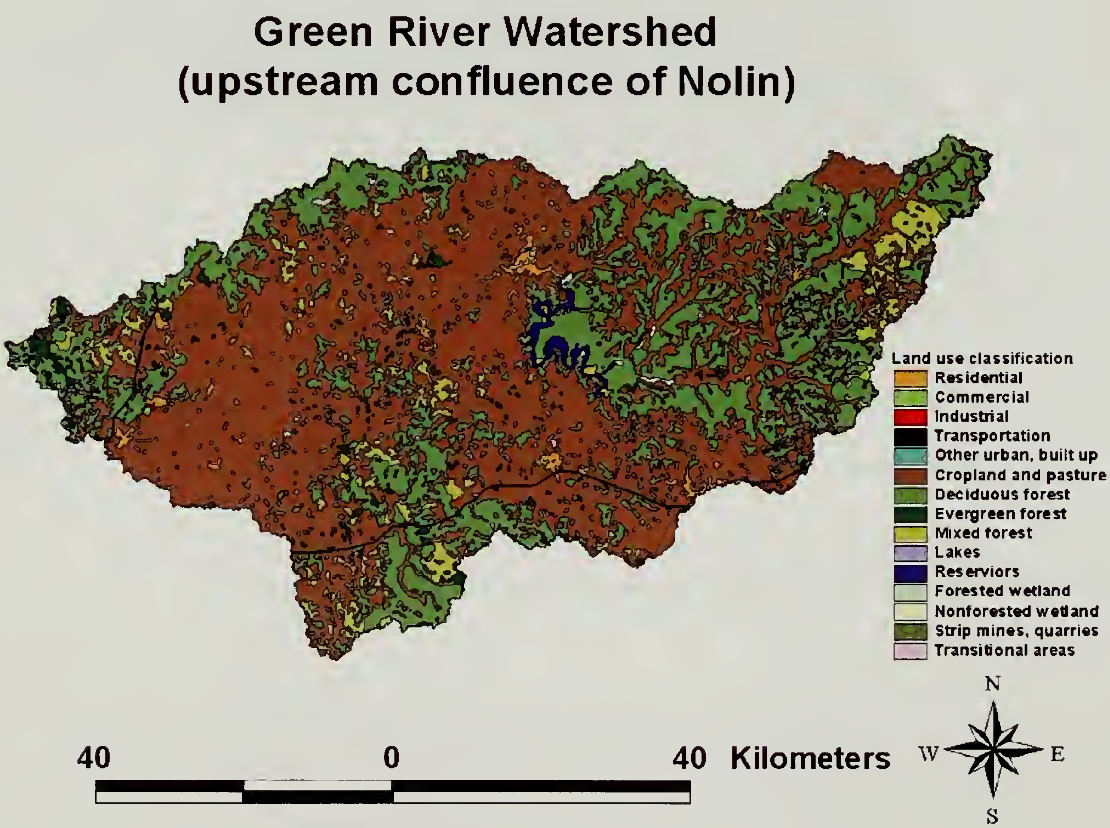


*Figure 36. Land use of the Green River watershed (upstream from the confluence of the Nolin) using the Anderson Level II classification based on a 1992 scene.*

*Table 15. Land use of the Green River watershed (upstream from the confluence of the Nolin) using the Anderson Level II classification based on a 1992 scene.*

| Land Use Classification | Area (hectares) | Percent coverage |
|---|---|---|
| Cropland and pasture | 309,503.1130 | 60.9 |
| Deciduous forest | 146,527.3110 | 28.8 |
| Mixed forest | 23,355.4220 | 4.6 |
| Residential | 12,472.0540 | 2.5 |
| Evergreen forest | 7916.0820 | 1.6 |
| Reservoirs | 3334.4390 | 0.7 |
| Transportation | 1781.9000 | 0.4 |
| Commercial and services | 1124.3640 | 0.2 |
| Transitional areas | 830.1980 | 0.2 |
| Forested wetland | 463.8650 | 0.1 |
| Non forested wetland | 441.3690 | 0.1 |
| Strip mines and quarries | 369.5400 | 0.1 |
| Other urban of built-up | 212.0560 | 0.0 |
| Industrial | 168.1940 | 0.0 |
| Lakes | 41.1450 | 0.0 |

## *Nolin River*

The Nolin River intersects the Green within the park, draining 1879 $km^2$ of Southcentral Kentucky. Land use is very similar to that of the Green with agrarian uses dominating 64% of the watershed, while forests cover 29% (Figure 37 and Table 16). Most of the forests occur in the lower portions of the watershed. The remaining 7% of the watershed is divided between 7115 hectares of residential lands, 2140 hectares of reservoirs (Nolin River Reservoir) and 1525 hectares of transportation corridors (Interstate 65 and the Western Kentucky Parkway). Commercial and industrial development is mainly limited to the headwaters in and around Elizabethtown. The past ten years has seen an increase in residential growth adjacent to the Nolin River Reservoir.

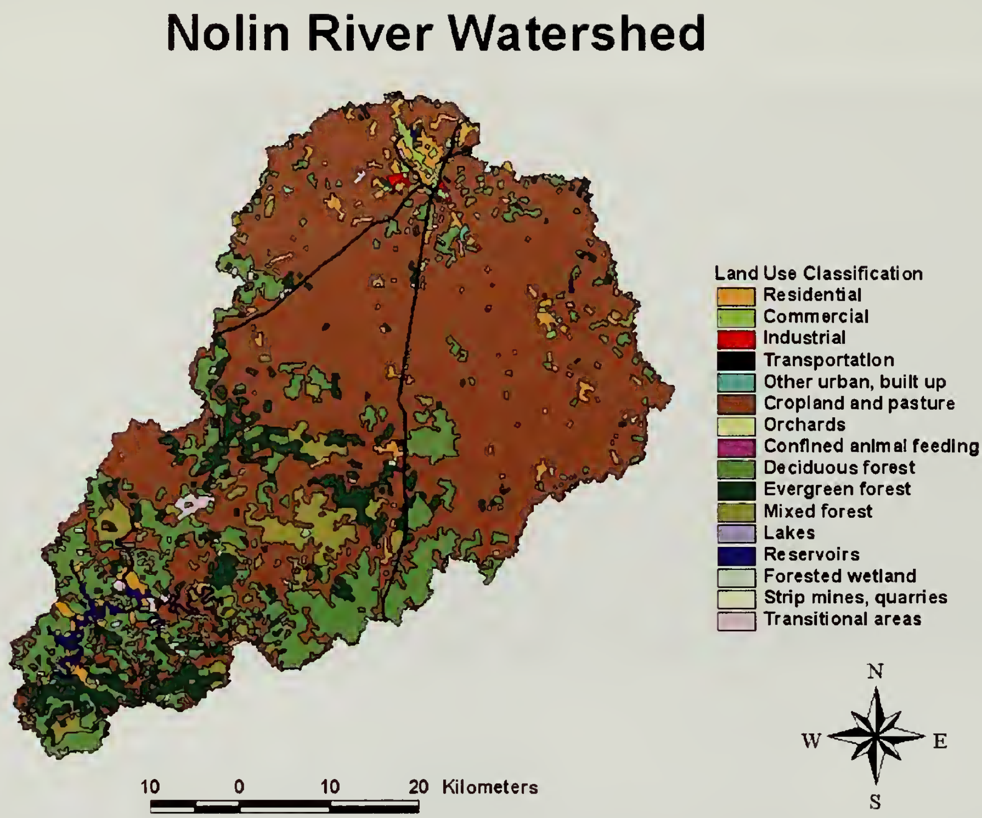


*Figure 37. Land use of the Nolin River watershed using the Anderson Level II classification based on a 1992 scene.*

*Table 16. Land use of the Nolin River watershed using the Anderson Level II classification based on a 1992 scene.*

| ***Land Use Classification*** | ***Area (hectares)*** | ***Percent coverage*** |
|---|---|---|
| Cropland and pasture | 120,241.2710 | 64.0 |
| Deciduous forest | 30,647.6850 | 16.3 |
| Evergreen forest | 14,122.3100 | 7.5 |
| Mixed forest | 9225.3200 | 4.9 |
| Residential | 7115.2270 | 3.8 |
| Reservoirs | 2140.1100 | 1.1 |
| Transportation | 1525.3410 | 0.8 |
| Transitional areas | 1096.1590 | 0.6 |
| Commercial and services | 945.2340 | 0.5 |
| Industrial | 284.5410 | 0.2 |
| Forested wetland | 274.6200 | 0.1 |
| Other urban of built-up | 130.8740 | 0.1 |
| Lakes | 72.5050 | 0.0 |
| Strip mines and quarries | 69.1050 | 0.0 |

## Land Use Change

As we begin this section, let the reader be aware that there is virtually no county-wide zoning within the park's karst watersheds. Warren County, comprising a few square kilometers in the southwestern headwaters is zoned, but as demonstrated throughout the county, is easily changed. The Mammoth Cave Water Quality Monitoring Program suggests that: 1) the water quality of the cave is correlative to the land use of the watershed; and 2) the most significant non-point source contamination occurs immediately following precipitation events as surface pollutants are quickly washed into the karst aquifer through numerous sinking streams and countless dolines. Aquatic biological inventories of Mammoth Cave also demonstrate an apparent correlation between biological integrity and recharge basin land use. Private lands recharge the most seriously degraded communities, including those containing federally endangered Kentucky Cave Shrimp.

As the ecosystem of the cave stream is a reflection of water quality, and if water quality is indeed a manifestation of land use, it is imperative that not only the land use of the recharge basin be known, but also tracked, updated, and analyzed at regular intervals. Gaining a better understanding of the relationships between changing land use of the recharge area and water quality can lead to a higher level of conservation and protection of the downstream cave ecosystem. It should be noted that adjacent land use change ranked high among parks of the Cumberland-Piedmont Network and will be an element of its vital signs monitoring program.

Central to long-term ecological monitoring, conservation, and protection of the aquatic ecosystem of Mammoth Cave is understanding the relationship between water quality and changing land use. Over the past ten years, the land use of thousands of hectares of private lands within the park's groundwater recharge basin has changed. Agricultural production shifts under normal rotation, market demands, and federal programs. Forests within the basin are continually logged. Homes, mostly beyond the service area of the regional sewer system, are being built and trucked into the area at an ever increasing rate. Industrial sites are being planned and developed. The USGS Louisville District Office studied the relationships between recharge basin land use and water quality and determined if correlations between the two can be sensed over one decade in a joint project with Mammoth Cave National Park. The results of this study will be presented later in this section.

The park contracted aerial photography of its recharge basin in March 1990. These 1:24,000 color infrared transparencies, have been classified (Anderson Level III) and ground-truthed by the park and Western Kentucky University into nearly 8,000 polygons. A total of 118 land use categories were delineated from the infrared transparencies including animal waste sites, field boundaries, specific cropping and conservation practices, single and multi-family residences, orchards, evergreen and deciduous forests, streams, farm ponds, and pasture/hay lands. These data have been annotated on clear plastic overlays and transferred to larger base maps and digitized into ArcView coverages.

If we are to fully understand the relationships between changes in recharge basin land use and water quality, statistical and interpretive analysis is needed. By using GIS, changes in land use were identified and tracked from 1990 to 2001. Combined with tabular water quality, biological inventory, and weather data it is possible to correlate water quality trends with evolving land uses. As we have classified land use coverage from 1990 and a 1990-1992 water quality dataset has been compiled, the first order was to correlate these data and determine if apparent relationships between land use and water quality are real. Secondly, to track evolving land use and water quality, a series of new aerial photography (leaf-off scene in the winter/early spring of 2001) were taken and compared with the 1997-1998 water quality dataset. This work also produced a framework to include future water quality and biological monitoring data generated by the park's Long Term Ecological Monitoring Program (NPS Prototype for Caves and Karst).

Although it was possible to closely track changes in watershed land use, correlation with water quality data proved difficult. Basically, the slight changes in land use over the ten year period did not produce statistically significant changes in water quality. This is not to diminish the quality nor the importance of the study as it has laid a framework for park managers to use over the coming decades.

### *Results*

The results of the USGS study are presented below. Although not a contributor of groundwater flow to the park, Suds Spring was included in this project as it is a potential habitat location for the endangered Kentucky Cave Shrimp. Nomenclature of the subbasins of the Turnhole Spring karst watershed used by the USGS differ slightly from those by now familiar to the reader.

| *USGS Subbasin Name* | *Standard Subbasin Name* |
|---|---|
| Turnhole 1 | Double Sinks and Turnhole |
| Turnhole 2 | Proctor |
| Turnhole 3 | Cave City |
| Turnhole 4 | Mill Hole |
| Turnhole 5 | Patoka Creek |

It is extremely important that the reader understand the presentation and interpretation of land use change results. The USGS study created GIS themes based on generalized land use categories, for example; agriculture, forest and development. These results demonstrate an element of land use change, but may be misleading at first glance. For example, let us consider the generalized category of agriculture within the Turnhole 5 (Patoka Creek) subbasin. The USGS plot (Figure 38) notes a 976 hectare decrease in agricultural land use. This figure is based on land use change on an Anderson Level III scale. If a single polygon changes its land use category from one scene to the next, even if it is within the same generalized category, it is considered change. A 12 hectare polygon changing from pasture to row crop would be considered change, even though there was no net change within the generalized category of land use. In order to consider land use change within the generalized categories, land use data were further subdivided and totaled to demonstrate change from one generalized category to another (shown in the accompanying tables). The above example of agricultural land use loss of 976 hectares, if subdivided (Table 20), shows that there was a loss of 943 hectares of row crops, a one hectare gain in livestock facilities, and a 970 hectare gain in pasture/haylands, resulting in a net gain of 28 hectares in agriculture. There was a change of agricultural activities, but little change (28 hectares) of total agriculture lands at the expense of another generalized land use. The graphs are displayed and interpreted below in this light. Following the presentation of the USGS figures, a watershed-based discussion of land use change will be made.

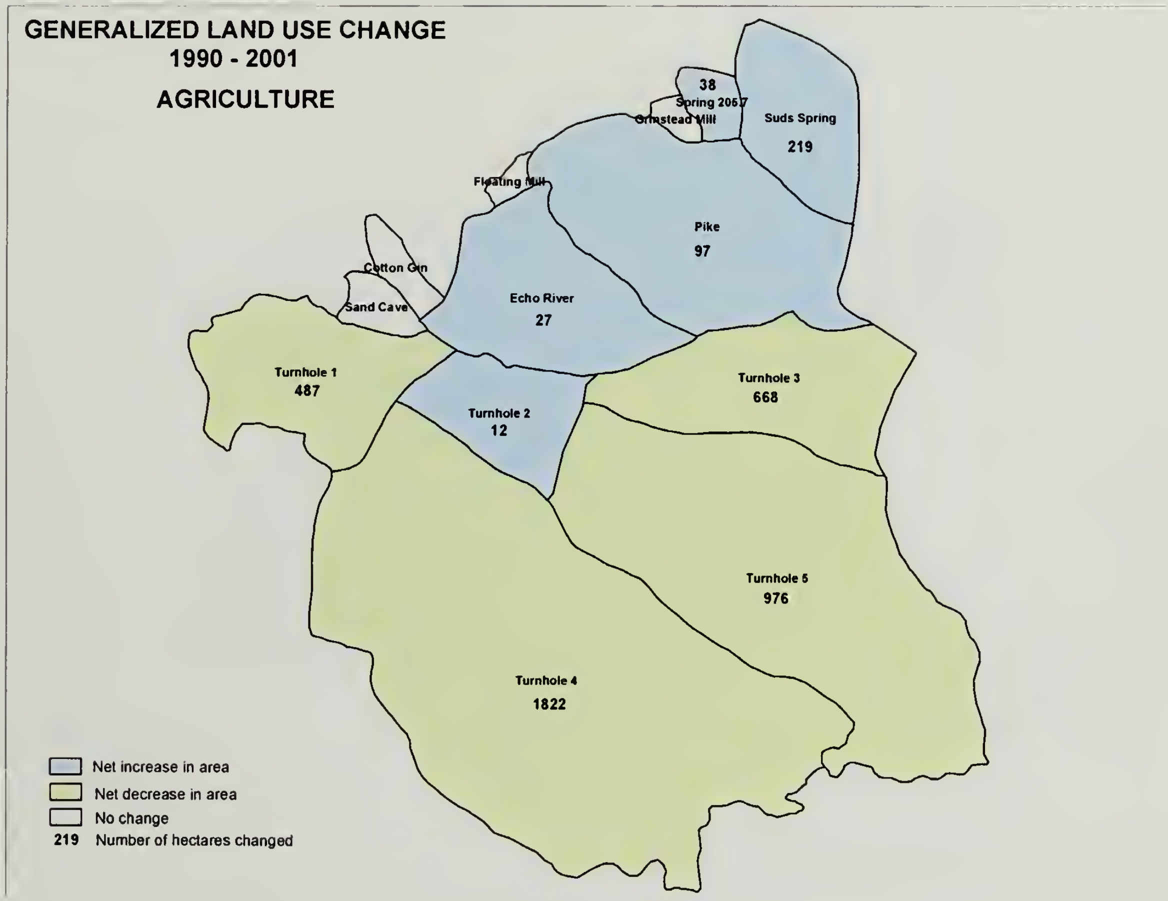


*Figure 38. Generalized land use change, agriculture*

Silviculture throughout the rural landscape of Southcentral Kentucky has been and will continue to be a major business as hardwoods are harvested on a continual basis (Figure 39). Changes in forest cover are mainly due to forest secession or cutting of standing timber. The greatest changes in forest cover were in the Patoka Creek (339 hectares) and Cave City (532 hectares) subbasins (Turnhole 5 and 3, respectively). Some apparent land use change is the result of changing forests over the ten-year period. For example, if a 50 hectare tract of land changed from "*61-100% crown cover-cedar dominant (Mixed 30-50%)*" to "*31-60% crown cover-evergreen dominant (Mixed 30-50%)*", a land use change of 50 hectares would be reported.

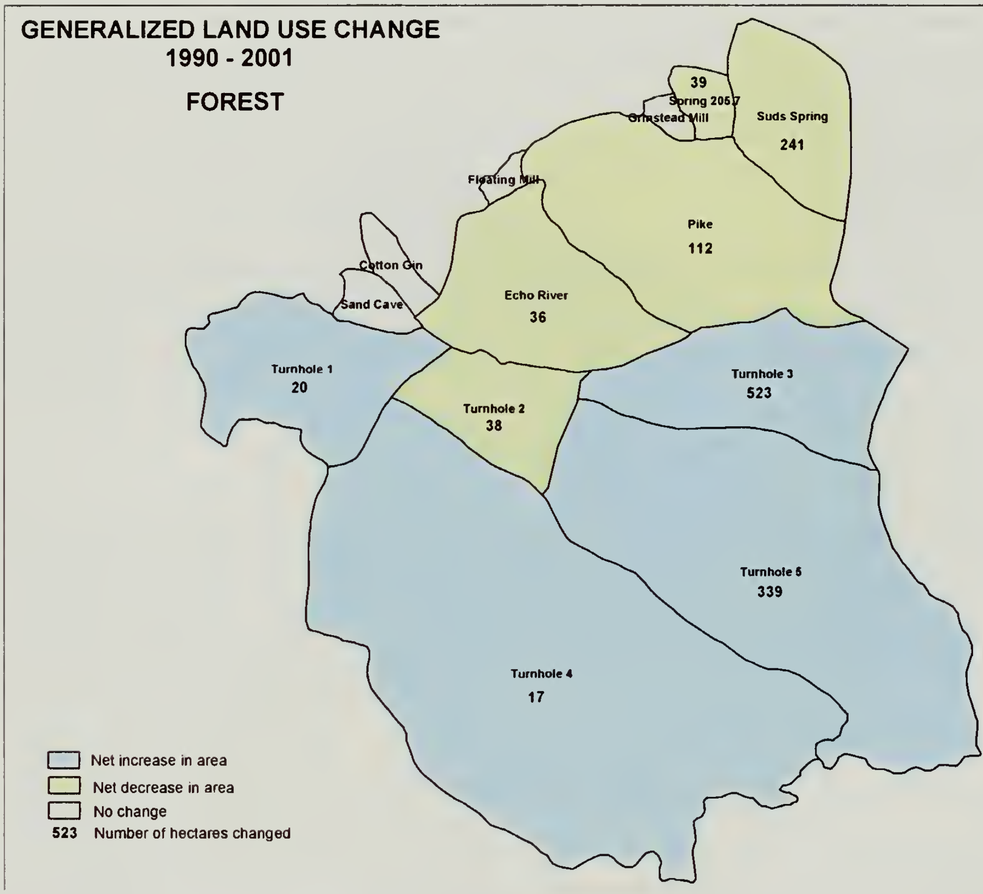


*Figure 39. Generalized land use change, forest.*

It is easy to be misled, based on a casual glance at Figure 38, that there was a great loss in agricultural lands, especially in the Turnhole Spring karst watershed. However, it must be noted that these data represent change from one land use category to another category. The majority of apparent land use change is the result of changing agricultural use of the land rather than the loss or gain of agricultural lands in general. For the most part the apparent loss of agricultural lands in the Turnhole basin is due to a change of row crop production to hayland and pasture uses. In this light, it is not surprising that the smallest change in agricultural uses is in the watersheds that are dominated by the park, those that experienced a loss in forest cover. There is, however, a conversion of agricultural (including "idle lands") to rural domestic development.

Each watershed saw an increase in "development" (Figure 40). Development activities, human based development, include domestic structures, roadways, commercial and industrial development. The past ten years has seen an increase in the number of homes either constructed on site, or prefabricated homes throughout the area. The Mill Hole subbasin experienced a net increase of 1857 hectares of developed lands. Most of this development is the result of farms being auctioned into small lots and developed into domestic dwellings. The Mill Hole subbasin is also home to the new Edmonson County Industrial Park.

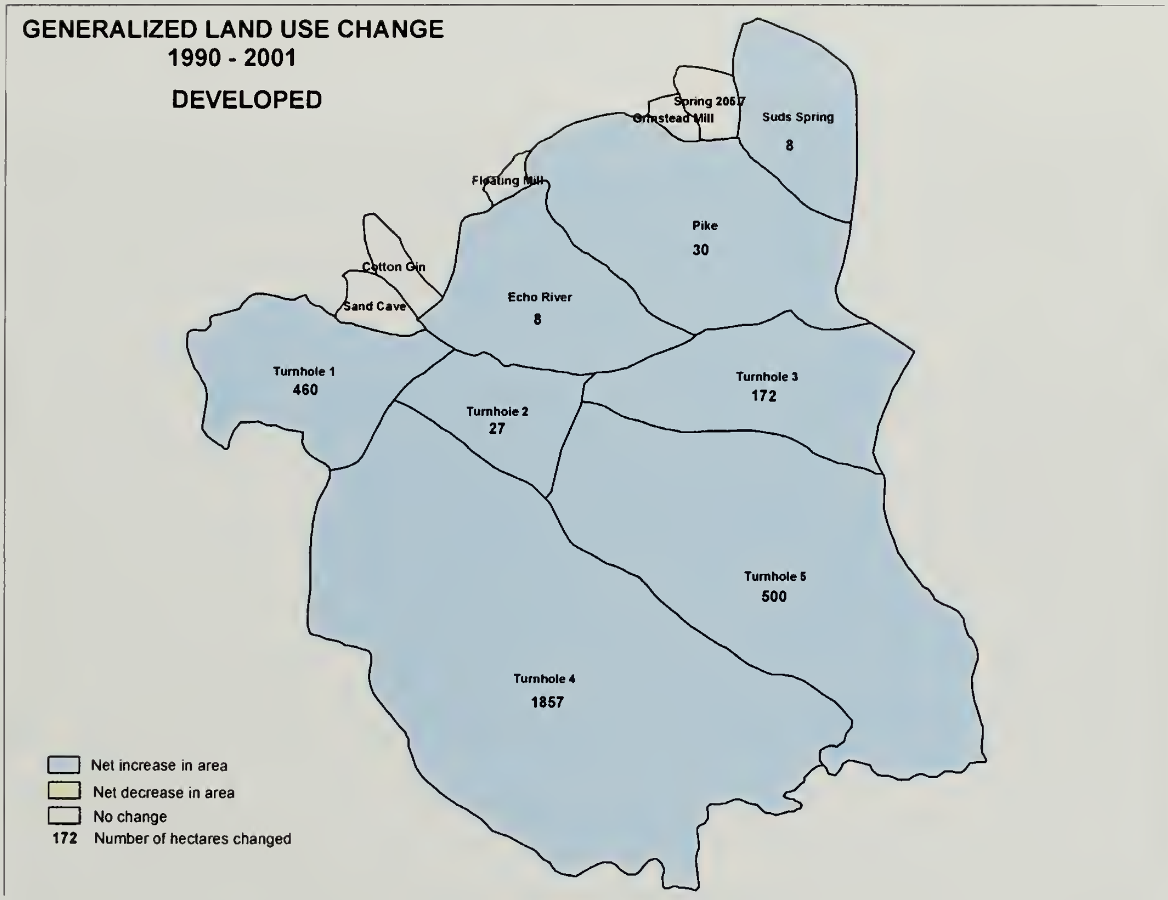


*Figure 40. Generalized land use change, development.*

To follow the format used throughout this document, each watershed will be discussed in turn. Nearly every basin and subbasin show similar patterns: conversion of row-cropped lands into pasture and haylands, a gain in rural domestic development at the expense (loss) of agricultural lands, nearly stable forest uses, and the gain in commercial and industrial development, again at the loss of agricultural lands, along the major transportation corridor. There was no change in what is considered urban domestic development.

Note that there is not a direct balance between the loss of one generalized category and the gain in another. These tables, for the sake of brevity, included only major land use codes within generalized categories. Other classifications, such as “Idle Land” contributes to this discrepancy. Land uses that have a direct impact on water quality were chosen. Tables are arranged into divisions of generalized land use categories (and summed) for the 1990 and 2001 scenes. The “Change” column is (area 2001) – (area 1990). This is important when interpreting the tables and land use change. For example, a “gain” in “clear cut” means that there was more clear cut land in 2001 when compared to 1990. Additional analysis (advanced land use code queries by polygon) is needed to confirm this rather course treatment.

### *Mile 205.7 Spring Karst Watershed*

The forest-dominated dominated basin’s land use remained stable, with the exception of the loss of four hectares of standing timber, apparently at the gain of four hectares of pasture and haylands (Table 17). No changes in residential development were detected.

*Table 17. Land Use Change, Mile 205.7 Spring karst watershed.*

| *MILE 205.7* | | 1990 (hectares) | 2001 (hectares) | Change (hectares) |
|---|---|---|---|---|
| | | | | |
| | *Row Crop* | 1 | 1 | 0 |
| | *Livestock* | 0 | 0 | 0 |
| | *Pasture* | 0 | 4 | 4 |
| *Agriculture* | | **1** | **5** | **4** |
| | | | | |
| *Idle Land* | | **0** | **0** | **0** |
| | | | | |
| | *Standing* | 303 | 299 | -4 |
| | *Clear cut* | 0 | 0 | 0 |
| *Forest* | | **303** | **299** | **-4** |
| | | | | |
| | *Urban* | 0 | 0 | 0 |
| | *Rural* | 3 | 3 | 0 |
| *Dwellings* | | **3** | **3** | **0** |
| | | | | |
| *Commercial* | | **0** | **0** | **0** |

### *Pike Spring Karst Watershed*

The most changed generalized land use was agriculture (Table 18). A theme that will be repeated throughout this exercise, there is a major change within the generalized category of agriculture as row-cropped lands were converted into pasture and haylands. Forested lands dominate the land use theme of this watershed. There was little change in forest cover. Another recurring change is the gain in residential development in rural lands. There is little development with the Pike Spring watershed aside from a three hectare increase in rural dwellings. This was, as will be discussed in the Turnhole Spring sections, at the expense of agricultural lands. There was a gain of 59 hectares in what is classified as "idle land". This was the only gain in this use in the park's watersheds and further analysis is needed to determine the cause.

*Table 18. Land Use Change, Pike Spring karst watershed.*

| ***PIKE SPRING*** | | **1990 (hectares)** | **2001 (hectares)** | **Change (hectares)** |
|---|---|---|---|---|
| | | | | |
| | ***Row Crop*** | 298 | 166 | -132 |
| | ***Livestock*** | 16 | 9 | -7 |
| | ***Pasture*** | 390 | 528 | 138 |
| ***Agriculture*** | | **704** | **703** | **-1** |
| | | | | |
| ***Idle Land*** | | **45** | **104** | **59** |
| | | | | |
| | ***Standing*** | 3072 | 3070 | -2 |
| | ***Clear cut*** | 55 | 58 | 3 |
| ***Forest*** | | **3127** | **3128** | **1** |
| | | | | |
| | ***Urban*** | 0 | 0 | 0 |
| | ***Rural*** | 39 | 42 | 3 |
| ***Dwellings*** | | **39** | **42** | **3** |
| | | | | |
| ***Commercial*** | | **0** | **0** | **0** |

### *Echo River Spring Karst Watershed*

There was little change in land use from 1990 to 2001 (Table 19). Recall that the majority of this basin is within the park, and that which is privately held is lightly developed. The majority of actual "development" is by the park service in the form of visitor service, maintenance, quarters, etc.

*Table 19. Land Use Change, Echo River Spring karst watershed.*

| ***ECHO RIVER*** | | **1990 (hectares)** | **2001 (hectares)** | **Change (hectares)** |
|---|---|---|---|---|
| | | | | |
| | ***Row Crop*** | 1 | 1 | 0 |
| | ***Livestock*** | 0 | 0 | 0 |
| | ***Pasture*** | 6 | 10 | 4 |
| ***Agriculture*** | | **7** | **11** | **4** |
| | | | | |
| ***Idle Land*** | | **0** | **0** | **0** |
| | | | | |
| | ***Standing*** | 2283 | 2282 | -1 |
| | ***Clear cut*** | 0 | 0 | 0 |
| ***Forest*** | | **2283** | **2282** | **-1** |
| | | | | |
| | ***Urban*** | 1 | 0 | -1 |
| | ***Rural*** | 8 | 8 | 0 |
| ***Dwellings*** | | **9** | **8** | **-1** |
| | | | | |
| ***Commercial*** | | **10** | **10** | **0** |

### *Patoka Creek Karst Watershed*

The area recharging Hawkins River experienced a conversion of 943 hectares of row crop lands into pasture and haylands (Table 20). Forest cover changed somewhat. Realize that the "gain" of 14 hectares of "clear cut" means that there was an additional 14 hectares of cut timberlands in 2001 when compared to 1990. There was an additional 50 hectares of rural residential development, in large part contributed by "idle" agricultural lands (which loss 29 hectares). A common practice in the past ten years are to sell, at auction, tracts of farm lands (typically marginal, or nearly idle farms), which are subdivided into lots (generally 0.1 to 0.5 hectares) and populated with mobile and modular homes. An additional 24 hectares of land experienced commercial development, namely the Edmonson County Industrial Park.

*Table 20. Land Use Change, Patoka Creek karst watershed (Turnhole 5).*

| ***PATOKA*** | | **1990 (hectares)** | **2001 (hectares)** | **Change (hectares)** |
|---|---|---|---|---|
| | | | | |
| | ***Row Crop*** | 2002 | 1060 | -943 |
| | ***Livestock*** | 13 | 14 | 1 |
| | ***Pasture*** | 1935 | 2905 | 970 |
| ***Agriculture*** | | **3950** | **3979** | **28** |
| | | | | |
| ***Idle Land*** | | **144** | **115** | **-29** |
| | | | | |
| | ***Standing*** | 2217 | 2225 | 8 |
| | ***Clear cut*** | 161 | 175 | 14 |
| ***Forest*** | | **2378** | **2400** | **22** |
| | | | | |
| | ***Urban*** | 44 | 44 | 0 |
| | ***Rural*** | 230 | 280 | 50 |
| ***Dwellings*** | | **274** | **324** | **50** |
| | | | | |
| ***Commercial*** | | **32** | **56** | **24** |

### *Cave City Karst Watershed*

The 25 $km^2$ area draining into Logsdon River experienced land use change common within the basins dominated by private lands (Table 21). Row cops were converted to pasture and haylands and rural dwellings increased. The overall "loss" in clear cut may be attributable to the secession of forests cut prior to 1990. Rural residential development is noted in a 27 hectare increase, at the expense of agricultural and idle lands.

*Table 21. Land Use Change, Cave City karst watershed (Turnhole 3).*

| ***CAVE CITY*** | | **1990 (hectares)** | **2001 (hectares)** | **Change (hectares)** |
|---|---|---|---|---|
| | ***Row Crop*** | 506 | 208 | -298 |
| | ***Livestock*** | 1 | 1 | 0 |
| | ***Pasture*** | 580 | 876 | 286 |
| ***Agriculture*** | | **1087** | **1085** | **-12** |
| ***Idle Land*** | | **68** | **59** | **-9** |
| | ***Standing*** | 1083 | 1121 | 38 |
| | ***Clear cut*** | 97 | 54 | -43 |
| ***Forest*** | | **1180** | **1175** | **-5** |
| | ***Urban*** | 0 | 0 | 0 |
| | ***Rural*** | 93 | 120 | 27 |
| ***Dwellings*** | | **93** | **120** | **27** |
| ***Commercial*** | | **35** | **37** | **2** |

### *Turnhole Spring Karst Watershed*

All subbasins of the Turnhole Spring karst watershed were combined (including the Patoka Creek and Cave City subbasins discussed above) for these data (Table 22), to be concordant with the water quality sampling point at Turnhole Spring. This, the park's largest subsurface watershed, experienced an alteration of row-cropped lands to pasture and haylands, and a total loss of agriculture of 130 hectares. Old clear cuts seceded at a pace faster than recent cuts as forest lands remained relatively stable. There was a great gain in rural domestic development. Some 231 hectares of rural lands (agriculture and idle lands) were developed for dwellings. Commercial and industrial development occurred, mainly along Interstate 65, including the fledgling Edmonson County Industrial Park, with an additional 51 hectares.

*Table 22. Land Use Change, Turnhole Spring karst watershed (Turnhole 1,2,3,4, and 5).*

| ***TURNHOLE*** | | **1990 (hectares)** | **2001 (hectares)** | **Change (hectares)** |
|---|---|---|---|---|
| | | | | |
| | ***Row Crop*** | 6096 | 2957 | -3139 |
| | ***Livestock*** | 119 | 176 | 57 |
| | ***Pasture*** | 7237 | 10189 | 2952 |
| ***Agriculture*** | | **13452** | **13322** | **-130** |
| | | | | |
| ***Idle Land*** | | **367** | **313** | **-54** |
| | | | | |
| | ***Standing*** | 8418 | 8490 | 72 |
| | ***Clear cut*** | 399 | 322 | -77 |
| ***Forest*** | | **8817** | **8812** | **-5** |
| | | | | |
| | ***Urban*** | 46 | 46 | 0 |
| | ***Rural*** | 813 | 1044 | 231 |
| ***Dwellings*** | | **859** | **1090** | **231** |
| | | | | |
| ***Commercial*** | | **82** | **133** | **51** |

# Aquatic Biology

Mammoth Cave National Park is, without a doubt, among the most biologically diverse parks in the national system. This diversity is reflected in the park's Turnhole Spring Karst Watershed aquatic biology, both in the Green and Nolin Rivers and in the extensive cave stream networks of Mammoth Cave. An aquatic species list of the park can be found in Appendix D.

## Surface Stream Fauna

### *Plankton*

A two-year study (2000-2002) by the University of Tennessee to provide an inventory and analysis of plankton was conducted on the Green River (Laughlin, 2003). This study was initiated by the park in order to inventory plankton prior to a possible infestation of the Green by the exotic zebra mussel (*Dreisssena polymorpha*). Zebra mussels have not yet been found in the river although mussel veligers have been observed in the upstream reservoir. Researchers collected 180 plankton samples from three sites representing the river's three flow regimes, free-flowing, transitional, and impounded. Recall from an earlier section that Lock and Dam Number Six, located on the downstream end of the park impounds the river for about half its course through the park. Three collections were made from each site each year, twice during summer base flow (June/July and August/September) and again during the higher flow periods coincidental with the flood-pool draw-down of the Green River Reservoir in November/December. This study inventoried both phytoplankton and zooplankton.

The inventory found a paucity of zooplankton in the Green, similar to numbers found in the Green River Reservoir. The most dominant group was Cladocera (*Bosmina longirostrus*) and Copepoda (*Mesocyclops edax*). Densities of *Bosmina* ranged from 0.01/L in September 2000 to 0.46/L in December 2001. *M. edax* densities ranged from 0.01/L to 0.53/L during the same samplings. No evidence of zooplankton was found at the free-flowing and transitional sites, and only limited evidence of zooplankton was found in the impounded sampling site. This planktonic distribution, albeit with limited collection numbers, seems to support the bi-zonation of the Green into the *Depositional* and *Erosional* zones proposed by Grubbs and Taylor (2004).

The green algae chlorophyta, was the most dominant phytoplankton phylum present, dominating 97% of species composition, and the majority was the genus *Chlororella*. Other filamentous Chlorophyta genera, like *Ulothrix* contributed minor portions of the phytoplankton densities. Cyanophyta (blue-green algae) and Chrysophyta (golden-brown algae) were found but in relatively low numbers.

The study concluded that, during the study period, the Green River within the park did not exhibit a true plankton community – a potomaplankton community that would be expected for a river – but rather a tachyplankton, or transient community. In other words, true reproduction of plankton is not evident as most, if not all plankton, are brought in from upstream sources. One caveat that the researchers noted was that the first four sampling rounds were taken during an extended drought.

### *Fish*

The fish fauna of the Green River is among the most diverse in the state and of national importance from the standpoint of fish zoogeography and conservation (Cicerello and Hannan, 1991). Kentucky has 226 native fish species (about one quarter of the nation's fish fauna) and the Green River represents two-thirds (151) of that total (Burr and Warren, 1986). This diversity is the result of the hydrogeologic history of the Green. Although not directly affected by the continental glaciation – glaciers never made it as far south as Kentucky – the resulting hydrology proved to isolate the Green River. At times it was populated by fishes of the coastal plain, and other times as a refugium of northern fishes displaced by glacial activity. Although much of the Green's fauna is extant, a large number of species are considered rare at the state and federal level, and all are impacted by habitat alteration (pollution and impoundments) (Cicerello and Hannan, 1991).

Much of what is known of the fishes of the park is summarized in "Survey and Review of the Fishes of Mammoth Cave National Park, Kentucky" by Cicerello and Hannan (1991). The authors sampled 24 sites on the Green in 1990 and found 52 species, including three considered rare in Kentucky. Acceptable literature and museum records document an additional 32 species from the park's surface and subsurface waters. Twenty-six of these were collected just prior to this study in or near the park, and the remaining six are old records and require verification (Cicerello and Hannan, 1991). A complete listing of fishes found in the park can be found in Appendix D.

Studies prior to Cicerello and Hannan (1991) concentrated on fish within the impounded and transitional flow regimes of the Green and Nolin Rivers, and used boat electrofishing equipment (Sickel, et al., 1979, and Laflin, 1988). This method of collection is selective of larger fishes and does not account for those found in the free-flowing section of the river. Cicerello and Hannan focused on the free-flowing section and small surface tributaries (notably Cub Run, Ugly and Buffalo Creeks where backpack shockers and seines were used).

During 2004, Dr. Philip Lienisch (Western Kentucky University) and his students have concentrated efforts along three fronts to accurately sample and monitor the park's fishes. One project was to determine if rainbow trout – stocked in the tailwaters of the Nolin Dam – are seeking refuge in the cool spring waters along the Green and if so, are entering the cave and impacting the endangered cave shrimp. This study relied on boat electro-shocking the river above and below spring runs, seining the spring runs, and setting gill nets in cave streams. No trout were found, let alone trout consuming shrimp.

Lienisch was also contracted to develop protocols for monitoring fish in the Green and its (limited) surface tributaries. This effort began in 2001 and continues through 2004 and employs both boat electro-shocking of the main stem of the Green and back-pack electro-shocking of Cub Run, Ugly Creek, and Buffalo Creek. Lienisch notes that there does not appear to be a drop in species diversity in the upper free-flowing river, and the lower impounded river as seen in other aquatic life (Personal Communications, Phil Lienesch, Professor of Biology, Western Kentucky University, 2004).

Additionally, Lienisch and his graduate students are conducting and inventory of epigean fish within select portions of cave streams. During 2003 and 2004, sites at Echo River (proximal to the divergence of Echo and Styx rivers, the Dead Sea, and Owl Cave) were outfitted with nets and light-traps to collect surface fish that found their way into the cave system. Gillnetting (224 net nights) produced only a few fish (white crappie and carp), while the light-traps collected 383 larvae and juveniles representing ten species and six families (Lienesch, 2004). Lienesch (2004) notes an increased light-trap catch rate after high water events.

### *Mussels*

Although it is up to speculation if the original human occupants appreciated the diversity of the Green River mussels, they no doubt valued their abundance. Throughout the Mammoth Cave area, and especially so in the lower sections of the river, archeological deposits of mussel shells are found. Along the Green, beginning in present day Butler County (one county downstream from the park) are several riverside mounds of mussel shells placed by the ancient peoples of the late Middle Archaic to the Late Archaic Periods (6000-3000 years bp) (Morey and Crothers, 1998). The largest mound covers nearly 10,000 $m^2$ and is several meters high and contains hundreds of human burials (Hensley, 1991). Results of Morey and Crother's study indicate that mussel species found in shell middens were consistent to those found in free-flowing conditions, unlike those found in this now-impounded reach.

Modern appreciation of mussel diversity was documented by Price (1900) in the listing of her collection made in Southcentral Kentucky, including what is now the park. Price related relative commonalties and general habitats of the mussels. Price's list did not give any information to specific collection localities and is of limited use (Ortmann, 1926). Scientific interest and recognition of the extent of mussel diversity of the Green continued with Ortmann (1926). Ortmann sampled two locations within the present bounds of the park; the riffle at Cave Island, and the riffles around a small island north of Great Onyx Cave, presumable either at the mouth of Big Spring Hollow or Three Sisters Island. Apparently Ortmann's locational data are of marginal improvement over Price. In any regard, Ortmann, having previously described the mussel fauna of the Cumberland and Kentucky Rivers, states that the Green has never been linked to the Cumberland as species that occur in the latter are not found any further north, and former marking the southern limit of many species. Later studies, including Isom (1974), which notes 77 mussel species in the Green, confirm Ortmann's opinion that the two rivers are of separate origin, as no Cumberland species are found in the Green.

The Nolin was sampled by Clench and van der Schalie in (1944), and found only eight species – this work was done prior to the creation of the Nolin Reservoir in 1963. Taylor

(1983) conducted a survey of the Nolin above the Reservoir and reported 21 species. Remember that the entire Nolin River within the park is impounded by Lock and Dam Number Six and directly below the Nolin Dam.

Cicerello and Hannan (1990) survey the mussel community within the park between 1987 and 1989. They collected 47 species at 42 locations including six federally listed species, and five considered rare by the state. Six species were not found by Cicerello and Hannan that were indicated in acceptable literature and museum records. Their survey notes that although 42 species were found in the free-flowing section of the river, only 13 species were found in the portion impounded by Lock and Dam Number Six.

Interest in Green River mussels continued as Layzer and Brady (2001) examined the effects of the operation of the Green River Dam on mussel reproduction between the dam and the park. They noticed that several species collected by Cicerello and Hannan (1990) did not show signs of recruitment. For example, the mussel *Actinonaias ligamentina*, which was common in Cicerello and Hannan's collection, was not found smaller than 85 mm. Hardison and Layzer (2001) hypothesize that the operation of the Green River Dam, which discharges large volumes of waters in the spring and early summer has effected reproduction of certain species. The results of the 2001 study indicate that most species of mussels are spawning in the Green. Even the *Actinonaias ligamentina* was found to be reproducing (11.4% of individuals < 50 mm) at the Munfordville station (immediately upstream of the park).

Mussel diversity, as rich as has been documented for the Green River, is in jeopardy. Several mussel species common a hundred years ago are now rare. Stacy Surgenor, park mussel biologist, notes that R.E. Call collected many mussels in the late 19$^{th}$ century that are uncommon today, notably the *Obovaia retusa* (Ringpink). Call collected nearly 30 *O. retusa* at one site in the present-day park, yet only two live specimens have been found in the past ten years in the entire United States. The same goes for the *Hemistena lata* (Crackling Pearly mussel). Where once common in the Green River, it has been extirpated from most of its range (Personal Communication, Stacy Surgenor, Mussel Biologist, Mammoth Cave National Park, 2004). A similar decline has been seen in the *Epioblasma rangiana*, once common but now found by only rigorous sampling efforts. Surgenor notes that *E. rangiana* is the most imperiled mussel in the Green, and that the *Epioblasma triquerta*, once common, is not found aside from "sub-fossil" shells. Other mussel species (*Pleurobema plenum, Pluerobema clava,* and the *Lampsilis abrupta*), found by Ortmann (1926) are on the Federal Endangered Species list, and are considered a rare find today (Personal Communication, Stacy Surgenor, Mussel Biologist, Mammoth Cave National Park, 2004).

Although many species have seen a decline in general numbers – it is difficult to determine population sizes from earlier works as these projects were for museum collections and zoological descriptions rather than a rigorous inventory – some species appear to be in good shape; *Actinonaisa ligamentina* (mucket), *Megalonaias nervosa* (washboard), and the *Amblema pilcata* (three ridge) (Personal Communication, Stacy Surgenor, Mussel Biologist, Mammoth Cave National Park, 2004). The listed *Cyrogenia stegaria* (Fanshell) still occurs in the Green above the park, and may represent the best population in the country. The park is currently constructing a mussel propagation facility along the banks of the Green in order to re-populate the river with rare species, including the *Hemistena lata.*

Aside from mussel inventories and the initiation of long-term mussel monitoring – current and planned biological monitoring to be discussed at the conclusion of this section – a recently-completed study has examined the bioaccumulation of toxins in the hard and soft tissues of Green River mussels. Kirkland (2001) sampled the long-lived *Actinonaias ligamentina* directly upstream of the park as well as midden collections dating to 5000 years bp. Soft and hard (nacre) tissues were analyzed for metals, organochloride pesticides, polyaromatic hydrocarbons, and polychlorinated benzenes. Kirkland's results are as follows:

> The analysis of shell nacre proved to be less important than initially thought. Most metals in the shell nacre were below detection limits and most mussels were aged between 30 and 40 years old, meaning recent disturbances would not be well represented. With the examination of the shells and the analysis of midden specimens, which were harvested almost 5000 years ago, several important details became evident.
> 1) The recent mussel specimens were exposed to excessive silt.
> 2) Although metal concentrations should not have decreased in the last 5000 years, some metals had become less available to the mussel nacre.
> 3) Mussel sizes had changed dramatically in the last 5000 years, probably in response to large-scale increases in nutrients.
>
> Analysis of the soft tissue produced data, which suggested metal concentrations were above recommended levels, and organochloride pesticides were 10 – 10,000 times above recommended levels. Statistical analysis of the data indicated the influence of land use as the primary factor affecting contaminant concentrations.

Kirkland (2001) concluded that land use change, and the impacts to water quality they bring (silt, metals, and pesticides) significantly influence the data. The differences between recent and midden samples supports this conclusion.

### *Benthic Macroinvertebrates, sans Mussels*

Widely accepted as excellent indicators of water quality – most states have devised or adapted protocols of biological integrity – benthic macroinvertebrates (BMI) have been long neglected in general inventories and monitoring in the park until recently. The first thorough account of the BMI of the Green River within the park began in the mid 1990's as Dr. Guenter Schuester (Eastern Kentucky University) and his students made an inventory (Schuester, et al., 1996a), developed a long-term monitoring plan (Schuester, et al., 1996b), and produced an exceptional MS thesis (Pond, 1996).

The inventory investigated shifts in the BMI community structure along a flow gradient, from the free-flowing through the impounded reaches of the Green. As part of the inventory, Schuester examined the effects of Lock and Dam Number Six on the longitudinal distribution of major taxonomic and functional feeding groups. A total of 17,531 individuals were collected from six sample locations representing 12 classes, 24 orders, 72 families, and 170 taxa (Schuester, et al., 1996a). The total collection can be summarized as:

| *Group* | *Abundance* | *Diversity* |
|---|---|---|
| Insects | 64% | 80% |
| Crustaceans | 9% | 3% |
| Gastropods | 2% | 5% |
| Oligochaetes | 1% | 8% |
| Other groups | 24% | 4% |

Major insect groups encountered during the inventory are represented by: Chironomidae (37 taxa), Ephemeroptera (25 taxa), Trichoptera (23 taxa), Coleoptera (17 taxa), and Odonata (15 taxa) (Scheuster, et al., 1996a). Scheuster claims that the BMI diversity and richness are quite high in the free-flowing section of the Green, a trait common to mid-order reaches of river systems, and demonstrates the impacts of the lock and dam to taxa richness, diversity, distributions and functional feeding groups. Many taxa common in the free-flowing zone were either eliminated or severely reduced in the impounded section, which was dominated by taxa associated with lentic systems (Scheuster, et al., 1996a). In general, several longitudinal trends, moving from the free-flowing to impounded sections of the river:
1.) A decrease in taxa richness.
2.) A reduction in EPT (Ephemeroptera, Plecoptera, and Trichoptera).
3.) A decline in diversity and evenness.
4.) A quantifiable difference in BMI composition
5.) An increase in the number of tolerant taxa and a decrease in intolerant taxa.
6.) A change from heterogeneous to homogenous substrates with increased amounts of organic material.
7.) A loss of riffle-run habitats in favor of run-pool habitats.

In a nutshell, the BMI community of the Green within the park is greatly influenced by the habitat alterations caused by Lock and Dam Number Six.

Pond's 1996 study echoed this conclusion and found a similar longitudinal functional feeding group compositional shift going from the lotic to lentic reaches of the river. Pond divided taxa into groups based on feeding methods. Species that rely on scraping and filtering were nearly eliminated in the impounded zone although well represented in the free-flowing zone. Pond claims that the most influencing effect of the dam is the higher degree of seasonal siltation in the slack-water of the impounded zone. Siltation reduces available habitat by covering the course substrate, leaving woody snag habitat as the only refugium.

Grubbs and Taylor (2004) furthered the understanding of longitudinal BMI taxa distribution and river flow regimes. Rather than separating the Green into the free-flowing, transitional, and impounded zones, Grubbs and Taylor demonstrated a clear lotic-lentic break at Cave Island – the beginning of what was once considered the transitional zone – and divided the river into the "erosional" (free-flowing) and the "impounded" (impounded and transitional) reaches (Figure 6). They note that the transitional and impounded zones were taxonomically indistinguishable. Grubbs and Taylor (2004) show that the park has three distinct BMI regime units; the erosional, impounded Green, and impounded Nolin (recall that the entire Nolin within the park is impounded). This is first known BMI sampling of the park's section of the Nolin.

### *Amphibians and Reptiles*

There has been a limited amount of work done with regards to aquatic amphibians in the park. Hibbard (1936) provided the first taxonomic sampling of the proposed park. Hibbard found two species of salamanders and five species of turtles in the Green River, and two salamanders and one frog associated with surface streams. The small farm ponds that once dotted the ridgetops provided the highest diversity with three species of salamanders, one turtle, and at least nine species of frogs either observed in the ponds or adjacent woodlands.

Dr. Floyd Scott (Austin Peay State University) began a program of long-term monitoring of amphibians in the ponds and small streams of the park in 1994 (Scott, 1997). Scott conducted bi-weekly surveys of six ponds (winter and early spring) to determine the number and percent survival of egg masses of *Ambystoma jeffersonianum* (Jefferson's Salamander), *A. maculatum* (Spotted Salamader), and *Rana sylvatica* (Wood Frog), and conduct summer surveys of salamander populations of ten stream reaches.

## Cave Aquatic Fauna

A great deal of Mammoth Cave's fame – beginning with early cave guide Stephen Bishop discovering eyeless fish in the base level streams in 1830s – has been product of one of the world's most diverse cave aquatic ecosystems. There are many early accounts and descriptions of aquatic cave biota flourishing in the mid to late 1800's as biologists from America and Europe traveled to these now-famous underground streams. It seems that the cave biologist's life is incomplete without a pilgrimage to Mammoth Cave.

Inventories or cave aquatic life began as an academic quest for Dr. Tom Poulson in the 1960s. Poulson, who studied a wide suite of biological and ecological targets, ranging from life history, morphology, and physiology to the general ecology of cave fish. Pearson and Jones, (1998) cite an increased focus along the lines and branching from

Poulson's work, with ecological studies by Barr and Kuehune (1971) and Culver (1982), and those regarding specific individual species, Holsinger and Leitheuser's inventory of the Kentucky Cave Shrimp (1982-1986), Lisowski's study of the habitat and behavior of the shrimp (1983), and Lewis who examined the recovery of the once grossly-polluted Hidden River cave (1993).

Poulson (1990), after nearly three decades of research, proposed a protocol for assessing groundwater quality using biotic indices. These protocols are in a sense adapted from indices of biological integrity (IBI) used for surface streams, but tailored to the communities, habitat, diversity and organism densities for streams of Mammoth Cave.

Using Poulson's modified IBI, Pearson and Jones (1998) conducted several years of inventory and IBI testing and developed a cave aquatic biological monitoring program for the park. They focused on ten primary sampling sites, recording details of passage morphology, stream characteristics, and substrates. In situ measurements of pH, SpC, and temperature were taken and samples collected for laboratory analysis of turbidity, alkalinity, hardness, chloride, sulfate, phosphorous, and nitrogen. Faunal survey techniques are governed by organism size. Large animals (fish, crayfish) are directly counted and identified to species and measured. A representative number are evaluated for health or condition characteristics. Smaller animals (isopods, amphipods) are surveyed by rock counts, where individual clasts are picked and scanned. Organisms are field identified to the lowest possible level.

## Exotic Species

In many respects, the Green and Nolin Rivers have not seen the ecologically crippling effects brought by the invasion of aquatic exotic species. That is not to say that several exotics do not exist within these streams, they do. Park mussel specialist Stacy Surgenor supplied the following information on the present knowledge of current aquatic exotic fauna as well as potential (some nearly certain) introductions.

Asian Clam, *Corbicula fluminea* - very widespread, overly abundant, present throughout Green River, and present in the park in vast quantities.

Zebra Mussel, *Dreisenna polymorpha* - in the Green near confluence with Ohio as far up as commercial barge traffic travels (200 km downstream of the park). Specialists suspect it will show up in the upper Green within 10 years. The most likely vector is an introduction into Green River Lake by a contaminated boat (this happened in Lake Cumberland a few years back, boater from Ohio had outboard motor cooling system packed full of zebra mussels). Zebra mussels could very possibly be introduced by contaminated canoes/kayaks below the dam. Many experts agree that a zebra mussel infestation of the Green within the park is definitely coming; it's just a matter of when, while other experts believe the spread of zebra mussels to the park to be unlikely.

Quagga Mussel (*Dreisenna bugensis*) showed up in the Great Lakes area a few years back (after the zebras invaded) and they are still confined to the Great Lakes area including the St. Lawrence River. Quaggas are native to Caspian Sea area, introduced through discharged freighter ballast water (same method of zebra introduction). Unfortunately, they feed year-round, non-stop (unlike zebras), can tolerate silty conditions where zebras do not do well, and can live in much deeper water. Some experts suspect it will gradually spread south, but zebras caused people to be more cautious about introductions, so it probably won't spread as fast as the zebra mussel did, but it could possibly show up in the Green River within a couple of decades (not an immediate threat). Some experts see the spread of the Quagga to park waters to be unlikely.

There are also several exotic fish species found within the park. Rainbow trout (*Onchorhynchus mykiss)* are currently stocked in the tailwaters of the Nolin Dam (only three km from the park boundary). These fish, native to the far western portions of the United States, have been introduced throughout the east, especially in the cold-water lake releases as a sport fish. Currently the Kentucky Department of Fish and Wildlife Resources (KDFWR) stock rainbows in the tailwaters of the Nolin Dam – to give an order of scale, 16,600 were stocked into this put-and-take fishery in 2000. The KDFWR also stocks rainbows within the Green River (upstream of the park) at Roundstone Creek.

Common Carp (native to Eurasia) - *Cyprinus carpio* was introduced at least 100 years ago and are common in the Green and Nolin Rivers within the park. Its cousin, the goldfish *Carassius auratus* is also found within the park's two surface rivers.

Similar to the mussels, the real potential for additional introductions of exotic fish exists. Mosquito fish (*Gambusia affinis*) are native to the United States, but their range is increasing, possibly due to bait bucket introductions or habitat modifications that favor it. These fish can tolerate warm temperatures and low dissolved oxygen levels, and have very high fecundity, but are short-lived. The mosquito fish was not collected in the park in the early 1990s but was found in the park in the past few years. Its native range is somewhat speculative, but experts suspect that it was not native to the Green River basin.

Asian Carp (bighead *Hypothalmichthys nobilis*, and silver *H. molitrix*): native to large rivers in China): are presently not within the Upper Green River watershed. They are in the Mississippi and lower Ohio, and have invaded the Cumberland and Tennessee Rivers. These fish are more at home in larger rivers and expected invasion, if it does occur, is not likely within the next ten years.

Sticklebacks (Genera *Culaea* and *Gasterosteus*) are currently not present in Upper Green. Sticklebacks are frequently introduced with baitfish shipments. These may be introduced to the Green River Basin by bait-bucket dumping.

In many respects it is beyond the means of resource managers to single-handedly remove and prevent the invasion of exotic species. Rivers flow into and out of the park from great distances, crossing the bounds of many government and private resource managers. The state itself, through its sport fishery programs, introduces tens of thousands of trout each year. In addition, thousands of recreational boaters launch into waters upstream of the park. The potential of introduction of exotics accompanies each launch and with each dump of an unused bait bucket. These issues are common throughout the park service and the nation at large. For decades not only was the practice in exotic introduction not discouraged, it was, and continues to be supported by state governments.

Aquatic exotic species seem to be covered by three distinct categories: sport fish (which are deliberately introduced), non-sport fish (locally introduced primarily by private individuals – grass carp for example), and other aquatic exotics which are introduced by accident or carelessness (zebra mussels).

The challenge for resource managers is manifold. Foremost, state and federal managers may have different management objectives. An example would be the KDFWR. This agency's mandate includes fishery management, and in the case of trout stocking, to reclaim an otherwise distorted fishery by the operation of a large reservoir – the native fishery was negatively impacted by cold–water release and thus stocked with cold-water-tolerant sport fishes. In addition to deliberate introduction of sport fish, an occasional accidental introduction of non-sport fish is ever-present and is beyond the direct regulation of state or federal governments. And nearly beyond any conservation or preservation control looms the accidental introduction of exotic non-fish species.

## Current and Planned Aquatic Biomonitoring

Mammoth Cave National Park is currently making the transition from inventories and surveys of biology to the park's Prototype program, as the NPS prototype for the Cave and Karst ecotype. It is anticipated that aquatic biological monitoring will occur with sufficient temporal and spatial concordance with the park's on-going water quality monitoring to aid in data interpretation. Currently several water quality locations are within specific stream reaches, and the rest are at the very least, integrators (at springs) combining all water quality from upstream reaches where biological monitoring occurs.

Leibfreid et al. (2005) describe a conceptual framework of long-term monitoring protocols to be implemented at the park central to the park's Prototype program. This program is ecosystem-based and issue-orientated and focuses on multi-parameter monitoring of ecological process pathways among the park's major component ecosystems (Leibfreid, et al., 2005). They describe three major ecosystems; terrestrial/forest, river-aquatic/fluvial, and a composite cave ecosystem with cave terrestrial and cave aquatic components. While the latter two are directly linked to aquatic resources, the former, terrestrial/forest, is linked via nutrient input to the cave and surface stream systems. Devised from the framework of three key major ecosystems and the subsequent development of conceptual models, Leibfreid et al. (2005) propose the following targets for long-term monitoring:

Cave Crickets
Allegheny Woodrats
Water Quality and Quantity
Ozone (air component)
Cave Air Quality
Cave Beetles
Fish Diversity
Atmospheric Deposition (air component)
Atmospheric Deposition (impacts component)
Benthic Macro-Invertebrates
Forest Pests
Cave Aquatic Fauna
Cave Bats
Ozone (impact component)
Plant Species of Concern
Adjacent Land Use
Vegetative Communities
Invasive Plants

# Management Authority

## Specific Laws

Mammoth Cave National Park has a very interesting and legislatively convoluted past, one that may well frustrate or thrill future Administrative Historians. Mammoth Cave does not have a clear-cut Enabling Legislation as many, more recent parks have. Instead, the park's Enabling Legislation can be pieced together by a succession of Congressional Bills and Reports that established the park.

As early as the late $19^{th}$ century, local landowners and promoters considered the idea of establishing a national park at Mammoth Cave – by that time the cave had become world famous and recognized as one of the "Seven Natural Wonders". Bills were introduced in Congress as early as 1911 – with each Bill requesting federal funds for land purchases – calling for the establishment of the park, although it was not until the mid-1920's did enough political momentum carry the action forward. Kentuckians eager for park status began promoting their notion and in January 1925 (H.R. 11980, S. 4109) called upon the Secretary of Interior to establish a committee (what was to be known as the Southern Appalachian National Parks Commission) to assess the potential and possibilities of creating the Shenandoah, Great Smoky Mountains, and Mammoth Cave National Parks. Their report to Congress, "Final Report of the Southern Appalachian National Park Commission" (June 30, 1931) states "Another geological feature of much interest is found in the thousands of sinkholes of varying sizes throughout as much of the drainage is carried to underground streams, there being few surface brooks or creeks." The US House of Representatives (Report No. 1178, and its companion Senate Report No. 823) summarize the Commission Report and states, "…thousands of people may find – in addition to the pleasure and interest derived from an inspection of the caves and their many features of interest – the most delightful outdoor recreation in boating and fishing on the Green and Nolin Rivers, lovely navigable streams flowing for miles through the proposed park."

## General Laws

The National Park Service was established on August 25, 1916 through the National Park Service Organic Act (39 Stat.535). This act created the National Park Service and directed it to "…regulate the use of federal areas known as national parks, monuments, and reservations…so as to conform to the(ir) fundamental purpose". The fundamental purpose, as defined by Congress, "…is to conserve the scenery and the natural and historical objects and wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations."

The General Authorities Act of 1970 (PL 91-383,84 Stat.825) instructed the National Park Service to "…include any area of land and water now or hereafter administered by the Secretary of the Interior through the National Park Service for park, monument, historic, parkway, recreational or other purposes." This act also stated that areas within the national park system "...though distinct in character, are united through their interrelated purposes and resources..." and that the national park system be "...preserved and managed for the benefit and inspiration of all the people of the United States..." This Act also stated that each park be administered in accordance with the provisions of any statute made specifically to that park, and that the Organic Act of 1916 would apply to the extent that it did not conflict with such specific statutes. It was the intent of this language to eliminate confusion with regards to the mission of many parks, primarily new lands designated as Historic Parks, Scenic Rivers, National Recreational Areas, and National Seashores. Prior to this Act, many of these newer units dealt with administrative and management conflicts in that their Enabling Legislation permitted activities that were in conflict with the Organic Act.

The Redwoods National Park Expansion Act of 1978 (PL 95-259, 92 Stat.163) amended the General Authorities Act and reaffirmed the mission of the National Park Service. The Act states "...protection, management, and administration of these areas shall be conducted in the light of the high public value and integrity of the National Park System and shall not be exercised in derogation of the values and purposes for which these various areas have been established, except as may have been or shall be directly and specifically authorized by Congress."

## Other Legislative Authority and Constraints

### *Federal Authorities*

*The National Environmental Policy Act (42 U.S.C. 4321-4347)*

The National Environmental Policy Act established federal policy and provided a formal process that considered environmental values into federal decision making. From this Act, the President's Council on Environmental Quality (CEQ) was created, which develops legal procedures for all federal agencies which propose actions that may effect the environment. The CEQ established a framework of documentation in accordance to the potential impacts on the human environment. These levels, in order from least to most severe, are the Categorical Exclusion (CE), the Environmental Assessment (EA), and the Environmental Impact Statement (EIS). For proposed actions which are deemed to have no impact, a CE is prepared that documents the facts that lead to the government's decisions. If the proposed action is not categorically excluded, the next step, the EA, is prepared. If all significant impacts can be successfully mitigated, and is not likely to cause controversy, a Finding of No Significant Impact (FONSI) can be drafted. If the proposed actions and decisions cannot be demonstrated to issue a FONSI, an EIS is prepared. An EIS would be needed if the proposal called for controversial actions or decisions, or what would be considered a major federal action – a major highway, dam or airport for examples. If managers are shrewd, and recognize the level of their proposal, an EA may be bypassed in favor of an EIS. An EIS is far more detailed examination of actions and decisions and includes public forums, review, and comments.

*Clean Water Act (33 U.S.C. s/s 1251 et seq.)*

Perhaps the single-most important environmental law affecting the water resources of Mammoth Cave National Park is the Clean Water Act (CWA). Passed by Congress and signed into law in 1970, the purpose of the CWA "...is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters."

The CWA requires each state to establish water quality standards, and review these standards in light of water quality measures every three years. States, under direction of the U.S. Environmental Protection Agency (USEPA), declared "designated uses" for key water bodies based upon human (drinking water, recreation) and biological (warm water, cold water) use. Each state is required to report on the status of these waters to Congress and must list any water body that is not meeting the standards, what is known as the 303d list. Furthermore, each state is required to establish Total Maximum Daily Loads (TMDLs) for these waters. As of 2003, most states have complied with this requirement or are in the latter stages of formulation. Kentucky released for public comment and review, proposed TMDLs in November 2005.

Another component of the CWA is the National Pollution Discharge Elimination System (NPDES). The intent of the NPDES is to document and set up a permitting system regulating point-source discharges. Again each state is obligated to create its own system of approving discharges of wastewaters into state water bodies. In 1987 amendments were made to the CWA to include stormwaters from municipal, commercial, and construction sites in the NPDES program.

*Endangered Species Act (7 U.S.C. 136; 16 U.S.C. 460 et seq.)*

Of similar importance to the CWA, the Endangered Species Act (ESA) of 1973 (and as amended in 1978, 1982, and 1988), serves as a powerful resource protection and conservation tool for the preservation and recovery of rare or declining species and their critical habitat. The ESA is of particular importance to water resources management at Mammoth Cave National Park as there are currently eight listed aquatic species within the park. Section 7 of the ESA requires federal agencies to consult with the U.S. Fish and Wildlife Service (USFWS) if their proposed actions or decisions may affect a species listed as threatened or endangered or their critical habitats.

*Federal Cave Resource Protection Act (16 U.S.C. 63)*

This Act states that "...significant caves on federal lands are an invaluable and irreplaceable part of the world's natural heritage..." and that "...in some instances, these significant caves are threatened due to improper use, increased recreational demand, urban spread, and a lack of specific statutory protection".

*Fish and Wildlife Coordination Act (16 U.S.C. 661 et seq.)*

This Act states that "...wildlife conservation shall receive equal consideration and be coordinated with other features of water resource development programs."" Federal agencies must consult with the USFWS, and similar state agencies, if proposed water resource development actions may result in an alteration of a water body.

*Federal Insecticide, Fungicide, and Rotenticide Act (7 U.S.C. s/s 135 et seq.)*

This law regulates the use and application of pesticides. It designates certain chemicals as restricted-use status, and requires certification for their use and application. Under this law, the USEPA retains authority to draft and enforce higher standards as new chemicals are developed and new evidence is provided demonstrating environmental damage from existing pesticides.

*Exotic Organisms, Invasive Species (Executive Orders 11987, 13112)*

Executive Order (EO) 11987 directs federal agencies, to the extent permitted by law, to restrict the introduction of exotic species into natural ecosystems, including waters, into lands owned or leased by the United States. Federal agencies are also required to promote state and local governments and private citizens to prevent the introduction of exotic species onto federal lands and waters. The possible accidental introduction of zebra mussels into the Green River is an example. EO 13112 addresses the prevention of introduction and control of invasive species, and recognizes the impacts to ecologic, economic, and human health.

*Floodplain Management (Executive Orders 11988)*

This EO requires federal agencies to "reduce the risk of flood loss...minimize the impacts of floods on human safety, health, and welfare, and...restore and preserve the natural and beneficial values of floodplains." Federal agencies must implement floodplain planning and consider all feasible alternatives which minimize the impacts to the floodplain prior to the construction of facilities. Locating facilities and structures outside the floodplain must be considered.

*Protection of Wetlands (Executive Orders 11990)*

These orders oblige federal agencies to "minimize the destruction, loss or degradation of wetlands, and preserve and enhance the natural and beneficial values of wetlands". Providing no alternatives are available, federal agencies must restrict activities to those which will have no adverse impacts to wetlands.

*National Parks Omnibus Management Act of 1998*

This Act attempts to improve the ability of the NPS to provide state-of-the-art management, protection, and interpretation of and research on the resources of the National Park System by:

- Assuring that management of units of the National Park System is enhanced by the availability and utilization of a broad program of the highest quality science and information;
- Authorizing the establishment of cooperative agreements with colleges and universities, including but not limited to land grant schools, in partnership with other Federal and State agencies, to establish cooperative study units to conduct multi-disciplinary research and develop integrated information products on the resources of the National Park System, or of the larger region of which parks are a part;
- Undertaking a program of inventory and monitoring of National Park System resources to establish baseline information and to provide information on the long-term trends in the condition of National Park System resources; and
- Taking such measures as are necessary to assure the full and proper utilization of the results of scientific study for park management decisions. In each case in which an action undertaken by the NPS may cause a significant adverse effect on a park resource, the administrative record shall reflect the manner in which unit resource studies have been considered. The trend in the condition of resources of the National Park System shall be a significant factor in the annual performance.

*Park System Resource Protection Act*

The Park System Resource Protection Act, 16 U.S.C. § 19jj, allows the NPS to seek compensation for injuries to park system resources and to use the funds recovered to restore, replace or acquire equivalent resources and to monitor and study such resources. Park system resources includes any living or non-living resource that is located within a park within the boundaries of a unit of the National Park System and is owned by the Federal Government. This is inclusive of natural resources, cultural resources, physical facilities and other resources that meet this definition.

*Clean Air Act of 1970*

This Act, as amended, regulates airborne emissions of a variety of pollutants from area, stationary, and mobile sources; establishes a nationwide program for the prevention and control of air pollution; and establishes National Ambient Air Quality Standards (NAAQS). Under the Prevention of Significant Deterioration provisions, the Act requires Federal officials responsible for the management of Class I Areas (national parks and wilderness areas) to protect the air quality related values of each area and to consult with permitting authorities regarding possible adverse impacts from new or modified emitting facilities. The 1990 amendments to this Act were intended primarily to fill the gaps in the earlier regulations, such as acid rain, ground level ozone, stratospheric ozone depletion and air toxics. The amendments identify a list of 189 hazardous air pollutants. The USEPA must study these chemicals, identify their sources, determine if emissions standards are warranted, and promulgate appropriate regulations.

### *National Park Service Regulations*

The National Park Service, along with every federal agency established by Congress, promulgates regulations necessary to fulfill its mission. The NPS Management Policies (2001) provide broad policy guidance for the management of National Park System units. These NPS policies and guidelines broadly require management of natural resources of the National Park System to maintain, rehabilitate, and perpetuate the inherent integrity of aquatic resources. Section 4.6 of the NPS Management Policies, specifically addresses water resource management including protection of surface waters and groundwater, water rights, water quality, floodplains, wetlands, and watershed and stream processes. It is NPS policy to determine the quality of park surface and ground water resources and avoid, whenever feasible, the pollution of park waters by human activities occurring within and outside of parks. Specifically, the NPS works with appropriate governmental bodies to: achieve the highest possible standards available under the Clean Water Act for protection of park waters; take all actions necessary to maintain or restore surface and ground water quality within the parks to be in compliance with the Clean Water Act and all applicable laws and regulations; and develop agreements with other governing bodies, where appropriate, to obtain their cooperation in maintaining or restoring the quality of park water resources. NPS Management Policies also direct the NPS to: manage watersheds as complete hydrologic systems; minimize human disturbance to natural upland processes that deliver water, sediment, and woody debris to streams; and manage streams to protect stream processes that create habitat features, including floodplains, riparian systems, woody debris accumulations, terraces, gravel bars, riffles, and pools.

Sections 4.8.1.2 and 4.8.2.2 of the NPS Management Policies address “karst” and “caves”, respectively. The policies state that the NPS will manage karst terrain to maintain the inherent integrity of its water quality, spring flow, drainage patterns, and caves. The policies also state that the NPS will manage caves in accordance with approved cave management plans to perpetuate the natural systems associated with the caves, such as karst and other drainage patterns, air flows, mineral depositions, and plant and animal communities.

In accordance with NPS Management Policies, the NPS will protect watershed and stream features mainly by avoiding impacts to watershed and riparian vegetation and allowing natural fluvial processes to proceed unimpeded. When conflicts between park infrastructure and stream processes are unavoidable, park managers will first consider relocating or redesigning infrastructure, instead of manipulating streams. However, where stream manipulation is inevitable, the NPS will use techniques that protect natural processes to the greatest extent practicable.

A series of DOs provides specific guidance for implementing park policy. Director Orders that deal with water resources issues are:

- DO – 2 the planning process

DO-2, *Park Planning*, was incorporated into the 2001 NPS Management Policies. In August 2004, new Park Planning Program Standards described earlier (*National Park Service Planning Framework* (Figure 1)) became official, replacing DO-2. Park planning helps define what types of resource conditions, visitor uses, and management actions will best achieve that mandate. The NPS is to maintain an up-to-date General Management Plan (GMP) for each unit of the National Park System. The purpose of the GMP is to ensure that each park has a clearly defined direction for natural and cultural resource preservation and visitor use. Mammoth Cave National Park has a dated (1983) GMP. A park's Resources Management Plan (RMP) describes the specific management actions needed to protect and manage the park's natural and cultural resources. Discipline-specific planning documents that complement the RMP (e.g., Fire Management Plan, Water Resources Stewardship Plan, etc.) are prepared for NPS units when warranted.

- DO – 12 compliance with NEPA

The National Environmental Policy Act of 1969 (NEPA) is considered to be the landmark environmental protection legislation that attempts to reach a balance between use and conservation of natural and cultural resources. NEPA requires all federal agencies to 1) prepare in-depth studies of the impacts and alternatives to proposed "major federal actions", 2) use the information contained in such studies in deciding whether to proceed with the actions, and 3) diligently attempt to involve the interested and affected public before any decision affecting the environment is mad. The 1916 National Park Service Organic Act directs the NPS to "conserve the scenery and the natural and historic objects and the wildlife herein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations."

Read together, the provisions of NEPA and the Organic Act of 1916 are consonant and jointly commit the NPS to make informed decisions that perpetuate the conservation and protection of park resources unimpaired for the benefit and enjoyment of future generations. Planning, environmental evaluation, and public involvement in management actions that may affect NPS resources are essential in carrying out the trust responsibilities of the NPS. Particularly, in this era of heightened environmental concern (at least in many public regards), it is essential that NPS management decisions 1) be scientifically informed, and 2) insist on resource preservation as the highest of many worthy priorities.

Mammoth Cave, like any unit of the NPS, complies with the NEPA process. The park has, on staff, a compliance officer, who, among other duties, makes sure that the NEPA process is followed for any proposed management action that may affect the environment. The park holds monthly meetings of its "Project Management Team" that reviews proposals and assures all NEPA, as well other compliance factors, are properly considered.

- DO – 35A sale of lease of park services, resources or water

This Order establishes the operational policies, procedures, and requirements for the sale or lease of park resources, including water, for activities outside the park, including the conditional authorization of the sale or lease of water resources. In regards to water resources, when an application is for the use of water outside the park, the use of water will be in accordance with the laws and regulations governing ownership and use of water and water rights. In addition, when a park's future resource protection or visitor needs dictate, the NPS will terminate the sale or lease of park waters.

- DO – 75 natural resources inventory and monitoring

Knowing the condition of natural resources within the NPS is fundamental to the Service's ability to protect and manage parks. Based on legal mandates and NPS policy, the major goals of the Servicewide inventory and monitoring (I&M) program are: 1) to inventory the natural resources and park ecosystems under NPS stewardship to determine their nature and status, 2) to monitor park ecosystems to better understand their dynamic nature and condition, 3) provide reference points for comparisons with other, altered environments, and 4) to integrate natural resources inventory and monitoring information into NPS planning, management, and decision making. Other goals include establishing natural resources inventory and monitoring as a standard practice throughout the NPS and forming partnerships with other natural resource agencies in order to pursue common goals and objectives.

DO-75 provides a guideline that 1) summarizes the reasons for inventory and monitoring of natural resources in units of the National Park System, 2) provides an overview of the Servicewide I&M program, including staff roles and functions, 3) describes a process for conducting I&M studies at the individual park level, 4) identifies major ecosystem components useful for resources inventory and long-term monitoring, and 5) provides data administration and reporting guidelines for the program.

Mammoth Cave was chosen as a "Prototype" park and is one of 14 parks in the Cumberland Piedmont Network (CUPN). Prototype status, while wrapped in funds sufficient to outfit an office with various resource specialists, requires the park to develop an array of protocols monitoring natural resources – expectantly protocols that are needed in other NPS units that contain caves and karst resources. The CUPN must too develop protocols that were identified by park managers as "vital signs" common throughout, or at least of high importance, to the network. The NPS I&M program combined these two entities for budget and work-plan purposes. At the time of this writing, the Phase III document, which includes protocols for water quality monitoring, has been finalized

(Leibfreid, et al., 2005). Included in this document is the Protocol Narrative and Standard Operating Procedures for Water Quality Monitoring in the CUPN.

- DO – 77 management of natural resources

Reference Manual #77 offers comprehensive guidance to NPS employees responsible for managing, conserving, and protecting the natural resources found in National Park System units. The Manual serves as the primary guidance on implementing Service-wide natural resource management in units of the National Park System. Specific natural resources pertaining to water addressed in the manual include the management, protection, and use of: fish and fishery resources; freshwater resources; marine resources; nonnative species; shorelines; and marine, freshwater, and barrier island resources.

*DO #77-1 and Procedural Manual #77-1: Wetland Protection*

The purpose of DO #77-1 is to establish NPS policies, requirements, and standards for implementing Executive Order 11990, *Protection of Wetlands* (42 FR 26961). The NPS adopts a goal of "no net loss of wetlands." In addition, the NPS will strive to achieve a longer-term goal of net gain of wetlands service-wide. DO #77-1 directs NPS units to conduct park-wide wetland inventories to help assure proper planning with respect to management and protection of wetland resources and sets forth the standard for defining, classifying, and inventorying wetlands. For proposed new development or other new activities or programs that are either located in or otherwise have the potential for adverse impacts on wetlands, the NPS will employ a sequence of: 1) avoiding adverse wetland impacts to the extent practicable; 2) minimizing impacts that could not be avoided; and 3) compensating for remaining unavoidable adverse wetland impacts via restoration of degraded wetlands. Where natural wetland characteristics or functions have been degraded or lost due to previous or ongoing human activities, the NPS will, to the extent appropriate and practicable, restore them to pre-disturbance conditions. Where appropriate and practicable, the NPS will not simply protect, but will seek to enhance natural wetland values by using them for educational, recreational, scientific, and similar purposes that do not disrupt natural wetland functions. Procedural manual #77-1 provides more detailed procedures by which the NPS will implement DO #77-1

DO #77-2 and Procedural Manual #77-2: Floodplain Management

DO #77-2 applies to all NPS proposed actions, including the direct and indirect support of floodplain development, that could adversely affect the natural resources and functions of floodplains, including coastal floodplains, or increase flood risks. In compliance with Executive Order 11988, *Floodplain Management*, it is NPS policy to preserve floodplain values and minimize potentially hazardous conditions associated with flooding. Specifically, DO #77-2 directs the NPS to:

- Protect and preserve the natural resources and functions of floodplains;
- Avoid the long- and short-term environmental effects associated with the occupancy and modification of floodplains;
- Avoid support of floodplain development and actions that could adversely affect the natural resources and functions of floodplains or increase flood risks; and
- Restore, when practicable, natural floodplain values previously affected by land use activities within floodplains.

When it is not practicable to locate or relocate development or inappropriate human activities to a site outside and not affecting the floodplain, NPS will:

- Prepare and approve a Statement of Findings (SOF), in accordance with procedures described in Procedural Manual #77-2;
- Take all reasonable actions to minimize the impact to natural resources of floodplains;
- Use non-structural measures as much as practicable to reduce hazards to human life and property; and
- Ensure that structures and facilities are designed to be consistent with the intent of the standards and criteria of the National Flood Insurance Program (44 CFR Part 60).

Procedural manual #77-2 establishes NPS procedures for implementing floodplain protection and management actions National Park System units in accordance with DO #77-2. The manual defines regulatory floodplains and the information required to delineate floodplains; defines the information required to evaluate hazards associated with the modification or occupation of floodplains; and provides requirements for managing activities that impact floodplains.

- DO – 83 Public Health

By the turn of the $20^{th}$ century, the NPS hosts over 300 million visitors each year. In order to provide for visitor enjoyment the NPS operates water and waste water facilities, and recreational opportunities like swimming. To ensure that these facilities and services are operated in a safe and healthful manner and according to existing public health laws and regulations, the NPS Public Health Program (PHP) conducts health risk and environmental compliance assessments.

Mammoth Cave National Park does not directly operate its drinking water or waste water systems – which are operated by the Caveland Environmental Authority – but communicates with the operator on a daily basis. One exception is the waste water treatment facility located at the Great Onyx Job Corps. This tertiary system is operated by the park and discharges into the Nolin River. The park is responsible for its operation and compliance with state regulations. The park also provides suitable backcountry waste systems in the form of self-contained barrel toilets at selected trailheads.

NPS unit managers will reduce the risk of waterborne diseases by ensuring that recreational water sites are operated properly, maintained and monitored in accordance with state or local regulations.

This concept seems to apply only to designated bathing beaches, which can be along rivers. Mammoth Cave National Park has not officially designated bathing beaches, on any particular section of river bank. By not designated specific bathing areas, the park is not required to monitor the quality of its waters as relative to primary contact recreation (swimming). This, of course, does not prevent thousands of people from swimming in the Green and Nolin rivers each year.

*Water Rights; Federal Law*

The federal reserved water right is a judicially-created water right—the result of a line of United States Supreme Court opinions dating back to 1907. *Winters v. United States,* 207 U.S. 564 (1908). The United States Supreme Court has held that where water is needed to fulfill the purposes of a reservation of federal land, Congress intended to reserve that amount of water needed to fulfill the purpose of the reservation. *United States v. New Mexico,* 438 U.S. 696, 701 (1978). Such reservations of water have been recognized for national forests, national parks, and national recreation areas. *Arizona v. California,* 373 U.S. 546, 601 (1963); *United States v. New Mexico, supra; Cappaert v. United States,* 426 U.S. 128 (1976).

In order to fully assess the existence and nature of a federal reserved water right associated with Mammoth Cave National Park, an examination of the legislation creating the park would be necessary. If needed to fulfill the purposes of the federal reservation, a federal reserved right may be either for consumptive purposes (i.e., involving diversion of water from the stream) or for non-consumptive purposes (i.e., involving natural *in situ* uses of water). A federal reserved right associated with these purposes would be limited to that amount needed to accomplish those purposes. The effective date of a federal reserved water right is the date the reservation was created. *Cappaert v.United States,* 426 U.S. 128, 147 (1976).

The applicability of the federal reserved rights doctrine to Mammoth Cave National Park is uncertain. The federal reserved rights doctrine originated in public land states, in situations where the federal government reserved land from the public domain for a federal purpose. In contrast, Kentucky is not a public land state and Mammoth Cave National Park was created through acquisition of private property rather than through reservation of the public domain. This calls into question the viability of a federal reserved right for the benefit of the park. There is federal case law indicating that a federal reserved right exists on lands acquired and incorporated into an Indian Reservation. *United States v. Anderson,* 736 F.2d 1358 (9$^{th}$ Cir. 1984). However, this holding has not yet been extended to lands acquired to fulfill national park purposes.

The existence of a federal reserved right can be confirmed, and its exact contours (purpose, amount, timing, source) ascertained, only through a court proceeding. Until such a proceeding, the existence and contours of a federal reserved right are matters of estimation.

### *Commonwealth of Kentucky Regulations*

Water Rights; State Law

In a water rights context, Mammoth Cave National Park's ability to protect its water and water-related resources is affected by both state and federal law. The more relevant aspects of each are summarized below. While preserving these legal remedies, the NPS's policy is to work with Kentucky water administrators to protect park resources and to seek resolution of water quantity conflicts through cooperation, communication, and consultation with other water claimants.

The State's policy regarding water resources is to encourage and support projects that control and store state water resources in order to ensure continued growth and development of the State. K.R.S. § 151.110(1)(a). The Natural Resources and Environmental Protection Cabinet ("Cabinet") is charged with developing a plan to, among other things, protect, conserve, and develop State water resources in a manner consistent with the State's duties to manage natural resources, the public's right to clean water, and the preservation of the natural, scenic, cultural, historic, and aesthetic values of the environment. K.R.S. § 151.112(1)(a).

In terms of water allocation doctrine, Kentucky is considered to be a regulated riparian state. With some exceptions, any person seeking to divert, withdraw, or transfer the public waters of the State must obtain a permit from the Cabinet. K.R.S. § 151.150(1). Public waters include the "water of any stream, lake, ground water, subterranean water, or other body of water." K.R.S. § 151.120(1). Excepted from the permit requirement are uses less than 10,000 gallons per day, domestic uses (one household), agricultural uses (with some exceptions), steam-powered electrical generating plants, and injection of water underground for oil and gas production. K.R.S. § 151.140. The Cabinet shall issue a permit if an investigation by the Cabinet indicates that the quantity, time, place or rate of withdrawal of public water will not be detrimental to the public interest or other permit holders. K.R.S. § 151.170(2). Any person aggrieved by the issuance, denial, or amendment of a permit may request a hearing. K.R.S. § 151.182(2).

Conditions are often imposed on a permit in order to provide protection for other water users and the aquatic environment, curtailing or ceasing diversion when flow levels reach a prescribed level. Though Kentucky may protect instream resources through permit conditions, the state does not recognize an independent water right for instream flows. Similarly, conditions may be imposed on permits in areas where diversion or pumping may impact local cave systems, but there is no program to protect the state's water-related cave-forming processes.

Mammoth Cave National Park maintains exclusive federal jurisdiction. State regulations can be used as a minimum standard, and can be modified to better protect and conserve water resources. At this time, Mammoth Cave National Park has not modified standards as defined by the Commonwealth. State regulations which pertain to water resources at Mammoth Cave National Park or within its watersheds are listed in Appendix E.

# Management Objectives

## Park Management Objectives

In apparent conflict to these directives, the National Park Service must also allow the public use and enjoyment of these lands and waters. Throughout the history of the Park Service, groups and individuals with differing opinions of how a park should or should not be managed have voiced their concerns, at times through the court system. To provide direction through this management mine-field, National Park Service policy requires each park to develop and implement a General Management Plan (GMP). The GMP for Mammoth Cave National Park was published in 1983. To further aid in the management of natural and cultural resources, a Resource Management Plan (RMP) was drafted in 1975, and re-written in 1989. The RMP was last updated in 1999, and has awaited NPS guidance for revision.

Although the park's 1983 GMP provided management guidance and allayed public fears of widespread changes in park management objectives, it provided little specific direction relative to management of park resources. This document was revised in accordance to service-wide goals into the "Mammoth Cave National Park Strategic Plan 2000-2005", and its subsequent 2005-2008 version. These documents, in adherence with the Government Performance and Results Act of 1993, sets specific management objectives and timetables. The park relies on the Strategic Plan (SP) as the current vision of management objectives.

The 2000-2005 SP defines the Mission Statement of the park as "The mission of Mammoth Cave National Park is to protect and preserve for the future the extensive limestone caverns and associated karst topography, scenic riverways, original forests, and other biological resources, evidence of past and contemporary lifeways; to provide for public education and enrichment through scientific study, and to provide for development and sustainable use of recreational resources and opportunities."

The 2000-2005 SP further defines park significance (with respect to water resources) as:

- The many types of geological features are the product of a unique set of conditions found nowhere else.
- The park and the surrounding area is believed to support one of the most diverse cave biotas in the world, with more than 130 species of fauna, of which 14 species are found nowhere else.
- Mammoth Cave is the core of the most understood karst areas in the world.
- Mammoth Cave contains an unusual variety of ecological niches that provide an abundance of plants and animals, including 11 endangered species.
- The park provides an abundance of recreation opportunities, surface and subsurface.

The 2000-2005 SP sets mission goals, which are conceptual descriptions of desired future conditions. As they are inclusive of the core of National Park Service goals, they are intended to continue indefinitely. Mission goals, which include water resources, are as follows:

- Park Goal Ia: The natural and cultural resources of Mammoth Cave National Park are managed as defined by legislation within the context of World Heritage Site and International Biosphere Reserve designations.
- Park Goal Ib: Mammoth Cave National Park serves as the core of a broad scientific and scholarly research effort that is applied directly to management decisions and contributes to the general knowledge base of social and natural processes of karst ecosystems.
- Park Goal IIa: Visitor safely enjoy and are satisfied with the availability, accessibility, diversity, and quality of park facilities, services, and appropriate recreational opportunities.

Pursuant to achieving these mission goals, the SP defined long-term goals to attain desired conditions by set times. The following goals are taken verbatim from the park's 2005-2008 SP:

- Ia1D Land health; Riparian areas: By Spetember 30,2008, 10 miles (31% or 32 miles) of Mammoth Cave National Park's stream and riparian miles achieve desired conditions where conditions are known and are specified in management plans.

- Ia2A Threatened or Endangered species: By September 30, 2008, 9 (69% of 13) of Mammoth Cave National Park documented federally listed threatened of endangered species are making progress towards recovery (i.e., improving, stable, or not as risk).

- Ia2B Species of Concern: By September 30, 2008, 17 (71% of 24) species of Mammoth Cave National Park populations of native plant and animal Species of Management Concern are managed to self-sustaining levels.

- Ia2C Invasive animal populations: By September 30, 2008 1 (100% of 1) of Mammoth Cave National Park invasive (non-native) animal and insect populations have been effectively controlled.

- Ia3 Air quality: By September 30, 200X8, Air quality in [park name] has remained stable or improved.

- Ia4A Water quality: By September 30, 2008 6 miles (18.75% of 32 miles) of streams and rivers of Mammoth Cave National Park meet water quality standards.

## Non-Park Management Objectives

### *Green River Conservation Reserve Enhancement Program*

Perhaps the greatest non-park entity that has the most potential to make a positive impact on the Green River within the park is the Green River Conservation Reserve Enhancement Program (CREP). The Kentucky Department of Fish and Wildlife Resources (KDFWR) spearheaded the development of a proposal to restore the riparian corridor of the main stem of the Green (from the Green River Reservoir and the park) and to implement agricultural Best Management Practices (BMPs) within the watershed. This USDA project is administered through the Farm Service Agency. On August 29, 2001, the United States Department of Agriculture (USDA) and the Commonwealth of Kentucky signed an agreement to implement a program adjacent to the main stem of the Green River between the Green River Dam and Mammoth Cave National Park (160 km). This section of the Green River watershed includes some 3,710 km$^2$, all draining into the park (Figure 41).

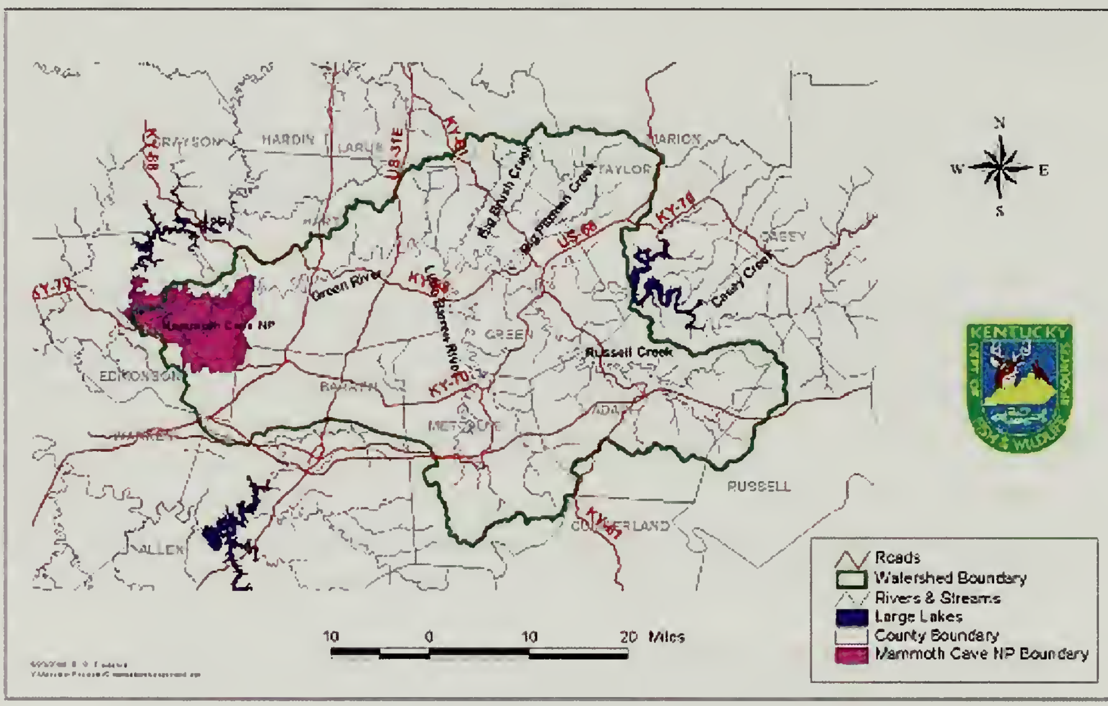


*Figure 41. The Green River Conservation Reserve Enhancement Program area depicting the watershed of the Green River effecting Mammoth Cave National Park.*

The overall budget calls for federal ($88M), state ($17M), and private funds of over $105 million over a 15-year period. The state will provide financial incentives to extend the life of the program and will seek to purchase conservation easements. The Kentucky Nature Conservancy is a primary partner in this program, offering the means to provide permanent conservation easements to landowners in addition to CREP contracts.

The overall objective of the Green River CREP is to restore up to 405 $km^2$ in the Green River watershed upstream of the park (Figure 42). CREP uses federal and state resources to protect and restore environmentally sensitive lands through the USDA Conservation Reserve Program. The program provides fiscal incentives to encourage land owners to voluntarily enroll in 10-15 year contracts, where lands are removed from agricultural production and plant native grasses and trees to improve water quality, reduce soil erosion, and improve wildlife habitat. The Green River CREP recognizes that the Green has one of the country's most diverse ecosystems, and is the most biologically rich tributary of the Ohio River.

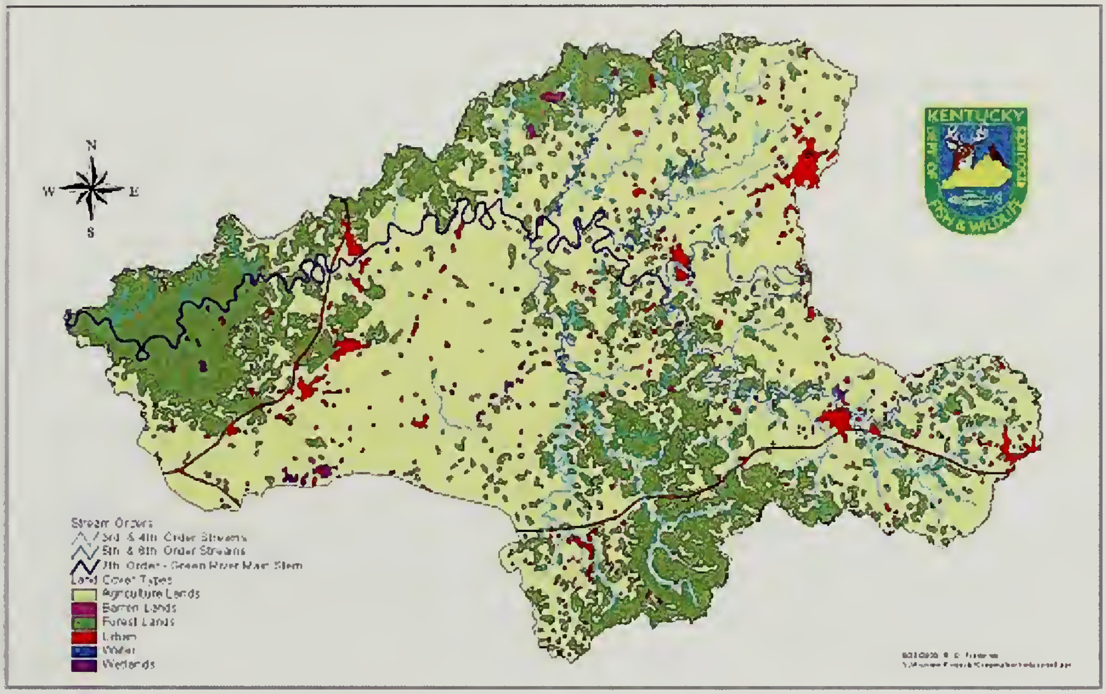


*Figure 42. Basic land cover types within the Green River CREP area. Note the limited amount of forest lands adjacent to the river throughout the middle of the watershed. Currently there is little, if any, riparian buffer between farming and silvicultural activities and the main stem of the Green. Mammoth Cave National Park is located in the extreme western (downstream) edge of the figure (the large forested track).*

Specific Green River CREP goals are to:

- Reduce by 10% the amount of sediment, pesticides, and nutrients entering the Green River and the Mammoth Cave System by growing strips of native grasses and trees along streams and around dolines.
- Protect wildlife habitat and populations, including threatened and endangered species.
- Restore riparian habitat along the Green River.
- Restore the subterranean ecosystem by targeting 1,000 high-priority dolines.

Active partners of the Green River CREP are:

USDA Farm Service Agency
USDA Natural Resources Conservation Service
The Office of the Governor
The Kentucky General Assembly
The Kentucky State Nature Preserves Commission
The Kentucky Soil and Water Conservation Commission
The Kentucky Division of Conservation
The Kentucky Division of Forestry
The Kentucky Division of Water
Kentucky Department of Fish and Wildlife Resources
The Nature Conservancy
Mammoth Cave National Park
Kentucky's Soil and Water Conservation Districts

***The Nature Conservancy, Green River Bioreserve***

In August, 1998, The Nature Conservancy (TNC) released the Green River Bioreserve Strategic Plan. They recognize the Green River among the most significant aquatic systems in the United States (TNC biodiversity rating of B1). They cite an interaction of geologic history, geology, habitat diversity, drainage size, and location as producing a center of endemism of rich biodiversity (Stansbery 1965, Burr and Page 1986, and Burr and Warren 1986). In recognition of its national biological importance, TNC developed this strategic plan for the long-term protection of the Green River watershed from the Green River Dam to the confluence of the Green and Nolin in the park – the same focus area of the Green River CREP.

Following are the goals of TNC's Green River Bioreserve Strategic Plan:

- Raise $150,000 in cash and pledges for operational expenses for director salary for a three-year period.
- Plant and maintain forested riparian zones along the Green and its major tributaries.
- Identify and protect groundwater recharge basins for drinking and surface waters, and for cave and surface-dwelling organisms.
- Enter long-term agreements (land acquisition, management agreements, conservation easements, leases, registries, and landowner contact of natural aquatic, terrestrial, and subterranean habitats necessary for ecosystem function, biodiversity, and viable populations of USFWS-listed and G1-G3 species).
- Restore natural hydrologic and temperature regimes of the main stem of the Green. Such activities will rely on negotiations with the USACE and their operational constraints of the Green River Lake and Dam.

- Work with federal, state, and local agencies for the removal of Lock and Dam

Number Six – thus restoring natural hydrology and biotic communities of the Green and the base level streams of Mammoth Cave.
- Work with the KDOW to improve water quality of point-source discharges, including proper operation and maintenance.
- Reduce or eliminate threats from non-indigenous organisms to the integrity of natural systems.
- Work with state, county, and city governments to assure that contingency plans and appropriate equipment is in place to respond to hazardous waste spills.
- Implement and support water quality monitoring, management, and research programs needed to protect and restore priority functions and biodiversity elements.
- Promote public and private sector partnerships and benefits, and develop a broad constituency to support and implement the bioreserve program.
- Establish a forest-bank to develop environmentally sound timber harvesting practices and ethics by creating a sustainable local industry that protects streams and supports local economies.
- Complete a stress analysis for the remainder of the bioreserve watershed to identify threats in addition to those along the main stem of the Green.

### *United Nations Educational Scientific and Cultural Organization*

On October 27, 1981, Mammoth Cave National Park was decreed a World Heritage Site for its exceptional natural features, its habitat for threatened and endangered species, and its association with events and persons of world historic and archeological significance National Park Service, 2004). This designation, as well as the following title, was granted by the United Nations Education Scientific and Cultural Organization.

Mammoth Cave National Park was first considered for an International Biosphere Reserve in 1986. A regional scientific panel was formed to consider candidate sites in the biogeographical provinces of the Interior Low Plateau. Mammoth Cave emerged as a strong candidate and applied to the Biosphere Program in the spring of 1988 (National Park Service, 2004). The Mammoth Cave Area Biosphere Reserve was designated in March 1990 and dedicated at the park on September 26, 1990.

A biosphere reserve, ideally, is a large, contiguous land base of sound ecological health which is protected. This portion is known as the "core" and is used to assess the effects of human manipulations in other adjacent land areas (zones of managed use). As the park is surrounded by karst areas of multiple uses, under varied ownerships (mostly private) where farming, light industry and tourism is the basis of the economy, the Mammoth Cave area is well suited for the Biosphere concept. The park serves as the core area where conservation and protection status is applied through land and resource management decisions. The managed use areas, originally defined as the park's groundwatersheds, are managed in cooperation with the core. International Biosphere status has been extremely important to many conservation efforts within this zone, including the regional sewer system and over $1M in agricultural best management practices.

The Mammoth Cave Biosphere Reserve is overseen by a group of locally-elected officials
(largely county Judge Executives). Due to the initial successes of the Biosphere Program, the Mammoth Cave Area Biosphere Reserve was expanded nearly one order of magnitude, from its original 833.77 km2 to 8287.27 km2 in 1996 (Kreitzer, 1998). This was essentially an expansion of the zone of managed use, as surrounding counties sought participation, while the core area remained the same. The Superintendent's Office states that while the Biosphere Reserve Program is still functioning, there has been less activity in recent years as a result of limitations on funding and staffing.

### *Barren River Area Development District*

The primary goal of the Barren River Area Development District (BRADD) is to assist local governments within its ten-county service area to preserve their communities' natural and physical resources. The BRADD is involved in supporting actions on the protection of natural resources through water management planning, wastewater management plans, air quality programs, and wise-growth policies. These focus objectives have created three sub-groups, comprised of locally elected officials and subject matter experts.

BRADD established the Natural Resources Planning Council to coordinate local and regional planning activities that involve federal, state, and local governments. The Council assists the BRADD Board of Directors in developing plans affecting the region's natural resources through data collection, research, mapping, goals formulation, and project reviews. The Council also helps the BRADD constituency with special programs related to waste disposal, disaster response, resources conservation, and water supply.

The Natural Resource Planning Council also hosts the Mammoth Cave Area Biosphere Reserve Advisory Council Subcommittee. This group administers research for the Biosphere and coordinates the exchange of information of research and development activities in regard to sustainable development.

The park has had a long history of cooperation with the BRADD. Tangible products have included the installation of a global positioning system base station for mapping projects in the Biosphere area, and the creation of a hazard-response map of Interstate 65, Louie Nunn Parkway and the CSX Railroad within the park's groundwatersheds. The BRADD also serves as a general coordinator for planning efforts, including water supply and wastewater plans.

### *Natural Resources Conservation Service*

The National Resources Conservation Service (NRCS), is the lead federal agency for conservation on private lands (National Resources Conservation Service, 2000). Originally established as the Soil Conservation Service by Congress in 1935, the NRCS is responsible for programs that promote soil and water conservation efforts on the nation's private and non-federal lands.

Each county within the park's watershed has a District Conservationist (with the exception of Edmonson County, where the office was dissolved in 1994). The park had much cooperation in the late 1980s and early 1990s with the District Conservationists to secure funding (through its sister fiscal agency, Farm Services Agency) to implement farming practices that increase farm productivity and conserve and improve water quality. The park and the NRCS recognize that the same materials that the farmer wishes to retain (soil, nutrients, agrichemicals), are the same materials that are considered water-borne pollutants when they leave the fields and enter the hydrologic system.

The best example of resource conservation and cooperation with the park and local NRCS offices is the Mammoth Cave Area Special Water Quality Project. In 1990, a group of private citizens drafted a document listing agricultural practices in the park's groundwatersheds and associated water quality concerns. From this group, the NRCS secured funding of $1M to install animal waste best management practices (BMPs) on farms within the watershed. Over 80 animal waste BMPs were installed in the form of solid waste stack-pads and liquid waste lagoons.

### *Mammoth Cave Resource Conservation District Council*

The Mammoth Cave Resource Conservation District Council (MCRC&D) is a ten-county wide rural planning association that promotes productive and sustainable agricultural practices and environmental health. Its mission is to invest in local people and projects to improve, restore, and enhance the quality of life in Southcentral Kentucky. The council, which meets quarterly, utilizes local community leadership to define problems and devise solutions. Citizens present issues to the MCRC&D for action and assistance, which may be in the form of technical and financial assistance, grant research, project planning, and administrative support. The Council has participated in resource conservation, water and sewer projects, transportation issues, tourism development, and recycling efforts over the past ten years.

### *US Army Corps of Engineers*

The USACE and water resource conservationists have a long history of conflict as the Corps' management directive is typically in conflict with maintaining natural flow regimes of rivers and streams. Over the past few years a dialogue has been established between the USACE Louisville District Office and environmental groups, notably TNC, that resulted in the modification of releases from the Green River dam.

Beginning in 1999, the USACE Louisville District Office and TNC worked to restore a more natural flow regime for the Green River below the dam. Recent years has seen the installation of rock bendway weirs along a highly eroding bank of the Green. The project was successful in restoring the natural flow channel of the river and the banks of the project area were planted with native hardwoods and grasses. The USACE has also agreed to modify dam operations to closely mimic flow and temperature ranges of the natural river system. Beginning in the fall of 2002, the USACE implemented a strategy to delay fall draw-down to winter pool elevations to better replicate late-fall rains and retain cooler dam releases until later in the year. Complimentary to delayed releases, the pool elevation of the lake remains higher and spring retention is therefore delayed, again more closely imitating natural spring flood events. The USACE is also changing basic release operations to control the temperature of released waters. In the past, the main gate was used, almost exclusively, drawing cold water from the bottom of the lake. They now use and adjust multi-level openings to assure that the temperature of release waters mimic pre-dam conditions. Although the park is 150 km downstream of the dam, release modifications are expected to create a positive impact to the park's aquatic resources in terms of river temperatures, and especially river stages, which affect the cave streams as well.

The USACE also owns the locks and dams downstream of the park (Figures 43 and 44). They have, by request of Congress, produced navigation studies of the Green and Barren Rivers. In their 1978 report, "Green and Barren Rivers, Preliminary Feasibility Report", the Corps states that modifications of the existing locks and dams, as well as channel alterations, are not economically feasible. They recommend the deactivation and abandonment of all structures upstream of Lock and Dam Number 2 on the Green. This includes Lock and Dam Number Six, decommissioned in 1951, located on the western (downstream) boundary of the park.

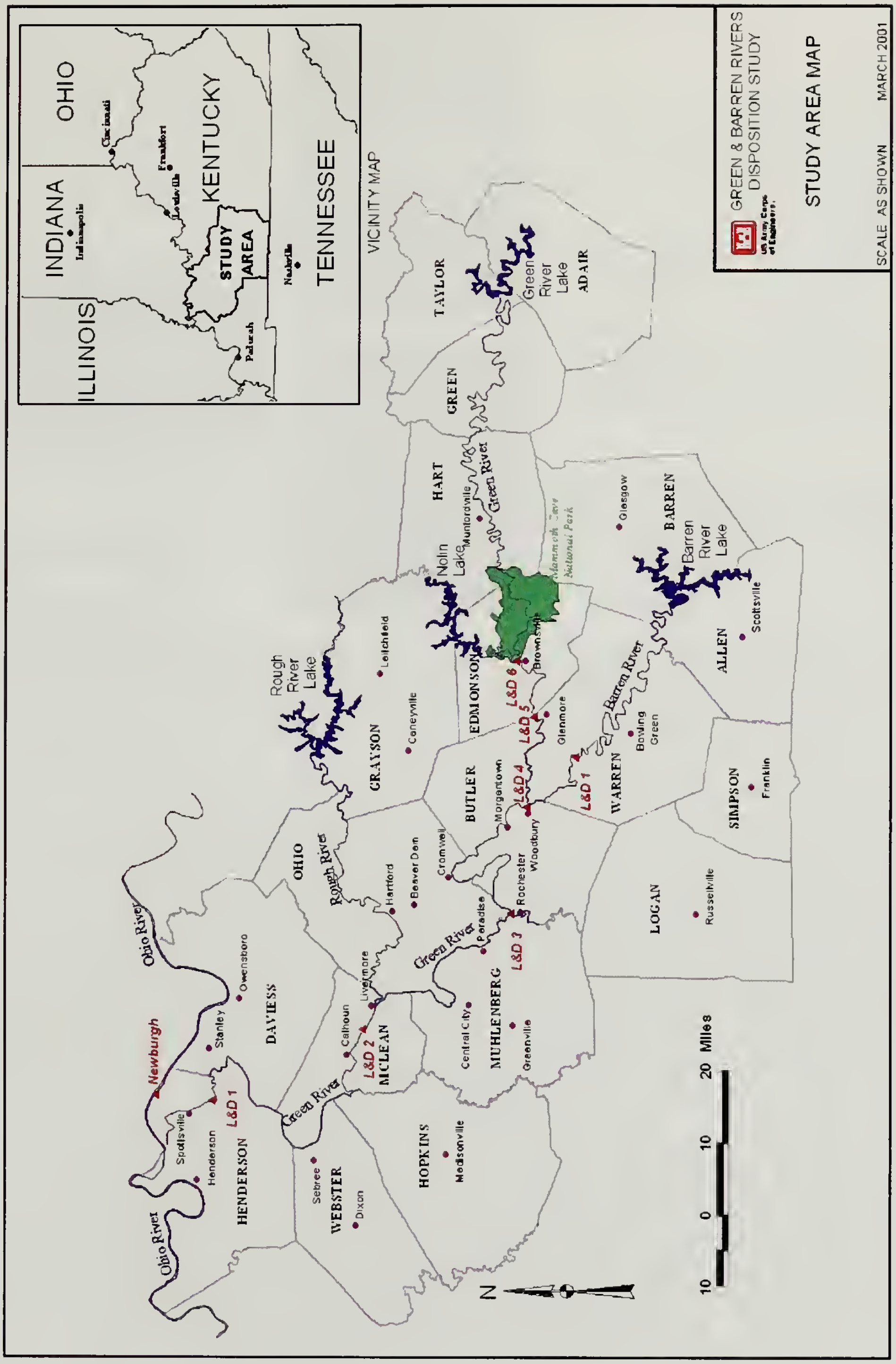


*Figure 43. USACE, 2001. Locks and Dams of the Green and Barren Rivers.*


*Figure 44. USACE, 2001. Lock and Dam Number Six.*

The USACE (2001) produced, again by request of Congress, a study released in 2001, "Green River Locks and Dams 3, 4, 5, and 6 and Barren River Lock and Dam 1 Disposition Study". The purpose of their report is to evaluate the existing navigation facilities located on the Green and Barren Rivers between Brownsville, Kentucky and Rochester, Kentucky on the Green River, and at Greencastle, Kentucky on Barren River. These facilities include Locks and Dams 3, 4, 5, and 6 on the Green River and Lock and Dam 1 on the Barren River. These facilities are the focus of this study because they are no longer being used for navigation. This evaluation will be used to make recommendation regarding the possible deauthorization and/or disposal of the facilities. The goal of the study is to provide data necessary to make recommendations as to possible deauthorization of the facilities at the 5 lock and dam sites. Upon a favorable finding regarding deauthorization of the facilities, the sites could then be disposed of using the provisions regarding surplus government property administered by the General Services Administration (GSA). This study was funded as part of a congressional addition to the FY 1995 Energy and Water Resource Appropriation Bill.

The report makes the following conclusions and recommendations:

Conclusions

- The existing navigation facilities at Green River Locks and Dams 3 through 6 and at Barren River Lock and Dam 1 are not serving the federal authorized purpose of commercial navigation and cannot reasonably be expected to do so in the foreseeable future.
- The continued caretaker status of the lock and dams is not justified for its authorized purpose, i.e., commercial navigation.
- Green River Locks and Dams 3 and 5 are serving incidental purposes, including water supply, and while there is significant nonfederal interest in maintaining these pools for that purpose, there is no federal interest or authority to maintain them for that purpose.
- Officials from the local communities using the Green River Locks and Dams 3 and 5 pools as water supply have indicated that there is strong local interest in assuming ownership of the properties.

Recommendations

In view of the conclusions set forth above, and after considering the expected social, economic, and environmental impacts, the following recommendations are made regarding the disposition of formerly used navigation facilities on the Green and Barren Rivers:

- The repairs and alterations recommended herein should be accomplished to provide for orderly disposal of the properties. This construction should be accomplished at full federal expense.
- Public Law 84-996 should be amended to add the words "the Green River, Kentucky, Locks and Dams 3 through 6, and Barren River, Kentucky, Lock and Dam 1" to the list of projects contained in Section 1 of that act. This act provides for the disposal of federally owned property at obsolescent canalized waterways.
- The land on the right bank of the Green River at Lock and Dam 6 should be conveyed directly to Edmonson County, Kentucky after the modifications recommended herein are accomplished.
- The properties at Green River Locks and Dams 3 and 5 should be directly conveyed to a local entity, after the modifications recommended herein are accomplished, once the correct entity is identified. If a local community or organization is not identified within 36 months of enactment of this amendment to PL 84-996, then the property should be disposed of through the normal Corps of Engineers and GSA property disposal procedures.
- The remaining properties should be disposed of through standard GSA and Corps of Engineers property disposal procedures. This includes the property on the left bank at Green River Lock and Dam 6, the remaining holdings at Green River Lock and Dam 4, and the property at Barren River Lock and Dam 1.
- If property disposal is unsuccessful after the projects are deauthorized, the properties should be abandoned, and no additional federal funds should be expended in the care and maintenance of these properties.

### *Cave Research Foundation*

The Cave Research Foundation (CRF), founded in 1957 as a non-profit organization, is the principle organization exploring and mapping Mammoth Cave. CRF goals are to promote cave exploration and documentation of caves and karst areas, to initiate and support cave and karst research, to aid in cave conservation and protection, and to assist with the interpretation of caves and karst to the public. The CRF provides the basic geographic layer necessary for cave protection and conservation – the cave map. CRF also provides support to park staff in various cave and water resource-related research and monitoring efforts. The CRF, with a national Memorandum of Understanding (MOU), as well as a local MOU with the park, contributes thousands of volunteer hours each year.

### *National Speleological Society*

The National Speleological Society (NSS) was formed in 1954 and has had a significant impact on cave protection, conservation, education, and restoration throughout the country over the past five decades. This organization is organized into subgroups of local "grottoes" which may participate in a variety of volunteer projects. Beginning in 1994, the NSS initiated a large volunteer project to remove old and abandoned creosote-treated wooden walkways leading to Echo River (a former tour route discontinued by the park in 1990). The project has removed over 300 m of this structure, and with approximately 45 m left to be removed, the project is scheduled for completion in 2005. Again, thousands of volunteer hours are provided each year from this dedicated group of cave conservationists.

### *Western Kentucky University*

The park and its nearest university have cooperated on many educational and conservation issues in the past. Since 1981, Western Kentucky University (WKU) has held cave and karst field courses in the park through its Center for Cave and Karst Studies. WKU's Hoffman Environmental Research Institute has completed two major NPS projects; water quality and land use inventory for the Abraham Lincoln Birthplace National Historic Site, and groundwatershed delineation relative to the Arthur Oilfield for Mammoth Cave National Park. WKU's Biotechnology Center is currently involved in a microbiological inventory of the cave. A recent WKU project which may positively affect the natural resources of the park is the establishment of the 272 hectare Upper Green River Biological Preserve. This tract of land (purchased through the Kentucky Heritage Land Conservation Fund), which lays on both sides of the Green directly upstream of the park, was dedicated in the spring of 2004. WKU plans to use this land for an "outdoor classroom", providing faculty and students a natural area for research and instruction. Mammoth Cave National Park, through a cooperative agreement, is in the process of establishing a mussel propagation facility on the Preserve.

### *Kentucky Department of Fish and Wildlife Resources*

The Kentucky Department of Fish and Wildlife Resources' mission is to manage for the perpetuation of the state's fish and wildlife resources and their use by present and future generations. Although the Department has no management authority within the park, their actions may impact park aquatic resources, both positively and negatively. For example, the Department has for years released rainbow trout into the tailwaters of the Nolin Dam, only three kilometers upstream of the park. These non-native fish have the potential to impact park fisheries and macroinvertebrates.

### *Kentucky Infrastructure Authority*

Within the Office of the Governor, the Kentucky Infrastructure Authority (KIA) was created in 1988 and provides oversight and low-interest loans for the development of municipal sewage systems, drinking water, solid waste and domestic septic systems. Under state law, each county must develop a wastewater plan – projecting future growth for 10-20 years – to assure that this vital infrastructure will be adequate to handle increased loads in a manner that will not harm the environment. The KIA will visit each county in the park's watershed in the next few years (Warren County was chosen as a pilot county and will finalize their plan in the spring of 2004). The park will be present at each county meeting within its groundwatershed (Warren, Barren, Edmonson, and Hart).

### *Caveland Environmental Authority*

The Caveland Environmental Authority (CEA), formally known as the Caveland Sanitation Authority (CSA), is a publicly-held incorporation which operates the regional sewage system, as well as local water supply areas – the CEA serves the park in both water and wastewater operations. The CEA (CSA) was born of the need to complete a regional sewage system to protect and conserve the groundwaters of the park (as much of their service area is within the heart of the park's karst basins. This regional system, funded in equal parts ($4M each) by grants from the USEPA, Kentucky Farmers Home (revenue bonds), the Commonwealth of Kentucky, and the National Park Service began construction in 1988 and was completed in 1996. This regional wastewater system receives flow from the park, and the communities of Park City, Cave City, and Horse Cave. Along its route from the park along KY 255, it picks up flow from several former package sewage plants permitted by the state's Pollution Discharge Elimination System. The system currently serves about 2,500 customers in parts of three counties (Edmonson, Barren, and Hart) with an average daily flow of 1,120 $m^3$. As each county develops wastewater plans, the CEA will play a prominent role in planning efforts in these counties.

### *Kentucky Department of Transportation*

The park's groundwatershed is traversed by some 20 km of Interstate 65 and 9 km of the Louie Nunn (formerly the Cumberland) Parkway. The Kentucky Department of Transportation (KDOT) takes the leading role in any actions that improve these routes, including efforts to mitigate environmental impacts caused by road runoff and spill retention. Interstate 65 is currently being widened to six lanes from the Kentucky-Tennessee boarder to Elizabethtown, Kentucky (145 km). This entire portion of the interstate is upon the karst of the Pennyroyal Plateau and the KDOT has been instructed by the Federal Highway Administration to treat runoff (maintained grass waterways) and install spill-retention structures along its course. The park has taken an active role in planning and design of this highway improvement project.

### *Kentucky Division of Water*

The Kentucky Division of Water's (KDOW) mission is to manage, protect, and enhance the water resources of the Commonwealth for present and future generations through voluntary, regulatory, and educational programs. The KDOW is charged with the responsibility for managing and protecting the state's waters, including lakes, streams, and rivers, and groundwater. The KDOW, as a component of the Kentucky Environmental Protection Cabinet, is responsible for setting water quality standards, including designated use classifications, for all state waters as directed and reviewed by the USEPA. Mammoth Cave National Park uses the state's standards for minimum limits for park waters for primary and secondary contact recreation, cold water aquatic habitat, and Outstanding Resource Waters.

A program of the KDOW is the volunteer efforts of the Kentucky Water Watch. Thousands of volunteers, statewide, take part in water quality monitoring efforts, including the Upper Green River (the drainage basin upstream of the confluence of the Green and Barren Rivers). The Water Watch goals are to improve water quality by implementing the interim and long-term goals of the Clean Water Act by monitoring the water quality across the state. The Upper Green River group has established nearly 100 stations, most upstream of the park, and has monitoring these sites at least three times per year since 1999.

# Water Resource Goals

Goals for water resources at Mammoth Cave National Park can be easily condensed into two main categories: Water quality and water quantity. Exotic species, which of course are also dependent on these two categories, are addressed in a separate water resource goal.

In a perfect world for park managers, all adverse impacts could be controlled by well-informed resource decisions that reflect a natural, unaltered system. Of course, a perfect world does not exist, at least for park managers, who are faced with complex threats and even more complex resolutions. As the park is downstream from a nearly 10,000 $km^2$ watershed, with over a dozen land managers and thousands of private land owners, park managers have limited options in directly managing the quality or quantity of water entering the park. Likewise, but on even a larger regional scale are the effects from air quality. Regional resource management issues are not new, nor are they limited to Mammoth Cave National Park. Throughout the Service, resource and park managers must find ways to work with local, state, and federal agencies, as well as the private citizen to affect a positive change towards a water resource goal.

Towards this end, a Water Resources Scoping Workshop was held at Mammoth Cave National Park in the early autumn of 2004. A list of participants and the prioritized accumulation of their efforts can be found in Appendix F. Water resources issues were listed during the day's discussion, and votes were cast (each participant was given six votes). It was the intention of this author to address each issue listed, regardless of issue strength, park need, or logistical reality, in general order of the vote, within the following narrative.

Throughout this section the reader will be presented several issues or factors that prevent reaching these water resource goals. The goals, seemingly beyond attainment, can be thought of as the ultimate endpoint. Each step along the way, each barrier to non-attainment that is crossed brings us closer to the goal. They are not intended to be reached in a single step, but rather in a series of small steps over decades. They can only be achieved by doing good and sound work with a progressive efficiency. As the park is the recipient for conservation efforts throughout the upper Green watershed, the park must be the leader in this effort. To quote the American writer Ken Kesey, “You don't lead by pointing and telling people some place to go. You lead by going to that place and making a case."

***Water Resource Goal:***

***Chemical (water quality) integrity of park waters is improved and/or maintained to support all native life and to meet or exceed designated use standards.***

Water quality, as related to organic and inorganic chemistry, suspended solids, bacterial, parameters is essential to maintain both a functioning ecosystem as well as recreational use. Contaminants, generated from both point and non-point sources, have been shown to impair biological integrity and cause human health problems in numerous waters throughout the United States. Results from the park's monitoring program has linked water quality with land use within watersheds – watersheds dominated by agricultural activities routinely have higher bacterial, pesticides, nutrients, and suspended solid concentrations than those dominated by undisturbed forests. Furthermore, results indicate that the bulk of water-borne contaminants are derived from non-point sources transported into the park following rainfall events. Contaminants are held in "virtual storage" on the land until surface runoff washed them into streams, both surface and subsurface. During low to base flow conditions, water quality parameters are generally within acceptable state standards as per designated uses. During flood to moderate flow conditions parameters such as pesticides and fecal coliform bacteria exceed state designated use limits for biological health and recreational contact.

The park is responsible, through various federal laws, to maintain quality of its waters (both chemical and physical) in such a manner as not to negatively impact native life. Park waters are generally classified by the state as "Cold Water Aquatic Habitat" (cave streams), and "Warm Water Aquatic Habitat" (surface streams). In addition, the Green and Nolin Rivers are designated as both "Secondary Contact" (wading) and "Primary Contact Recreational Waters" (swimming) relating to human activities. Existing state standards do not included all possible parameters that may cause a negative impact to aquatic fauna.

**Factors preventing or impeding the achievement of this Water Resource Goal**

*Domestic sewage disposal*

Sewage disposal covers the range of on-site disposal (found throughout the ubiquitous rural lands and in many of the smaller villages) to municipal collection and treatment systems in the larger towns. Urban areas within the immediate park karst groundwatersheds, including the towns of Park City and Cave City, are connected to a regional sewage collection and treatment system (it also receives waste water from the park).

Although the regional sewer system, administered by the Caveland Environmental Authority, serves population centers within the park's karst groundwatersheds south of the Green River, the majority of area residents rely on some form of on-site sewage disposal. Most of these on-site systems are a combination of septic tanks and leech fields. As the rural population of Southcentral Kentucky grows – typically through the sale and subsequent division of farm lands into rural subdivisions – increased pressures from on-site sewage disposal will be placed on the park's water resources.

*Agricultural non-point source runoff*

Approximately 95% of the park's surface watersheds and over 50% of its groundwatersheds lie outside and upstream of the park boundary. This area, primarily privately owned, is dominated by agricultural land use. Although the park, through legal mandate, can control and positively influence land uses and associated contaminants within the park, it cannot control nor dictate land uses beyond its borders.

Consider the land use within the Green River basin draining into the park. Approximately 61% of the 5,085 $km^2$ watershed is classified as agricultural lands (Kentucky land use classification, Anderson Level II). Likewise the park's karst groundwatersheds are dominated by agrarian land uses. The 345 $km^2$ Turnhole Spring Karst Groundwatershed was classified in 2001 (Anderson Level III). Agricultural land use comprised 133 $km^2$, and is further sub-classified as 102 $km^2$ pasture, 30 $km^2$ row crop, and 1 $km^2$ confined animal feeding, a total of 39% of the watershed, or 42% if park lands are subtracted from the basin.

*Airborne contaminants*

Even more beyond the control of direct park influence is air, and thus, precipitation quality. All water flowing through the park, regardless of basin ownership, is ultimately derived from atmospheric precipitation – except very small amounts of deep-source waters rising through bedrock fractures and into karst watersheds. In many ways, the quality of surface and groundwaters in the park can be no better than that which falls from the sky, in addition to compounds and elements that are imported to the watershed by dry deposition.

The Federal Land Managers' Air Quality Related Values Workgroup's (FLAG) Phase I report (2000) designated Air Quality Related Values (AQRVs) in freshwater ecosystems include lakes and streams and their associated flora and fauna. FLAG states that sensitive receptors include water chemistry and clarity, phytoplankton, zooplankton, fish, amphibians, macroinvertebrates, and benthic organisms. Water chemistry indicators that respond to deposition include pH, ANC, conductance, cations and anions, metals, and dissolved oxygen. Physical indicators, such as water clarity, and biological indicators, including species diversity, abundance, condition factor and productivity of fish, amphibians, macroinvertebrates, and plankton can also be used to detect deposition effects in aquatic ecosystems.

There are numerous large permitted activities within a 100 km radius of Mammoth Cave National Park – of course these do not take into account the vast amount of mobile emission sources. Within this immediate airshed, in 1999, permitted emissions of >180,000 metric tons (MT) of $SO_2$, >90,000 MT of $NO_x$, >4,500 MT of VOC, and >18 MT of $NH_3$. Wet deposition at the park from 1983 through the summer of 2004 (Hg data are from September 2002 through December 2003) can be summarized in Table 23.

*Table 23. Wet deposition at Mammoth Cave National Park.*

| Paameter | Range | Average | Trend |
|---|---|---|---|
| $SO_4$ | 1 to 20 mg/l | 3 mg/l | Decreasing |
| $NO_3$ | 1 to 15 mg/l | 2 mg/l | No change |
| $NH_3$ | 0.1 to 3.5 mg/l | 0.3 mg/l | No change |
| pH | 3.5 to 8.0 SU | 4.5 SU | Increasing |
| Hg | 1 to 45 μg/l | 10 μg/l | Increasing |

Dry deposition is also monitoring at the park. During the same time period $SO_4$ ranged from 3 to 14 $\mu g/m^3$ (average of 6 $\mu g/m^3$) while $NO_3$ has ranged from 2 to 8 $\mu g/m^3$ (average of 3 $\mu g/m^3$).

*Endocrine Disruptors*

Endocrine systems, also know as hormone systems, are found in all animals. Endocrines (hormones) are produced in various glands and are responsible for a variety of life-functions including reproduction and growth. Endocrines interface with cells throughout the body that contain compatible receptors. An endocrine disruptor is a compound that either mimics an endocrine, causing the body to over-respond or respond at inappropriate times, or blocks the effects of a hormone. In the past decade some researchers have proposed that anthropogenic chemicals are disrupting the endocrine systems of both humans and wildlife. A variety of chemicals, namely PCBs and dioxin, have been found to cause adverse developmental and reproductive effects in fish and wildlife.

The USEPA, through its Endocrine Disruptor Screening Program, states that very few of the 87,000 chemicals produced today have been sufficiently tested for possible endocrine disruptive characteristics. There has been no inventory or monitoring of these compounds in park waters. There is also no information of the specific effects of these compounds on the aquatic biota found in park waters.

*Urban and Transportation Corridor Impacts*

Throughout the park's watersheds lay scores of small communities, ranging in size from a few hundred to several thousand, and thousands of kilometers of transportation corridors of interstate and federal highways, state and county roads, and rail lines. Imbedded throughout the basins are various degrees of chemical and fuel storage, and industrial complexes. The lack of county-wide zoning is common to Southcentral Kentucky. Both urban and light industrial development, as agricultural lands are parceled and sold, occurs with little or no planning, especially in respect to waste water issues. Again, as with any land use issue beyond park boundaries, the park has little influence and no direct control.

Unlike many non-karst areas of the country, stormwater runoff and disposal upon and into the karst requires special engineering considerations. Rather than to simply retain and dispose of stormwater into a nearby surface waterway, developers in Southcentral Kentucky commonly dispose stormwater into Class V injection wells which deliver water directly into cave streams. The community of Bowling Green (not within the park's watershed) has over 1,000 Class V wells. Mammoth Cave National Park has anticipated new USPEA regulations of the treatment and release of stormwaters by installing dual-stage stormwater treatment units at each parking lot within the park.

Each year an average of six reported spills have occurred along Interstate 65 where it crosses the park's karst groundwatershed. Although the majority of these spills involve ruptured truck fuel tanks – typically loosing 50 to 250 liters of diesel – there have been much larger fuel spills (approximately 15,000 liters spilled on August 28, 2001) within the groundwatershed. Adjacent watersheds have not been as lucky as the past decades have seen spills of printer's ink, cyanide, and a train derailment which resulted in the loss of an untold amount of Agent Orange defoliant. No known spills of industrial storage units have been reported in the past decades. State law requires that each storage facility to have chemical inventories and spill containment plans.

*Water Quality Impacts from Lock and Dam Number 6*

Water samples have been routinely taken from the pooled section of the Green and Nolin Rivers as part of the park's Water Quality Monitoring Program since 1990. Beginning in July 2002 an additional site was established at the eastern edge of the park where the Green enters park lands. Enough data has been collected to this point (over 30 paired samples to make water quality comparisons between the upstream (free-flowing) and downstream (impounded) sections. Water quality of both sites are nearly identical, with small exceptions being lower turbidity, higher temperature, and lower bacterial counts during summer base flow condidiotns. It is anticipated that the upstream site will remain part of the park's long-term water quality monitoring efforts.

The majority of the concerns of Lock and Dam Number Six are of physical aspects of flow and its alteration to aquatic habitat. These issues can be found in the following Water Resource Goal.

*Lack of "Cause and Effect" Relationships between Water Quality and Aquatic Life*

Central to this water resource goal is achieving and maintaining water quality such that it supports native aquatic life. Since 1990, the park has supported a water quality monitoring program. This plan, which is based on the USGS NQWA program, has involved monthly non-conditional synoptic sampling at 13 fixed integrator sites. The main purpose of the program is to create a long-term data set for trend analysis and to directly support and aid the interpretation of aquatic biological inventorying and monitoring.

While biologists in other states have developed Indices of Biological Integrity (IBI), there has not been a similar IBI for Kentucky (although many aquatic biologists have adapted that of the State of Ohio for a stop-gap measure). This approach will at least give a sense of biologic integrity of surface streams, but there are questions regarding a similar IBI for cave streams. Biologists are currently working on a cave stream IBI, but there are unique problems working in a cave environment including sample technique and the simple and sparse community structure.

In any case, there is no research relative to establishing cause-and-effect relationships with specific rare, threatened or endangered aquatic species found in the park. There are general cause-and-effect relationships for aquatic life – for example LD-50 of flathead minnows for atrazine, but how this and other contaminants effect cave shrimp, for example, is unknown.

*Public Education and Environmental Enforcement*

There is little doubt that the general public is better informed about environmental issues than at any point in our history. Educational activities from grade school curriculum through pesticide application licensing and agricultural extension services have made the public aware of many issues, some specific to living on a karst landscape.

It cannot be expected for 100% compliance of regulations and a consummate knowledge of environmental issues of the general public. State regulators are often overwhelmed by workloads and cannot respond to every complaint.

**Comprehensive Strategy: Water Quality Monitoring**

Central to measuring the effectiveness of any efforts to achieve and maintain water quality is routine water quality monitoring. The park has operated a Water Quality Monitoring Program since 1990. This Program, with logic and rationale based on the USGS National Water Quality Assessment Program, samples 13 fixed integrator sites each month, synoptically on a fixed calendar date. The program ran from 1990 through 1998 on the set NQWA schedule for long-term monitoring – that is, two years of monthly sampling followed by five years of inactivity, then back to two years of sampling, and so on. This original Program called for monthly non-conditional synoptic sampling (described above), coupled with storm pulse sampling and topical monitoring (Table 24).

*Table 24. Cycle of water quality monitoring activities.*

| Fiscal Year | Monitoring Activity |
|---|---|
| 2004 | Monthly Non-Conditional Synoptic Monitoring |
| 2005 | Monthly Non-Conditional Synoptic Monitoring |
| 2006 | Data Analysis and Reporting, Topical Sampling |
| 2007 | Storm Pulse Monitoring |
| 2008 | Storm Pulse Monitoring |
| 2009 | Data Analysis and Reporting, Topical Sampling |
| 2010 | Topical Sampling |

In the early 1990's, the Park Hydrogeologist developed an initial protocol for storm-pulse sampling. This rigorous sampling strategy was based on data from the monthly program indicating that the majority of contamination was from agricultural non-point sources washed into the surface and cave streams following a rain event. In 1994, the park began full protocol development as several storm pulses were monitored (typical monitoring requires round-the-clock sampling at two fixed locations for a period of several days – over the duration of the event). Results provided resource managers with an excellent, high-resolution dataset describing contaminant maxima during the course of the pulse. It was the intention that storm pulse monitoring would occur during the five "off years" of the monthly synoptic sampling. The storm pulse sampling phase of the overall Water Quality Monitoring Program would sample two storms per year for a two year period.

The program has undergone redirection from the Science and Resources Management Division Chief in the past few years. The "two-on – five-off" NQWA rotation was abandoned for continual monthly sampling. In addition, the parameter list was expanded to include analytes that were demonstrated by prior data to at, or normally below detection limits, let alone MDLs. Most recently, the program has reverted by to the recommended NQWA rotation, supplemented with peripheral, topical studies.

A program that evolves by becoming more cost-effective and statistically robust can act as cornerstone in every facet of the park's aquatic monitoring program. A program that changes on the whim and notion reflective of individual interests may serve the present but will fail the future.

**Resource Management Actions: Water Quality Monitoring**

1. Continue USGS NWQA-based monthly non-conditional synoptic sampling to provide a long-term water quality data record at fixed integrator sites to allow trend analysis. Sampling should adhere to the two-year-on, five-year-off schedule as originally designed, again, following the NWQA model.

2. Re-establish storm pulse monitoring at key locations. Past efforts concentrated on the major cave streams of Logsdon and Hawkins Rivers. These sites should be included in future sampling, with the addition of a site on the Green River at the

location of the USGS monitoring station. Storm pulse monitoring should occur over a two year period and sample a minimum of two events per year. Storm sampling should begin during the second "off year" of the monthly non-conditional synoptic sampling. This would provide a period of data analysis and reporting of collected data. The year after storm pulse monitoring would provide a similar period of data analysis and reporting of storm pulse results.

3. During any given year, especially during the "Data Analysis and Reporting" years, the park must be able to respond to a variety of "topical" sampling activities. Such sampling would be based on the results of routine monthly and storm pulse monitoring. Topical sampling includes both parametric and spatial realms. For example, if monthly sampling indicated abnormal base-flow fecal coliform levels in a particular watershed, a topical sampling event would occur that would greatly increase the number of sampling locations within that watershed to pin-point the source. Likewise, data and land use changes may require topical sampling to expand beyond the set parameters to determine if a new contaminant threat exists. Two topical studies commenced in FY06; quarterly major ion water quality inventory of selected upland ponds, and monthly non-conditional synoptic sampling of four river sites looking for *chlorella*, chlorophyll-a, and non-purgable organic carbon.

4. Establish, for the purpose of public health advisories, a reliable surrogate relationship between easily and instantly measured parameters (turbidity or SpC for example) and *e. coli.* The end result, if such a relationship is found, a way to advise the public when primary or secondary contact recreation is not advised.

**Measurable Results: Water Quality Monitoring**

At a minimum, water quality monitoring, as described above, will provide park managers with not only a long-term dataset for trend analysis, it will also determine contaminant maxima during periods of high contaminant transport, as well as provide the flexibility to further examine water quality anomalies.

These data will be immediately used to determine if park waters are meeting the state's designated use standards – which should be used as a minimum attainment goal. Few monitoring endeavors are as simple to judge as water quality data, as the USEPA, through the state, has set limits for various contaminants as per designated uses.

**Comprehensive Strategy: Watershed Land Use Monitoring**

Watershed land use has been identified by the park's Water Quality Monitoring Program as a key driver affecting water quality. Watersheds with the highest water quality are those with the most undisturbed and natural land use. Conversely, watersheds dominated by agricultural and urban land use have the poorest water quality. The park contracted aerial photography in 1990 and classified land uses within the park's karst groundwatersheds according to Anderson Level III standards. The park repeated the same process in 2001.

In addition the Commonwealth of Kentucky regularly (at an interval no greater than ten years) performs Anderson Level III land use classifications for the entire state. From these data park managers can track changes in land use within the Green and Nolin River watersheds.

**Resource Management Actions: Watershed Land Use Monitoring**

1. The park should obtain from the state, Anderson Level III land use scenes for its karst groundwatersheds. Recharge generated from these, largely privately-held lands directly impact the overall water quality of the cave streams and springs. Likewise, regular updating on the state-wide land use classification will track changes for the greater surface watersheds. It is very possible that as land use classification becomes more reliable, accurate, and scene data are common, state or federal land use classification may be free or at low cost in the future.

2. While the state provides its own funding resources for flight and photographic costs, as well as classification, the park must use these data to provide a detailed examination within its groundwatersheds (Anderson Level III is needed to document the small-scale changes that are not classified at the coarser Level II). The commonwealth plans to update and make available at no charge, Anderson Level III landuse data. Such re-classification and detailed examination of land use and change within the park's watersheds should be done at least every ten years.

**Measurable Results: Watershed Land Use Monitoring**

Every ten years the park would have an excellent, detailed classification of land uses within its karst groundwatersheds. These scenes are paired with water quality data to associate changes in land use with corresponding changes in water quality.

**Comprehensive Strategy: Air Quality Monitoring**

Mammoth Cave National Park is a Class I area as designated by the Clean Air Act, as amended. This act gives Federal Land Managers (FLMs) an "affirmative responsibility" to protect air quality and AQRVs within Class I areas. An AQRV is a resource that may be adversely affected by a change in air quality. The resource may include visibility or a specific scenic, cultural, physical, biological, ecological, or recreational resource identified by the FLM for a particular area. FLMs are responsible for reviewing air quality permit applications from proposed new or modified major sources near Class I areas, and determining the potential impacts, if any, that may result from source emissions. FLMs take into account the particular resources and AQRVs that would be affected; the frequency and magnitude of any potential impacts; and the direct, indirect, and cumulative effects of any potential impacts. In making these determinations, FLMs are mandated to err on the side of resource protection.

Since 1983, Mammoth Cave has performed air quality monitoring. This program, considered to be one of the finest in the NPS, has expanded from collecting continuous meteorological data and wet and dry deposition and ozone, to a state-of-the-art station with many compounds measured in real-time, including an array of gaseous parameters. The park also monitors particulate matter, visibility, and has hosted a real-time mercury analyzer (on loan from the state).

**Resource Management Actions: Air Quality Monitoring**

1. The park must, as required by the Clean Air Act, monitor the quality of its air. Specifically, with respect to water quality issues, these efforts must continue to include the monitoring of key compounds and elements associated with wet and dry deposition.

2. Secondly, the NPS must develop Depositional Analysis Thresholds (DATs) for AQRV for the park. Although the park is conducting wet and dry depositional monitoring, which is critical to DAT development, there is no standard set.

3. Permit Review:

As a federal land manager of a Class I area, the park must review and provide input to any proposed permitted source within 100 km of the park. The following discussion of Depositional Analysis Thresholds was supplied by the NPS Air Resources Division (ARD) as developed in cooperation with the USFWS (2001). This joint effort developed criteria for evaluating the contribution of additional nitrogen (N) or sulfur (S) to deposition within Class I areas by creating DATs. The NPS and FWS have developed this DAT equation in response to requests by permitting authorities and permit applicants to continue to develop consistent, predictable permit review processes, and to expedite the permit review process. In developing DATs, the NPS and USFWS seek to further improve the process by providing a quantitative method with which to evaluate sulfur deposition in Class I areas.

A DAT is *the additional amount of N or S deposition within a Class I area, below which estimated impacts from a proposed new or modified source are considered insignificant.* The DAT for a park or refuge will be compared with the amount of additional deposition resulting from a source, as modeled using CALPUFF or other appropriate models. The N DAT represents total N, including both wet and dry deposition. Total nitrogen includes NO, $NO_2$, $HNO_3$, $NO_3$, $NH_3$, and $NH_4$. The S DAT represents total S deposition. Total N and total S were selected in order to be consistent with conventions used in deposition loading, to represent the total amount of N and S inputs received in an ecosystem and to be compatible with CALPUFF model outputs.

DAT determinations are formulated by calculating a background condition for S and N (separate values for the eastern and western portions of the country) which is likely within the range of natural variability for these ecosystems. Once natural background deposition numbers are determined, FLMs have a responsibility to determine what fraction of this deposition could be added to existing natural and anthropogenic deposition amounts within an ecosystem and still be considered insignificant. The NPS and FWS selected very conservative natural background numbers from the range of values presented in scientific literature, and have determined that all combined anthropogenic sources could contribute up to 50% of this conservative natural background value without triggering concerns regarding resource impacts. Likewise the park is concerned with cumulative effects of deposition. It is beneficial to the FLMs, the permitting authority, and the applicant to determine what amount, if any, a new source could contribute to total deposition while having a reasonable assurance that cumulative deposition from all new sources would not exceed 50% of natural background.

**Measurable Results: Air Quality**

Like water quality monitoring, there are set standards for air quality parameters. While the former is based upon designated use standards for each waterbody, the park must conform to standards set for Class I areas. Air quality as set by the USEPA National Ambient Air Quality Standards include CO, Pb, $NO_x$, $PM_{10}$, $PM_{2.5}$, $O_3$, and $SO_x$. The existing Mammoth Cave Air Quality Monitoring Program is sufficient to determine if those standards are met.

Wet and dry deposition criteria are more important to direct impacts to the park's water quality. These standards have not yet been established. In order to do so the park must determine, through DAT, determine depositional limits that effect AQRVs.

The DAT is a deposition threshold, not necessarily an adverse impact threshold. The DAT is the additional amount of deposition that triggers a management concern, not necessarily the amount that constitutes an adverse impact to the environment. Both the NPS and the FWS utilize a case-by-case approach to permit review. Adverse impact determinations will be considered on a case-by-case basis for modeled deposition values that are higher than the DAT. This approach considers the best scientific information available for each park or refuge to assess existing as well as potential future deposition impacts. The magnitude of the deposition that an individual source would contribute as well as the sensitivity of the ecosystem must be considered. At present there is no equation that would, in all situations, allow an FLM to determine whether or not a source of N or S deposition would cause or contribute to an adverse impact. Therefore, FLMs will continue to use scientific data and information, in conjunction with modeling, to evaluate whether or not an adverse impact would occur. FLMs must also take into account site-specific information for each Class I area. This would include evaluating the potential deposition impacts from a source not just in relation to the DAT, but with other factors as well, such as whether adverse impacts resulting from deposition have been documented, or are suspected, in that specific Class I area.

## Comprehensive Strategy: Aquatic Biological Monitoring

The ultimate recipient and beneficiary of water quality are aquatic organisms. They are subject to both chronic and acute contamination. Interest in aquatic biology at Mammoth Cave began in the mid-nineteenth century upon the discovery of various cave-adapted species. An appreciation of the immense biodiversity of the Green River began about one hundred years later. From the early days of fascination through species descriptions by classic naturalists, the park has, in recent years, initiated aquatic biological inventories of both surface and subsurface streams, including fish, mussels, and benthic macroinvertebrates (BMI), and cave organisms. By most all accounts, the park now has a reasonably complete aquatic faunal inventory. Mammoth Cave National Park, through its Prototype program, has identified "vital signs" and has chosen to develop monitoring protocols for fish, BMI, mussels (protocols due in 2006).

## Resource Management Actions: Aquatic Biological Monitoring

The park's LTEM program is highly focused on aquatic monitoring. By 2006, protocols for monitoring fish, BMI, mussels, and cave aquatic fauna will be complete.

The general goals for the overall Prototype program are:

1. Determine status and track trends in selected attributes as indicators of the condition of park ecosystems to allow managers to make better-informed decisions.
2. Provide early warning of abnormal changes in conditions of selected resources.
3. Provide data to better understand the dynamic nature and function of park ecosystems.
4. Provide data to meet legal mandates related to natural resource protection and visitor enjoyment.
5. Provide a means of measuring progress towards performance goals.

At this time, thanks primarily to various researchers and aquatic biologists who have worked at the park over the past 15 years, the LTEM program has a "head-start" in protocol development.

Fish

- Assembled baseline data on Green & Nolin River fish diversity as a key sampling design development step.
- On hand tested and refined ready-to-use sampling methodology (seining & electro-shocking techniques).
- Developed a set of evaluated sampling sites (need to select some additional sites).
- Initiated a coop agreement with Western Kentucky University to field test sampling design using the established methods and sites.
- Long-term monitoring will likely involve annual or biennial fish sampling at selected sites in the park.

BMI

- An existing protocol that was developed for the park by Schuster, et al. 1996 and has been implemented biennially at the park since 2002.
- Standard sampling methods include the use of Hester-Dendy Multiplate samplers and Rock baskets. An Index–of–Biological-Integrity (IBI) is calculated.
- The protocol has been reviewed by the park's USGS-BRD Ecologist and it will undergo revision/redevelopment and reformatting to meet NPS/USGS-BRD standards.

Cave Aquatics

- An existing protocol that was developed for the park by Pearson and Jones, 1996 and has been implemented biennially at the park since 1998.
- Sampling methods include visual surveys and measurements of selected organisms. A Modified Index–of–Biological-Integrity (IBI) is calculated.
- The protocol has been reviewed by the park's USGS-BRD Ecologist and it will undergo revision/redevelopment and reformatting to meet NPS/USGS-BRD standards.

Mussels

- Assembled baseline data on Green River mussel diversity and muskrat predation on mussels as a key sampling design development step.
- On hand sampling methodology (transect & quadrat excavation, and mussel shell midden collection techniques) currently under evaluation.
- Developed a set of evaluated sampling sites (need to select some additional sites).
- Long-term monitoring will likely involve annual or biennial mussel sampling at selected sites in the park.

One of the overall impediments to the biological side of water quality issues is a simple lack of "Cause and Effect" relationships between water quality and aquatic life. Too many times when a resource manager is pressed to make a definitive statement to the public regarding the well being or threats to aquatic life by a particular contaminant, he or she is loss for direct evidence.

In many ways, finding cause and effect relationships between various stressors and aquatic life represent small but important pieces of the bridge linking biological, physical, and chemical characteristics of the park's waters. Currently we, as park managers, rely on a collection of anecdotal evidence, estimates and projections of what is best for the system as a whole. Very little direct evidence exits directly linking one stressor to the detriment of one particular specie.

Of course, to examine a single specie and relate its health and reaction to a single stressor may not be efficient or very effective. Aquatic communities, on the other hand, may prove too broad a band to determine specific effects of even single stressors. Ecologists may wish to study functional groups, and even more specifically, those that require the same habitat.

Typically managers are at a loss to predict the effects of, for example, increasing levels of nitrate on a darter. It is difficult to defend or predict the effects of a particular environmental stress on a darter if the only information readily available relies on data gathered from flat-head minnow exposure.

**Measurable Results: Aquatic Biological Monitoring**

Contingent on the effectiveness of monitoring design, park managers should have an excellent picture of aquatic biology. Each major biologic category is covered, and in combination with water quality data, will yield critical information to demonstrate the overall well-being of the aquatic ecosystem. It is anticipated that IBIs specific to Kentucky waters will be developed by the state and approved by the USEPA. Until that time the park may adapt suitable IBIs from Ohio to judge the quality of the aquatic community. Similarly, the park is tasked through its Long Term Ecological Monitoring Program, to develop an IBI for cave aquatics. Once this IBI is peer-reviewed and accepted, the park will have a biological meter to gauge the health of the cave aquatic ecosystem.

**Comprehensive Strategy: Public Outreach**

Education of the public is central to the mission of the Park Service. Each year hundreds of thousands of people visit Mammoth Cave National Park. Millions more travel the park's karst groundwatersheds, and many thousands live within the greater watershed. Public outreach/education may also include working with local agencies in the development and installation of various Best Management Practices (BMPs) to reduce or eliminate water quality issues affecting the park.

The park's karst groundwatershed is traversed by 20 km of Interstate 65, an equal length of the CSX railroad, and eight km of the Cumberland Parkway. Each year there are several accidents that spill fuels and other hazardous chemicals into the park's karst aquifer. Many other private land uses are found throughout the park's surface and subsurface watersheds that are linking to non-point source runoff, including stormwater, agriculture, and silviculture.

**Resource Management Actions: Public Outreach**

Public outreach/education may be viewed in many forms. Obviously, educational opportunities are easily exploited for the over 350,000 annual ranger-led visitors who tour the cave each year. An environmental education message or theme is common to most ranger-led activities. The park's Environmental Education Program provides an excellent service by visiting many local schools and hosting scores of school groups in the park each year. This program makes direct educational contact with an average of 20,000 students per year.

The park was very active in cooperative efforts with the USDA Natural Resources Conservation Service in the early 1990's. Over one million dollars of cost-share funding was made available by the USDA for the design and installation of animal waster BMPs within the park's karst groundwatershed. In recent years the park has been active as a partner with the USDA Green River Conservation Reserve Enhancement Program (CREP). This program focuses on restoration of the riparian corridor of the main stem of the Green River between the dam and the park (160 km) and agricultural BMPs within this watershed. Spanning ten years with funds totally $110 million, the overall goals of the program is to reduce soil erosion, protect and restore riparian hardwood forests, and improve water quality.

Mammoth Cave has taken an active role in environmental leadership by installing parking lot run-off filters at eight locations in the park. These units are dual-stage (oil/grit and organic filters) stormwater treatment facilities designed to reduce or largely eliminate parking lot contaminants from entering the cave.

The park has also had a productive history dealing with the Kentucky Division of Oil and Gas. Prior to a recent increase in oil exploration, the park and the state worked together to draft legislation to better protect the waters of the park. Now drillers must fully case wells from the surface to 100 feet below the lowest cave-forming limestone.

**Measurable Results: Public Outreach**

Of all aspects of defining measurable results, Public Outreach/Education is the most difficult. Where other monitoring efforts have set standards to judge against, delineating measurable results within this category is nebulous, at best. Ultimately any gains in public education and outreach will be made in the improvement of water quality and aquatic habitat.

**Priority: Water Quality**

It is not particularly feasible to rank the following priorities, as each is tied to the other, and the failure of one will cause the failure of all.

1.) Continue water quality monitoring program. WQ program should be modified, as discussed above, in order to provide the park a sound long-term dataset applicable for trend analysis, as well as provide information relative to storm-pulse events, with the flexibility for topical sampling.
2.) Continue air quality (wet/dry precipitation) monitoring as described above.
3.) Develop Depositional Analysis Thresholds for Air Quality Related Values for the park.
4.) Develop protocols for fish, BMI, mussel, and cave aquatic monitoring.
5.) Initiate monitoring program for fish, BMI, mussel, and cave aquatics.
6.) Continue to support all external activities and environmental educational programs that promote water quality and aquatic habitat improvements within the watershed.

***Water Resource Goal:***

***Hydrologic (water quantity) integrity of park waters (surface and ground waters) is improved and/or maintained to support natural geomorphic processes of fluvial and aquifer systems and to support native life.***

The most pressing, direct, and proximal alteration to the hydrology of the Green and Nolin Rivers and cave streams is Lock and Dam Number Six. Several key park species (including six mussels and a freshwater cave shrimp, all federally listed) are directly and immediately affected by this decommissioned, low-head dam. The Green (15 km) and Nolin (11 km) Rivers are impounded by Lock and Dam Number Six. Each listed mussel species is reliant on shallow, free-flowing condition, and, like many other mussel species, are not found in the pooled section. Twenty-six km of endangered species habitat has been severely altered. The cave shrimp are found within the major, slow-flowing base-levels of the cave. Unknown kilometers of their habitat are altered by this decommissioned structure as most of their habitat is not accessible.

Water quantity issues, while not currently on the scale of the American west, are beginning to generate interest within the park's watersheds. Current development trends will increase the use of water for domestic water supply, agriculture, and recreational use. Water quantity, in terms of minimum flow requirements to support a functional aquatic ecosystem, as well as flow modifications that alter the intensity, periodicity, and sediment erosion and deposition can greatly impact aquatic fauna. During drought conditions water demand remains relatively constant (little or no water conservation measures are used in this area of the country) and minimum flow requirements become important. Dams, both upstream and downstream affect the natural flow of the river and cave streams. Landuse practices within the rivers' riparian corridors can alter the sediment flux into the stream by bank destabilization, altering stream morphology, thus changing habitat for aquatic wildlife.

**Factors preventing or impeding the achievement of this Water Resource Goal**

*Lack of Knowledge of Fluvial Geomorphology of the Green River*

The past decade has seen an increased interest in the water quality and aquatic biology of the Green. The park has operated a water quality monitoring program and has initiated the inventory of fish, mussels, and other benthic macroinvertebrates. While much is known about water quality – links to land use, fate and transport of contaminants – and the distribution and density of aquatic life, little is known of important habitat structure. The foundation of aquatic habitat is the fluvial morphology of the stream.

At this point it is not possible to determine the effects, either positive or negative, on the many flow alterations of the Green and Nolin Rivers. These rivers both have rather large flood-control structures upstream of the park – the Nolin River Reservoir Dam (14 km upstream of the park boundary) and the Green River Reservoir Dam (160 km upstream of the park boundary). Both structures have greatly altered the flow of the rivers through the park – most obvious is the reduction in the amplitude of spring flood events (as the reservoirs retain flow to raise a recreational pool), and an increase in late autumn flow events as the lakes draw down to winter pool. Flooding frequency, duration, and intensity are the main factors governing the shape and function of river morphology, channel bank erosion, sediment fate and transport, and thus habitat quality.

Subsequent to morphologic knowledge of the rivers (both surface and subsurface) is the movement of sediment. Very little is known about stream sediments, either from re-entrainment of in-stream sediment, or “new” sediment being delivered into the stream. We know that many aquatic organisms, mussels for example, are extremely dependent on sediment issues. We also know that riverbed sediments downstream from the Gorin Mill Karst Groundwatershed contain high amounts of toxic metals and congeners of dioxin. However, basic information regarding the fate and transport of sediments are unknown.

*Ecological Flow Requirements for Threatened and Endangered Species and Habitat Quality*

Again, the main impediment to achieving this aspect of the water resource goal is the lack of basic knowledge. Most of the listed species are sessile and perhaps more dependent on a minimum flow condition than more ambulatory organisms. In either case, aquatic life in the rivers and cave streams are of course dependent on minimum flow requirements. No information is currently available to determine minimum flows.

The only source of large amounts of irrigation waters within the park’s karst groundwatersheds is via wells drilled into the karst aquifer. While it is predictable that the local effects of a large water well may have on aquatic life, no studies have been initiated to determine minimum flows.

*Impacts from Dams*

As stated earlier, the flow of the Green and Nolin Rivers within the park is affected by large recreational reservoirs upstream of the park. Operation of these dams alter, as all dams do, the hydrology of the river downstream – of course, upstream the river is now a lake. Not only do dams affect essential riverine processes like flood frequency and amplitude, and sediment flux, they also change water temperature. These USACE-operated projects draw water from the reservoirs by either a gate release (at the bottom of the dam) or a stand-pipe (positioned at a variable depth below the surface), or a combination of the two. The gate is the largest release structure, releasing the bulk of flood flow, while the stand-pipe is capable of delivering minimum flows. It is common practice for operators to rely upon the gate, delivering cold water into the river, for most releases.

Beginning in 2002, through a cooperative agreement between the USACE and The Nature Conservancy (TNC), an experimental reoperation period was implemented at the Green River Project. Under this experiment, the USACE attempted to reach two basic goals; release water in a manner more similar to pre-dam conditions, and to with more natural temperatures. To reach this end, the USACE delayed its fall draw-down from October to mid-November and delayed its spring retention from late-March to late April. This lessened the large flow events in the fall – typically when pre-dam flows were low – and allowed the large spring flood events to occur. In addition, the USACE is relying more upon the stand-pipe releases – moving the vertical position of the intake to respond to varying lake temperatures – to release waters with a temperature signature closer to pre-dam conditions.

The USACE has recently evaluated the reoperational experiment, which is required after at three-year trial. The have been able to not only operate the Project successfully under this new model, they have actually had less complaints about flooding from downstream land-owners. TNC has reported that preliminary temperature and biological monitoring has shown a positive effect of the reoperation. The USACE has now proposed, with full support of TNC and the park, to make these experimental changes permanent.

Lock and Dam Number Six is a reoccurring topic throughout this document. It is by far the single-most achievable ecologic issue at Mammoth Cave. The USACE stated in their Dispositional Study of dams on the Green and Barren Rivers that Lock and Dam Number Six should be removed. The Corps sees the structure as both a legal and fiscal liability. The park is on record of wanting the dam removed. Local, politically-vocal opposition is the main obstacle in the way of way of achieving the core of this Water Resource Goal.

Impacts of flow, at least the amount of flow can be gauged by in-stream sensors. Currently there are continuously-recording stream flow sensors at the Green and Nolin Dams, Campbellsville, Munfordville, and Mammoth Cave (the latter three within the Green) and at Lock and Dam Number Six (downstream from the confluence of the rivers. There are no gauges currently operational on the major surface and subsurface tributaries of the rivers. The foremost question is; are there sufficient flow gauges to answer water quantity questions?

*Recharge Boundary Definition*

Central to any water resources conservation effort is an understanding of the watershed boundary. Unlike non-karst areas where one can simply define the watershed topographically, defining catchment areas in karst terrains require dye-tracer studies. Mammoth Cave has long been a laboratory of dye-tracing work, beginning with the dye traces in 1925 – a fellow named Anderson was conducting this trace for the Louisville Gas and Electric to demonstrate that ground water can travel through adjacent ridges which would pose engineering problems for a proposed high-dam on the Green River near Pike Spring Throughout the 1970's the park's hydrologist, Dr. James Quinlan and associates conducted several hundred dye traces that resulted in a general definition of the park's karst watersheds. This pioneering work was followed by current park Hydrologist Joe Meiman and associates on the north side of the Green River. Both studies gave park managers, for the first time, a concept of the watersheds they are charged to protect and conserve. While these studies greatly increased our understanding of the source of park waters, it was not possible to fully define watershed boundaries to a small scale. Vast stretches across the Sinkhole Plain are defined in general by a limited number of traces. Along the eastern and western boundaries either an educated guess or specialized traces are required to determine flow direction. While this has not presented a major problem in the past – managers were glad to have this general picture – the increased level of land development within the park's karst watersheds calls for a more definite boundary.

*Restoration of Flow at Haney Springs*

The Haney Limestone creates a perched karst aquifer atop the Big Clifty Sandstone. Several Haney Springs served as water supplies for both the Civilian Conservation Corps (of the 1930s and early 1940s) and the park (until the mid 1970s). These springs still contain remnants of flow and catchment structures. In some cases all that remains is a small headwall and a few sections of pipe. Others retain larger structures, including flow diversion and reservoir (tanks). Presently there is no flow removed from the springs. Water has long-since filled containment structures and overflows into the spring runs, where it eventually (within minutes) sinks into the underlying Girkin Limestone.

**Comprehensive Strategy: River Morphologic Inventory and Monitoring**

Typical to many multi-discipline projects, it is very important that the components listed below are closely coordinated with all researchers. It is fiscally impossible, for example, to assess stream morphology along the entire Green. However, through input from aquatic biologists, geomorphologists could target specific habitats of concern. Similar coordination is necessary most every potential project discussed below.

The Green River is the focus of a multi-year conservation effort headed by the USDA. This project, the Green River Conservation Reserve Enhancement Program (CREP) is the recipient of over $100 million dollars over the first decade of the 21st century. These funds are used to purchase conservation easements along the main stem of the Green, promote and enhance native riparian vegetation, and to install agricultural best management practices throughout the watershed from the Green River Reservoir Dam and the park. While no initial funds were provided for monitoring the environmental effects of the program. During fiscal year 2005, funds were allocated to initiate physical (sediment) and biological monitoring. In order to make the most effective use of data generated by this monitoring effort, a comprehensive description of the fluvial morphology, specifically targeted to aquatic habitat and measures of the effectiveness of the CREP program, should begin.

Evidence through a few samples taken at the base-flow water line along the Green River within the park has indicated an increase in sedimentation beginning in approximately 1800. This coincides with a major shift in land use as settlers began to clear the forested uplands and plow the prairies of the Pennyroyal Plateau. The same sediment time-stamp was found beneath a silt bank in Logsdon River (Mammoth Cave). As part of this same study, sediment quality was examined. Sediments derived from the Gorin Mill karst watershed (draining into the Green upstream of the park) were found to contain high levels of toxic metals (chromium, cadmium and copper) and dioxin congeners. A two-year WRD-funded project, slated to begin in FY06, will further define the extent of the contaminated sediments and collect mussel tissue in contaminated zones to determine if the metals are being taken into these animals.

A sediment fate and transport monitoring program should be initiated. This program should tie into goals of the fluvial geomorphic study, in that it should focus on specific habitats of interest for aquatic life and the effectiveness of measures brought about by the CREP initiative.

Coupled with the two proposed studies above, a related project examining sediment fate and transport of cave streams should begin. During flood events cave streams can transport tremendous sediment loads. While flow velocities of surface streams are limited due to gradient and channel morphology, cave streams typically conduct pipe-full flow during flood events. At these times flow velocities can be very high (the highest approached 10 m/s at Logsdon River during the March 1, 1997 flood) as any additional flow through a fixed cross-sectional area must be met with an increase in velocity. It is expected that due to these dynamics, sediment fate and transport through a cave stream will be significantly different that in a surface stream.

To rephrase a quote often attributed to the philosopher Will Durant, "Life exists by geomorphic consent, and is subject to change without notice". Even in natural flow conditions free of anthropogenic manipulations and influx, the river is ever changing. The principle components that maintain the morphology of the river, and thus habitat are: flow magnitude, frequency and magnitude of ecologically significant flows, flow duration, flow timing, and the rate of change between flow magnitudes. Combinations of these elements create desirable or undesirable habitat for aquatic species. Jowett (2003) states that water depth, velocity, and substrate size are the best predictors of benthic habitat. Substrate stability and fine sediment deposition also influence benthic invertebrate abundance, with reduced abundance where substrates are frequently disturbed or where fines accumulate (Jowett, 2003).

The determination of minimum flow requirements should be considered a vital component to the above-mentioned projects, and viewed in the light of not only how much water is above a mussel bed, but how flows affect habitat. Any investigator of minimum flows must work closely with people researching geomorphology of the river and the fate and transport of sediments, as well as biologists inventorying the river.

The aforementioned study by Jowett (2003) proposes a hydraulic formula to predict substrate stability and deposition of fine sediment. Hydraulic conditions near or at the surface of the stream bed may be a more direct influence of benthic invertebrates than either the water depth of the mean velocity in the water column above them.

**Resource Management Actions: Stream Processes and Function**

1. Fully support, through funding, personnel or logistical, efforts by institutions currently assessing and monitoring fluvial function of the Green River. The Green River CREP is primarily focused on riparian restoration along the main stem of the Green. Groups such as the USGS and Western Kentucky University (WKU) are developing programs to assess sediment fate and transport down the Green. In each of the following statements, all efforts must be closely coordinated with biologists who are monitoring the biota of the river and riparian corridor.
2. Develop proposal with the USGS and WKU to assess and describe current morphologic attributes of the Green River with special emphasis on federally listed specie habitat.
3. Continue to provide logistical support for graduate students in assessing cave stream sediments. Currently we know, from one carbon-date, that at least one section of Logsdon River experienced a sediment influx event in the early 19$^{th}$ century that greatly alters hydrologic function in this stream.
4. Working with the Kentucky Division of Water, make an assessment of current and projected water needs (withdraw) from the Green River watershed upstream of the park, as well as the park's groundwatersheds south of the Green.
5. Work with the USGS and WKU in developing a basin model for the Green upstream of the park to determine flow characteristics. Parameters to consider would include precipitation, evapotranspiration, water withdraw and dam operations.
6. Work with USFWS to determine minimum flow requirements for federally listed aquatic species and compare to information gathered in the two preceding statements.

**Measurable Results: Stream Processes and Function**

Foremost a carefully-designed and well-integrated program with elements listed above resources managers to assess the impacts of the Green River CREP. As more of the Green's riparian corridor is reclaimed to natural vegetation and ecologic function, and agricultural best management practices are installed throughout the watershed, such assessment and monitoring should determine if the CREP is reducing sediment influx.

Secondly, and on a more local scale, river morphologic monitoring targeted to species of concern will allow managers and biologists to determine the effects of habitat change on species occurrence, distribution and density.

Measurable results from topics such as minimum flow requirements are a bit more nebulous. Models can be made and minimum flow requirements determined, although the degree of certainty may be fairly low. If such flow requirements can be made, the measurable results can be as simple as monitoring flow in key sections of the river.

**Comprehensive Strategy: Removal of Lock and Dam Number Six**

The single-most significant improvement to the integrity of park waters would be achieved by the removal of Lock and Dam Number Six. It is directly impacting the in-park habitat of seven federally listed species. The owner, the US Army Corps of Engineers (USACE) does not wish to maintain the structure. Each year the numerous leaks in and around the lock and dam increases. During the late summer of 2004, approximately 7 cms were observed flowing through and around the lock chamber. Both the park and the USACE are very concerned about the growing possibility of nature taking its course on the removal of this structure. A catastrophic failure may cause harm to life and property downstream.

An Environmental Assessment on the proposed removal of the dam was prepared as part of the USACE disposition study, and an Environmental Baseline Study was done by Gulf Engineers and Consultants. The USACE concluded that there would not be significant negative impacts for dam removal. It is anticipated that removal of the dam will produce positive effects, and an Environmental Impact Statement (EIS) will have to be prepared. If needed, the USACE will produce the EIS in cooperation with the park.

The time-line for removal, if that is ever approved would be at least two years. The USACE would request appropriations to develop construction plans for the removal in one fiscal year and then the construction funds in the following fiscal year. In all likelihood it would take three years following Congressional acceptance of the USACE request to get to actual construction to remove Lock and Dam Number Six.

The park will be responsible for projects needed to cope with the removal of the pool, such as ferry operation. At both Houchins and Mammoth Cave Ferries, approach ramps will need to be extended to the lowered pool. Mammoth Cave Ferry may need more extensive work that may include the periodic dredging of the channel on the north bank. The park is pursing funding to renovate, improve, and expand facilities for the Mammoth Cave Ferry, and pre-design planning, which will develop and analyze alternatives, is funded for FY05. Ideally, funding from Congress would be appropriated in FY07 for the design of the preferred alternative following approval by the NPS Development Advisory Board. Construction funding would then need to be appropriated in FY08. The intent of the project is to improve the operation of the ferry, and to provide boat and canoe launch facilities.

It must be also recognized that the pool level of the Nolin River at the base of the Nolin Dam is equal to the crest of Lock and Dam Number Six. Changes along the entire portion of the Nolin downstream of the dam will be greatly altered. Tributaries downstream of the dam are very limited and do not add appreciably to the flow. The park must work with the USACE in strictly adhering to minimum flow requirements of the Nolin Dam.

**Resource Management Actions: Removal of Lock and Dam Number Six**

1. Develop and promote a dialogue with elected officials, USACE, USFWS and other agency officials, and the general public on the myriad issues related to the removal of Lock and Dam Number Six.
2. Assemble all relevant data needed to cooperate with the USACE in the preparation of an EIS.
3. Continue all current work towards improving operation of Mammoth Cave and Houchins Ferries to operate in a lower pool of the Green River.
4. Work with the USACE in the reoperations, with special focus on minimum flow requirements for the Nolin River Reservoir.

**Measurable Results: Removal of Lock and Dam Number Six**

The ultimate measurable result will be the absence of Lock and Dam Number Six. Actual measurable results will be seen through aquatic biomonitoring of the Green and Nolin Rivers and the base-level cave streams. Goals should be a return of free-flowing conditions resulting in repopulation of the currently pooled section to reflect that of the free flowing section.

**Comprehensive Strategy: Refinement of Karst Watershed Maps**

One can envision countless additional dye traces to further refine the karst groundwatershed boundaries of the park. The first step in this effort should focus on developing a strategy. Certain sections of the basin boundaries are controlled topographically. They include portions of the basins which are recharged by concentrated allogenic means – draining the argillaceous limestones of the Glasgow Uplands and the silisiclastics of the Chester Questa. This leaves the portions of the watershed boundaries that cross the autogenically-recharged Sinkhole Plain. Careful examination of existing dye-trace inputs overlain by the most current land use layers (Anderson III) would allow researchers to prioritize new dye injection sites. As the refined boundary is developed, special consideration for high-flow traces should follow, as it is typical, especially along watershed boundaries, to have divergent flow from a single input. That is, under certain flow conditions, dye, and thus groundwater, may flow into two adjacent watersheds.

**Resource Management Actions: Refine Karst Groundwatershed Maps**

1. Identify and prioritize sections of the karst watersheds of the park, south of the Green River, to conduct the dye traces that will better define the existing boundaries. All steps of this study should be done in coordination with the Kentucky Division of Water, Groundwater Branch.
2. Develop MSAccess database or Geodatabase for all tracing activities.
3. Conduct dye traces – it may take two to three years to complete.
4. Publish results via the Kentucky Geologic Survey Karst Atlas series maps.

**Measurable Results: Refine Karst Groundwater Maps**

Measurable results are quite clear and definite. Dye traces are completed, with key traces repeated during high flow conditions, and the boundary is better defined. The Principle Investigator should realize that it is nearly impossible to trace every doline where the boundary crosses the Sinkhole Plain. A measure of professional judgment must be used that tracing is complete to the degree that sound land management decisions can be based.

**Comprehensive Strategy: Resolution of Hydrologic Issues Pertaining to Historic Flow Structures at Haney Springs**

Although seemingly a simple and direct project, the removal of historic flow structures from Haney Springs will prove challenging from the point of cultural resources compliance. The first step would be to make a careful assessment of the springs and possible impact from the flow structures. Is there an issue?...and if so, how can it be resolved?

Each of the Haney Springs targeted have some degree of culturally historic infrastructure. These structures – ranging from pipes to masonary walls and retention tanks – are on the park's Historic Register (Personal Communication, Robert Ward, Cultural Resources Specialist, Mammoth Cave National Park, 2005). Any modification of any portion of the flow structures, being headwalls, low dams, pipes, divergence or holding structures must undergo a series of cultural compliance.

**Resource Management Actions: Resolution of Hydrologic Issues Pertaining to Historic Flow Structures at Haney Springs**

1. Determine if, in fact, present existing historic flow structures are indeed negatively affecting water resources of the park (cause-and-effect). This must be done for every spring in question. This assessment should include recommendations for resolving hydrologic management concerns.
2. Complete all relevant cultural resources compliance documentation.
3. Resolve hydrologic management concerns by implementing recommendations.

**Measurable Results: Resolution of Hydrologic Issues Pertaining to Historic Flow Structures at Haney Springs**

Direct measures are easily demonstrated by resolution of hydrologic management issues associated with the Haney Springs. However, measurable results as they pertain to water resources, specifically aquatic species is more difficult. Monitoring of the aquatic community directly downstream of the Haney Spring could occur, but at this time there the cause-and-effect relationship has not been established. As each Haney spring flows a short distance across the Big Clifty Sandstone, before sinking into the Girkin Limestone, if one were interested in impacts to the cave aquatic community, one must monitor the stream originating from particular sink points. This will be difficult as to this date, through all the exploration of the Mammoth Cave System, no cave streams (no doubt vertical shafts) have been found directly associated with such Haney spring recharge. They of course do exist, but remain undiscovered.

**Priority: Water Quantity**

1. Continue efforts on all fronts from public education, political dialogue, and cooperation with the USCAE working towards the removal of Lock and Dam Number Six.
2. Continue development of multi-discipline studies, with the Green River CREP at the core that synthesizes all aspects of aquatic habitat. Including river/stream morphology, sediment fate and transport, ecologic flow targeted to specific habitats.
3. Continue to support efforts to gain basic knowledge on the nature, fate and transport of sediments in the active flow level of the cave.
4. Refine karst watershed basin boundaries where appropriate.
5. Determine if historic flow structures at Haney Springs are causing an impact to the park's water resources, and formulate recommendations to mitigate or eliminate any negative impacts to hydrologic processes.

***Water Resource Goal:***

***Exotic species are removed from the park and future introduction of exotics is prevented***

In many respects, the Green and Nolin Rivers have not seen the ecologically crippling effects brought by the invasion of aquatic exotic species. That is not to say that several exotics do not exist within these streams, they do.

Park mussel biologist Stacy Surgenor supplied the following information on the present knowledge of current aquatic exotic fauna as well as potential (some nearly certain) introductions.

Asian Clam, *Corbicula fluminea* - very widespread, overly abundant, present throughout Green, here in the park in vast quantities.

Zebra Mussel, *Dreisenna polymorpha* - in the Green near confluence with Ohio as far up as commercial barge traffic travels (approximately 160 km downstream of the park). Specialists suspect it will show up in the upper Green within 10 years. The most likely vector is an introduction into Green River Lake by a contaminated boat (this happened in Lake Cumberland a few years back, boater from Ohio had outboard motor cooling system packed full of zebra mussels). Many experts agree that a zebra mussel infestation of the Green within the park will happen, it's just a matter of when, while other experts believe the spread of zebra mussels to the park to be unlikely.

Quagga Mussel (*Dreisenna bugensis*) showed up in the Great Lakes area a few years back (after the zebras invaded) and they are still confined to the Great Lakes area including the St. Lawrence River. Unfortunately, they feed year-round, non-stop (unlike zebras), can tolerate silty conditions where zebras do not do well, and can live in much deeper water. Some experts suspect it will gradually spread south, but zebras caused people to be more cautious about introductions, so it probably won't spread as fast as the zebra mussel did, but it could possibly show up in the Green River within a couple of decades (not an immediate threat). Some experts see the spread of the Quagga to park waters to be unlikely. Quaggas are native to Caspian Sea area, introduced through discharged freighter ballast water (same method of zebra introduction).

There are also several exotic fish species found within the park. Rainbow trout (*Onchorhynchus mykiss)* are currently stocked in the tailwaters of the Nolin Dam (only three km from the park boundary). These fish, native to the far western portions of the United States, have been introduced throughout the east, especially in the cold-water lake releases as a sport fish. Currently the Kentucky Department of Fish and Wildlife Resources (KDFWR) stock rainbows in the tailwaters of the Nolin Dam – to give an order of scale, 16,600 were stocked into this put-and-take fishery in 2000. The KDFWR also stocks rainbows within the Green River (upstream of the park) at Roundstone Creek.

Common Carp (native to Eurasia) - *Cyprinus carpio* was introduced at least 100 years ago and are common in the Green and Nolin Rivers within the park. Its cousin, the goldfish *Carassius auratus* is also found within the park's two surface rivers.

Similar to the mussels, the real potential for additional introductions of exotic fish exists. Mosquito fish (*Gambusia affinis*) is native to the United States, but range is increasing, possibly due to bait bucket introductions or habitat modifications that favor it. These fish can tolerate warm temperatures and low dissolved oxygen levels, and have very high fecundity, but are short-lived.) The mosquito fish was not collected in the park in the early 1990s but was found in the park in the past few years. Its native range is somewhat speculative, but experts suspect that it was not native to the Green River basin.

Asian Carp (bighead *Hypothalmichthys nobilis*, and silver *H. molitrix*): native to large rivers in China): are presently not within the Upper Green River watershed. They are in the Mississippi and lower Ohio, and have invaded the Cumberland and Tennessee Rivers. These fish are more at home in larger rivers and expected invasion, if it does occur, is not likely within the next ten years.

Sticklebacks (Genera *Culaea* and *Gasterosteus*) currently not present in Upper Green. Sticklebacks are frequently introduced with baitfish shipments. These may be introduced to the Green River Basin by bait-bucket dumping.

**Factors preventing or impeding the achievement of this Water Resource Goal**

In many respects it is beyond the means of resource managers to single-handedly remove and prevent the invasion of exotic species. Rivers flow into and out of the park from great distances, crossing the bounds of many government and private resource managers. The state itself, through its sport fishery programs, introduces tens of thousands of trout each year. In addition, thousands of recreational boaters launch into waters upstream of the park. The potential of introduction of exotics accompanies each launch and with each dump of an unused bait bucket. These issues are common throughout the park service and the nation at large. For decades not only was the practice in exotic introduction not discouraged, it was, and continues to be supported by state governments.

Aquatic exotic species seem to be covered by three distinct categories: sport fish (which are deliberately introduced), non-sport fish (locally introduced primarily by private individuals – grass carp for example), and other aquatic exotics which are introduced by accident or carelessness (zebra mussels).

The challenge for resource managers is manifold. Foremost, state and federal managers may have different management objectives. An example would be the KDFWR. This agency's mandate includes fishery management, and in the case of trout stocking, to reclaim an otherwise distorted fishery by the operation of a large reservoir – the native fishery was negatively impacted by cold–water release and thus stocked with cold-water-tolerant sport fishes. In addition to deliberate introduction of sport fish, an occasional accidental introduction of non-sport fish is ever-present and is beyond the direct regulation of state or federal governments. And nearly beyond any conservation or preservation control looms the accidental introduction of exotic non-fish species.

**Comprehensive Strategy**

Perhaps the resolution of no other water resource issue is reliant upon a combination of education and cooperation. While the vectors of introduction of aquatic exotic species are well-known, accidental or deliberate, the prevention of introduction remains difficult at best. Viewed against a historic national backdrop of federally and state initiated exotic introduction – the late 19$^{th}$ well through the middle of the 20$^{th}$ centuries are replete with countless efforts – preventing the introduction of a species into the waters of Mammoth Cave National Park will be a challenge for park managers for the foreseeable future.

The park cannot even begin to move towards this Water Resource Goal without a long-term commitment to working with other agencies and education of the public. The park should promote the formation of a working group – including representatives of local universities, KDOW, USACE, USGS, and USFWS – to assess the present state of exotics within the Green River watershed. Once known, the group can determine what action, if any, can be taken. This group would also focus pubic education, primarily upon lands each manages. For example, signage relative to exotic species and their impact to native communities, should be designed and installed at public access points along the Green within the park.

In some cases the park may be faced with an exotic that cannot be extricated, at least by means of today's techniques. Some species impact the native community more than others. Some have the capacity to severely warp this native ecosystem. In any case, decades from now park managers and researchers would be well served of a full inventory and account of the aquatic community of park rivers as they exist today. Such an inventory, including measures of species density, would serve as a restoration goal in future efforts.

**Resource Management Actions: Aquatic Exotic Species**

It must be stated up front that no program that targets exotic species control or removal can be successful without complete cooperation and coordination with all resource managers within the watershed. Programs must be willing to "go the distance" and keep up the effort for many years to be successful. A vital component to these efforts must include a great deal of public awareness/education.

1. Complete park inventory of extant aquatic species to create a "restore-point" prior to the introduction of additional exotic species and further invasion of existing exotics.
2. Determine, through search of previous inventories (throughout the Green River watershed) exotic species currently found. Work must be done in concert with state agencies (KDFWR and Kentucky State Nature Preserves Commission, KSNPC).

3. Determine which species pose the greatest threat to the water resources of the park.

**Measurable Results: Aquatic Exotic Species**

A simple, prioritized list of currently inventoried exotic species with clearly described threats will result. This list will serve as a starting point to eliminate those exotics found in the park as well as the watershed as a whole – as aquatic species tend to travel (even sessile animals as mussels by veligers) throughout a watershed.

The final point above will give park managers a real sense of current aquatic species found in park waters prior to further infestation of existing or the introduction of new species. The park currently has several exotics and more are on the way. Such an inventory will allow future park managers a "restore-point" to target future restorative efforts.

The above task is by far the easiest of this section to complete. The following will take a long-term and concentrated effort by the park and all state and federal aquatic resource managers within the watershed.

**Priority: Aquatic Exotic Species**

1. Complete inventory, with measures of specie density, of extant aquatics on the Green and Nolin Rivers.
2. Compile inventory of existing aquatic exotics through current fish, mussel, and BMI Inventory and Monitoring Program.
3. Work with state and federal river managers for list of exotic species found within the Green and Nolin Rivers.
4. Determine threat levels for each exotic.
5. Devise program for the eradication of each species in cooperation of state and federal agencies.
6. Promote activities that educate the public on the spread and consequences of introduction of exotics.
7. Continue to track exotics and the effectiveness of the above programs through long-term monitoring program for fish, mussels and BMI.

## Summary


Much is known of the water resources of Mammoth Cave National Park. Extensive biological inventories, years of water quality data, detailed land use classification laid against a backdrop of the most intensively dye-traced karst terrane in the world provides the park manager with a wealth of information. The park has enjoyed long-time research relationships with several universities, federal, state and local agencies. The water resources of Mammoth Cave National Park are certainly world-class. The Green River, with one of the most diverse aquatic communities in the country, is the hydraulic focus of all waters draining into and through the park. Each park stream, the rare surface streams or the ubiquitous cave streams and springs, drains to the Green.

Over the long course of the geomorphic and biologic histories of Mammoth Cave an ecosystem evolved within the bounds of natural stressors such as flood, drought and fire. Approximately 200 years ago the limits of natural disturbances, in terms of both severity and frequency, was altered as pioneers settled on the Pennyroyal Plateau. We are now well within a progression of land use change. Within the watershed of the Green, and likewise with the karst groundwatersheds of the park, are numerous stressors to the aquatic ecosystem. Each land use, from the chronic inputs of non-point source contaminants (nutrients, pesticides, and sediment for example) to the acute sources toxic spills (accidental releases) has the potential to affect the waters and dependent wildlife of the park. Physical changes of the park's hydrology are severely altered flow regimes, and thus aquatic habitat. The 100 year old Lock and Dam Number Six impounds the Green through its lower course through the park, as well as all base-level cave streams recharging the river. The entire course of the Nolin through the park is impounded by this structure.

These alterations have warped the natural aquatic ecosystems of the park, both surface and cave, by changing nutrient flow, habitats, and introducing contaminants into what we inventory and monitor today. Species once common may now be rare. Flow conditions that were once uncommon now occur with great frequency. Although much is known regarding the abundance and distribution of aquatic life, little is known of their limits to anthropogenic stresses. For example, what is the limit to habitat siltation for the Kentucky Cave Shrimp? How much of its prime habitat has been altered by the impounded Green? How do they respond to eutrophication? There are some stressors that the park can directly eliminate, primarily the removal of Lock and Dam Number Six. Others, such as land use within its watershed will be more difficult to effect.

Ultimately it is the responsibility of the National Park Service, and specifically its managers, to conserve and protect the aquatic resources of Mammoth Cave National Park. Judgment of success or failure is reserved not by this, but by future generations.

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# Appendix A

## Water Quality Parameters, Standards, and Graphical Display of Water Quality Data

**Discharge** is the anchor of all water quality data. Discharge data are used to compute the mass flux, or loading, of a particular constituent. Mass flux yields valuable insight as to the mode of contaminant entrainment and transport through the karst aquifer.

**Specific Conductance** provides a quick analysis of where, temporally, the sample is taken relative to the last flood pulse. For a given site, a relatively low specific conductance indicates that the system is not at base flow and still affected by a recent recharge event. Specific conductance also indicates the overall dissolved solid load.

**Water temperature** is a low-cost method of rapidly assessing relative transport times of the water sampled. A water temperature close to that of antecedent recharge would indicate rapid transfer and flow rates. These data may be used to demonstrate the hydrogeologic provenance of a contaminant.

**Dissolved oxygen** is another field measurement that provides information on the general biological condition of the water. This measurement is a gross indicator of aquatic ecosystem health. Field measurements provide the investigators "real time" analysis of samples which may alert park managers to declining conditions.

The **pH** of each sample will be taken to determine the hydrogen activity of the water. Besides being a fundamental ecologic parameter, pH is needed to calculate carbonate saturation indices.

**Turbidity** is a low-cost approximation of the total suspended sediment load of the water. A high suspended sediment load indicates a high erosion rate within the recharge basin. In a highly vadose flow system, high turbidity is a harbinger of an approaching flood pulse. Our research has also show a high correlation between turbidity and pesticides.

**Fecal coliform bacteria** are a simple test to approximate the general bacterial load of the water. The presence of coliforms in sufficient numbers indicates fecal contamination of water by a warm-blooded animal. Past fecal coliform levels have ranged from 0-8000 colonies per 100 ml.

**Triazine-class herbicides** represent the most common and durable pesticides used in the Mammoth Cave area. The compounds, including atrazine, simazine, and cyanazine, are analyzed using an immuno-assay method. While this method, which has been in use at Mammoth Cave since 1990, cannot yield accurate quantitative results, samples which qualitatively indicate a concentration of greater than 1 ppb are sent to a contract laboratory for mass spectrographic/gas chromatographic analysis. This method can be thought of as a screening test which greatly reduces the need for expensive organic analysis. The current program uses a refined and approved assay technique for all samples.

**Nitrate-nitrogen** values can be a useful predictor of eutrophication. A high nitrogen-nitrate concentration indicates a high nutrient load, which, depending upon other parameters such as bacterial counts, may be from septic waste, animal waste, and fertilizer sources.

**Chloride** is an inexpensive test which may indicate the presence of oil field brines, road salts, or other sources. A natural concentration of chloride between 5 and 15 ppm exists in the Mammoth Cave area.

**Bromide** occurs in the groundwaters of the Mammoth Cave region that are impacted by oil field brines. There has been an explosion in oil and gas exploration adjacent to the park in the past two years.

**Sulfate** can be coupled with chloride analysis to suggest the type of pollution. Low chloride and high sulfate may indicate natural dissolution of sulfate minerals if the mass flux is relatively constant, high chloride with low sulfate may indicate contamination by road salt, and high chloride and high sulfate may indicate brines.

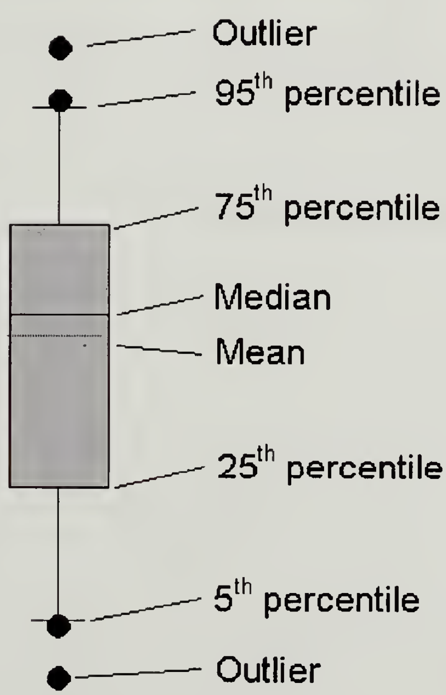
**Calcium, magnesium, and alkalinity** (bicarbonate ion) are the dominant natural cations and anion found in carbonate aquifers. These ions are useful in determining the temporal and hydrologic position of the sample relative to the last recharge event. More specific than conductance, these ions may indicate the provenance of a contaminant as related to transfer and storage.

**Inorganic metals** to be monitored in this program include *aluminum*, antimony, arsenic, barium, beryllium, boron, cadmium, *calcium*, chromium, cobalt, copper, gold, *iron*, *lead*, lithium, *magnesium*, manganese, nickel, *phosphorous*, *potassium*, selenium, *silicon*, silver, *sodium*, *strontium*, *sulfur*, thallium, tin, vanadium, and *zinc*. Elements in italics were found during the 1990-1992 Water Quality Inventory Project. Although not every element listed is needed to track water quality, they were included at no additional cost in the ICP analysis.

| **Parameter** | **Method** |
|---|---|
| Discharge | Wading staff and Marsh-McBirney 201D velocity sonde |
| Specific Conductance | Omega CDH-70 SpC/Temp. meter (+/- 0.001 mS), or eq. |
| Water Temperature | Omega CDH-70 SpC /Temp. meter (+/- 0.1 $^{o}$C), or eq. |
| Dissolved Oxygen | Hach DO175 meter (+/- 0.01 mg/L), or eq. |
| pH | Hach EC10 meter (+/- 0.01 units), or eq. |
| Alkalinity | Hach, phenolphthalein sulfuric acid titration (+/- 5 mg/L) |
| Turbidity | Turner 40-100 nephelometer (+/- 0.1 to +/- 1.0 ntu) |
| Fecal Coliform | Millipore membrane filter method, MFC broth (+/- 1) |
| Triazine Assay | Millipore immuno-assay (+/- 0.001 mg/L) |
| Nitrate-Nitrogen | Hach, cadmium-reduction/spectrometer (+/- 0.1 ppm) |
| Chloride | SW846-9056 (MDL 1 mg/L) |
| Bromide | SW846-9056 (MDL 1 mg/L) |
| Sulfate | SW846-9056 (MDL 5 mg/L) |
| Aluminum | EPA 200.7 and SW846-6010A,B (ICP) (MDL 19 μg/L) |
| Antimony | EPA 200.7 and SW846-6010A,B (ICP) (MDL 51 μg/L) |
| Arsenic | EPA 200.7 and SW846-6010A,B (ICP) (MDL 50 μg/L) |
| Barium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 0.7 μg/L) |
| Beryllium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 2.4 μg/L) |
| Boron | EPA 200.7 and SW846-6010A,B (ICP) (MDL 23 μg/L) |
| Cadmium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 6 μg/L) |
| Calcium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 23 μg/L) |
| Chromium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 8 μg/L) |
| Cobalt | EPA 200.7 and SW846-6010A,B (ICP) (MDL 12 μg/L) |
| Copper | EPA 200.7 and SW846-6010A,B (ICP) (MDL 7 μg/L) |
| Gold | EPA 200.7 and SW846-6010A,B (ICP) (MDL 12 μg/L) |
| Iron | EPA 200.7 and SW846-6010A,B (ICP) (MDL 6 μg/L) |
| Lead | EPA 200.7 and SW846-6010A,B (ICP) (MDL 71 μg/L) |
| Lithium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 3 μg/L) |
| Magnesium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 30 μg/L) |
| Manganese | EPA 200.7 and SW846-6010A,B (ICP) (MDL 2 μg/L) |
| Nickel | EPA 200.7 and SW846-6010A,B (ICP) (MDL 49 μg/L) |
| Phosphorus | EPA 200.7 and SW846-6010A,B (ICP) (MDL 121 μg/L) |
| Potassium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 1210 μg/L) |
| Selenium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 129 μg/L) |
| Silicon | EPA 200.7 and SW846-6010A,B (ICP) (MDL 34 μg/L) |
| Silver | EPA 200.7 and SW846-6010A,B (ICP) (MDL 6 μg/L) |
| Sodium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 18 μg/L) |
| Strontium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 1 μg/L) |
| Sulfur | EPA 200.7 and SW846-6010A,B (ICP) (MDL 30 μg/L) |
| Thallium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 68 μg/L) |
| Tin | EPA 200.7 and SW846-6010A,B (ICP) (MDL 426 μg/L) |
| Vanadium | EPA 200.7 and SW846-6010A,B (ICP) (MDL 4 μg/L) |
| Zinc | EPA 200.7 and SW846-6010A,B (ICP) (MDL 4 μg/L) |

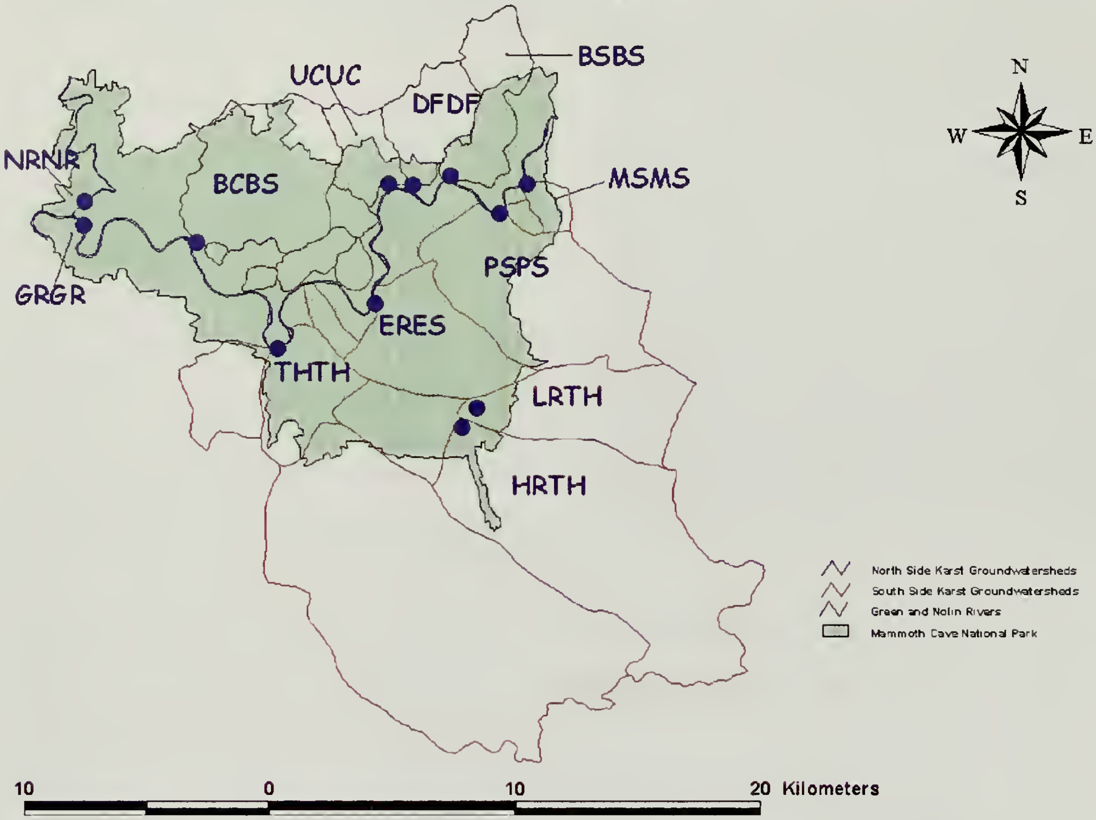
Key to Graphs:

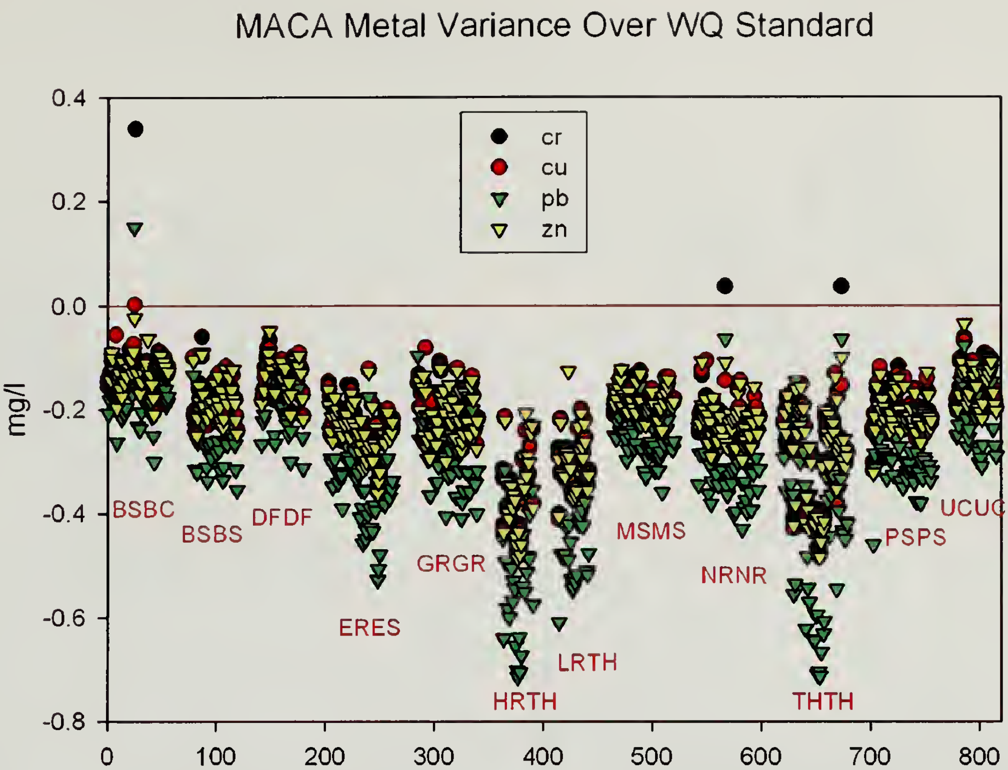
| Site Name | Site Code |
|---|---|
| Mile 205.7 Spring | MSMS |
| Pike Spring | PSPS |
| Big Spring | BSBS |
| Doyle's Ford Spring | DFDF |
| Ugly Creek Spring | UCUC |
| Echo River Spring | ERES |
| Turnhole Spring | THTH |
| Hawkins River | HRTH |
| Logsdon River | LRTH |
| Buffalo Spring | BCBS |
| Green River | GRGR |
| Nolin River | NRGR |




Key to following water quality box-plots.

## Monthly Non-conditional Synoptic Water Quality Sampling Sites




MACA Metal Variance Over WQ Standard
mg/l
cr
cu
pb
zn
BSBC
BSBS
DFDF
ERES
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LRTH
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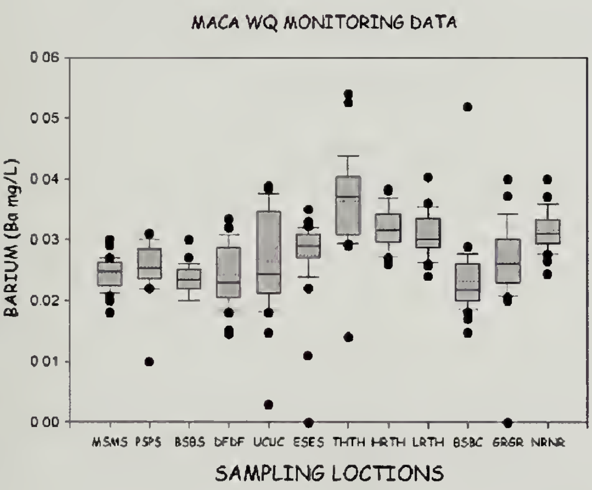
NRNR
THTH
PSPS
UCUC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BARIUM (Ba mg/L)
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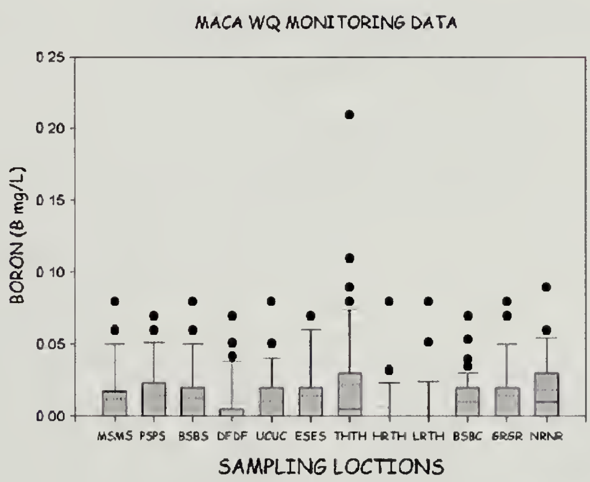
SAMPLING LOCTIONS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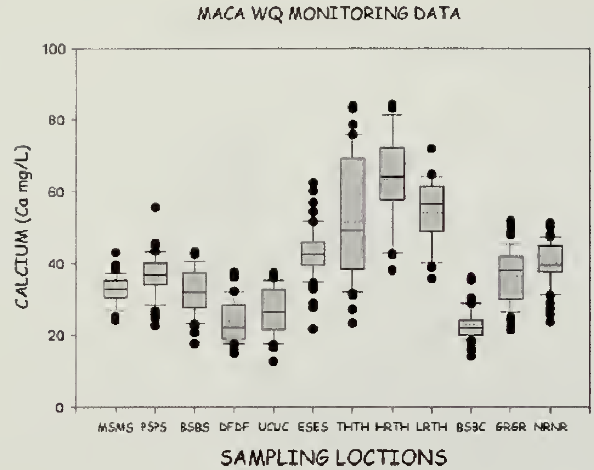
SAMPLING LOCTIONS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CALCIUM (Ca mg/L)
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80
60
40
20
0
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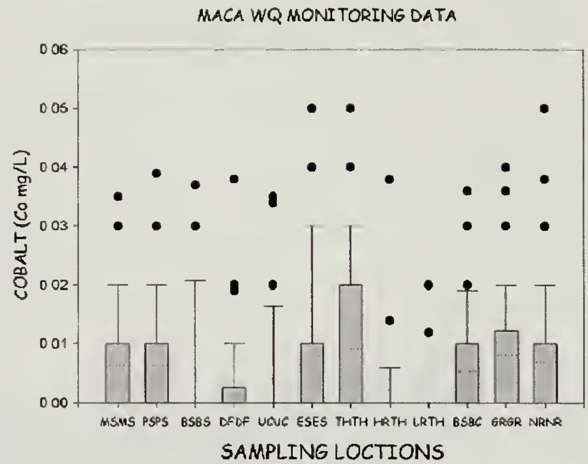
SAMPLING LOCTIONS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COBALT (Co mg/L)
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0.02
0.01
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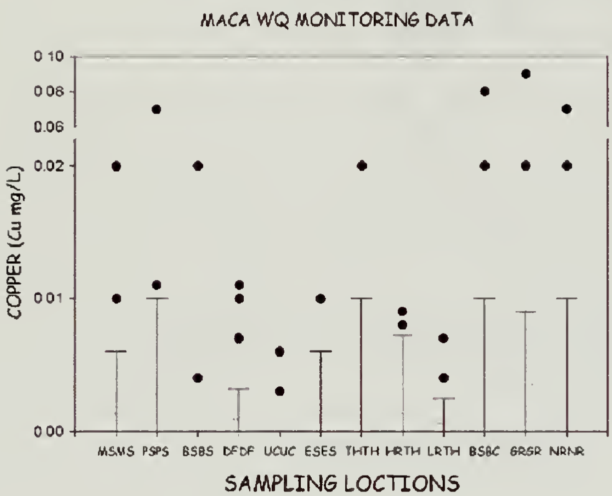
SAMPLING LOCTIONS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COPPER (Cu mg/L)
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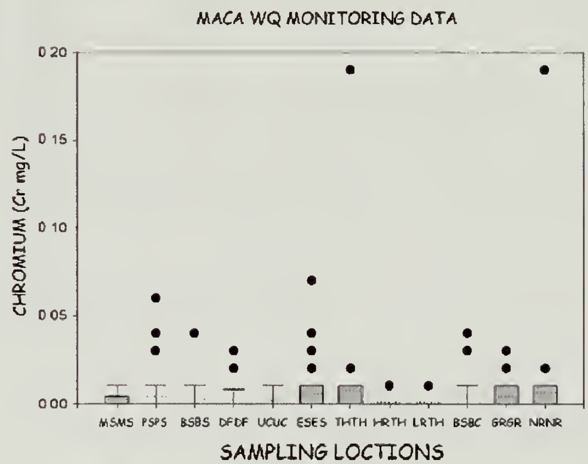
SAMPLING LOCTIONS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CHROMIUM (Cr mg/L)
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0.05
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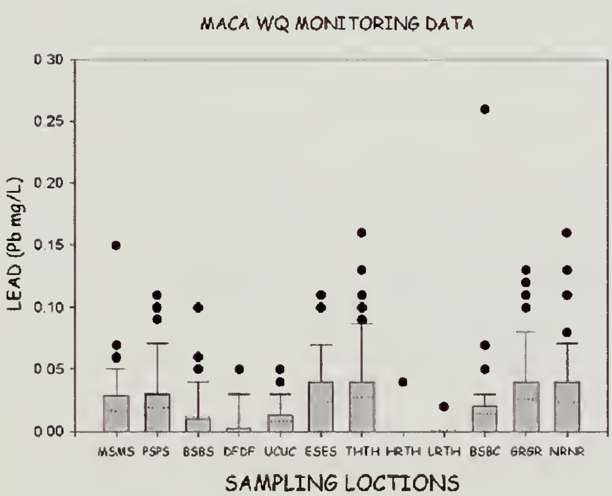
SAMPLING LOCTIONS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LEAD (Pb mg/L)
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0.25
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0.05
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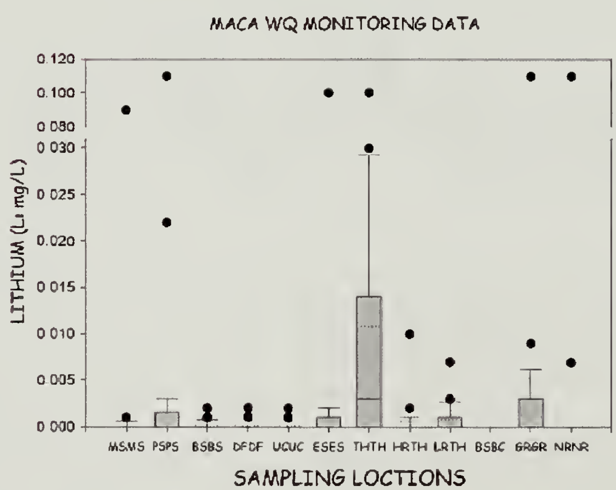
SAMPLING LOCTIONS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0.080
0.030
0.025
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0.010
0.005
0.000
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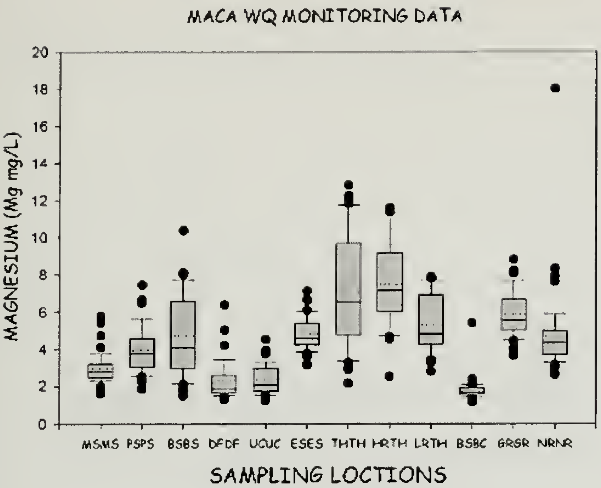
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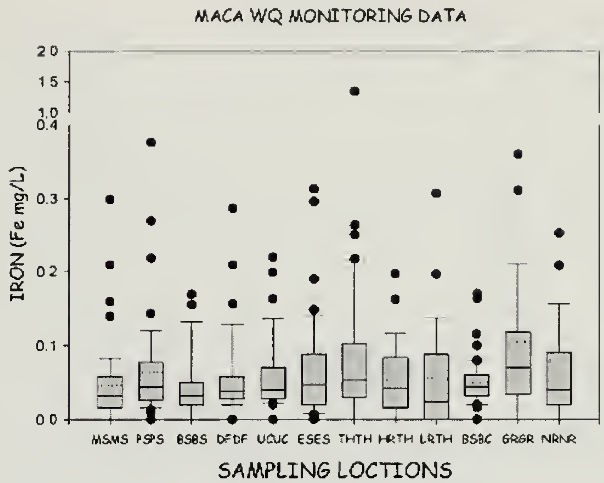
SAMPLING LOCTIONS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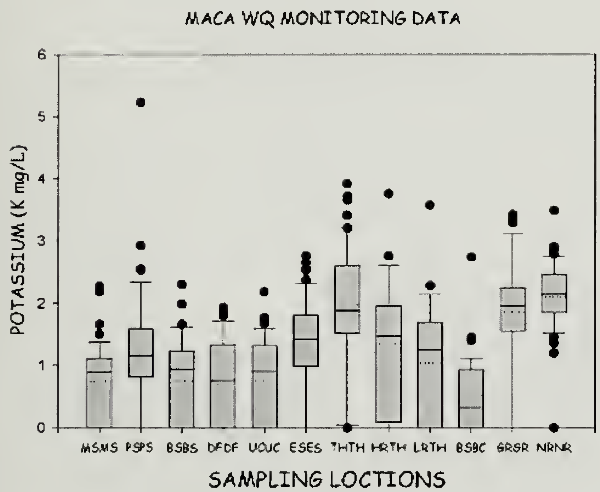
SAMPLING LOCTIONS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POTASSIUM (K mg/L)
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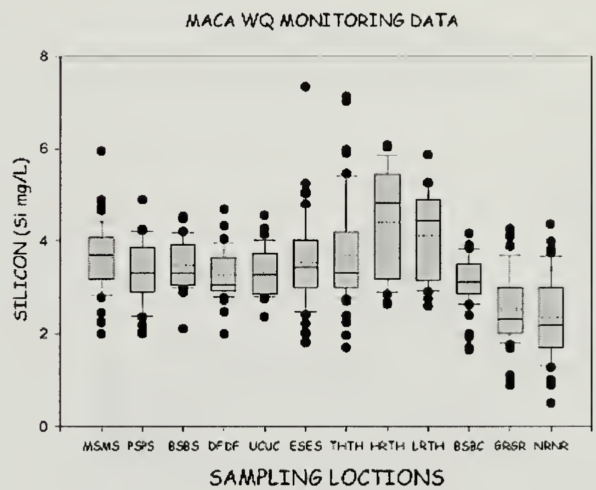
SAMPLING LOCTIONS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SILICON (Si mg/L)
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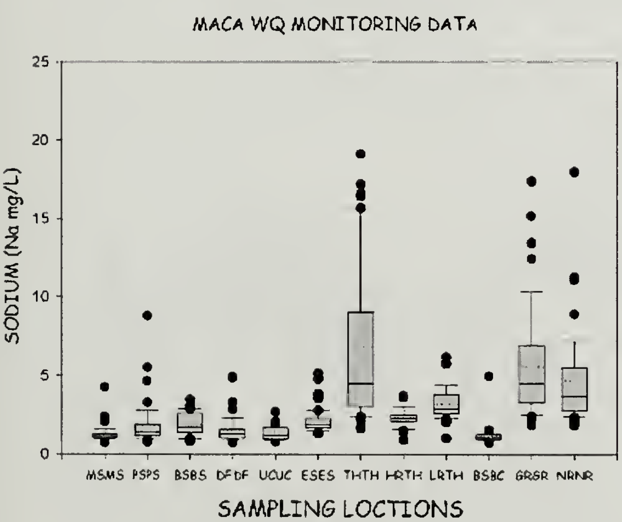
SAMPLING LOCTIONS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SODIUM (Na mg/L)
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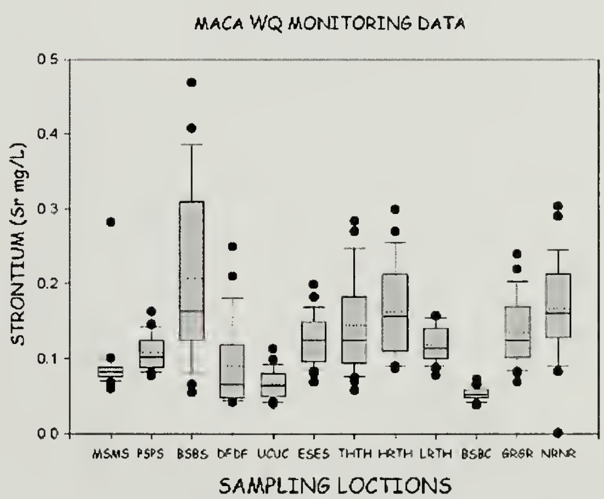
SAMPLING LOCTIONS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STRONTIUM (Sr mg/L)
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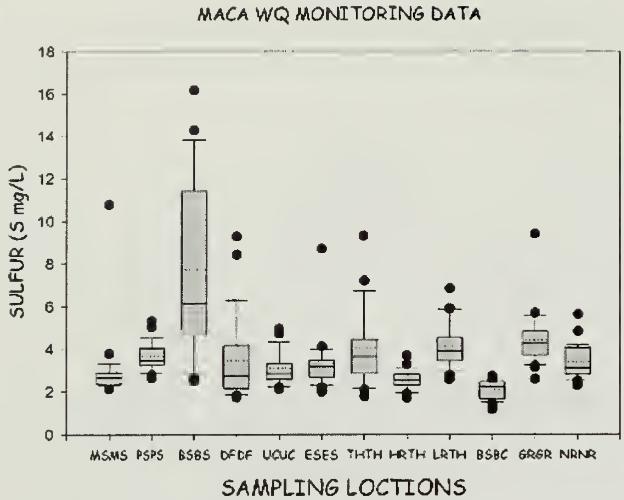
SAMPLING LOCTIONS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SULFUR (S mg/L)
0
2
4
6
8
10
12
14
16
18
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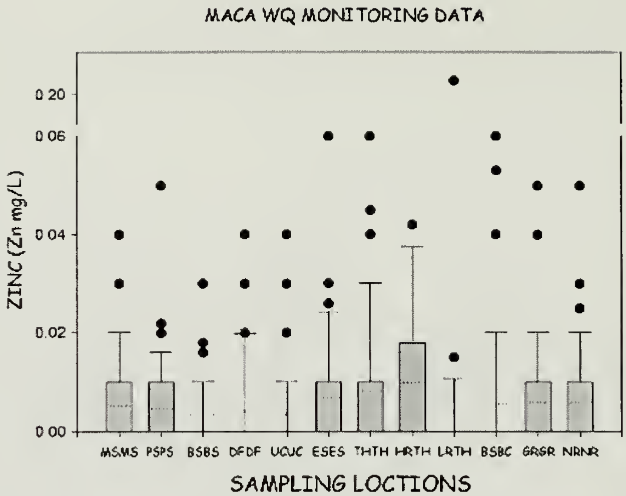
SAMPLING LOCTIONS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ZINC (Zn mg/L)
0.00
0.02
0.04
0.06
0.20
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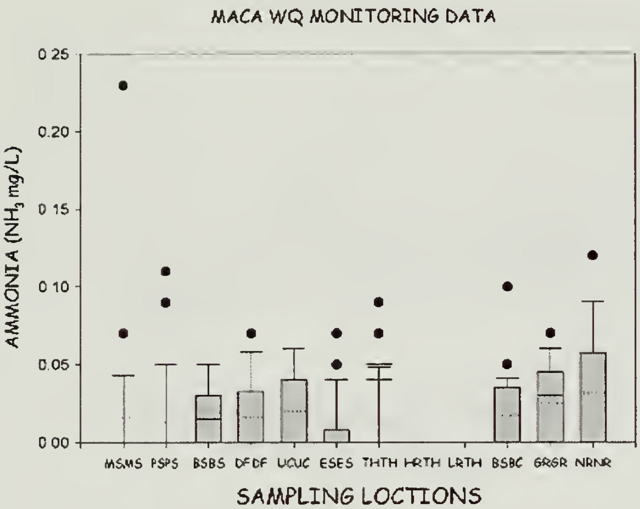
SAMPLING LOCTIONS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AMMONIA (NH3 mg/L)
0.00
0.05
0.10
0.15
0.20
0.25
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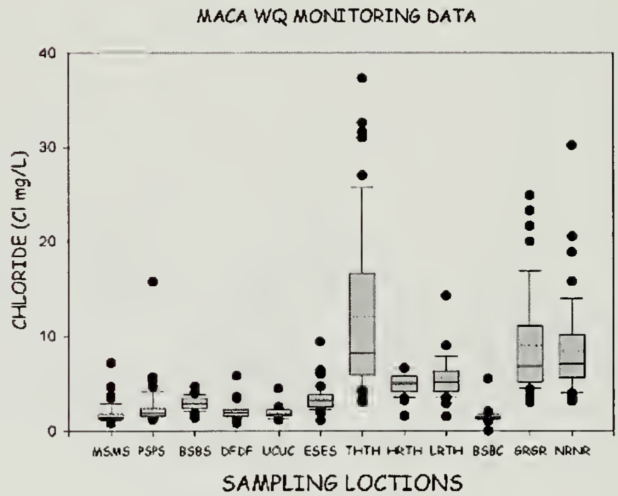
SAMPLING LOCTIONS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CHLORIDE (Cl mg/L)
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10
20
30
40
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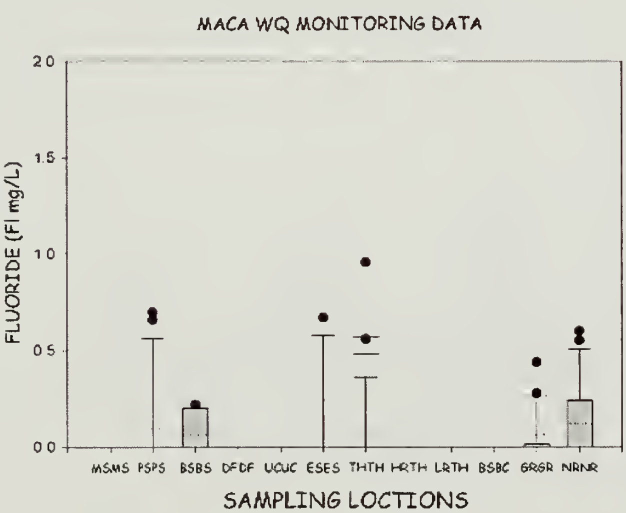
SAMPLING LOCTIONS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FLUORIDE (Fl mg/L)
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0.5
1.0
1.5
2.0
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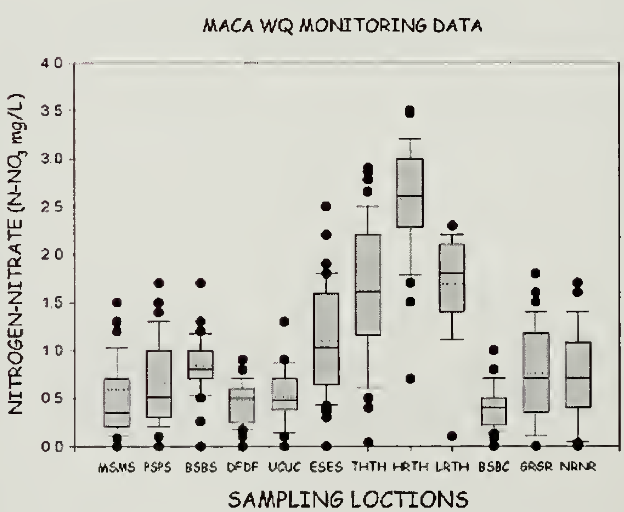
SAMPLING LOCTIONS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NITROGEN-NITRATE (N-NO3 mg/L)
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0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
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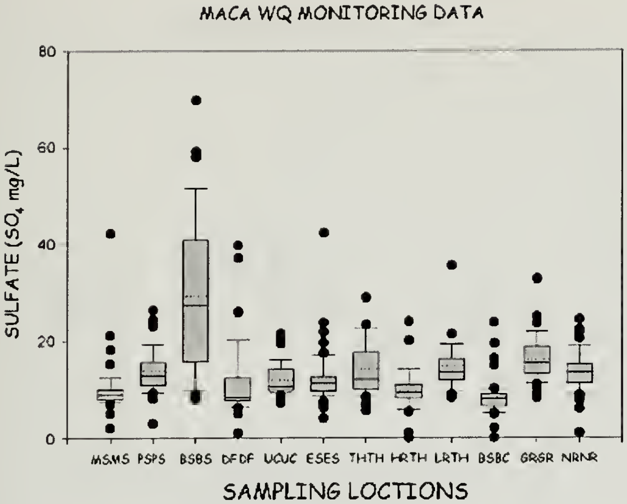
SAMPLING LOCTIONS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SULFATE ($SO_4$ mg/L)
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20
40
60
80
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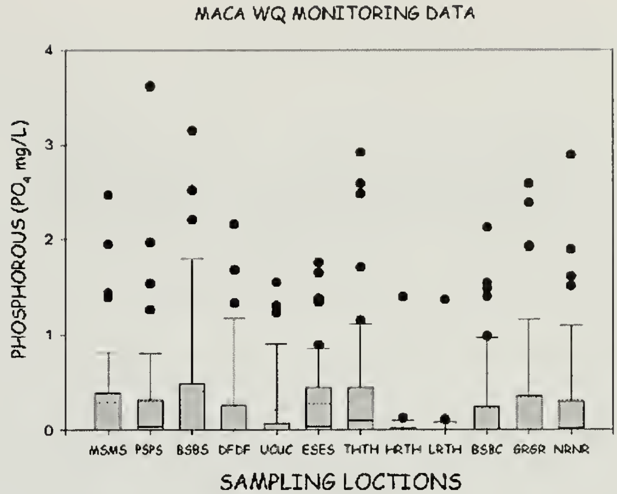
SAMPLING LOCTIONS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PHOSPHOROUS ($PO_4$ mg/L)
0
1
2
3
4
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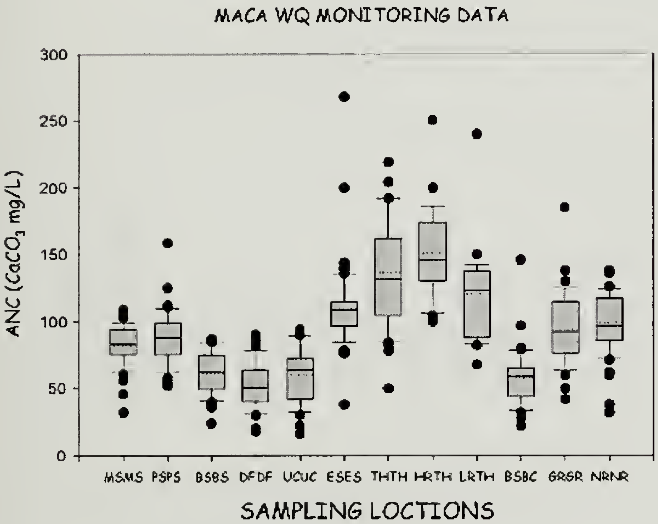
SAMPLING LOCTIONS


MACA WQ MONITORING DATA
ANC ($CaCO_3$ mg/L)
0
50
100
150
200
250
300
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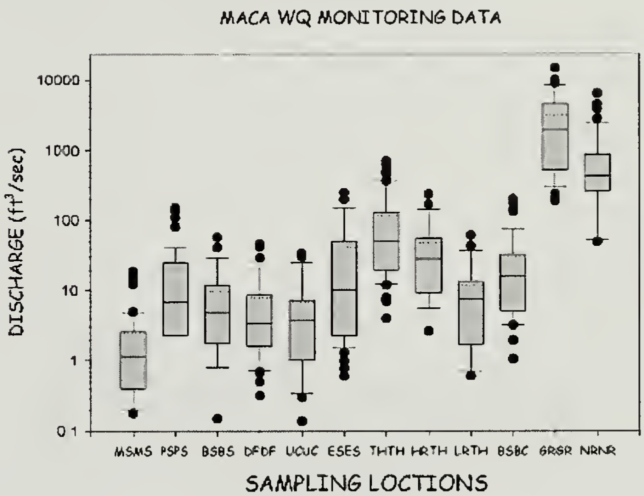
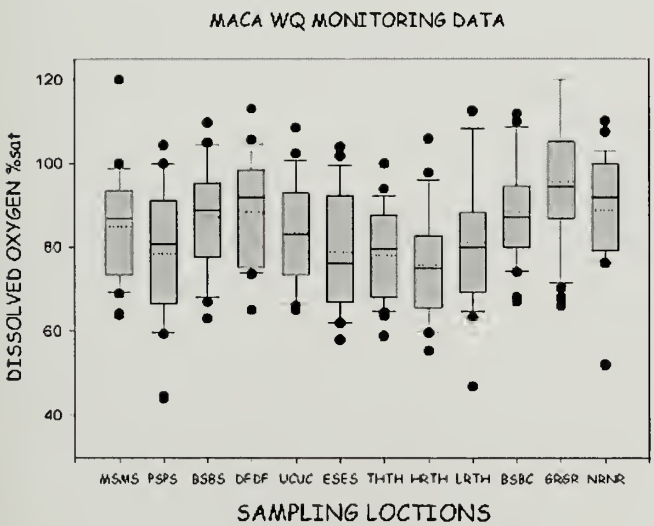
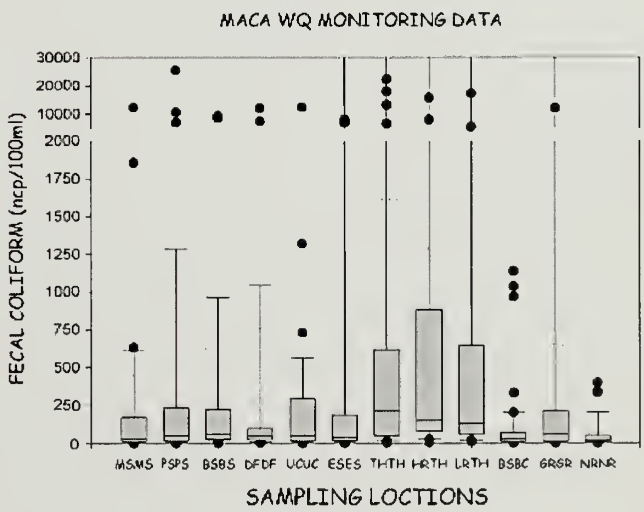
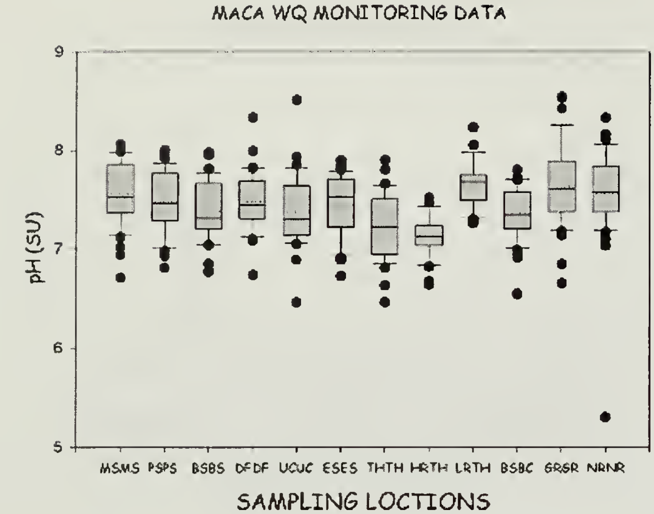
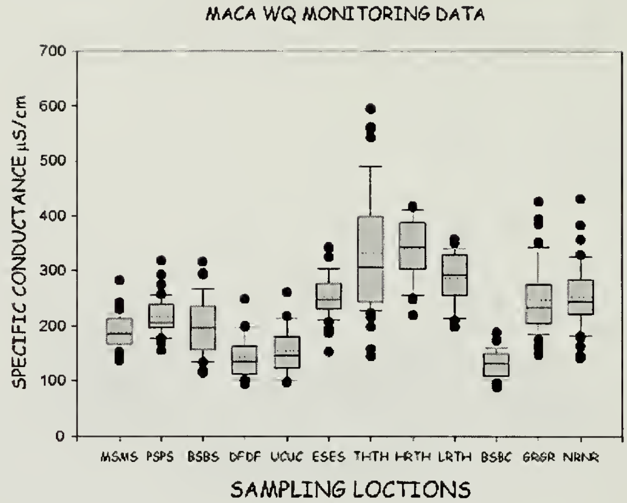
SAMPLING LOCTIONS

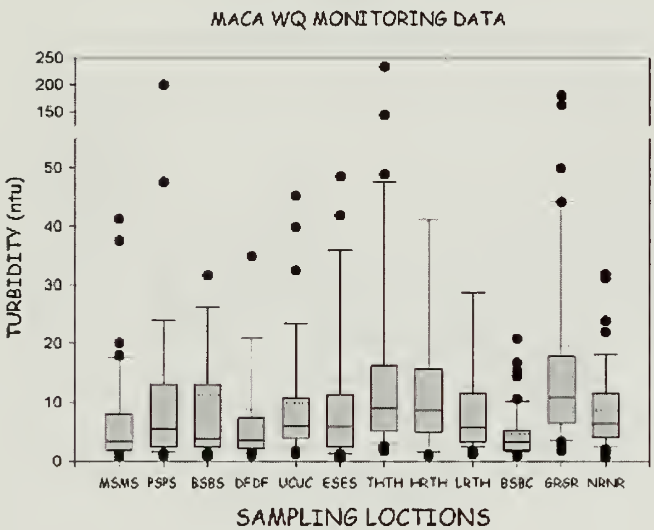

MACA WQ MONITORING DATA
DISCHARGE ($ft^3$/sec)
0.1
1
10
100
1000
10000
MSMS PSPS BSBS DFDF UCUC ESES THTH HRTH LRTH BSBC GRGR NRNR
SAMPLING LOCTIONS

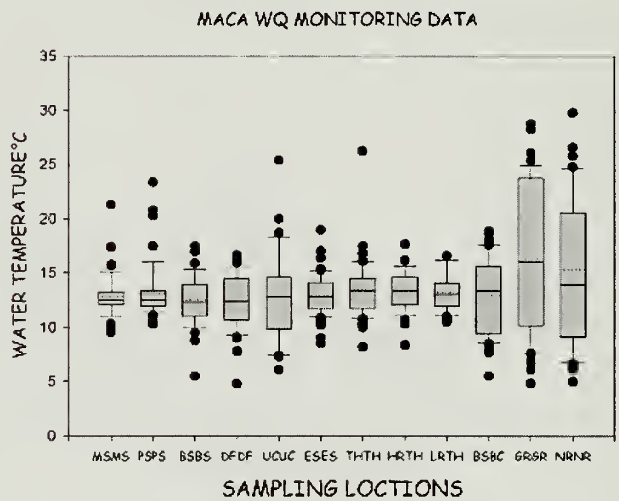

MACA WQ MONITORING DATA
DISSOLVED OXYGEN %sat
40
60
80
100
120
MSMS PSPS BSBS DFDF UCUC ESES THTH HRTH LRTH BSBC GRGR NRNR
SAMPLING LOCTIONS


MACA WQ MONITORING DATA
FECAL COLIFORM (ncp/100ml)
0
250
500
750
1000
1250
1500
1750
2000
10000
20000
30000
MSMS PSPS BSBS DFDF UCUC ESES THTH HRTH LRTH BSBC GRGR NRNR
SAMPLING LOCTIONS


MACA WQ MONITORING DATA
pH (SU)
9
8
7
6
5
MSMS PSPS BSBS DFDF UCUC ESES THTH HRTH LRTH BSBC GRGR NRNR
SAMPLING LOCTIONS


MACA WQ MONITORING DATA
SPECIFIC CONDUCTANCE µS/cm
700
600
500
400
300
200
100
0
MSMS PSPS BSBS DFDF UCUC ESES THTH HRTH LRTH BSBC GRGR NRNR
SAMPLING LOCTIONS


MACA WQ MONITORING DATA
TURBIDITY (ntu)
250
200
150
50
40
30
20
10
0
MSMS PSPS BSBS DFDF UCUC ESES THTH HRTH LRTH BSBC GRGR NRNR
SAMPLING LOCTIONS

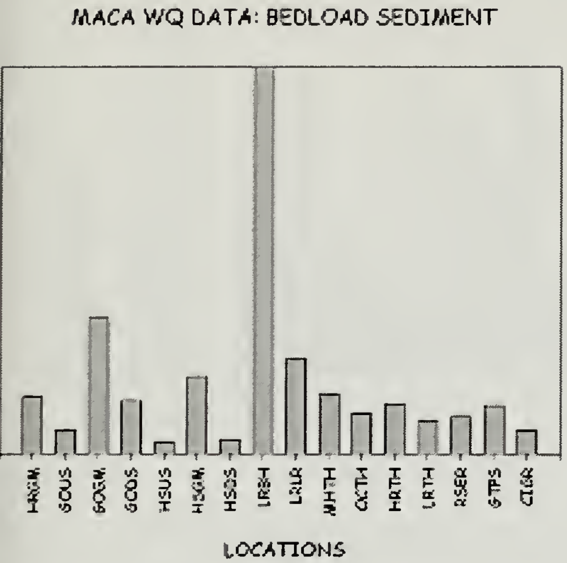

MACA WQ MONITORING DATA
WATER TEMPERATURE°C
35
30
25
20
15
10
5
0
MSMS PSPS BSBS DFDF UCUC ESES THTH HRTH LRTH BSBC GRGR NRNR
SAMPLING LOCTIONS

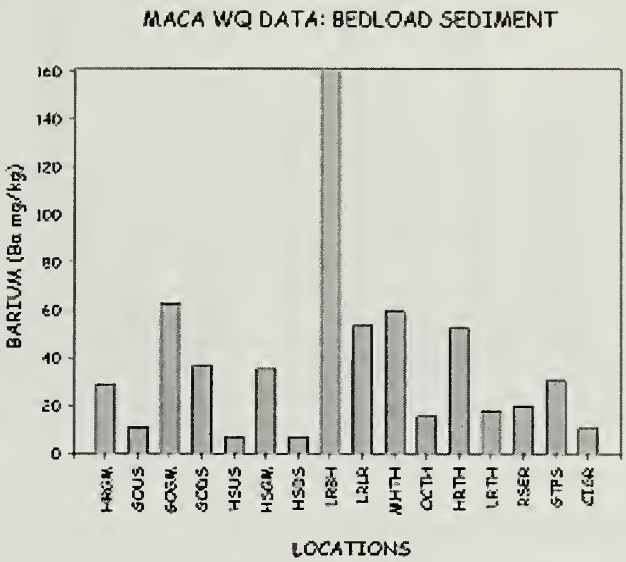
# Appendix B

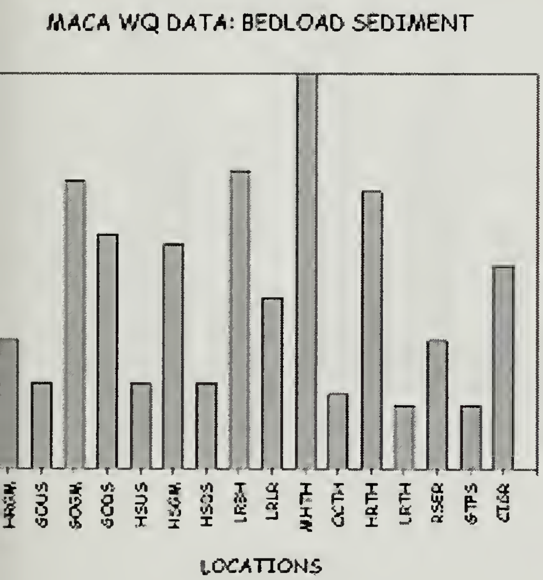
# Bedload Sediment Metal Analysis

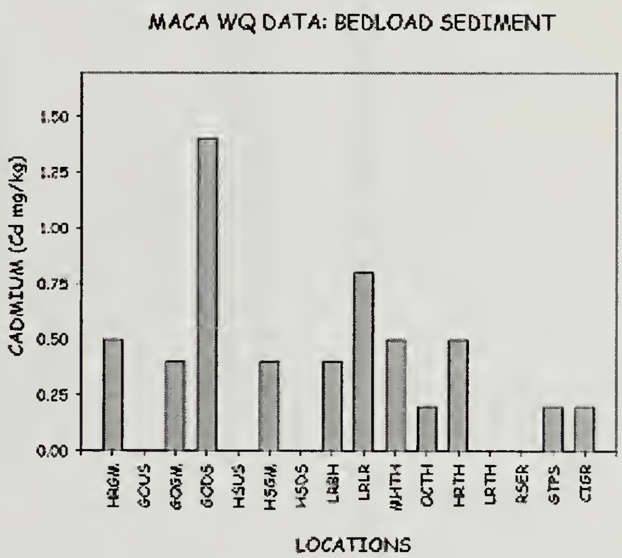
| Site | Description |
|---|---|
| HRGM | Hidden River Cave; downstream of metal plating waste disposal |
| GOUS | Green River; upstream of Gorin Mill Spring |
| GOGM | Gorin Mill Spring |
| GODS | Green River; downstream of Gorin Mill Spring |
| HSUS | Green River; upstream of Hicks Spring |
| HSGM | Hicks Spring |
| HSDS | Green River; downstream of Hicks Spring |
| LRBH | Lost River Blue Hole; Bowling Green, Kentucky |
| LRLR | Lost River Rise; Bowling Green, Kentucky |
| MHTH | Mill Hole |
| OCTH | Owl Cave; Mammoth Cave National Park |
| HRTH | Hawkins River; Mammoth Cave National Park |
| LRTH | Logsdon River; Mammoth Cave National Park |
| RSER | River Styx; Mammoth Cave National Park |
| GTPS | Golden Triangle; Mammoth Cave National Park |
| CIGR | Green River; at Crump Island, Mammoth Cave National Park |

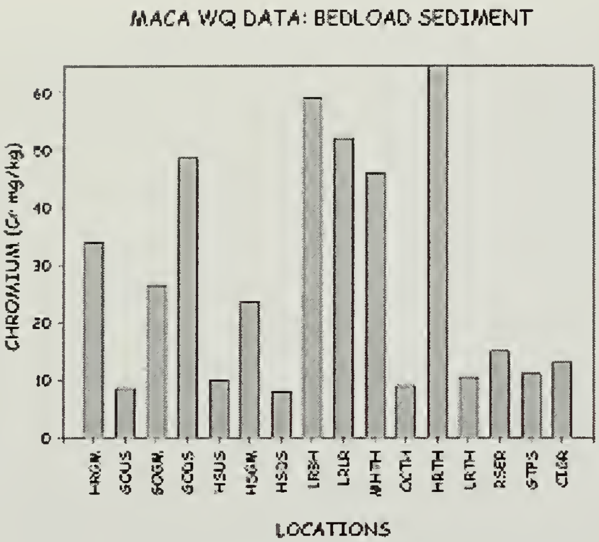
Map locations of sediment and water quality sites can be found on Plates 2 and 3.

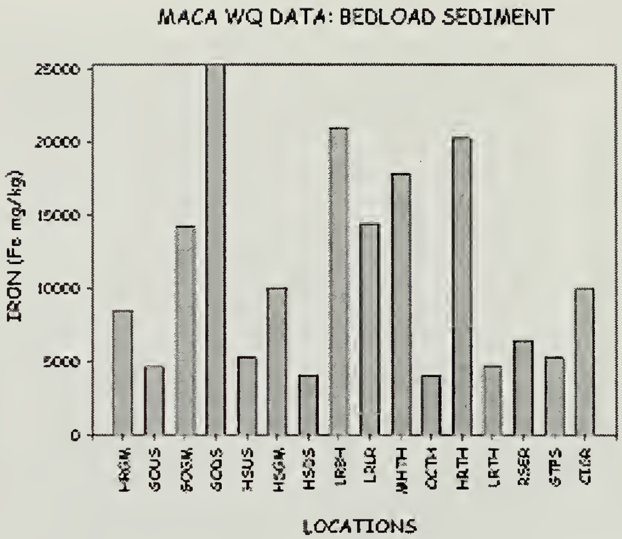

MACA WQ DATA: BEDLOAD SEDIMENT
HRGM
GOUS
GOGM
GODS
HSUS
HSGM
HSDS
LRBH
LRLR
WHTH
OCTH
HRTH
LRTH
RSER
GTPS
CIGR
LOCATIONS

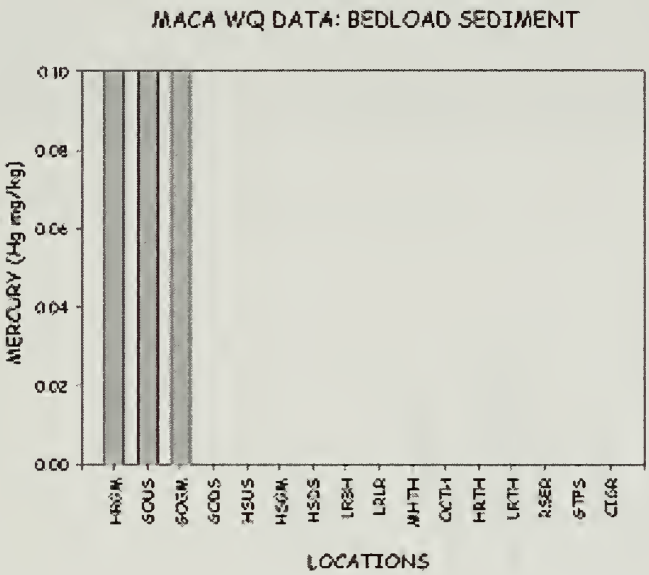

MACA WQ DATA: BEDLOAD SEDIMENT
BARIUM (Ba mg/kg)
160
140
120
100
80
60
40
20
0
HRGM
GOUS
GOGM
GODS
HSUS
HSGM
HSDS
LRBH
LRLR
WHTH
OCTH
HRTH
LRTH
RSER
GTPS
CIGR
LOCATIONS

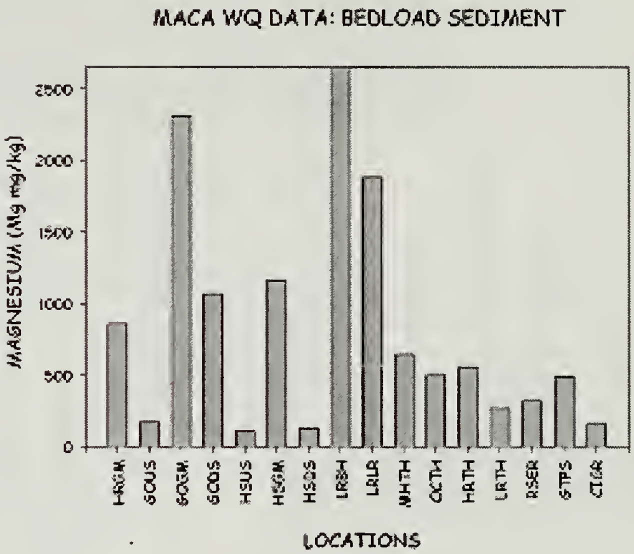

MACA WQ DATA: BEDLOAD SEDIMENT
HRGM
GOUS
GOGM
GODS
HSUS
HSGM
HSDS
LRBH
LRLR
WHTH
OCTH
HRTH
LRTH
RSER
GTPS
CIGR
LOCATIONS

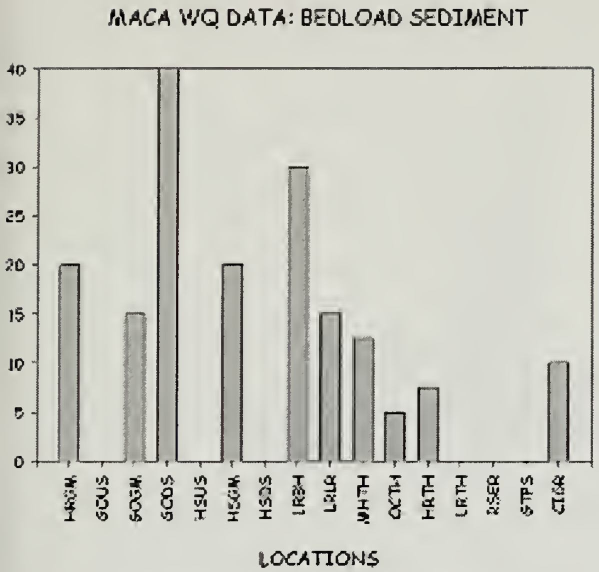

MACA WQ DATA: BEDLOAD SEDIMENT
CADMIUM (Cd mg/kg)
1.50
1.25
1.00
0.75
0.50
0.25
0.00
HRGM
GOUS
GOGM
GODS
HSUS
HSGM
HSDS
LRBH
LRLR
WHTH
OCTH
HRTH
LRTH
RSER
GTPS
CIGR
LOCATIONS

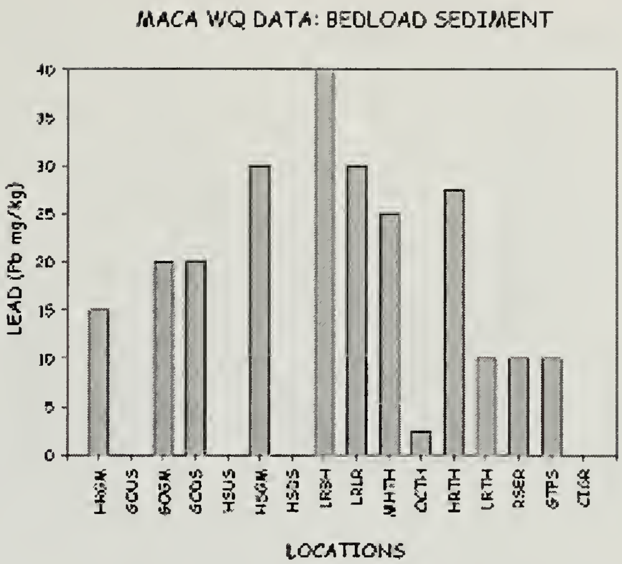

MACA WQ DATA: BEDLOAD SEDIMENT
CHROMIUM (Cr mg/kg)
0
10
20
30
40
50
60
HRGM
GOUS
GOGM
GODS
HSUS
HSGM
HSDS
LRBH
LRLR
NHTH
OCTH
HRTH
URTH
RSER
GTPS
CTGR
LOCATIONS

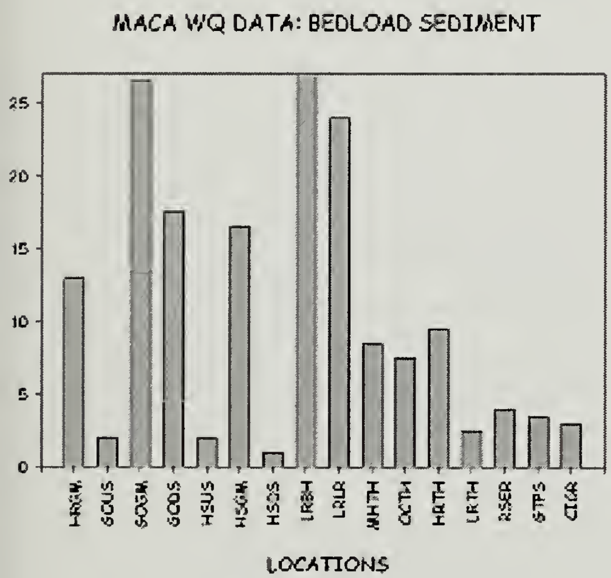

MACA WQ DATA: BEDLOAD SEDIMENT
IRON (Fe mg/kg)
0
5000
10000
15000
20000
25000
HRGM
GOUS
GOGM
GODS
HSUS
HSGM
HSDS
LRBH
LRLR
NHTH
OCTH
HRTH
URTH
RSER
GTPS
CTGR
LOCATIONS

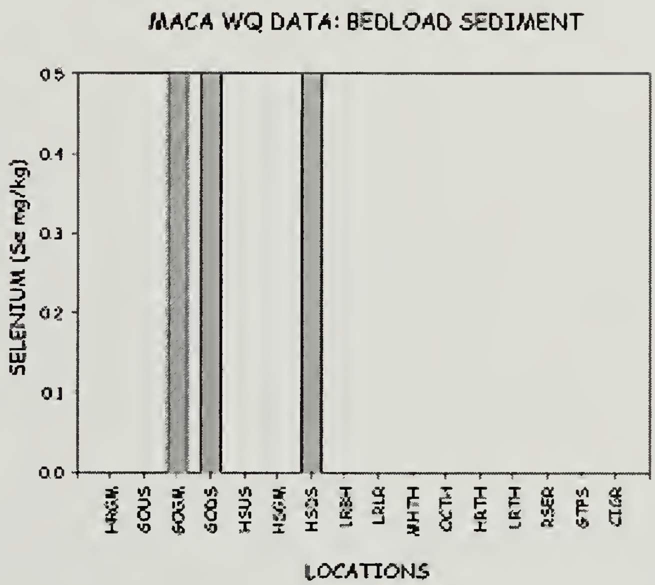

MACA WQ DATA: BEDLOAD SEDIMENT
MERCURY (Hg mg/kg)
0.00
0.02
0.04
0.06
0.08
0.10
HRGM
GOUS
GOGM
GODS
HSUS
HSGM
HSDS
LRBH
LRLR
NHTH
OCTH
HRTH
URTH
RSER
GTPS
CTGR
LOCATIONS

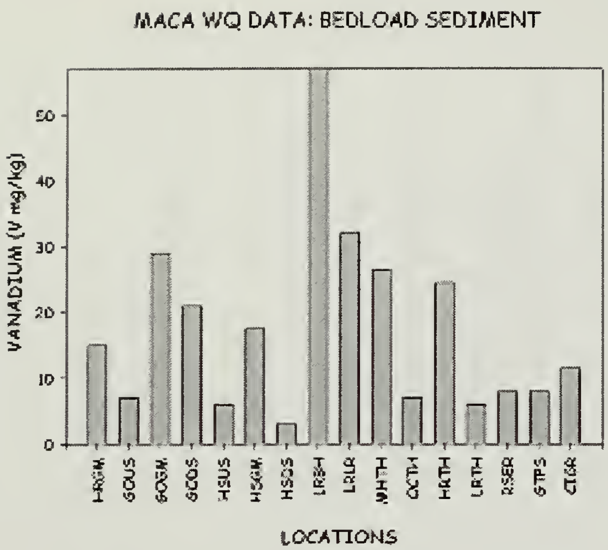

MACA WQ DATA: BEDLOAD SEDIMENT
MAGNESIUM (Mg mg/kg)
0
500
1000
1500
2000
2500
HRGM
GOUS
GOGM
GODS
HSUS
HSGM
HSDS
LRBH
LRLR
NHTH
OCTH
HRTH
URTH
RSER
GTPS
CTGR
LOCATIONS

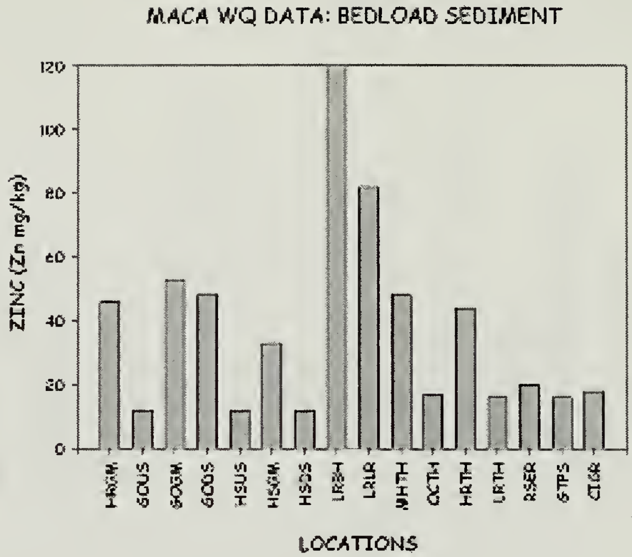

MACA WQ DATA: BEDLOAD SEDIMENT
LOCATIONS
HRGM GOUS GOGM GODS HSUS HSGM HSDS LRBH LRLR WHTH OCTH HRTH LRTH RSER GTPS CIGR


MACA WQ DATA: BEDLOAD SEDIMENT
LEAD (Pb mg/kg)
LOCATIONS
HRGM GOUS GOGM GODS HSUS HSGM HSDS LRBH LRLR WHTH OCTH HRTH LRTH RSER GTPS CIGR


MACA WQ DATA: BEDLOAD SEDIMENT
LOCATIONS
HRGM GOUS GOGM GODS HSUS HSGM HSDS LRBH LRLR WHTH OCTH HRTH LRTH RSER GTPS CIGR


MACA WQ DATA: BEDLOAD SEDIMENT
SELENIUM (Se mg/kg)
LOCATIONS
HRGM GOUS GOGM GODS HSUS HSGM HSDS LRBH LRLR WHTH OCTH HRTH LRTH RSER GTPS CIGR


MACA WQ DATA: BEDLOAD SEDIMENT
VANADIUM (V mg/kg)
0
10
20
30
40
50
HRGM
GCUS
GOGM
GCDS
HSUS
HSGM
HSDS
LRBH
LRLR
NHTH
CCTH
HRTH
LRTH
RSER
GTPS
CTGR
LOCATIONS


MACA WQ DATA: BEDLOAD SEDIMENT
ZINC (Zn mg/kg)
0
20
40
60
80
100
120
HRGM
GCUS
GOGM
GCDS
HSUS
HSGM
HSDS
LRBH
LRLR
NHTH
CCTH
HRTH
LRTH
RSER
GTPS
CTGR
LOCATIONS

# Appendix C

## Tables of Detailed (Anderson Level III and Level II) Groundwatershed Land Use

*Land use of the Mile 205.7 Spring karst watershed. Anderson Level III, sorted by area*

| Land Use Classification, Mile 205.7 karst watershed | Area (hectares) | Percent Coverage |
|---|---|---|
| 61-100% crown cover (Deciduous) | 123.168 | 39.5 |
| 31-60% crown cover (Deciduous) | 85.502 | 27.4 |
| 61-100% crown cover-hardwood dominant (Mixed 30-50%) | 32.379 | 10.4 |
| 61-100% crown cover (Evergreen-valley types) | 26.891 | 8.6 |
| 61-100% crown cover-evergreen dominant (Mixed 30-50%) | 18.293 | 5.9 |
| 61-100% crown cover-cedar dominant (Mixed 30-50%) | 15.509 | 5.0 |
| 31-60% crown cover-hardwood dominant (Mixed 30-50%) | 4.903 | 1.6 |
| 31-60% crown cover-cedar dominant (Mixed 30-50%) | 4.129 | 1.3 |
| 210B-Row crop with Residue single crop | 1.117 | 0.4 |
| Idle land | 0.260 | 0.1 |
| Farm Ponds - 1 - 5 acres | 0.232 | 0.1 |
| 210A-Row crop no Residue single crop | 0.115 | 0.0 |

*Land use of the Pike Spring karst watershed. Anderson Level III, sorted by area.*

| Land Use Classification Pike Spring karst watershed | Area (hectares) | Percent coverage |
|---|---|---|
| 61-100% crown cover (Deciduous) | 1051.986 | 26.3 |
| 61-100% crown cover-cedar dominant (Mixed 30-50%) | 704.131 | 17.6 |
| 61-100% crown cover-hardwood dominant (Mixed 30-50%) | 354.615 | 8.9 |
| 210B-Row crop with Residue single crop | 277.517 | 6.9 |
| 31-60% crown cover (Deciduous) | 249.391 | 6.2 |
| 31-60% crown cover-hardwood dominant (Mixed 30-50%) | 216.113 | 5.4 |
| 61-100% crown cover (Evergreen-valley types) | 197.775 | 4.9 |
| 61-100% crown cover-evergreen dominant (Mixed 30-50%) | 126.803 | 3.2 |
| 31-60% crown cover-cedar dominant (Mixed 30-50%) | 122.069 | 3.1 |
| Fair pasture:uneven growth and condition minimal maintenance | 119.322 | 3.0 |
| Good pasture:well maintained | 92.661 | 2.3 |
| Poor pasture:sparse cover often gullied | 73.75 | 1.8 |
| Woodland pasture:10% >= Crown cover | 53.113 | 1.3 |
| 31-60% crown cover-evergreen dominant (Mixed 30-50%) | 53.054 | 1.3 |
| Idle land | 43.434 | 1.1 |
| Cedar glades | 33.848 | 0.8 |
| Forest clearcut area: shrub/brush regeneration | 33.016 | 0.8 |
| 210A-Row crop no Residue single crop | 32.474 | 0.8 |
| Farmstead with accompanying structures | 28.132 | 0.7 |
| 31-60% crown cover (Evergreen-valley types) | 25.141 | 0.6 |
| 10-30% crown cover-hardwood dominant (Mixed 30-50%) | 12.563 | 0.3 |
| Forest clearcut area: recent | 11.959 | 0.3 |

| **Land Use Classification Pike Spring karst watershed (continued)** | **Area (hectares)** | **Percent coverage** |
|---|---|---|
| Feedlot loafing area | 11.578 | 0.3 |
| Forest clearcut area: reforested | 11.03 | 0.3 |
| Farm ponds - Smaller than 1 acre | 8.734 | 0.2 |
| Heavily overgrazed pasture:usually small feeding areas | 7.754 | 0.2 |
| Single Family Low Density (Below 2 Acres) | 6.801 | 0.2 |
| Farm Ponds - 1 - 5 acres | 6.668 | 0.2 |
| Grass | 6.228 | 0.2 |
| 10-30% crown cover (Deciduous) | 4.471 | 0.1 |
| Mobile Home | 4.255 | 0.1 |
| 210S -Strip Cropped:alternating strips of cult - noncult. | 3.516 | 0.1 |
| Partially forested feedlot: 10% or greater crown cover | 3.283 | 0.1 |
| Double Cropped:winter cover such as winter wheat barley rye | 2.499 | 0.1 |
| 10-30% crown cover (Evergreen-valley types) | 1.927 | 0.0 |
| 10-30% crown cover-cedar dominant (Mixed 30-50%) | 1.341 | 0.0 |
| Swine feeding operation | 0.997 | 0.0 |
| Plantation (Evergreen-valley types) | 0.981 | 0.0 |
| Garden | 0.857 | 0.0 |
| Trees/Shrub | 0.755 | 0.0 |
| Farm Ponds - 5 - 10 acres | 0.656 | 0.0 |
| Cemetery | 0.527 | 0.0 |
| Water tank | 0.467 | 0.0 |
| Religious | 0.141 | 0.0 |

*Land use of the Echo River Spring karst watershed. Anderson Level III, sorted by area.*

| **Land Use Classification Echo River Spring karst watershed** | **Area (hectares)** | **Percent coverage** |
|---|---|---|
| 61-100% crown cover (Deciduous) | 876.593 | 37.7 |
| 61-100% crown cover-cedar dominant (Mixed 30-50%) | 411.71 | 17.7 |
| 61-100% crown cover (Evergreen-valley types) | 295.325 | 12.7 |
| 31-60% crown cover (Deciduous) | 243.748 | 10.5 |
| 31-60% crown cover-cedar dominant (Mixed 30-50%) | 173.809 | 7.5 |
| 31-60% crown cover-hardwood dominant (Mixed 30-50%) | 101.625 | 4.4 |
| 61-100% crown cover-hardwood dominant (Mixed 30-50%) | 71.64 | 3.1 |
| 61-100% crown cover-evergreen dominant (Mixed 30-50%) | 64.608 | 2.8 |
| Campground | 17.82 | 0.8 |
| 31-60% crown cover (Evergreen-valley types) | 10.2 | 0.4 |
| 210B-Row crop with Residue single crop | 8.088 | 0.3 |

| Land Use Classification Echo River Spring karst watershed (continued) | Area (hectares) | Percent coverage |
|---|---|---|
| Single Family Medium Density (2-5 Acres) | 7.553 | 0.3 |
| Grass | 4.821 | 0.2 |
| 10-30% crown cover-hardwood dominant (Mixed 30-50%) | 4.696 | 0.2 |
| Park | 4.695 | 0.2 |
| Commercial - other | 4.674 | 0.2 |
| Institutional - other | 4.108 | 0.2 |
| Trees/Shrub | 3.773 | 0.2 |
| Good pasture:well maintained | 2.91 | 0.1 |
| Resort | 2.62 | 0.1 |
| 10-30% crown cover-cedar dominant (Mixed 30-50%) | 2.53 | 0.1 |
| 10-30% crown cover (Deciduous) | 2.062 | 0.1 |
| Lake 1 - 5 acres | 1.19 | 0.1 |
| Cedar glades | 1.044 | 0.0 |
| Apartment/condominium complex | 0.922 | 0.0 |
| Gas | 0.675 | 0.0 |
| Junkyard | 0.649 | 0.0 |
| Mini Warehouse | 0.627 | 0.0 |
| Sewage Treatment | 0.425 | 0.0 |
| Cemetery | 0.384 | 0.0 |
| Other urban or built-up (tennis court) | 0.368 | 0.0 |
| Mobile Home | 0.341 | 0.0 |
| Forest clearcut area: shrub/brush regeneration | 0.339 | 0.0 |

*Land use of the Turnhole Spring karst watershed, Cave City Subbasin (Logsdon River). Anderson Level III, sorted by area.*

| Land Use Classification, Turnhole Spring karst watershed, Cave City Subbasin (Logsdon River) | Area (hectares) | Percent coverage |
|---|---|---|
| Good pasture:well maintained | 456.17 | 18.2 |
| 210B-Row crop with Residue single crop | 453.663 | 18.1 |
| 61-100% crown cover (Deciduous) | 427.244 | 17.1 |
| 61-100% crown cover-hardwood dominant (Mixed 30-50%) | 274.043 | 11.0 |
| 61-100% crown cover-cedar dominant (Mixed 30-50%) | 231.669 | 9.3 |
| Forest clearcut area: shrub/brush regeneration | 72.727 | 2.9 |
| Idle land | 68.176 | 2.7 |
| 210A-Row crop no Residue single crop | 52.43 | 2.1 |
| Major highway ROW | 49.114 | 2.0 |
| Single Family Low Density (Below 2 Acres) | 42.674 | 1.7 |

| Land Use Classification, Turnhole Spring karst watershed, Cave City Subbasin (Logsdon River), (continued) | Area (hectares) | Percent coverage |
|---|---|---|
| 31-60% crown cover-cedar dominant (Mixed 30-50%) | 40.598 | 1.6 |
| Farmstead with accompanying structures | 38.254 | 1.5 |
| Cedar glades | 33.881 | 1.4 |
| Amusement park | 27.302 | 1.1 |
| Woodland pasture:10% >= Crown cover | 23.171 | 0.9 |
| Forest clearcut area: recent | 21.836 | 0.9 |
| Campground | 20.167 | 0.8 |
| 31-60% crown cover-hardwood dominant (Mixed 30-50%) | 17.108 | 0.7 |
| Strip development | 16.312 | 0.7 |
| 31-60% crown cover (Deciduous) | 14.205 | 0.6 |
| Fair pasture:uneven growth and condition minimal maintenance | 12.836 | 0.5 |
| Single Family Medium Density (2-5 Acres) | 12.31 | 0.5 |
| Commercial - other | 12.202 | 0.5 |
| Heavily overgrazed pasture:usually small feeding areas | 11.815 | 0.5 |
| Double Cropped:winter cover such as winter wheat barley rye | 11.589 | 0.5 |
| Grass | 8.46 | 0.3 |
| Farm Ponds - 1 - 5 acres | 6.933 | 0.3 |
| Christmas trees | 5.308 | 0.2 |
| Trees/Shrub | 5.096 | 0.2 |
| Mobile Home | 4.965 | 0.2 |
| 10-30% crown cover (Deciduous) | 3.94 | 0.2 |
| Retail activity | 3.73 | 0.1 |
| Service-other | 3.033 | 0.1 |
| Farm ponds - Smaller than 1 acre | 2.66 | 0.1 |
| Gas | 2.497 | 0.1 |
| Barren land w/o sediment control structures/practices | 1.99 | 0.1 |
| 61-100% crown cover-evergreen dominant (Mixed 30-50%) | 1.903 | 0.1 |
| Religious | 1.433 | 0.1 |
| 10-30% crown cover-cedar dominant (Mixed 30-50%) | 1.377 | 0.1 |
| Cemetery | 1.257 | 0.1 |
| Feedlot loafing area | 1.06 | 0.0 |
| Abandoned quarry | 0.567 | 0.0 |
| Garden | 0.481 | 0.0 |
| Junkyard | 0.449 | 0.0 |
| Lake smaller than 1 acre | 0.352 | 0.0 |
| Lake 1 - 5 acres | 0.346 | 0.0 |
| Water tank | 0.164 | 0.0 |

*Land use of the Turnhole Spring karst watershed, Patoka Creek Subbasin (Hawkins River). Anderson Level III, sorted by area.*

| Land Use Classification, Turnhole Spring karst Watershed, Patoka Creek Subbasin | Area (hectares) | Percent coverage |
|---|---|---|
| Good pasture:well maintained | 1696.616 | 20.6 |
| 210B-Row crop with Residue single crop | 1691.8 | 20.6 |
| 61-100% crown cover (Deciduous) | 1479.065 | 18.0 |
| 61-100% crown cover-cedar dominant (Mixed 30-50%) | 562.112 | 6.8 |
| 61-100% crown cover-hardwood dominant (Mixed 30-50%) | 542.529 | 6.6 |
| 210A-Row crop no Residue single crop | 370.726 | 4.5 |
| Double Cropped:winter cover such as winter wheat barley rye | 213.318 | 2.6 |
| 31-60% crown cover-cedar dominant (Mixed 30-50%) | 166.002 | 2.0 |
| Forest clearcut area: shrub/brush regeneration | 164.368 | 2.0 |
| Idle land | 147.666 | 1.8 |
| Major higway ROW | 119.776 | 1.5 |
| Farmstead with accompanying structures | 107.91 | 1.3 |
| Single Family Low Density (Below 2 Acres) | 91.929 | 1.1 |
| Golf course | 91.274 | 1.1 |
| Heavily overgrazed pasture:usually small feeding areas | 84.858 | 1.0 |
| Woodland pasture:10% >= Crown cover | 77.443 | 0.9 |
| 210S -Strip Cropped:alternating strips of cult - noncult. | 58.277 | 0.7 |
| Resort | 51.145 | 0.6 |
| Fair pasture:uneven growth and condition minimal maintenance | 50.123 | 0.6 |
| Active quarry | 49.32 | 0.6 |
| 31-60% crown cover-hardwood dominant (Mixed 30-50%) | 49.105 | 0.6 |
| Predominantly residential (>50%) | 44.641 | 0.5 |
| Campground | 44.185 | 0.5 |
| Amusement park | 43.092 | 0.5 |
| 31-60% crown cover (Deciduous) | 31.189 | 0.4 |
| Single Family Medium Density (2-5 Acres) | 29.571 | 0.4 |
| Commercial - other | 22.016 | 0.3 |
| 10-30% crown cover-cedar dominant (Mixed 30-50%) | 17.164 | 0.2 |
| Farm ponds - Smaller than 1 acre | 14.696 | 0.2 |
| Cedar glades | 12.241 | 0.1 |
| Feedlot loafing area | 9.446 | 0.1 |
| Abandoned quarry | 9.398 | 0.1 |
| Heavy industry | 9.162 | 0.1 |

| **Land Use Classification, Turnhole Spring karst Watershed, Patoka Creek Subbasin (continued)** | **Area (hectares)** | Percent coverage |
|---|---|---|
| Poor pasture:sparse cover often gullied | 7.919 | 0.1 |
| Barren land w/o sediment control structures/practices | 6.608 | 0.1 |
| 61-100% crown cover-evergreen dominant (Mixed 30-50%) | 6.062 | 0.1 |
| Cemetery | 5.561 | 0.1 |
| Farm Ponds - 1 - 5 acres | 5.503 | 0.1 |
| Perennial stream (less than 100 feet wide) | 5.445 | 0.1 |
| Communication | 4.488 | 0.1 |
| 61-100% crown cover (Evergreen-valley types) | 4.293 | 0.1 |
| Railroad | 3.899 | 0.0 |
| Educational | 3.599 | 0.0 |
| Lake 1 - 5 acres | 3.203 | 0.0 |
| Swine feeding operation | 2.703 | 0.0 |
| Gas | 2.302 | 0.0 |
| Grass | 2.238 | 0.0 |
| Park | 2.03 | 0.0 |
| Religious | 2.003 | 0.0 |
| 10-30% crown cover (Deciduous) | 1.917 | 0.0 |
| Wetland | 1.52 | 0.0 |
| Retail activity | 0.954 | 0.0 |
| Service-other | 0.767 | 0.0 |
| Christmas trees | 0.713 | 0.0 |
| Mobile Home | 0.674 | 0.0 |
| Trailer park | 0.462 | 0.0 |
| Poultry feeding operation | 0.456 | 0.0 |
| Junkyard | 0.391 | 0.0 |
| Low brush- (less than 10') | 0.37 | 0.0 |
| Lake smaller than 1 acre | 0.329 | 0.0 |
| Archaeological site | 0.234 | 0.0 |
| Water tank | 0.2 | 0.0 |
| 10-30% crown cover-hardwood dominant (Mixed 30-50%) | 0.142 | 0.0 |

*Land use of the Turnhole Spring karst watershed, Mill Hole Subbasin. Anderson Level III, sorted by area.*

| Land Use Classification, Turnhole Spring karst Watershed, Mill Hole Subbasin | Area (hectares) | Percent coverage |
|---|---|---|
| 210B-Row crop with Residue single crop | 2966.902 | 21.2 |
| Good pasture:well maintained | 2506.14 | 17.9 |
| 61-100% crown cover (Deciduous) | 2404.814 | 17.1 |
| 61-100% crown cover-cedar dominant (Mixed 30-50%) | 1340.286 | 9.6 |
| 61-100% crown cover-hardwood dominant (Mixed 30-50%) | 834.352 | 5.9 |
| Fair pasture:uneven growth and condition minimal maintenance | 653.89 | 4.7 |
| Woodland pasture:10% >= Crown cover | 554.051 | 4.0 |
| Heavily overgrazed pasture:usually small feeding areas | 363.301 | 2.6 |
| 210A-Row crop no Residue single crop | 296.85 | 2.1 |
| 31-60% crown cover-hardwood dominant (Mixed 30-50%) | 261.298 | 1.9 |
| Farmstead with accompanying structures | 187.947 | 1.3 |
| Major higway ROW | 149.876 | 1.1 |
| Idle land | 141.985 | 1.0 |
| Double Cropped:winter cover such as winter wheat barley rye | 124.432 | 0.9 |
| Single Family Low Density (Below 2 Acres) | 121.017 | 0.9 |
| Single Family Medium Density (2-5 Acres) | 107.347 | 0.8 |
| Feedlot loafing area | 79.077 | 0.6 |
| 31-60% crown cover-cedar dominant (Mixed 30-50%) | 74.03 | 0.5 |
| 31-60% crown cover (Deciduous) | 73.375 | 0.5 |
| Poor pasture:sparse cover often gullied | 71.469 | 0.5 |
| 210S -Strip Cropped:alternating strips of cult - noncult. | 65.786 | 0.5 |
| 61-100% crown cover-evergreen dominant (Mixed 30-50%) | 58.688 | 0.4 |
| Golf course | 55.708 | 0.4 |
| Farm ponds - Smaller than 1 acre | 53.421 | 0.4 |
| Forest clearcut area: shrub/brush regeneration | 49.587 | 0.4 |
| Resort | 45.701 | 0.3 |
| Forest clearcut area: reforested | 38.726 | 0.3 |
| Farm Ponds - 1 - 5 acres | 36.056 | 0.3 |
| Forest clearcut area: recent | 35.625 | 0.3 |
| Recently burned crop field | 27.687 | 0.2 |
| Railroad | 24.378 | 0.2 |
| Plantation (Evergreen-valley types) | 21.542 | 0.2 |
| 10-30% crown cover-hardwood dominant (Mixed 30-50%) | 19.251 | 0.1 |
| Barren land w/o sediment control structures/practices | 17.706 | 0.1 |

| Land Use Classification, Turnhole Spring karst Watershed, Mill Hole Subbasin (continued) | Area (hectares) | Percent coverage |
|---|---|---|
| Predominantly residential (>50%) | 15.127 | 0.1 |
| Active quarry | 14.974 | 0.1 |
| 61-100% crown cover (Evergreen-valley types) | 13.303 | 0.1 |
| 210B-Row crop with Residue single crop | 12.128 | 0.1 |
| Mobile Home | 10.877 | 0.1 |
| 10-30% crown cover (Deciduous) | 9.968 | 0.1 |
| Partially forested feedlot: 10% or greater crown cover | 8.067 | 0.1 |
| Grass | 7.763 | 0.1 |
| Single Family High Density (more than 6/acres) | 6.036 | 0.0 |
| Cattle feeding operation | 5.829 | 0.0 |
| Low brush- (less than 10') | 5.573 | 0.0 |
| Farm Ponds - 5 - 10 acres | 5.086 | 0.0 |
| Cedar glades | 4.944 | 0.0 |
| Subdivision under construction | 4.817 | 0.0 |
| Service-other | 3.318 | 0.0 |
| Cemetery | 3.011 | 0.0 |
| Heavy industry | 2.898 | 0.0 |
| Junkyard | 2.855 | 0.0 |
| Religious | 2.745 | 0.0 |
| Retail activity | 2.677 | 0.0 |
| Dairy | 2.444 | 0.0 |
| Lake 1 - 5 acres | 2.419 | 0.0 |
| Trailer park | 2.298 | 0.0 |
| Commercial - other | 2.138 | 0.0 |
| Wetland | 1.969 | 0.0 |
| 31-60% crown cover-evergreen dominant (Mixed 30-50%) | 1.809 | 0.0 |
| Medium brush- (10'-20') | 1.53 | 0.0 |
| Swine feeding operation | 1.342 | 0.0 |
| Toll Booth | 1.29 | 0.0 |
| Sewage Treatment | 1.219 | 0.0 |
| Lake smaller than 1 acre | 0.931 | 0.0 |
| Exposed bedrock | 0.907 | 0.0 |
| Institutional - other | 0.614 | 0.0 |
| Substation | 0.41 | 0.0 |
| Water tank | 0.288 | 0.0 |
| Garden | 0.269 | 0.0 |

*Land use of the Turnhole Spring karst watershed, Proctor Subbasin. Anderson Level III, sorted by area.*

| Land Use Classification, Turnhole Spring karst watershed, Proctor Subbasin | Area (hectares) | Percent coverage |
|---|---|---|
| 61-100% crown cover-cedar dominant (Mixed 30-50%) | 540.418 | 42.4 |
| 61-100% crown cover (Deciduous) | 476.519 | 37.4 |
| 61-100% crown cover-hardwood dominant (Mixed 30-50%) | 188.082 | 14.8 |
| 61-100% crown cover (Evergreen-valley types) | 17.556 | 1.4 |
| 31-60% crown cover (Deciduous) | 13.977 | 1.1 |
| Campground | 11.194 | 0.9 |
| 61-100% crown cover-evergreen dominant (Mixed 30-50%) | 7.565 | 0.6 |
| Forest clearcut area: recent | 4.671 | 0.4 |
| 210B-Row crop with Residue single crop | 4.151 | 0.3 |
| Forest clearcut area: shrub/brush regeneration | 4.095 | 0.3 |
| Low brush- (less than 10') | 3.169 | 0.2 |
| 10-30% crown cover-cedar dominant (Mixed 30-50%) | 2.572 | 0.2 |
| Good pasture:well maintained | 0.845 | 0.1 |
| Lake 1 - 5 acres | 0.288 | 0.0 |
| 31-60% crown cover-hardwood dominant (Mixed 30-50%) | 0.002 | 0.0 |

*Land use of the Turnhole Spring karst watershed, Double Sink Subbasin. Anderson Level III, sorted by area.*

| Land Use Classification, Turnhole Spring karst watershed, Double Sink Subbasin | Area (hectares) | Percent coverage |
|---|---|---|
| 210B-Row crop with Residue single crop | 244.689 | 21.8 |
| Good pasture:well maintained | 234.627 | 20.9 |
| 61-100% crown cover (Deciduous) | 202.293 | 18.0 |
| Fair pasture:uneven growth and condition minimal maintenance | 67.662 | 6.0 |
| 31-60% crown cover (Deciduous) | 55.777 | 5.0 |
| 61-100% crown cover-hardwood dominant (Mixed 30-50%) | 52.083 | 4.6 |
| 31-60% crown cover-hardwood dominant (Mixed 30-50%) | 47.162 | 4.2 |
| Heavily overgrazed pasture:usually small feeding areas | 36.791 | 3.3 |
| 61-100% crown cover-cedar dominant (Mixed 30-50%) | 29.536 | 2.6 |
| 210A-Row crop no Residue single crop | 21.651 | 1.9 |
| Single Family Low Density (Below 2 Acres) | 20.432 | 1.8 |
| Farmstead with accompanying structures | 19.108 | 1.7 |
| Idle land | 11.622 | 1.0 |
| Plantation (Evergreen-valley types) | 10.196 | 0.9 |
| 61-100% crown cover-evergreen dominant (Mixed 30-50%) | 9.949 | 0.9 |
| 61-100% crown cover (Evergreen-valley types) | 6.791 | 0.6 |
| Forest clearcut area: reforested | 5.922 | 0.5 |
| Double Cropped:winter cover such as winter wheat barley rye | 5.895 | 0.5 |
| Poor pasture:sparse cover often gullied | 4.938 | 0.4 |
| Woodland pasture:10% >= Crown cover | 4.415 | 0.4 |
| Farm Ponds - 1 - 5 acres | 4.032 | 0.4 |
| Farm ponds - Smaller than 1 acre | 3.913 | 0.3 |
| Feedlot loafing area | 3.893 | 0.3 |
| Grass | 3.592 | 0.3 |
| 210S -Strip Cropped:alternating strips of cult - noncult. | 2.913 | 0.3 |
| Forest clearcut area: recent | 2.346 | 0.2 |
| Mobile Home | 2.169 | 0.2 |
| 10-30% crown cover (Evergreen-valley types) | 2.083 | 0.2 |
| Community Complex | 1.727 | 0.2 |
| Single Family Medium Density (2-5 Acres) | 1.507 | 0.1 |
| 10-30% crown cover-cedar dominant (Mixed 30-50%) | 1.221 | 0.1 |
| Garden | 1.139 | 0.1 |
| Christmas trees | 0.783 | 0.1 |

| Land Use Classification, Turnhole Spring karst watershed, Double Sink Subbasin (continued) | Area (hectares) | Percent coverage |
|---|---|---|
| 31-60% crown cover-cedar dominant (Mixed 30-50%) | 0.766 | 0.1 |
| Cemetery | 0.656 | 0.1 |
| 10-30% crown cover (Deciduous) | 0.357 | 0.0 |
| 10-30% crown cover-hardwood dominant (Mixed 30-50%) | 0.247 | 0.0 |
| Lake 1 - 5 acres | 0.247 | 0.0 |

*Land use of the Turnhole Spring karst watershed, Turnhole Subbasin. Anderson Level III, sorted by area.*

| Land Use Classification, Turnhole Spring karst watershed, Turnhole Subbasin | Area (hectares) | Percent coverage |
|---|---|---|
| 61-100% crown cover-cedar dominant (Mixed 30-50%) | 515.273 | 43.6 |
| 61-100% crown cover (Deciduous) | 288.834 | 24.4 |
| 61-100% crown cover-hardwood dominant (Mixed 30-50%) | 74.808 | 6.3 |
| Good pasture:well maintained | 50.892 | 4.3 |
| 31-60% crown cover-cedar dominant (Mixed 30-50%) | 46.656 | 3.9 |
| Fair pasture:uneven growth and condition minimal maintenance | 41.757 | 3.5 |
| 210B-Row crop with Residue single crop | 41.342 | 3.5 |
| Heavily overgrazed pasture:usually small feeding areas | 30.959 | 2.6 |
| 31-60% crown cover (Deciduous) | 15.523 | 1.3 |
| Double Cropped:winter cover such as winter wheat barley rye | 14.968 | 1.3 |
| Farmstead with accompanying structures | 7.991 | 0.7 |
| Plantation (Evergreen-valley types) | 7.864 | 0.7 |
| Woodland pasfure:10% >= Crown cover | 7.839 | 0.7 |
| Single Family Low Density (Below 2 Acres) | 5.693 | 0.5 |
| 61-100% crown cover (Evergreen-valley types) | 5.364 | 0.5 |
| 31-60% crown cover-hardwood dominant (Mixed 30-50%) | 5.149 | 0.4 |
| 210A-Row crop no Residue single crop | 4.618 | 0.4 |
| 61-100% crown cover-evergreen dominant (Mixed 30-50%) | 3.82 | 0.3 |
| Poor pasture:sparse cover often gullied | 3.311 | 0.3 |
| Idle land | 2.308 | 0.2 |
| 10-30% crown cover-cedar dominant (Mixed 30-50%) | 1.699 | 0.1 |
| Farm Ponds - 1 - 5 acres | 1.673 | 0.1 |
| Feedlot loafing area | 1.441 | 0.1 |
| Farm ponds - Smaller than 1 acre | 1.211 | 0.1 |
| 10-30% crown cover (Deciduous) | 1.111 | 0.1 |
| Mobile Home | 0.262 | 0.0 |
| 10-30% crown cover (Evergreen-valley types) | 0.205 | 0.0 |

Groundwatersheds, North Side

*Land use of the Big Spring karst watershed. Anderson Level II, sorted by area.*

| Land Use Classification, Big Spring Karst Watershed | Area (hectares) | Percent coverage |
|---|---|---|
| DECIDUOUS FOREST | 758 | 50.0 |
| EVERGREEN FOREST | 335 | 22.1 |
| LOW INTENSITY RESIDENTIAL | 282 | 18.6 |
| MIXED FOREST | 140 | 9.2 |

*Land use of the Doyle's Ford karst watershed. Anderson Level II, sorted by area.*

| Land Use Classification, Doyle's Ford Karst Watershed | Area (hectares) | Percent coverage |
|---|---|---|
| EVERGREEN FOREST | 787 | 62.2 |
| LOW INTENSITY RESIDENTIAL | 210 | 16.6 |
| DECIDUOUS FOREST | 189 | 14.9 |
| MIXED FOREST | 74 | 5.8 |
| OPEN WATER | 5 | 0.4 |

*Land use of the Ugly Creek karst watershed. Anderson Level II, sorted by area.*

| Land Use Classification, Ugly Creek Karst Watershed | Area (hectares) | Percent coverage |
|---|---|---|
| DECIDUOUS FOREST | 546 | 65.9 |
| LOW INTENSITY RESIDENTIAL | 107 | 12.9 |
| MIXED FOREST | 87 | 10.5 |
| EVERGREEN FOREST | 86 | 10.4 |
| OPEN WATER | 2 | 0.2 |

*Land use of the Buffalo Creek Spring karst watershed. Anderson Level II, sorted by area.*

| Land Use Classification, Buffalo Creek Karst Watershed | Area (hectares) | Percent coverage |
|---|---|---|
| DECIDUOUS FOREST | 2091 | 64.7 |
| EVERGREEN FOREST | 729 | 22.6 |
| MIXED FOREST | 185 | 5.7 |
| LOW INTENSITY RESIDENTIAL | 179 | 5.5 |
| OPEN WATER | 48 | 1.5 |

# Appendix D

# Aquatic Species Lists

## Fish Species of Mammoth Cave National Park

From, Cicerello and Hannan (1991)

| | |
|---|---|
| *Anguilliformes* | |
| Anguillidae | |
| *Anguilla rostrata* | american eel |
| *Atheriniformes* | |
| Atherinidae | |
| *Labidesthes sicculus* | brook silverside |
| *Clupeiformes* | |
| Clupeidae | |
| *Alosa chrysochloris* | skipjack herring |
| *Dorosoma cepedianum* | gizzard shad |
| *Cypriniformes* | |
| Catostomidae | |
| *Catostomus commersoni* | white sucker |
| *Hypentelium nigricans* | northern hog sucker |
| *Ictiobus bubalus* | smallmouth buffalo |
| *Minytrema melanops* | spotted sucker |
| *Moxostoma anisurum* | silver redhorse |
| *Moxostoma carinatum* | river redhorse |
| *Moxostoma duquesnei* | black redhorse |
| *Moxostoma erythrurum* | golden redhorse |
| *Moxostoma macrolepidotum* | shorthead redhorse |
| Cyprinidae | |
| *Campostoma oligolepis* | largescale stoneroller |
| *Carassius auratus* | goldfish |
| *Cyprinella spiloptera* | spotfin shiner |
| *Cyprinella whipplei* | steelcolor shiner |
| *Cyprinus carpio* | common carp |
| *Ericymba buccata* | silverjaw minnow |
| *Erimystax dissimilis* | streamline chub |
| *Hybopsis amblops* | bigeye chub |
| *Luxilus chrysocephalus* | striped shiner |
| *Lythrurus ardens* | blueside shiner |
| *Macrhybopsis aestivalis* | speckled chub |
| *Macrhybopsis storeriana* | silver chub |
| *Notemigonus crysoleucas* | golden shiner |
| *Notropis ariommus* | popeye shiner |
| *Notropis atherinoides* | emerald shiner |
| *Notropis buccatus* | silverjaw minnow |
| *Notropis buchanani* | ghost shiner |
| *Notropis photogenis* | silver shiner |

## Fish Species of Mammoth Cave National Park (continued)

| | |
|---|---|
| Cyprinidae, Continued | |
| *Notropis rubellus* | rosyface shiner |
| *Notropis spilopterus* | spotfin shiner |
| *Notropis volucellus* | mimic shiner |
| *Opsopoeodus emiliae* | pugnose minnow |
| *Phenacobius uranops* | stargazing minnow |
| *Phoxinus erythrogaster* | southern redbelly dace |
| *Pimephales notatus* | bluntnose minnow |
| *Pimephales vigilax* | bullhead minnow |
| *Semotilus atromaculatus* | creek chub |
| *Cyprinodontiformes* | |
| Fundulidae | |
| *Fundulus catenatus* | northern studfish |
| *Fundulus notatus* | blackstripe topminnow |
| *Esociformes* | |
| Esocidae | |
| *Esox americanus* | redfin or grass pickerel |
| *Esox masquinongy* | muskellunge |
| *Osteoglossiformes* | |
| Hiodontidae | |
| *Hiodon tergisus* | mooneye |
| *Perciformes* | |
| Centrarchidae | |
| *Ambloplites rupestris* | rock bass |
| *Lepomis cyanellus* | green sunfish |
| *Lepomis gulosus* | warmouth |
| *Lepomis macrochirus* | bluegill |
| *Lepomis megalotis* | longear sunfish |
| *Lepomis microlophus* | redear sunfish |
| *Micropterus dolomieu* | smallmouth bass |
| *Micropterus punctulatus* | spotted bass |
| *Micropterus salmoides* | largemouth bass |
| *Pomoxis annularis* | white crappie |
| *Pomoxis nigromaculatus* | black crappie |
| Moronidae | |
| *Morone chrysops* | white bass |
| Percidae | |
| *Ammocrypta pellucida* | eastern sand darter |
| *Crystallaria asprella* | crystal darter |
| *Etheostoma bellum* | orangefin darter |

## Fish Species of Mammoth Cave National Park (continued)

| | |
|---|---|
| *Etheostoma blennioides* | greenside darter |
| *Etheostoma caeruleum* | rainbow darter |
| *Etheostoma flabellare* | fantail darter |
| Percidae, Continued | |
| *Etheostoma maculatum* | spotted darter |
| *Etheostoma nigrum* | johnny darter |
| *Etheostoma rafinesquei* | kentucky darter |
| *Etheostoma spectabile* | orangethroat darter |
| *Etheostoma stigmaeum* | speckled darter |
| *Etheostoma tippecanoe* | tippecanoe darter |
| *Etheostoma zonale* | banded darter |
| *Percina caprodes* | logperch |
| *Percina copelandi* | channel darter |
| *Percina evides* | gilt darter |
| *Percina phoxocephala* | slenderhead darter |
| *Percina sciera* | dusky darter |
| *Stizostedion vitreum* | walleye |
| Sciaenidae | |
| *Aplodinotus grunniens* | freshwater drum |
| *Percopsiformes* | |
| Amblyopsidae | |
| *Amblyopsis spelaea* | northern cavefish |
| *Chologaster agassizi* | spring cavefish |
| *Typhlichthys subterraneus* | southern cavefish |
| *Salmoniformes* | |
| Salmonidae | |
| *Oncorhynchus mykiss* | rainbow trout |
| *Scorpaeniformes* | |
| Cottidae | |
| *Cottus carolinae* | banded sculpin |
| *Semionotiformes* | |
| Lepisosteidae | |
| *Lepisosteus osseus* | longnose gar |
| *Siluriformes* | |
| Ictaluridae | |
| *Ictalurus punctatus* | channel catfish |
| *Noturus eleutherus* | mountain madtom |
| *Pylodictis olivaris* | flathead catfish |

# Mussel Species of Mammoth Cave National Park

From, Cicerello and Hannan (1990)

Species Collected/Confirmed in park by Cicerello and Hannan 1990

**Unionoida**

| Scientific Name | Common Name |
|---|---|
| *Actinonaias ligamentina carinata* | Mucket |
| *Actinonaias ligamentina ligamentina* | Mucket |
| *Amblema plicata* | Threeridge |
| *Anodonta grandis* | Giant floater |
| *Anodonta imbecillis* | Paper pondshell |
| *Anodonta suborbiculata* | Flat floater |
| *Cumberlandia monodonta* | Spectaclecase |
| *Cyclonaias tuberculata* | Purple wartyback |
| *Cyprogenia stegaria** | Fanshell |
| *Ellipsaria lineolata* | Butterfly |
| *Elliptio crassidens* | Elephant-ear |
| *Elliptio dilatata* | Spike |
| *Epioblasma rangiana** | Northern riffleshell |
| *Epioblasma triquetra* | Snuffbox |
| *Fusconaia flava* | Wabash pigtoe |
| *Fusconaia subrotunda* | Long-solid |
| *Lampsilis cardium* | Plain pocketbook |
| *Lampsilis fasciola* | Wavy-rayed lampmussel |
| *Lampsilis ovata* | Pocketbook |
| *Lampsilis siliquoidea* | Fatmucket |
| *Lampsilis teres* | Yellow sandshell |
| *Lasmigona complanata* | White heelsplitter |
| *Lasmigona costata* | Fluted-shell |
| *Leptodea fragilis* | Fragile papershell |
| *Ligumia recta* | Black sandshell |
| *Megalonaias nervosa* | Washboard |
| *Obliquaria reflexa* | Threehorn wartyback |
| *Obovaria retusa** | Ring pink |
| *Obovaria subrotunda* | Round hickorynut |
| *Plethobasus cyphyus* | Sheepnose |
| *Pleurobema clava** | Clubshell |
| *Pleurobema coccineum* | Round pigtoe |
| *Pleurobema cordatum* | Ohio pigtoe |
| *Pleurobema plenum* | Rough pigtoe |
| *Pleurobema pyramidatum** | Pyramid pigtoe |

**Unionoida, Continued**

| | |
|---|---|
| *Potamilus alatus* | Pink heelsplitter |
| *Ptychobranchus fasciolaris* | Kidneyshell |
| *Quadrula cylindrica* | Rabbitsfoot |
| *Quadrula metanevra* | Monkey face |
| *Quadrula nodulata* | Wartyback |
| *Quadrula pustulosa* | Pimpleback |
| *Quadrula quadrula* | Mapleleaf |
| *Strophitus undulatus* | Squawfoot |
| *Tritogonia verrucosa* | Pistolgrip |
| *Truncilla donaciformis* | Fawnsfoot |
| *Truncilla truncata* | Deertoe |
| *Villosa ortmanni* | Kentucky creekshell |

**Veneroida**

| Scientific Name | Common Name |
|---|---|
| *Corbicula fluminea*** | Asian clam |

## Species Reported in park pre-1987, based on museum records and/or published reports

**Unionoida**

| Scientific Name | Common Name |
|---|---|
| *Alasmidonta marginata* | Elktoe |
| *Alasmidonta viridis* | Slippershell mussel |
| *Hemistena lata** | Cracking pearlymussel |
| *Venustaconcha ellipsiformis**** | Ellipse |
| *Villosa lienosa* | Little spectaclecase |

## Potential additions to park fauna based on presence in Green River drainage outside of park boundary

**Unionoida**

| Scientific Name | Common Name |
|---|---|
| *Anodontoides ferussacianus* | Cylindrical papershell |
| *Arcidens confragosus* | Rock-pocketbook |
| *Epioblasma obliquata** | Catspaw |
| *Lampsilis abrupta** | Pink mucket |
| *Leptodea leptodon** | Scaleshell |
| *Potamilus ohiensis* | Pink papershell |
| *Quadrula apiculata* | Southern mapleleaf |
| *Simpsonaias ambigua* | Salamander mussel |

**Unionoida, Continued**

| | |
|---|---|
| *Toxolasma lividus* | Purple lilliput |
| *Toxolasma parvus* | Lilliput |
| *Uniomerus tetralasmus* | Pondhorn |
| *Villosa fabalis* | Rayed bean |
| *Villosa iris* | Rainbow |

* Federally Endangered

** Introduced exotic from southeast Asia

*** Cicerello and Hannan (1990) note the only reported occurrence of this species in KY is a single record from Mammoth Cave National Park (Call 1900). However, it inhabits streams north of central Illinois and Indiana and its occurrence in KY is questionable.

## Benthic Macroinvertebrate Species of Mammoth Cave National Park

From: Dr. Scott Grubbs, Professor of Biology, Western Kentucky University, 2001-2002, unpublished data.

| | **Genus, species** |
|---|---|
| PORIFERA | |
| CNIDARIA | |
| | *Hydra* sp. |
| PLATYHELMINTHES | |
| | Turbellaria |
| NEMATODA | |
| ANNELIDA | |
| | Oligochaeta |
| MOLLUSCA | |
| | *Corbicula fluminea* |
| | *Ferrissia* sp. |
| | *Laevapex fuscus* |
| | *Fossaria* sp. |
| | *Physella* sp. |
| | *Helisoma* sp. |
| | *Leptotoxis* sp. |
| | *Pleurocera* sp. |
| ARTHROPODA | |
| | Hydracarina |
| | *Crangonyx* sp. |
| | *Hyalella azteca* |
| | immature Cambaridae |
| | *Orconectes* sp. |
| | *Lirceus* sp. |
| | Collembola |
| | *Argia* sp. |
| | *Enallagma* sp. |
| | *Calopteryx* sp. |
| | *Hetaerina* sp. |
| | *Basiaeschna* sp. |
| | *Boyeria vinosa* |
| | *Dromogomphus* sp. |
| | *Gomphus* sp. |
| | *Hagenius brevistylus* |
| | immature Libelludidae |
| | *Macromia* sp. |
| | *Neurocordulia* sp. |
| | *Baetis* sp. |

## Benthic Macroinvertebrate Species of Mammoth Cave National Park, continued

*Procloeon* sp.
immature Baetidae
*Caenis* sp.
*Ephemerella* sp.
*Eurylophella* sp.
*Serratella* sp.
*Hexagenia* sp.
*Heptagenia* sp.
*Stenacron* sp.
*Stenonema* sp.
*Isonychia* sp.
*Choroterpes* sp.
*Leptophlebia* sp.
*Anthopotamus* sp.
*Tricorythodes* sp.
*Pteronarcys dorsata*
*Allocapnia* sp.
*Strophopteryx fasciata*
*Taeniopteryx* sp.
*Anmphinemura* sp.
*Acroneuria* sp.
*Neoperla* sp.
*Perlesta* sp.
*Perlinella drymo*
*Brachycentrus* sp.
*Cheumatopsyche* sp.
*Hydropsyche* sensu lato
*Macrostemum* sp.
*Hydroptila* sp.
*Orthotrichia* sp.
*Mystacides* sp.
*Nectopsyche* sp.
*Oecetis* sp.
*Triaenodes* sp.
*Pycnopsyche* sp.
*Chimarra* sp.
*Cyrnellus fraternus*
*Neureclipsis* sp.
*Nyctiophylax* sp.
*Polycentropus* sp.
*Microvelia* sp.
*Metrobates* sp.

Benthic Macroinvertebrate Species of Mammoth Cave National Park, continued

*Rheumatobates* sp.
*Corydalis cornutus*
*Sialis* sp.
*Helichus* sp.
*Ancyronyx variegatus*
*Dubiraphia* sp.
*Macronychus glabratus*
*Optioservus* sp.
*Stenelmis* sp.
*Psephenus herricki*
*Dineutus* sp.
*Gyretes* sp.
*Gyrinus* sp.
*Berosus* sp.
*Scirtes* sp.
Noctuidae
Ceratopogonid larval morphotype I
*Atrichopogon* sp.
*Bezzia/Palpomyia* sp.
*Ceratopogon* sp.
*Culicoides* sp.
*Probezzia* sp.
Chironomdiae
Empididae larval morphotype I
*Chelifera* sp.
*Hemerodromia* sp.
*Pericoma* sp.
*Psychoda* sp.
Ephydridae
*Simulium* sp.
*Chrysops* sp.
*Pseudolimnophila* sp.

# Aquatic Herptile Species of Mammoth Cave National Park

Dr. Floyd Scott, Austin Peay University, 2002, unpublished data.

| Common Name | Scientific Name | Upland pools, springs, streams, temporary water bodies | River and associated floodplain |
|---|---|---|---|
| Jefferson Salamander | *Ambystoma jeffersonianum* | Yes | |
| Spotted Salamander | *Ambystoma maculatum* | Yes | |
| Marbled Salamander | *Ambystoma opacum* | Yes | |
| Eastern Tiger Salamander | *Ambystoma tigrinum* | Yes | |
| Eastern Hellbender | *Cryptobranchus a. alleganiensis* | | Yes |
| Northern Dusky Salamander | *Desmognathus fuscus* | Yes | |
| Southern Two-lined Salamander | *Eurycea cirrigera* | Yes | |
| Longtail Salamander | *Eurycea l. longicauda* | Yes | |
| Cave Salamander | *Eurycea lucifuga* | Yes | |
| Four-toed Salamander | *Hemidactylium scutatum* | Yes | |
| Common Mudpuppy | *Necturus maculosus* | | Yes |
| Red-spotted Newt | *Notophthalmus v. viridescens* | Yes | |
| Midland Mud Salamander | *Pseudotriton montanus diastictus* | Yes | |
| Northern Red Salamander | *Pseudotriton r. ruber* | Yes | |
| Blanchard's Cricket Frog | *Acris crepitans blanchardi* | Yes | Yes |
| American Toad | *Bufo americanus* | Yes | Yes |
| Fowler's Toad | *Bufo fowleri* | Yes | Yes |
| Eastern Narrowmouth Toad | *Gastrophryne carolinensis* | Yes | |
| Cope's Gray Treefrog | *Hyla chrysoscelis* | Yes | Yes |
| Mountain Chorus Frog | *Pseudacris brachyphona* | Yes | |
| Northern Spring Peeper | *Pseudacris c. crucifer* | Yes | Yes |
| Upland Chorus Frog | *Pseudacris triseriata feriarum* | Yes | |
| Bullfrog | *Rana catesbeiana* | Yes | Yes |
| Green Frog | *Rana clamitans melanota* | Yes | Yes |
| Pickerel Frog | *Rana palustris* | Yes | Yes |
| Southern Leopard Frog | *Rana sphenocephala utricularia* | Yes | Yes |
| Wood Frog | *Rana sylvatica* | Yes | |
| Eastern Spadefoot | *Scaphiopus holbrookii* | Yes | Yes |
| Eastern Spiny Softshell | *Apalone s. spinifera* | | Yes |
| Common Snapping Turtle | *Chelydra s. serpentina* | Yes | Yes |
| Midland Painted Turtle | *Chrysemys picta marginata* | Yes | Yes |
| Common Map Turtle | *Graptemys geographica* | | Yes |
| Ouachita Map Turtle | *Graptemys ouachitensis* | | Yes |
| Mud Turtle | *Kinosternon subrubrum* | Yes | |
| Eastern River Cooter | *Pseudemys concinna* | | Yes |
| Common Musk Turtle | *Sternotherus odoratus* | | Yes |
| Eastern Box Turtle | *Terrapene carolina* | Yes | |
| Red-eared Slider | *Trachemys scripta elegans* | Yes | Yes |
| Northern Water Snake | *Nerodia s. sipedon* | | Yes |

| | | |
|---|---|---|
| Queen Snake | *Regina septemvittata* | Yes |

## Cave Aquatic Species of Mammoth Cave National Park

Dr. William Jones, University of Louisville, 2002, Unpublished data.

P. Platyhelminthes
- C. Turbellania
  - *Sphalloplana percocea*
  - *Sphalloplana buchanani*

P. Tardigrada
  - *Macrobiotus sp.*

P. Mollusca
- C. Gastropoda
  - *Antroselates spiralis*

P. Annellida
- C. Oligochaeta
  - *Aeolosoma sp.*

P. Arthropoda
- C. Copepoda
  - *Maraenobiotus sp.*
  - *Moraria sp.*
  - *Nitocra sp.*
  - *Parastenocaris sp.*
- C. Decapoda
  - *Palaemonias ganteri*
  - *Oconectes pellucidus*
  - *Cambarus tenebrosus*
- C. Isopoda
  - *Caecidotea stygia*
  - *Caecidotea bicrenata*
- C. Amphipoda
  - *Stygobromus vitreus*
  - *Stygobromus excilis*
  - *Crangonyx packardi*

P. Vertebrata
- C. Osteichthyes
  - *Typhlichthys subterraneus*
  - *Amblyopsis spelaea*
  - *Chologaster tenebrosus*
  - *Cottus carolinea*

# Appendix E

# Commonwealth of Kentucky Law Specific to Water Resources

401 KAR 5:002 Definitions for 401 KAR Chapter 5

Section 1 – Definitions
Section 2 – Federal Regulations Adopted without Change
Section 3 – Incorporation by Reference

401 KAR 5:026 Designation of Uses of Surface Waters

Section 1 – Scope of Designation
Section 2 – Redesignation of Surface Waters
Section 3 – Documentation for Redesignation
Section 4 – Procedures for Redesignation
Section 5 – Surface Water Use Designations
Section 6 – Incorporation by Reference

401 KAR 5:029 General Provisions

Section 1 – Antidegradation Policy
Section 2 – Withdrawal of Contaminated Water
Section 3 – Sample Collection and Analytical Methodology
Section 6 – Federal Regulation Adopted without Change

401 KAR 5:030 Antidegradation Policy Implementation Methodology

Section 1 – Implementation of Antidegradation Policy
Section 2 – Procedure for Recategorizing Waters
Section 3 – Surface Water Categories

401 KAR 5:031 Surface Water Standards

Section 1 – Nutrient Limits
Section 2 – Minimum Criteria Applicable to All Surface Waters
Section 3 – Use Designations and Associated Criteria
Section 4 – Aquatic Life
Section 6 – Recreational Waters
Section 7 – Outstanding State Resource Waters
Section 9 – Exemptions to Criteria for Specific Surface Waters
Section 10 – Exemptions to Criteria for Individual Dischargers
Section 11 – Incorporation by Reference

401 KAR 5:037 Groundwater Protection Plans

Section 1 – Definitions

401 KAR 30:031 Environmental Performance Standards

Section 13 – Karst

401 KAR 34:060 Groundwater Protection

Section 1 – Applicability
Section 2 – Required Programs
Section 3 – Groundwater Protection Standard
Section 4 – Hazardous Constituents
Section 5 – Contamination Limits
Section 8 – General Groundwater Monitoring Requirements

401 KAR 45:130 Citing Requirements for Special Waste Landfills

Section 1 – Buffer zones
Section 2 – Flood Plains

401 KAR 48:050 Citing Requirements for Special Waste Landfills

Section 1 – Buffer zones
Section 2 – Flood Plains

401 KAR 48:200 Land-farming and Composting

Section 8 – Operating Requirements

902 KAR 10:150 Domestic Septic Disposal Site Approval Requirements

Section 4 – Site Approval Procedures

KRS 146.241 – Designation of streams in Wild River System.

KRS 224.50-860 – Requirements for person registered as an accumulator, transported, or processor of waste tires.

KRS 433.875 – Unlawful dumping, disposal, or burning within a cave.

# Appendix F

## Participants and Results of Mammoth Cave National Park Water Resources Management Plan Scoping Workshop

*Issues Scoping Workshop Participants, September 14, 2004*

Joe Meiman, MACA
Angie Crain, USGS
Stacy Surgenor, MACA
Robert Woodman, MACA/USGS
Bobby Carson, MACA
Steve Thomas, MACA
Mark Ayers, USGS
Jay Nelson, KY Dept. of Natural Resources
Mark Depoy, MACA
George Williams, USCOE
Don Weeks, NPS-WRD
David Vana-Miller, NPS-WRD
William Pearson, University of Louisville
Anthony Velasco, USFWS
Dale Reynolds, KY DOW
Judith Petersen, KWA
Richie Kessler, TNC
Steve Kenworthy, Western KY University
Joe Ray, KY DOW
Ouida Meier, Western KY University
Michael Uthank, USGS
David Burton, Barron River District Health Dept.
Andy Ernest, Western KY University
Tim Slattey, City of Bowling Green
Rezaul Mahmood, Western KY University
Sreedevi Dawadi, Western KY University
Michael Ruhl, Western KY University

*Desired Conditions Meeting Participants, September 15, 2004*

Joe Meiman, MACA
Robert Woodman, MACA/USGS
Steve Thomas, MACA
David Vana-Miller, NPS-WRD
Don Weeks, NPS-WRD

# ISSUES SUMMARY

## WATER QUALITY

(*8 votes*) Onsite sewage disposal systems (PRIDE program).

Planning without zoning in most counties.

Trend of agricultural lands converted to high-density residential.

(*5 votes*) Stormwater runoff...including impacts from golf courses (arsenic from herbicides).

(*1 vote*) Improper houseboat disposal (estimated that < 10% of users use pumpout stations at marinas in COE-managed areas).

(*1 vote*) Declassification of upper Green River to non-impaired status (not 303d listed) for fecal coliform...some don't agree with decision based on data.

(*4 votes*) Do we know of any runoff water quality data from CSX railroad?

(*9 votes*) Agricultural runoff (non-regulated poultry industry, cattle – pastureland > cropland 3:1).

(*2 votes*) Hg deposition with increase in coal fired power plants (ask for coal analysis on weekly basis).

(*7 votes*) Hazardous material spills/releases along I-65. Lack of BMPs applied to transportation corridor...signage along corridors needed, notification procedures when hazmat release occurs.

Upstream abandoned oil wells. Is there a potential for wells to become online with increasing oil prices?

(*4 votes*) Sewer infrastructure...are they leaking?...is O&M adequate?

(*1 vote*) Outstanding State Resource Waters - no regulatory teeth to designation.

Increase in water lines as development increases in watershed, therefore more independent sewage treatment systems to meet high-density development.

Encountering new suite of herbicides in watershed?

Loss of forested land to agricultural and residential lands. Quality of timber harvest techniques lack regulatory requirements and enforcement.

Acidic deposition on perched waters above the non-buffered sandstone unit.

Horseback riding...erosion, bacteria and sediment problems along horse trails.

(*5 votes*) Lack of quality regulatory enforcement...need to educate more about karst systems.

(*4 votes*) Effects of L&D 6 on water quality.

**GROUNDWATER**

(*3 votes*) Need to define recharge areas upstream of MACA Boundaries.

(*3 votes*) Public education on karst.

(*1 vote*) Trimodal Transpark development.

**SURFACE WATER HYDROLOGY**

(*2 votes*) Restoration of "Haney Springs"

(*5 votes*) Paucity of stream gages in watershed.

(*1 vote*) Expansion needed of Mesonet sites…ties into needed more stream gages.

(*4 votes*) L&D 6 impacts

(*3 votes*) Green River Dam…working closely with TNC to modify flow patterns, temperature, and floodplain inundation.

(*1 vote*) Nolin River Dam…what is being done at Green River Dam needs to be done here.

(*3 votes*) Increases in water withdrawal for drinking water…some discussions on selling water.

Water rights…need for ecologically-based instream flows for aquatic flora and fauna.

**WETLANDS/RIPARIAN**

Lack of inventory of wetlands outside of MACA boundaries.

(*1 vote*) Temporary sinkhole "ponds" after rainfall…not in NWI?

(*4 votes*) Channel bank erosion…fluvial dynamics have changed via regulated flows.

(*7 votes*) Geomorphic studies of Green River needed within MACA boundaries and upstream.

Lack of riparian buffer upstream of park streams and sinkholes.

Need more consistency in Farm Bill Programs involving sinkholes…need to be reviewed as riparian systems.

**AQUATIC BIOLOGY**

(*6 votes*) Ecological flow requirements for T&E species and habitat quality (i.e., aquatic cave shrimp).

(*5 votes*) Sedimentation issues on biota…both sediment quality and quantity.

Stocked rainbow trout in tailwaters of Nolin Dam.

(*1 vote*) impacts on mussel distribution.

Impacts of atrazine in fish tissue on glochidia.

(*6 votes*) impacts on aquatic communities and T&E species (i.e., aquatic cave shrimp) by endocrine disruptors.

Bioaccumulation of heavy metals in biota.

Continued emphasis on long-term monitoring of fauna.

(*3 votes*) Systems ecology and landscape interactions.

(*1 vote*) Green List

Impact of toxic spills on biota.

(*2 votes*) Exotic Species: veligers of zebra mussels in reservoirs...potential great impact. Potential black carp, silver carp, round goby. Presence of species in riparian (e.g., garlic mustard).

Loss of American Elms and Butternut.

Need to develop Biological Indices of Integrity for mainstem Green River.

Acid deposition impacts on biota.

Lack of information (e.g., aquatic fungi, microbes, troglobitic snail, endemic crayfish (bottlebrush crayfish)).

**VISITOR USE**

(*1 vote*) Horseback riding and water quality issues.

(*2 votes*) Recreational water quality issues.

Need to warn public re: health advisories (i.e., Hg contamination).

Recreational fishing issues (i.e., rainbow trout stocking).

Impacts from mountain biking.

Impacts from boating (houseboats, canoes, kayaks)...physical disturbance on benthos...human waste and graywater disposal.

(*1 vote*) Education needed...(e.g. do not collect mussels, proper human waste disposal).

Awareness of transportation corridors and visitor use and associated impacts.

(*3 votes*) Educational Program needed on the ecological benefits to removal of L&D 6.

Litter control along streams.

(*1 vote*) Interpretation of mitigative/restorative effects in MACA.

Hotel parking lot runoff erosion from concentrated outfalls.

**AIR**

(*2 votes*) Acid deposition.

(*2 votes*) Mobile source analysis.

**FIRE**

(*1 vote*) Impacts on Kentucky Cave Shrimp from siltation.

(*1 vote*) Accelerant (Napthalene) impacts on aquatic resources.

(*2 votes*) Mobilization of Hg.

**LANDUSE**

Restoration of riparian zones upstream of MACA.

Loss of tobacco farming with increase in pastureland.

Population density and waste disposal increasing.

(*1 vote*) Transpark development.

Smart growth education needed.

(*2 votes*)

**PARTNERSHIPS**

(*1 vote*) Need partnerships with those communities that benefit economically from proximity of MACA.

(*4 votes*) Need Biosphere Reserve Coordination.

Establish Edmonson and Barren county solid waste coordination to clean up dumps.

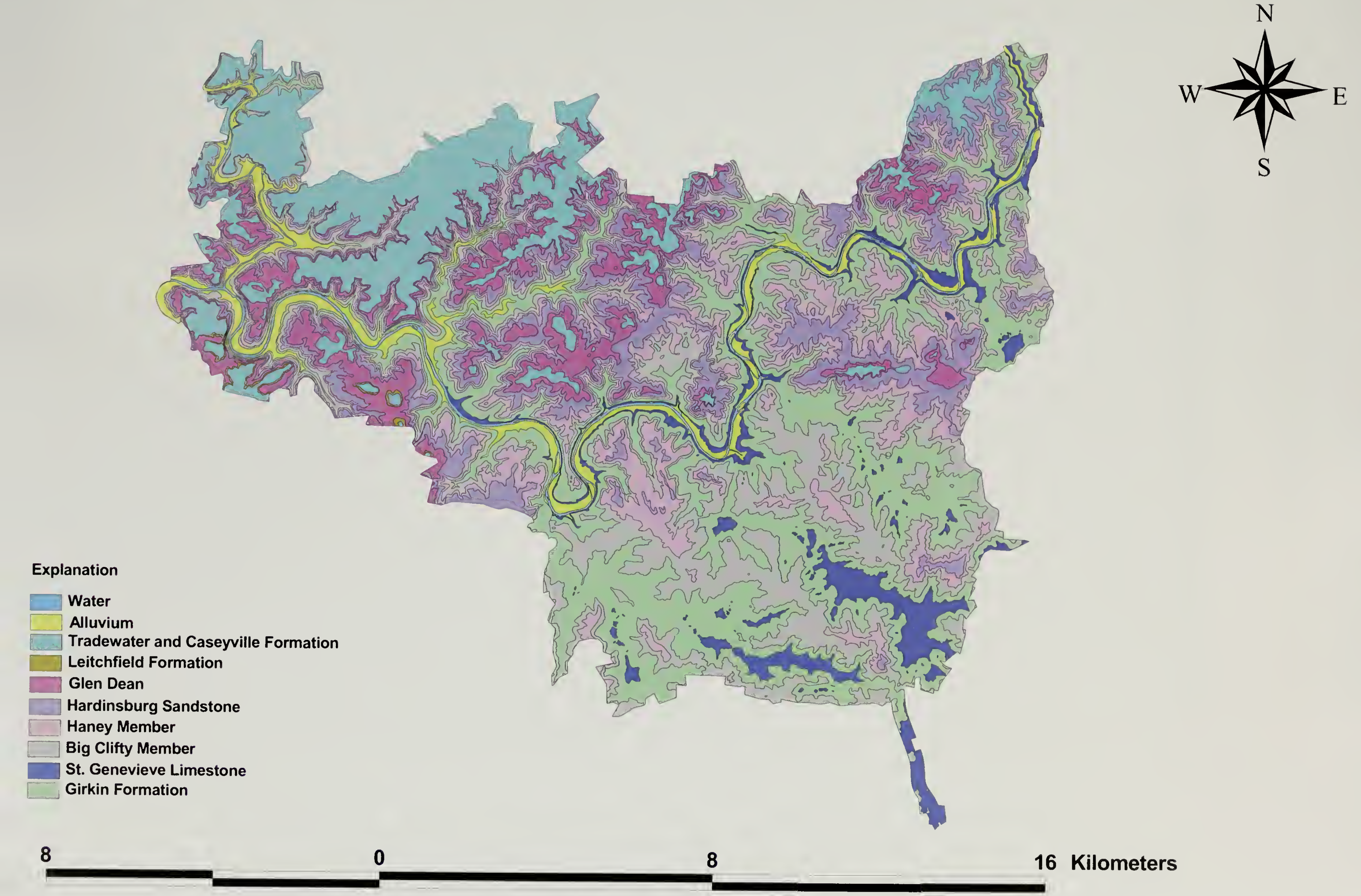
(*1 vote*) Establish Green River Research Consortium.

Establish education outreach with MACA vendors.

(*2 votes*) Organize Green River cleanup day.

# Plate 1. Geology of Mammoth Cave National Park

# Geology of Mammoth Cave National Park



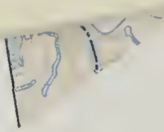

Source: USGS 1:24,000 Geologic Quadrangle Maps, digitized by the Kentucky Geological Survey

# Plate 2. Karst Atlas Map, Beaverdam 30'x60' Quadrangle

**Plate 3. Karst**

ional Park

# Plate 3. Karst Atlas Map, Campbellsville 30'x60' Quadrangle



tional Park

As the nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

MACA D-131, April 2006