GIS Best Practices

GIS for Cave and Karst

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ESRI

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What Is GIS?

Making decisions based on geography is basic to human thinking. Where shall we go, what will it be like, and what shall we do when we get there are applied to the simple event of going to the store or to the major event of launching a bathysphere into the ocean's depths. By understanding geography and people's relationship to location, we can make informed decisions about the way we live on our planet. A geographic information system (GIS) is a technological tool for comprehending geography and making intelligent decisions.

GIS organizes geographic data so that a person reading a map can select data necessary for a specific project or task. A thematic map has a table of contents that allows the reader to add layers of information to a basemap of real-world locations. For example, a social analyst might use the basemap of Eugene, Oregon, and select datasets from the U.S. Census Bureau to add data layers to a map that shows residents' education levels, ages, and employment status. With an ability to combine a variety of datasets in an infinite number of ways, GIS is a useful tool for nearly every field of knowledge from archaeology to zoology.

A good GIS program is able to process geographic data from a variety of sources and integrate it into a map project. Many countries have an abundance of geographic data for analysis, and governments often make GIS datasets publicly available. Map file databases often come included with GIS packages; others can be obtained from both commercial vendors and government agencies. Some data is gathered in the field by global positioning units that attach a location coordinate (latitude and longitude) to a feature such as a pump station.

GIS maps are interactive. On the computer screen, map users can scan a GIS map in any direction, zoom in or out, and change the nature of the information contained in the map. They can choose whether to see the roads, how many roads to see, and how roads should be depicted. Then they can select what other items they wish to view alongside these roads such as storm drains, gas lines, rare plants, or hospitals. Some GIS programs are designed to perform sophisticated calculations for tracking storms or predicting erosion patterns. GIS applications can be embedded into common activities such as verifying an address.

From routinely performing work-related tasks to scientifically exploring the complexities of our world, GIS gives people the geographic advantage to become more productive, more aware, and more responsive citizens of planet Earth.

GIS for Cave and Karst

GIS offers a variety of tools and capabilities used in the management, analysis, and visualization of cave and karst information, increasing our knowledge and helping make informed decisions.

- GIS is used for inventory and field data collection, both on the surface of the earth and underground, and is a powerful tool for collecting and integrating a wide variety of data.

- Mapping and publishing capabilities allow users to create high-quality maps and disseminate and share information in a variety of formats.

- Three-dimensional capabilities offer unique ways to visualize cave and karst features.

- Spatial query and data management tools facilitate the efficient storage and retrieval of information.

- Spatial analysis and modeling functions contribute to the discovery and understanding of patterns and relationships with the environment as a whole.

All these features make GIS an essential technology for cave and karst mapping, management, conservation, and analysis.

Developing a Cave Potential Map for South Dakota's Wind Cave Using GIS

By Rodney D. Horrocks, Cave Resource Management Specialist
Wind Cave National Park, Hot Springs, South Dakota

Since the discovery of Wind Cave in South Dakota in 1881, numerous cavers have been drawn to explore its complex mazes. Since 1902, 166 km have been surveyed in the cave, and the boundaries have expanded to fill a 1.6–1.9 km rectangle. A famous diary quote by an early Wind Cave explorer, Alvin McDonald, says, "Have given up the idea of finding the end of Wind Cave." This is as true today as it was in 1891 when it was written. It is common to hear cavers participating in the current survey effort remark about the "endless" potential of the cave. As the boundaries of the cave have enlarged, many hypotheses on its potential extent have been proposed, even going so far as speculating on a connection with Jewel Cave, 29.44 km to the northwest.
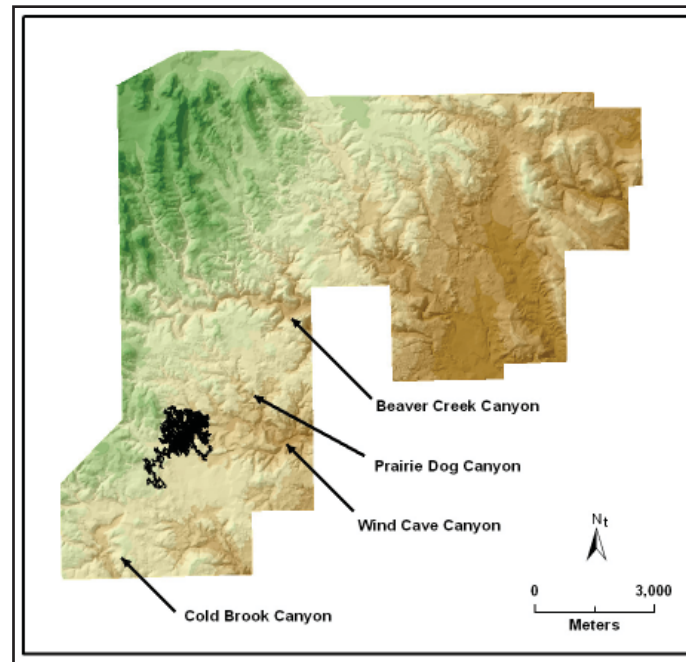

Location of Wind Cave within Wind Cave National Park. The Wind Cave survey lineplot (black) was generated using COMPASS software and imported to GIS format and georeferenced using the CaveTools extension for ArcView. The cave data is plotted atop a digital elevation model (DEM) which has been shaded showing higher elevations in green and lower elevations in brown.

For years, cavers based the potential size of Wind Cave on barometric wind studies done by Herb Connecticut in 1966. Those studies suggest that the current volume of the surveyed cave represents only 2.5 percent of the total volume of 5.5 x 1,010 m^3. The current volume of the surveyed portions of Wind Cave is 1.4 x 109 m^3. As the boundaries of the cave have enlarged, many hypotheses on passage extent have been proposed. This study, however, speculated that a GIS-based cave potential model might be a more accurate method to predict the amount of potential surveyable passage in Wind Cave than barometric wind studies could provide.

Historically, it had been difficult to get park managers to recognize that Wind Cave may extend beyond its current boundaries, especially when additional park infrastructure was being planned outside of known cave boundaries. Unless the cave survey had been extended below a particular area, it was assumed that no cave existed there. Although this concept of a cave potential map was first developed after hearing about these attitudes, actual development of the model identified its limitations as a management tool. However, this project was partially instigated because managers cannot wait until a cave of this magnitude has been completely surveyed to develop their management policies. It was realized that an estimation of the potential extent and surveyable length of Wind Cave and a means to address the Wind/Jewel connection theory constitute the main benefit of this model.

As the concept of a cave potential map developed, it was decided that this model could address four issues: (1) the maximum likely extent of Wind Cave, (2) the surveyable length of the cave, (3) the Wind/Jewel Cave connection hypothesis, and (4) surface land management shortcomings that existed near the known cave.

Although previous researchers have analyzed Wind Cave's potential extent based on individual disciplines, no one had attempted to use geology, hydrology, airflow, and cave survey data together to quantify the potential extent of Wind Cave. GIS provided the perfect tool to accomplish this task.
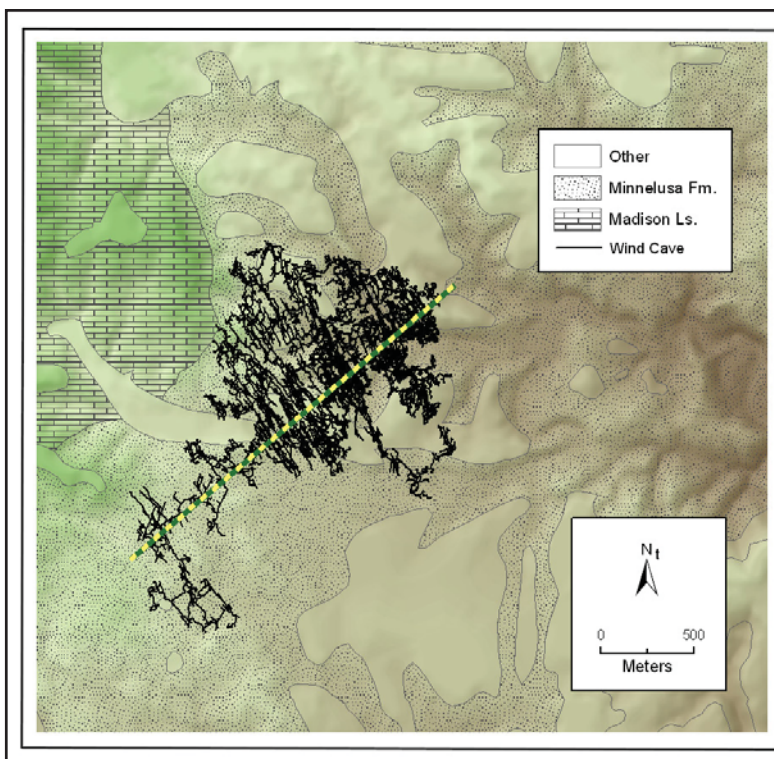
Relationship of the Madison Limestone outcrops to the Wind Cave survey. The major trend of the cave is marked with a yellow and green striped line. The Minnelusa Formation is located directly above the cave. This illustration was created by combining a shaded relief DEM, geology layer, and survey lineplot.

We initially analyzed the region surrounding Wind Cave and identified some preliminary large-scale factors that could limit cave passage development. We theorized that the current erosional surface and the water table could provide those limiting boundaries. Blowholes and the cave survey data also provided additional clues on the potential extent of the cave.

With these preliminary limiting boundaries in hand, we hypothesized that other geologic factors would also have had a significant effect on the development of Wind Cave including erosional surfaces, structural geologic factors, mode of speleogenesis, and paleo-injection points. We also hypothesized that such data as the profile view of the Wind Cave survey, cave radio

location depths, surface outcrops, cave levels, airflow, and passage density would all offer additional clues on the likely extent of Wind Cave. Once we identified these additional limiting factors and data sources, individual GIS layers provided buffers and overlays for further refining potential boundaries of the cave. In the future, as we learn more about these limiting factors, the cave potential boundaries will need further modification.

Using GIS   GIS was used to accomplish several tasks including the development of a spatial model that was used to verify our preliminary cave potential map, the visualization of those results, and the development of maps to demonstrate cave potential and support management requirements and decisions. The GIS tools used were ArcView; ArcView Spatial Analyst; ArcView 3D Analyst; and CaveTools, a third party extension used to incorporate cave survey data into the GIS.
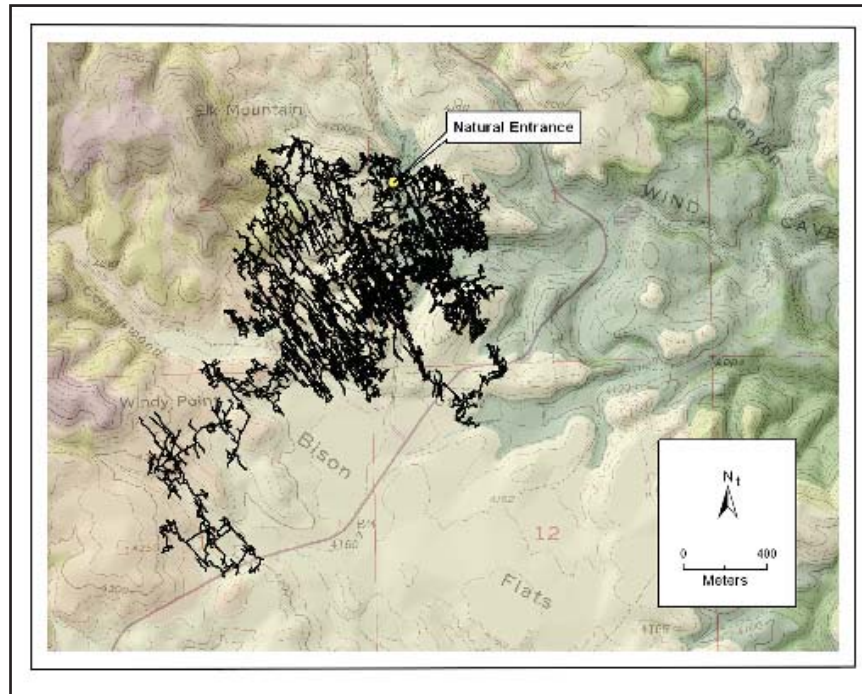
Wind Cave entrance location and surface relief. A DEM was used to create a surface upon which the Wind Cave USGS digital raster graphic (DRG) was draped, along with a hillshaded TIN derived from the DEM and the Wind Cave survey lineplot.

GIS data layers were collected and derived from a variety of sources. Digital line graph (DLG) files were used to create hydrography, hypsography, and transportation layers. Contour lines from the DLG hypsography layer were used to generate a triangular irregular network (TIN) elevation model from which slope, aspect, and other layers used for visualization were derived. Blowholes and cave entrance locations were imported from field GPS readings. Cave survey data was converted from COMPASS plot files to ESRI shapefiles format and georeferenced based on GPS locations of surface survey stations. Digitized park boundaries, digital orthophoto quads (DOQs), and geologic maps were also incorporated into the GIS. One of the first maps produced using the GIS showed the relationship of the outcrop of the Madison Limestone to the current surveyed cave extent.

Using the ModelBuilder functionality in ArcView Spatial Analyst, an interactive model diagram was constructed incorporating various spatial processes such as buffering, proximity, and weighted overlays. A cave potential surface was generated by weighting proximity to certain features, such as known entrances and blowholes, and combining these derived cave potential surfaces using weighted overlays with other factors such as geology, potentiometric surfaces, and current cave extents. In addition, the volumetric constraints for cave potential were further defined by generating 3D surfaces that represented the limiting bounds of the intersection of the Madison Limestone along its strike and dip with the upper and lower limits of the historic and present water table elevations. Area calculations using the GIS were made of the known extent of the cave and the potential area for cave development, and these were used to calculate the potential cave length based on current parameters.

Summary

Analysis of the Wind/Jewel Cave connection hypothesis resulted in the conclusion that a connection between the two caves is an unlikely scenario. Although such a connection could not be totally eliminated as a possibility, it is a remote possibility.

Once the analysis had been completed, we used the buffers and overlays to draw an outline around the area that represents the likely maximum extent of Wind Cave, creating the Wind Cave Potential Map. Approximately 97 percent of those boundaries fall inside of the current boundaries of Wind Cave National Park. The current boundaries of the cave were found to be one-tenth of the area of the total potential of the cave, as identified by this exercise.
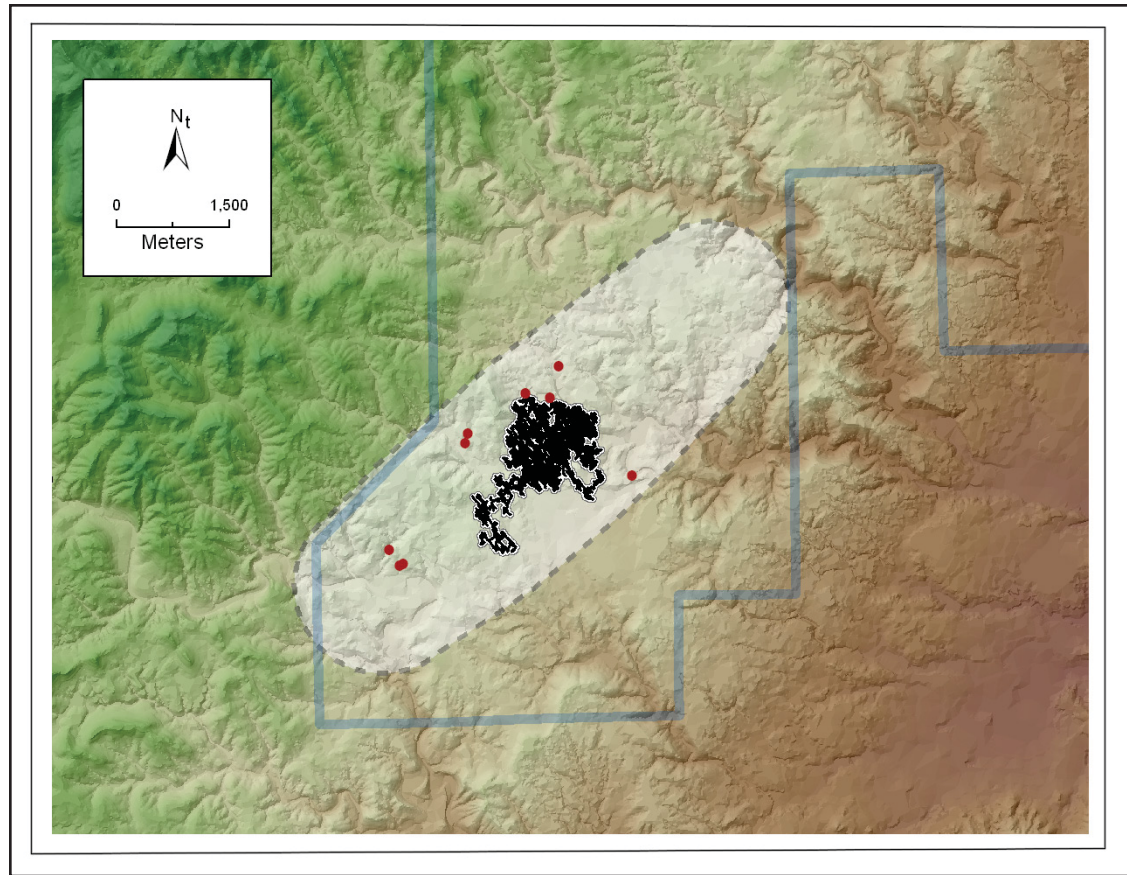
Cave Potential boundary for Wind Cave representing the likely maximum extent of humanly accessible portions of Wind Cave. The boundary for cave development is shown in light gray. Currently surveyed cave passages are shown in black; blowholes are shown as red dots.

By calculating passage density for the current cave boundaries and then for the maximum potential boundaries, a minimum and maximum potential surveyable length was calculated for Wind Cave. We predicted that the cave could have approximately 400 km of surveyable passage, if the cave is not extended beyond the current boundaries. If the cave is extended to all edges of the potential boundary, Wind Cave could have almost 1,800 km of surveyable passage, assuming similar passage density throughout the potential area. Since the current

163 km surveyed represent no more than 40 percent of the minimum predicted length of the cave or as little as 9 percent of the maximum predicted length of the cave, it is obvious that a tremendous amount of surveyable passage remains in the system. However, based on airflow and cave development patterns, it is unlikely that the cave will continue in all directions to the edge of the identified cave potential boundaries; even if it did, it is unlikely that cavers would be able to physically push the cave to those boundaries.

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Karst GIS Advances in Kentucky

Possible Interstate 66 Routes Scrutinized

By Lee J. Florea, I-66 Special Project, National Speleological Society, University of South Florida; Randall L. Paylor, Kentucky Speleological Survey, Kentucky Geological Survey; Larry Simpson, National Speleological Society; Jason Gulley, Purdue University

Karst: terrain with distinctive characteristics indicative of bedrock dissolution by groundwater. Karst features include sinkholes, sinking streams, and caves.

Karst is an integral part of the landscape of Kentucky, with approximately 55 percent of the state underlaid by karstic limestone in three of seven physiographic provinces and along the margins of the eastern and western Kentucky coal fields. The abundance of karst in Kentucky affects everything from the state's biodiversity to the history of human settlement. Widespread and intense karstification of the region poses tremendous environmental impact issues due to continued population growth and industrialization.
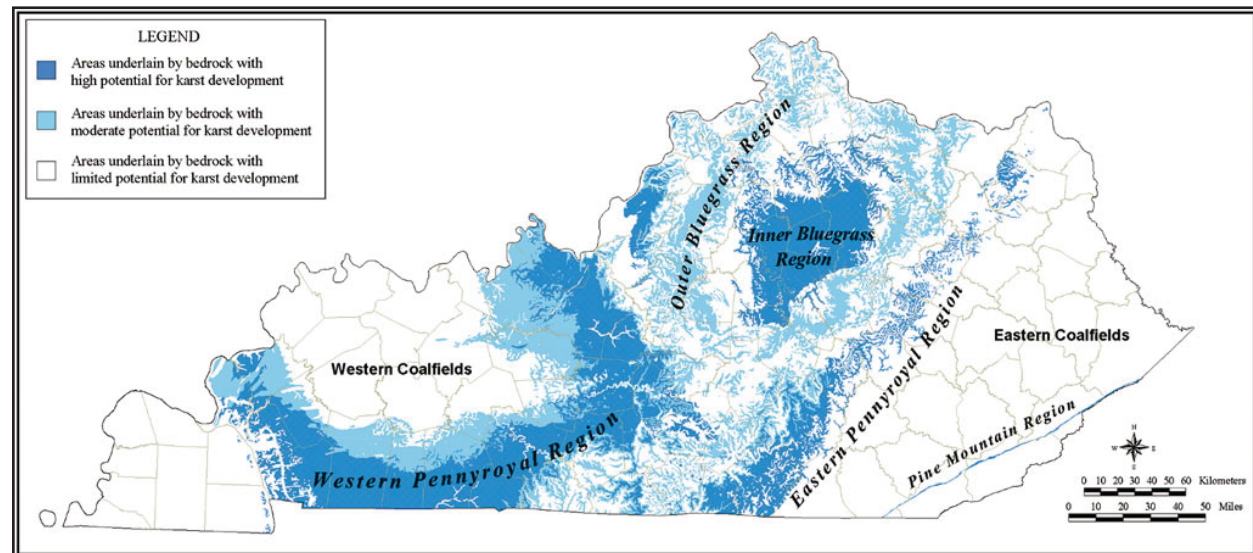
Karst map of Kentucky showing study areas

Interstate 66 and Development Issues

When the Kentucky Transportation Cabinet (KTC) in 1999 unveiled possible routes for the section of Interstate 66 between London and Somerset, Kentucky, karst researchers became concerned. This proposed corridor traversed undeveloped woodlands inside and outside the Daniel Boone National Forest, crossed several high-quality watersheds, and threatened severe damage to cave and karst resources. In response, the I-66 Special Project of the National Speleological Society (NSS) in cooperation with the Sloans Valley Conservation Task Force, Kentucky Heartwood, Somerset Pulaski County Concerned Citizens, and dozens of other organizations initiated an extensive and cooperative karst data gathering campaign in the region.

The effort focused on collecting, maintaining, and presenting a GIS of karst resources in Pulaski County, Kentucky, using ArcView software. The first level of data included a point location database of cave entrances and associated karst features provided by locals and members of the caving community. A second layer of information included scanned and georeferenced (registered to real-world coordinates) cave maps. From these raster images, polygons outlining the passages were digitized to display regions in which surveyed caves were known to lie underneath the surface. A third layer of information included sinkhole polygons digitized from depression contours on 7.5-minute topographic quadrangles. The final layer of information in the GIS was vector representations of the corridor alternatives for the I-66 Special Project. This information was provided by KTC. All data was created using NAD83 datum and the Kentucky State Plane South 1983 coordinate system.

The data developed by this effort was used in several ways. Overlays of the corridor alternatives with a 1,000-foot buffer combined with conduit polygons, sinkholes, and cave entrance data were used to determine potential karst impacts for each alternative. Conduit polygons and sinkhole coverages for the area affected by the proposed corridors were provided to KTC and its consultants for incorporation in a second planning study (released in June 2000) to address the concerns raised by the first. Images produced using the data were presented in publications and at various presentations throughout the region to help others understand the concerns.

The Results

The impact of the GIS work to date by the I-66 Special Project, NSS, in Kentucky has been significant. Due to a combination of public opinion and evidence provided through karst GIS development, the second planning study for I-66 recommended a more northerly corridor, which avoided the primary environmental problems of the earlier route including many known cave and karst resources.

The efforts of the I-66 Special Project have opened the door to other research in the region, including a cave-cricket/beetle predatation study, cave diving exploration in regional aquifers, and geomorphic studies of regional caves. Other research stemming from this collected data has detected evidence of a previously unknown fault though sinkhole and conduit alignments.

The Kentucky Speleological Survey

Because of the cooperative atmosphere of the I-66 research, a desire to gather and organize the extensive karst data for all of Kentucky prompted the formation of the Kentucky Speleological Survey (KSS) during 1999 and 2000. KSS was formed to serve as a statewide database and repository for cave- and other karst-related data. The establishment of KSS is an important step toward proper planning and zoning in karst regions, implementation of best management practices for karst, and advancing the state of knowledge about karst through research.

The utilization of GIS as an integral component of KSS's data gathering and archiving activities was emphasized during organization. Currently, KSS uses ArcView linked to Access databases and spreadsheets to manage all its spatial data. This allows the user to link multimedia data such as narrative files, scanned maps, and cave photographs to the primary spatial index of feature locations. This will provide the framework needed for an eventual, fully integrated database of material without the need for paper copies.

Sinkhole Digitization Project

An example of one of the issues that KSS is addressing arose during the work in Pulaski County for the I-66 efforts. The interstate development problem illuminated the need for a detailed statewide sinkhole delineation. Following a review of the results of the I-66 Special Project, NSS, and considering the ongoing groundwater investigations occurring at the Kentucky Geological Survey (KGS), a decision was made to complete a sinkhole digitizing effort for all of Kentucky on a 1:24,000 scale.

The sinkhole digitization required that several data issues be addressed. These included the representation of complex uvalas (sinkholes with multiple sink points), differences in contour intervals between topographic quadrangles and their effects on data resolution, and manipulation of United States Geological Survey hypsography files.
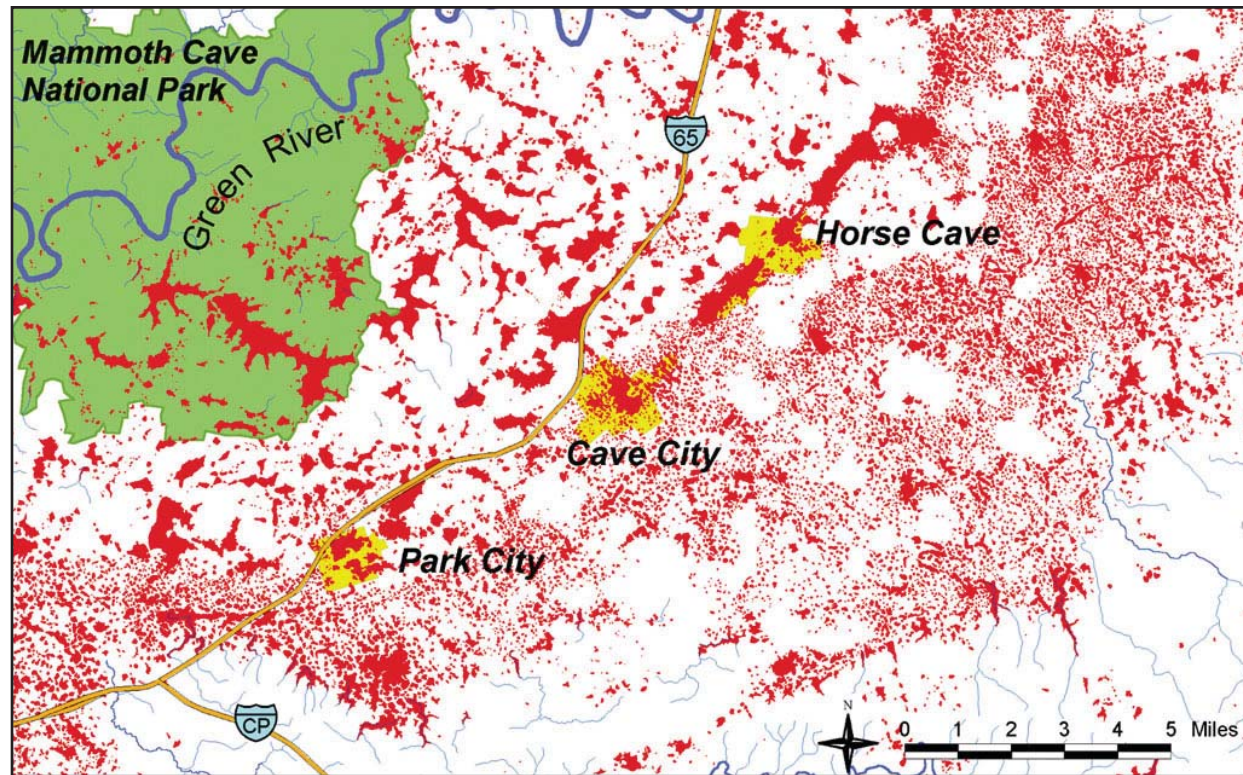
Sinkhole distribution for Western Kentucky area.

The statistics generated by the KSS sinkhole digitization project are impressive. Nearing completion, more than 62,000 sinkholes have been digitized to date for Kentucky. The combined area of these polygons suggests that approximately 3 percent (more than 1,200 square miles) of the surface of Kentucky lies within a topographically mapped sinkhole. The sinkhole digitization effort has also helped KGS develop more effective dye tracing methods due to the recognition of regional sinkhole lineaments.

The completed statewide sinkhole coverage will be published through KSS and KGS and will include a descriptive folio and data CD-ROM. The coverage will be useful for many purposes including planning, resource management, cave and karst research, groundwater studies, and statistical analysis.

Continuing Study   A 3D model of the Sloans Valley Cave System is being developed using ArcView with the ArcView Spatial Analyst and ArcView 3D Analyst software extensions. The GIS is nearing completion and will be used to model water levels, cave stream and reservoir water mixing, siltation, and landfill runoff routes through the cave.

(Reprinted from the Winter 2002/2003 issue of *ArcNews* magazine)

Timpanogos Cave National Monument, Utah, Applies GIS

Three-Dimensional Visualization Aids Both Study and Recreation

By B.E. McNeil, J.D. Jasper, D.A. Luchsinger, and M.V. Ransmeier

Timpanogos Cave (TICA) National Monument is a 250-acre site surrounded by forest service wilderness areas and easily accessible by more than one million people along the Wasatch Front, Utah. It is set in American Fork Canyon, a limestone canyon with geologically spectacular cliffs, avalanche chutes, pinnacles, and caves. The monument was created in 1922 to protect the Timpanogos Cave system, a set of three caverns perched in a cliff band 1,500 feet above the canyon floor. The cave system is known for its spectacular coloration and abundance of helictites. More than 70,000 visitors tour the caves each year and are placing increasing demands on the resources.

Rockfall danger to the trail as seen from the cave entrance looking northwest. Note the visitors on the trail in the bottom left and the loose rockfall debris directly above and below them. Red lines on trail warn visitors of dangerous rockfall areas. (Photo courtesy of J. Jasper)

GIS has long been known as a valuable tool to better manage, interpret, and maintain resources. It is also a proven decision support system. With these benefits in mind, the managers at TICA sought to implement this valuable technology. Having worked closely over the years with ESRI's Cave and Karst Program and also with ESRI's Conservation Program, TICA chose to implement ArcView 3.2 with the ArcView Spatial Analyst and ArcView 3D Analyst extensions. TICA management then requested data development and GIS planning technical assistance from the National Park Service Intermountain Region GIS Support Office in Denver, Colorado. This request led to the development of a comprehensive GIS plan and the beginning of collaborations with the University of Denver Department of Geography. This last collaboration has been very fruitful; many of the data layers and applications presented in this report are the result of undergraduate and graduate research.

Applications

Data collection and development are paramount to applications in a GIS. Data development for a GIS must be customized to requirements and barriers of the study area. At TICA, all data must be high resolution, be highly accurate, and function relative to the extreme topography and/or three-dimensional cave environment. Data has been collected and developed from a variety of sources including GPS, hard-copy maps, existing information databases, and aerial photography. Many applications are made possible through the development of a high-resolution Digital Terrain Model (DTM). The DTM serves as the key base layer for TICA's GIS. This two-meter resolution DTM has been created through digitizing and interpolating 10-foot contour lines obtained from a hard-copy, 1 inch = 100 feet scale map. The terrain model has been checked for accuracy through the collection of 75 randomly distributed, highly accurate GPS control points. The accuracy and resolution of the DTM allows the GIS at TICA to visualize features and model phenomena in ways not possible with commonly available terrain models.

A demonstration of the power and usefulness of the DTM has come through the completion of a rockfall hazard model. The unstable Deseret Limestone geology, steep topography, and multitude of visitors all combine to make rockfall a hazard of much concern for managers at TICA. While rockfall chutes and many hazard-prone areas along the trail to the cave are well known, the GIS is now a powerful tool to quantify and objectify the rockfall hazard to TICA visitors, employees, and structures. The relative hazard model uses the DTM to delineate rockfall paths and determine slope while incorporating a vegetation map to account for friction. The velocity of falling rocks could be calculated for every location (grid cell) in a hazard area. Using this method, the rock's velocity is calculated at each cell using a mathematical equation

accounting for friction, gravity, horizontal distance, and vertical distance of the rock's fall. As the equation was translated into an ArcInfo GRID modeling environment, the velocity was calculated through running the FLOWLENGTH GRID command over a cost-distance surface simulating resistance to rockfall. Because it was not possible or necessary to obtain exact rockfall velocities, the model results in output maps representing hazard in relative terms (e.g., low, high, and extreme), identifying dangerous rockfall paths. These maps are used by TICA management as planning and decision making tools for source area stabilization and hazard mitigation.
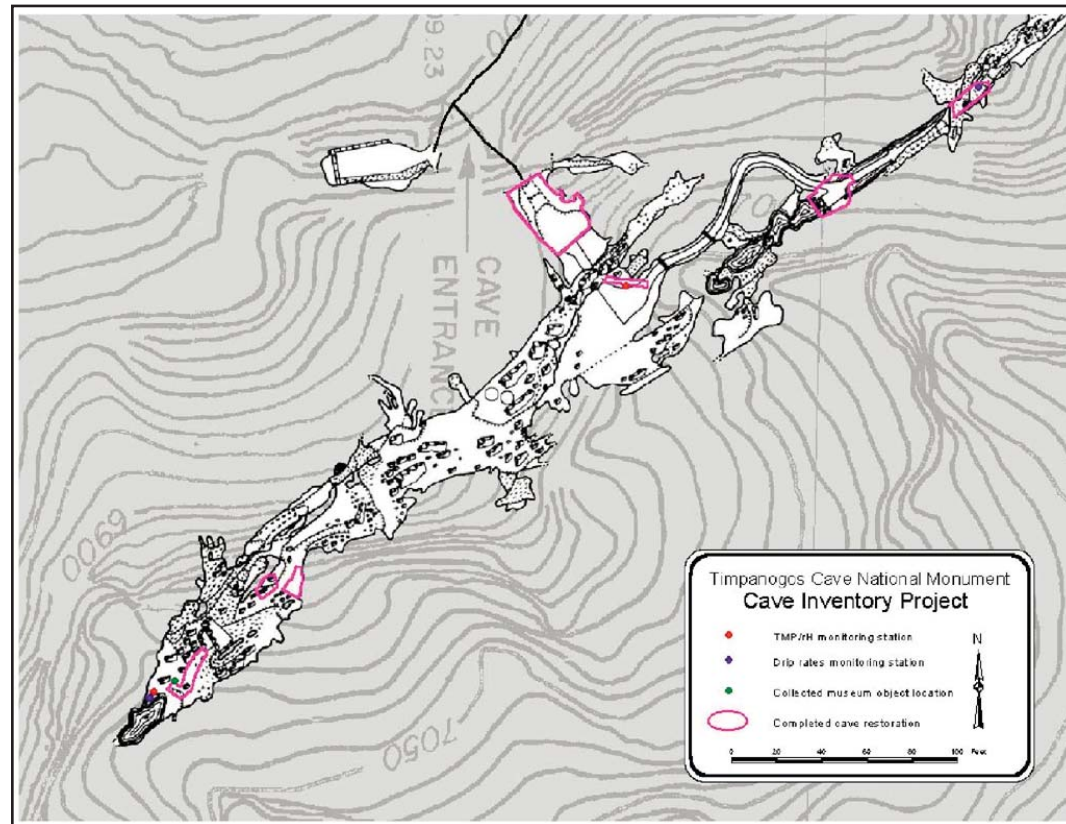
The georeferenced cave map showing overlying 10-foot contour lines.

Visualizing and a Virtual Field Trip

The DTM and the GIS now allow management at TICA to visualize the cave and overlying terrain for purposes ranging from interpretation to natural resource management. Using the DTM and cave maps as background images, the park interpretive staff and the University of Denver have created a virtual field trip. While this field trip is structured and realized in a Web-based design, it is inherently a GIS application, interactively displaying and managing spatial information in the form of maps. The TICA virtual field trip is designed in a Web-based format to embrace the largest possible virtual visitor population and allow that population the freedom to explore the cave and cave trail from anywhere at any time.
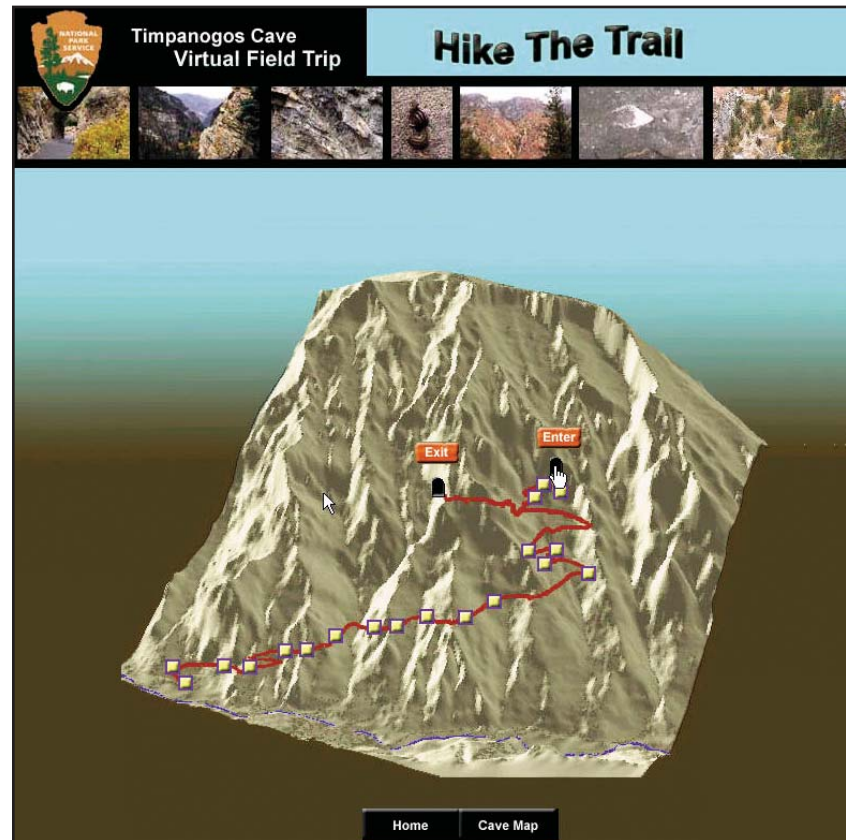
Virtual field trip Web screen.

The inspiration to create a virtual field trip for TICA arose largely out of the limited accessibility to the caves and the limited nature of interpretation along the trail leading to the caves' entrance. Because the Timpanogos Cave system is located high on the south wall of the American Fork Canyon, visitors must climb 1,065 feet in elevation over 1.5 miles of hard-surfaced trail to reach the entrance to the caves. This climb is challenging for most visitors and actually prevents a significant population from being able to reach the caves at all. During the late fall and winter months, the trail is completely closed to the public because of dangerous ice and snow on the trail as well as increased rockfall hazard. Virtual field trips enable people to experience the full resources of TICA regardless of their physical condition or the time of year. It is hoped that TICA will soon be able to provide access to the virtual field trip from its visitor center so that during times of inclement weather or when visitors find themselves unable to hike the trail, they will be able to enjoy the park.

Visitors to TICA's virtual field trip may choose to "hike the trail" or "tour the cave" from the home page (www.nps.gov/tica/index.htm).

Visualizing and Natural Resource Management

Natural resource management has also benefited greatly from the visualization opportunities of the GIS at TICA. One of the most basic gains in understanding the cave resource has come through visualizing the cave and its overlying topography. The three-dimensional cave line plot is created through reading the survey coordinates (distance, bearing, and altitude) into COMPASS software (www.fountainware.com/compass). The CAVETOOLS extension of ArcView will then convert the COMPASS data to a three-dimensional ArcView shapefile. GPS locations of surface features identifiable on the original cave survey are used to georeference the three-dimensional shapefile.

Creating GIS layers of cave features is problematic since aerial photography and GPS techniques are not possible. To overcome these obstacles, a scanned Timpanogos Cave map was georeferenced to the line plot shapefile. This map provides an excellent base for recording and planning management actions. The cave map is the ultimate utility for management of cave-related data. Currently the park is documenting its cave cleaning efforts, photomonitoring points, habitat zones, electrical corridors, place names, and significant cave features. GIS

provides the framework for managing all this data in its natural, spatially interconnected environment. Powerful resource management decisions and conclusions are now available because of this more spatially aware information management.

(Reprinted from the Fall 2002 issue of *ArcNews* magazine)

GIS Sheds Light on Underground Wilderness

The Greatest Cave Restoration Success Story in the United States

Hidden River Cave is located directly beneath the Town of Horse Cave in south central Kentucky. Providing shelter and water to native Americans for untold centuries, the cave holds an underground river that became the source of drinking water for the Town. At the beginning of this century, the river was harnessed to furnish hydroelectricity to the Town. The cave was also commercialized and shown to tourists from 1912 through 1943.

Groundwater pollution from domestic and industrial sewage was one of the factors that led to the cave's closing in 1943. For 50 years Hidden River Cave was little more than an open sewer. Although it was known that wastes were entering the cave, there was no understanding of the relationship between cave passages and the Town. Researchers began surveying the cave in 1989, mapping more than seven miles, but they were unable to create an accurate picture of the relationship between the underground passages and the surface terrain.

The Cave Research Foundation, currently leading the survey effort in the cave, was provided the software tools to do the job through the ESRI Conservation Program. Using ArcView GIS and the ArcView 3D Analyst and ArcView Spatial Analyst extensions, the Cave Research Foundation integrated cave survey data with USGS surface data to reveal the spatial relationship between the underground passages and the Town, clearly showing how local surface waste disposal sites fed directly into the cave.

This is not an isolated instance of the importance of having adequate geospatial tools for studying caves and karst (i.e., irregular limestone regions with sinks, underground streams, and caverns). In recent years the significance of karst and caves has achieved widespread recognition. As pointed out by the National Park Service's National Cave Management coordinator, Ronal Kerbo, cave and karst systems are important for two major reasons.

First, most of the nation's freshwater resources are groundwater. About 25 percent of the groundwater is located in cave and karst regions. The National Geographic Society notes that water resources are a critical concern as society enters the 21st century. The protection and management of these vital water resources are critical to public health and to sustainable economic development.

Second, caves are storehouses of information on natural resources, human history, and evolution. Recent studies indicate that caves contain valuable data that is relevant to global climate change, waste disposal, groundwater supply and contamination, petroleum recovery, and biomedical investigations. Caves also contain data that is pertinent to anthropological, archaeological, geological, paleontological, and mineralogical discoveries and resources.

None of the components of this interlocking set of resources can be fully understood without understanding their systemic relationships with the many other components. Understanding, protecting, managing, and conserving such an extraordinarily rich and complex set of resources requires tools capable of integrating, manipulating, and querying the information used to describe their many facets. GIS provides those tools.

In 1997, recognizing that GIS technology was rapidly becoming one of the most effective approaches to cave and karst resource management, the Cave Research Foundation established a GIS Resource Development Program. The goal of the program is to assist CRF personnel, federal agency staff, and other researchers access and utilize spatial data, GIS applications, and other software tools for the purpose of cave and karst resource management. A longer term goal is to use GIS to develop a collective knowledge and support base for cave conservation, protection, and management.

The importance of cave and karst research was also recognized at ESRI with the establishment of a Cave and Karst section in the ESRI Conservation Program and an ESRI Cave and Karst Special Interest Group that meets at the annual ESRI User Conference.

The CRF GIS Resource Development Program is drawing together GIS expertise to assist in the development of Cave and Karst Information Systems (CKIS). CRF GIS personnel include individuals with broad and varied expertise, who can provide resources, support, assistance, services, and tools to aid researchers in both understanding and effectively managing caves and karst.

Critical requirements in the CKIS development process are a survey of currently used software and methods, an inventory of existing data and data formats, a user needs assessment, a knowledge of training needs, and the initiation of a core CKIS prototype that can be tested and elaborated to provide specific tools and applications suited to the varying needs of different users.

In the case of Hidden River Cave, a few simple tools provided critical information about the mysterious world beneath a small rural town in Kentucky. The cave is now operated by the American Cave Conservation Association, which relocated their national headquarters to Horse Cave with the goal of restoring Hidden River Cave and establishing a museum and educational center at the site. Today, thousands of visitors and school children annually tour Hidden River Cave and the American Cave Museum at the cave's entrance. The cave, which has been called "the greatest cave restoration success story in the United States," is now open year-round to visitors. Guided tours lead visitors to views of the underground river and a turn-of-the-century hydroelectric generating system that once supplied the Town above with water and electric power.

(Reprinted from the Fall 2000 issue of *ArcNews* magazine)

Spatial Analysis of an Ancient Cave Site

By Holley Moyes, State University of New York at Buffalo and
Dr. Jaime J. Awe, University of New Hampshire

The Western Belize Regional Cave Project (WBRCP) has conducted investigations at the ancient Mayan cave site of Actun Tunichil Muknal since 1996. GIS is being used as a mapping and analytical tool in the investigation of the cave's Main Chamber, the area most intensively and extensively used by the ancient Maya.

GIS introduces a new way of seeing the world.

GIS has made it possible to analyze depositional patterns of artifact placement as well as catalog and quantify artifacts. It has provided a well-structured descriptive and analytical tool that has been instrumental in the identification of spatial patterns and will facilitate future regional analysis and intersite comparisons of archaeological data.

GIS has most frequently been employed in archaeological studies for large-scale regional analyses and predictive modeling of settlement patterns and land use. The potential of GIS as a tool for the organization and analysis of spatial data within a single site has hardly been tapped.

About the Project

The WBRCP is directed by one of the authors, Dr. Jaime Awe of the University of New Hampshire. The project is funded by the Social Science and Humanities Research Counsel of Canada. Project work has included the creation of a GIS to investigate the Main Chamber of Actun Tunichil Muknal. This ancient Mayan cave site is located on a tributary of the Roaring Creek River.

A stream, originating within the cave, runs through its five-kilometer length and culminates at the cave's eastern entrance in a deep green pool. The Main Chamber occupies a high elevation passage above the main tunnel system some 500 meters from the cave entrance. The chamber consists of a series of rooms containing at least 718 artifacts, many of which were broken. Cross-dating of the ceramic assemblage suggests that the chamber was used during the Terminal Classic Period (830-950 C.E.).

A stream, originating within the cave, runs through its five-kilometer length and culminates at the cave's eastern entrance in a deep green pool.

Project Goals

The goals of the project were to record and provenience artifact data, catalog artifact attributes, and analyze deposition patterns. Many of the artifacts in the Main Chamber are cemented to the floor by flowstone (calcium carbonate), which has prevented looters from stealing them and archaeologists from collecting them. This unusual circumstance made the site an ideal location for establishing a natural museum. Because the cave may become a future ecotourist destination, cataloging the artifact assemblage is essential for its conservation and management.

Throughout ancient Mesoamerica caves functioned as ritual spaces—a tradition that has continued to the present day. Many researchers believe that caves were used as a ritual venue to petition gods that controlled the renewal and sustenance of the earth as well as the creation and perpetuation of life itself. Although there is good general understanding of ancient cave use, the nature of the actual rituals that were performed in caves remains a mystery. To complicate matters, archaeologists suspect that there may have been a good deal of variation in use from one cave to another. Isolating these different types of uses starts with a more sophisticated approach to the analysis of each cave.

Viewing Artifacts Two Ways

Since the largest part of the artifact assemblage in Actun Tunichil Muknal consists of sherds (broken pieces) of fairly standard Maya ceramic vessels, it was clear that the usual analysis of artifact attributes would not yield significant insights into the nature of ritual or possible intersite variation in cave use. Artifacts deposited in Actun Tunichil Muknal are assumed to be the remains of ancient rites, direct offerings to deities, or both. By viewing artifact distributions on both local and global scales, researchers hoped that patterns could be discerned in the way artifacts were deposited and associated. These patterns would offer insight into the use of space that could help to determine how the site was used and which rituals were performed.

To meet these goals, the project needed software that could handle large quantities of data as well as create visual displays of that data. Although CAD or DBMS systems organize data and produce images, these systems are not designed to create new data. GIS provided an easily manipulated database, a method for visual display of data, and a tool for the analysis of spatially referenced data—all advantages over other systems considered. In addition, the geographic position and attributes for every artifact in the chamber can be located on a single map that can be viewed globally or in sections.

Using GIS   Field mapping was done using tape and compass. Artifacts were recorded in one-meter square grids that were transferred to the basemap. The paper map was plotted on a scale of 1:60 to enhance detail and accuracy. The map, digitized using ArcInfo, contained morphological features of the cave shown in line and polygon coverages and artifact locations recorded in a point coverage. Artifacts were given discrete eight-digit ID numbers that were coded by artifact class.

The cave's morphological features were divided into seven categories: alcoves, boulders, breakdown, niches, pools, stalagmites/stalactites, and walls and walkways. Each feature category was made into a separate coverage, and these files were imported into ArcView GIS. Attributes were added to the artifact point coverage.

Using this data, a map of the chamber illustrating the cave features and placement of artifacts was produced. The ability to view the site at different scales is one of the major advantages of GIS. Assessments could be made concerning the overall spatial layout of artifacts by globally viewing the cave and its contents. Smaller areas could also be examined so that a more fine-grained analytical approach could be used. Both global and detail maps were easily produced using the ArcView GIS layout function.
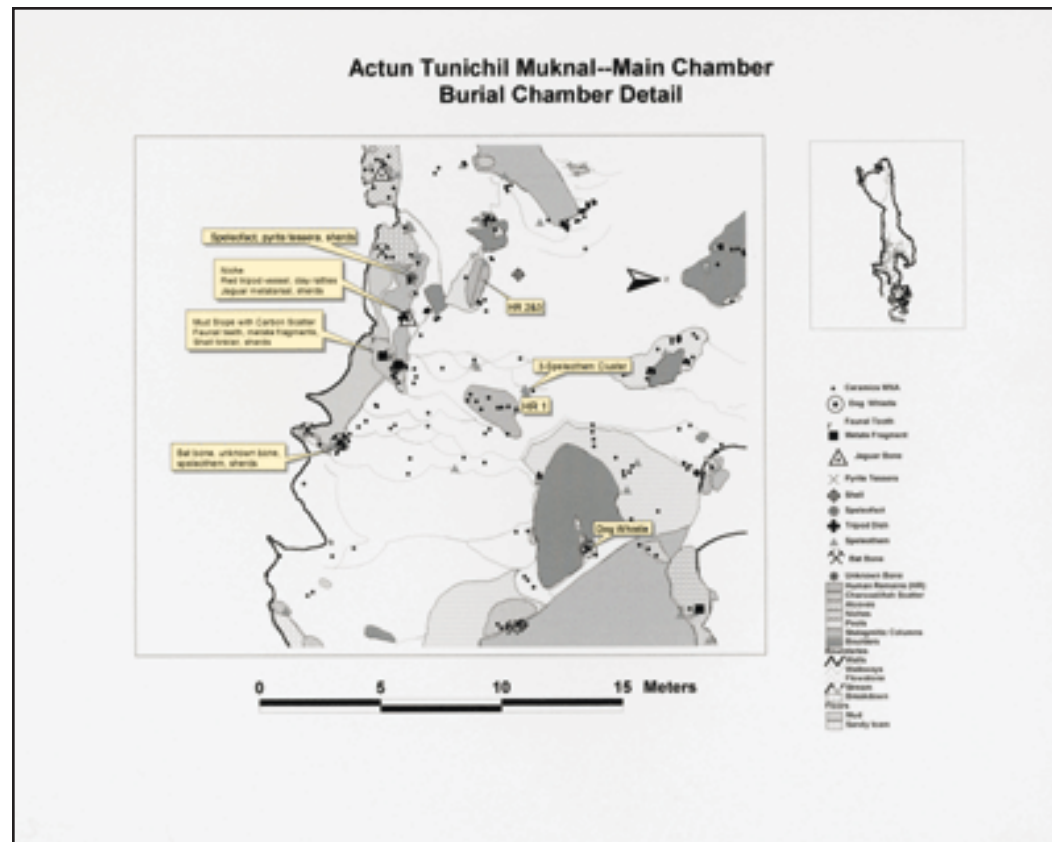
By generating shapefiles from the artifacts classes and buffering these shapefiles,
the relationships between artifact classes could be determined.

By using GIS as a management tool, artifacts could not only be quantified but could also easily be reorganized and reassigned into subclasses. The artifact ID numbers simplified this task, allowing rapid production of data tables. By generating shapefiles from the artifacts classes and buffering these shapefiles, the relationships between artifact classes could be determined.

For example, by displaying the data for the locations of all the ceramic bowls in the cave and creating buffers around these artifacts, it was possible to search for correlation between bowls and other artifact classes. The buffer function also made it possible to determine if particular

categories of morphological features of the cave were preferred for ritual activities. Buffers for geomorphic feature coverages were created so that counts for the number of artifacts falling within these zones could be generated.

A New Approach to Archaeological Interpretation

Specific aspects of ritual behavior were quantified using GIS. For instance, findings showed that the most common artifact in the cave was a ceramic jar that was traditionally used to hold water. These jars represented 29 percent of the total assemblage of the cave. It was also discovered that 51 percent of all artifacts were located in pools.

The data generated by the GIS was compared with ethnographic and ethnohistoric reports of cave use in the region. Using these sources, a hypothesis was developed that the rituals conducted in the cave pertained to water and may have been conducted to propitiate or honor deities associated with rain or floods. These rituals included both seasonal and calendrical renewal rites. This information has led to additional lines of inquiry and a deeper understanding of cave use.

Conclusion

GIS was instrumental in implementing a new approach to interpreting the archaeological record. This approach combined quantitative and qualitative data. Although this project represents a single site, data generated in this fashion can be compared with data from other cave sites as new databases are created using GIS. This provides concrete units of analyses that may be used in comparing the ritual function of sites both within the region and for areas outside the region.

About the Authors

Holley Moyes is an Integrative Graduate Education and Research Training (IGERT) fellow in Mesoamerican archaeology at the State University of New York at Buffalo. The IGERT program, sponsored by the National Science Foundation, awards a fellowship for cross-disciplinary study of GIS. Moyes' graduate work is in speleoarchaeology and the study of ancient Mayan religion.

Dr. Jaime J. Awe is an assistant professor of archaeology at the University of New Hampshire and director of the Western Belize Regional Cave Project. He is a native Belizean and serves as the director of the Belize Department of Archaeology.

All photos courtesy of Holley Moyes

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Building a Groundwater Protection Model

By Rhonda M. Glennon, ESRI, and
J. Alan Glennon, University of California, Santa Barbara

This tutorial uses the new tools from ArcGIS 9 to build a model that performs multiple geoprocessing operations to study groundwater contamination issues in Kentucky's Mammoth Cave Watershed. It requires ArcGIS 9 Desktop with an ArcView, ArcEditor, or ArcInfo license. ArcGIS 9 provides a comprehensive set of geoprocessing tools and a new framework for working with them. At ArcGIS 9, ArcToolbox became a dockable window integrated into ArcMap and ArcCatalog, rather than the stand-alone application in ArcGIS 8.3. Tools can be run using dialog boxes, within scripts, and as commands typed in a command line window or can be linked in a visual modeling environment—the ModelBuilder window.

In ArcGIS, a model is a representation of a system of processes that performs operations on GIS datasets. Through the visual model building interface, proposed analyses are more easily translated into ordered steps. Models allow data and tools to be linked together in a user-defined sequence that structures and automates geoprocessing tasks such as buffering, converting, overlaying, or selecting data.

Working With Model Elements and Processes

Model diagrams are viewed and edited in the ModelBuilder window, which can be opened from the ArcToolbox window. A model is built from one or more processes. A process is formed by connecting various component elements for input data, a tool, and output data. Project data elements are visual representations of the geographic input data that exists before the model runs. Tool elements signify operations to be performed on input data. The output data elements represent derived data elements that can also serve as input data for other processes. Scripts or other models can be embedded within a model.

If all the elements of a model are colored, that model is ready to run. The default element colors are blue for project data, yellow for tools, and green fo derived data elements. Once a process has executed successfully, drop shadow is added to the tool and all derived elements. To enhance efficiency, when new processes are added to the model after other processes have been run, only new processes will be run unless the parameter values of existing processes have been modified or the user specifies that the entire model be run.

This model of the Mammoth Cave Watershed covers approximately 300 square kilometers and exhibits karst geology, which is characterized by caves, sinkholes, rapid groundwater flow, and few surface streams. Karst systems, such as Mammoth Cave Watershed, are vulnerable to contamination, and groundwater quality in these areas is often closely related to land use practices.

Building the Groundwater Protection Model

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Amounts of agricultural chemicals have often been measured in the Mammoth Cave Watershed groundwater. Sinking streams—streams that flow on the surface before draining into the karst underground—are typical avenues for unfiltered contamination to drain into groundwater. All surface streams eventually disappear and drain into the subsurface in the Mammoth Cave Watershed. Runoff from steep-sloped crop fields is one likely source of these agricultural chemicals.

By linking these considerations, crop fields on sloped lands near streams can be identified. These areas are likely to possess a greater influence on the watershed's groundwater quality. Steps from such a conceptual model can be visually organized and translated into the ModelBuilder environment in a straightforward manner.

Setting Up the Tutorial

This model organizes clip, buffer, and intersection processes that will be performed on four geodatabase feature classes—watershed, slopes, landuse, and streams. Using the ArcGIS 9 Spatial Analyst extension, the slope data for this tutorial was created from digital elevation models (DEMs), reclassified by steepness, and converted to polygon features. The model first clips the slope layer to the area of the watershed, then identifies areas with the greatest slopes. Next, the model identifies the crop fields from a landuse layer and creates a buffer around the surface streams. By calculating two spatial intersections, the model locates the crop fields that are situated on slopes and within the stream buffer.
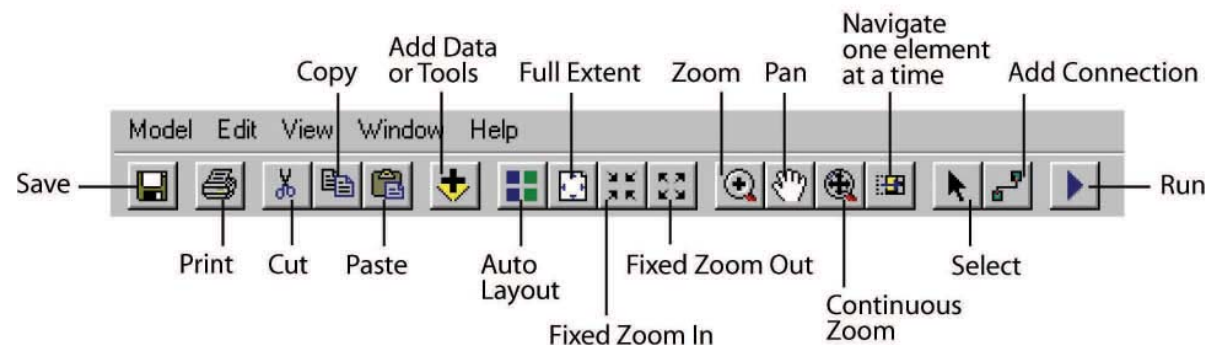
Toolbar for ModelBuilder.

1. Download and unzip the sample dataset from ArcUser Online (www.esri.com/arcuser) to create the cave_modelbuilder folder. Start ArcMap and open the project map document, cave_model.mxd, from the cave_modelbuilder folder. Add the ArcToolbox window to ArcMap by clicking the Show/Hide ArcToolbox button on the ArcMap Standard toolbar.

2. Right-click the ArcToolbox folder at the top of the ArcToolbox window and choose New Toolbox. Name the toolbox Cave Tutorial Tools and press the Enter key. By default, new toolboxes are stored in \Documents and settings\<yourlogin>\Application Data\ESRI\ ArcToolbox. The default location of My Toolboxes folder can be changed by choosing Tools > Options from the Standard menu. Click the Geoprocessing tab and browse to the new default location.

3. Right-click Cave Tutorial Tools and choose New > Model. A new model is added to the toolbox and is opened in the ModelBuilder window.

4. In the ModelBuilder window, choose Model > Model Properties from the menu bar. Click the General tab and type "Cave Groundwater Protection Model" in both the Name and Label text boxes to give the model a more descriptive name.

5. Setting a current workspace eliminates the need to browse to or type the entire path to the data location each time a tool is run. Click the Environments tab and double-click General Settings to invoke the Current Workspace text box. Check the box next to Current Workspace and click the Values button. In the Environment Settings dialog box, click General Settings to show the Current Workspace. Click the Browse button and navigate to the cave_modelbuilder folder, then click arcuser_cave_tutorial.mdb and click Add. Click OK on all dialog boxes.
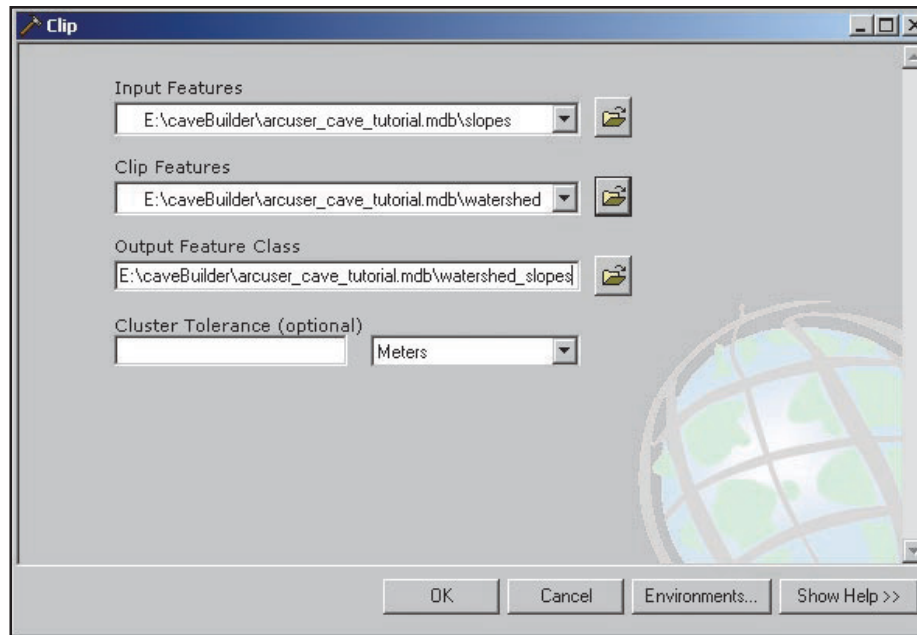
Drag the Clip tool to the model, open its dialog box, add the Input Features and Clip Features parameter values, and rename the Output Feature Class.

Clip Data to Study Area

The first process added to the model clips the slopes to the size of the watershed study area.

1. To set the layer that will be clipped and the layer will serve as the cookie cutter, click on Analysis, then Extract to expand those folders. Drag the Clip tool to the model and double-click it to open its dialog box. Click the Input Features parameter drop-down. In the dialog box, click on slopes to set as the Input Feature parameter value and click on watershed to set it as the Clip Features parameter value. The Clip tool and the Output Feature Class elements are linked automatically. Rename the Output Feature Class to watershed_slopes. Click OK.

2. Tools in ArcToolbox can be quickly located using the Search box. Click the Search tab at the bottom of the ArcToolbox window, type Make Feature Layer in the Search box, and click the Search button. Click Make Feature Layer in the results list and click the Locate button to see this tool on the Favorites tab. Drag the Make Feature Layer tool into the model. The Make

Feature Layer tool allows a Structured Query Language (SQL) expression to be executed. The results generated by this tool are stored in memory as a temporary layer during the current ArcGIS session.

3. Click the Add Connection button on the toolbar at the top of the ModelBuilder window. The cursor will change to a magic wand. Click the watershed_slopes derived data element and drag a connector line to the Make Feature Layer tool.

4. Double-click on the Make Feature Layer tool to open its dialog box. Type steep_slopes for the Output Layer parameter value. Expressions can be saved, shared, and reused. A SQL expression created for this tutorial, slopesquery.exp, will be loaded. Click the SQL button and click the Load button on the Query Builder dialog box. Navigate to the cave_ modelbuilder folder, select slopesquery.exp, and click the Open button to load it. Running this query identifies slopes greater than or equal to five degrees and places them in the new layer. Click OK on all dialog boxes.
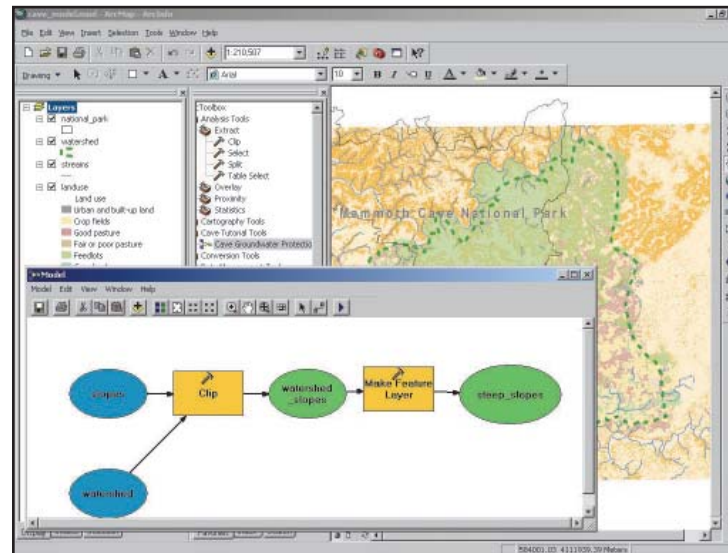
Click the SQL button and create the expression [Land_Use_Type] = 'Crop fields' in the query box.
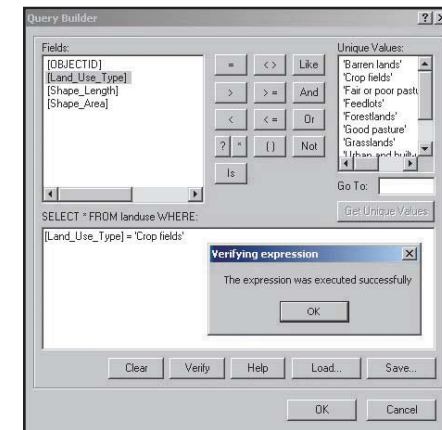
Optionally, if the diagram is getting crowded, resize the ModelBuilder window by dragging a window corner. The Auto Layout tool, located in the ModelBuilder toolbar, can also be used to redistribute model elements. Choose Window > Overview Window to open a window showing

the extent of the entire model and the current location to navigate through the model when zooming in or out.

Identify Crops on Steep Slopes

Crop lands are important to this study because groundwater contamination can be caused by agricultural chemicals. The query in this step identifies crop land located on steeply sloping land. To find potential sources of bacteria or nitrates, a query could be constructed that identifies feedlots.
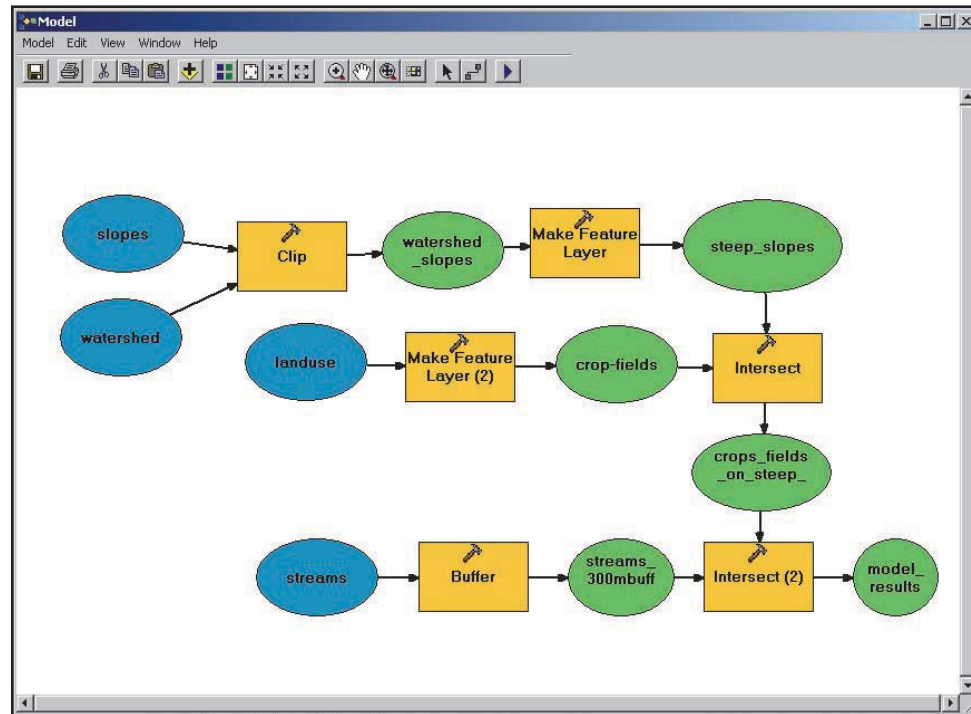
This model organizes clip, buffer, and intersection processes that will be performed on four geodatabase feature classes—watershed, slopes, landuse, and streams—to identify crop fields on steeply sloping land that is near streams.

1. Drag another Make Feature Layer tool into the model; this tool is labeled as Make Feature Layer (2) in the model. Open the Make Feature Layer (2) tool's dialog box. Click landuse in the Input Features parameter drop-down and type 'crop_fields' for the Output Layer parameter value.

2. Click the SQL button. Create the expression [Land_Use_Type] = 'Crop fields' in the query box. Double-click Land_Use_Type, in the Fields list and click the Equal sign. Click the Get Unique Values button and double-click 'Crop fields'. Click the Verify button to make sure the expression contains no errors. Click OK on all dialog boxes.

3. Click the Index tab at the bottom of the ArcToolbox window and type Intersect in the keyword box. Click Intersect (analysis) in the list and drag the Intersect tool into the model. This tool will find features that are geometrically common to the two input layers, and it will be used to identify the crop fields that are located on steep slopes.

4. Connect the crop_fields element and the steep_slopes element to the Intersect tool. Open the Intersect tool dialog box and type crops_fields_on_steep_slopes for the Output Feature Class. Click OK.

5. In the Model menu, click Save.

Buffering Streams   The next step is to buffer the streams so the crop fields on steep slopes that are located on slopes and within the stream buffer can be identified.

1.   In the ArcToolbox window, type Buffer in the keyword list on the Index tab. Click Buffer (analysis) and click the Locate button so you can see the tool on the Favorites tab. Drag the Buffer tool into the model.

2. Open the Buffer tool's dialog box. Click streams in the Input Features parameter drop-down and type streams_300mbuffer for the Output Feature Class. Under Distance, type 300 for the Linear unit and make sure that Meters is selected in the drop-down. Click the Dissolve Type drop-down and choose ALL so all the buffers are dissolved into a single feature. Click OK.

3. Locate the Intersect tool from the Overlay toolset in the Analysis toolbox and drag it to the model. It will be used to identify the crops fields that are on steep slopes and within the streams buffer.

4. Connect the streams_300mbuffer and crop_fields_on_steep_slopes elements to the Intersect (2) tool. Open the Intersect (2) tool dialog box. Type model_results as the name of the Output Feature Class and click OK.

5. Right-click the model_results element and choose Add To Display so the feature class will be added to the map once the model runs.

6. The model is ready to run. First save it. Choose Model > Run Entire Model from the ModelBuilder menu. When a process is running, status messages appear on-screen and the tool element's symbol turns red.
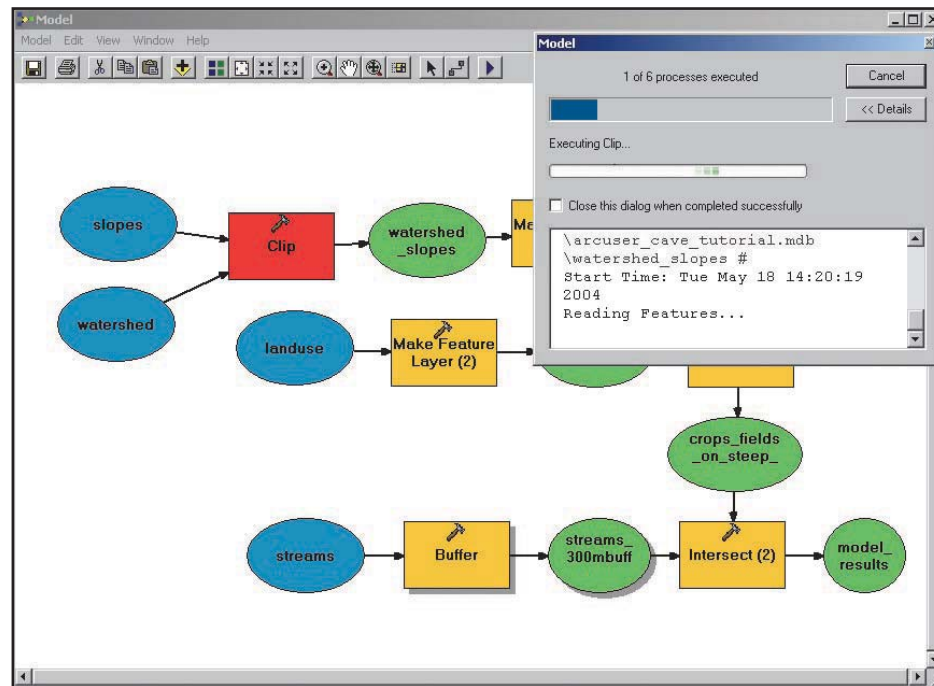
When the model is run, the tool element for each active process turns red and status messages appear on-screen. The resulting feature class is added to the map.

The new model_results feature class is added to the map. Right-click the model_results layer in the ArcMap Table of Contents and change its fill color to a shade of red to highlight these features. Optionally, choose Select By Location or Select By Attribute to select an entire crop field polygon by selecting crop field features in the land use layer that intersect the features in the model_results layer.

Modifying and Sharing the Model

By examining the slopes, land uses, and stream buffers, the analysis in the tutorial identifies several hundred targets for study that may yield higher-than-normal influence on Mammoth Cave's groundwater quality. The model and its processes can also be modified and adapted for other studies. For example, when investigating potential sources of runoff from petroleum products in the Mammoth Cave Watershed, the query in the Make Feature Layer (2) process could identify urban areas such as roads, oil wells, and dumps. By setting the SQL expression parameter for the Make Feature Layer (2) tool as a variable and exposing it as a model parameter, the user could replace that expression with a different one. Model parameters are labeled with a P in the ModelBuilder window.

Sharing models can extend their usefulness by allowing others to add input. Adding documentation can also make it easier to share a model with others. Documentation for a model process can include text, bulleted lists, graphics, hyperlinks, and other items. This information appears under the Help for the model. It is opened from within the ArcToolbox window as a table of model elements containing the name of the process and the description added by the user. Models can be exported to a variety of graphic formats so images of the model can be placed in the Help for a model, in a dialog box, or other documents. The ArcToolbox Documentation Editor also provides templates for adding to Help for a model and creating the model metadata that can include information about its authors and use restrictions.

A model can be exported to one of three scripting languages—Python, JScript, and VBScript. Scripting allows for additional automation, advanced batch processing, and the inclusion of more advanced logic. After being exported as a script, a model can be distributed as a text document, added to a toolbox, and run as a tool. Sharing the toolbox containing a model is another way to share a model. However, the data, scripts, and other associated files with a model need to be provided. On the General tab of the Model Properties dialog box, check the box to store relative path names so others won't have to reconstruct file locations.
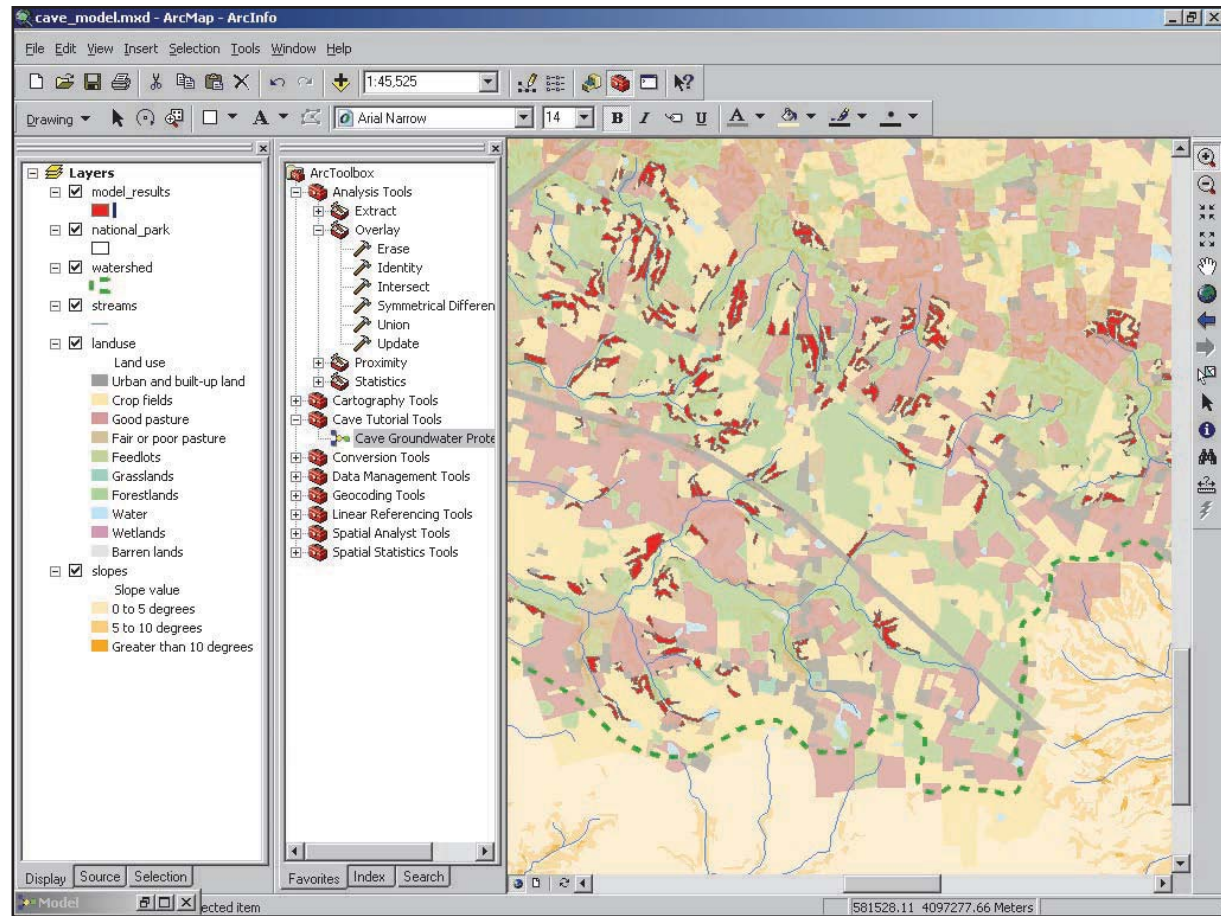
To highlight the identified areas, change the model_results layer to red.

Conclusion   Models are a particularly useful addition to ArcGIS. GIS models and objects can initiate a series of complex and iterative functions on other features within a spatial database. These advanced spatial analyses can be completed with ArcView or ArcEditor, but additional tools are available when using ArcInfo and the ArcGIS extension products.

**A Glossary of
Geoprocessing Terms**

Connector—A visual representation of the relationship between elements in a model. Connectors join elements together to create processes.

Geoprocessing—A GIS operation used to manipulate data stored in a GIS workspace. A typical geoprocessing operation takes an input dataset, performs an operation on that dataset, and returns the result of the operation as an output dataset.

Derived data—Data created by running a geoprocessing operation on existing project data. Derived data from one process can serve as input data for another process.

Model—An abstraction and description used to represent objects, processes, or events. In geoprocessing, a model consists of one process or a sequence of processes connected together.

Model parameter—A type of parameter exposed in a model that displays in a model's dialog box and allows for input.

Parameter—A characteristic of a tool. Values set for parameters define a tool's behavior during run time.

Process—A tool and its parameter values. One process, or multiple processes connected together, creates a model.

Project data—Geographic input data that exists before a geoprocessing tool is run.

Tool—An entity in ArcGIS that performs such specific geoprocessing tasks as clip, split, erase, or buffer. A tool can belong to any number of toolsets and toolboxes.

Variable—A container that holds a value that can be changed. In the context of a model, a variable can be created and its value used in place of a parameter value. A variable is created when data is dragged into the ModelBuilder window or a value for input dataset parameters is supplied inside a tool's dialog box.

About the Authors

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Exploring the Karst Landscape of Cockpit Country

By Parris Lyew-Ayee, School of Geography and the Environment, University of Oxford

Editor's note: Parris Lyew-Ayee, a doctoral student in the School of Geography and the Environment, University of Oxford, United Kingdom, is using GIS in his study of karst geomorphology not only as a research tool but also to manage and optimize his fieldwork. He is working in a unique region in the interior of western Jamaica called Cockpit Country. The area's thousands of depressions, caused by the erosion of limestone, were thought to resemble cockfighting arenas of 17th century England. Its rugged terrain has limited human incursions and helped preserve the area's biodiversity.

With its deep karst depressions surrounded by residual hills, the Jamaican Cockpit Country is the type area for the cockpit variety of karst landscape. GIS was used to conduct a comprehensive morphometric *[shape measurement]* survey of the landscape and its features to unambiguously characterize the nature of cockpit karst in its type area and compare these landscapes with noncockpit karst areas as well as distinctly nonkarst areas from other parts of the planet. Such detailed morphometric investigations would provide information about how such landscapes evolved and the factors that control their development.

Digital terrain analyses, ranging from geostatistical investigation of the variography of the terrain to analysis of the scaling properties of karsts, as well as digital landform analysis involving the automatic delineation of karst features, were all conducted using GIS. *[Variography is an aspect of geostatistics concerned with interpreting variograms, which plot variance as a function of distance of separation.]* Additionally, virtual reality scenes were also created to represent the landscape in a photorealistic manner that furnished perspectives of the landscape that would be unavailable from the ground.

IKONOS satellite imagery of part of Cockpit Country was draped on a triangulated irregular network (TIN) representation of the terrain to provide photorealistic depictions of the study areas that were useful both before and after fieldwork.

Morphometric analysis of karst terrain has been going on since the 1970s, although the use of sophisticated computer-based techniques has not been rigorously applied to karst areas. This research involves many original methods used to describe the landscape and landforms of the Cockpit Country of Jamaica as well as adapting techniques used in other branches of geomorphology, landscape ecology, and mineral exploration. The unique characteristics of the cockpit karst landscape can then be quantified, and methods aimed at conservation and

environmental management of such areas can be devised.

This work required topographic data that was supplied through digitizing 1:12,500-scale contour maps. Creating digital elevation models (DEMs) from sources such as imagery or radar was prohibitively expensive. Instead, GPS spot heights collected in the field were integrated with the contour data and converted to vector points so that DEMs could be created. The variography of the topographic data could also be examined using geostatistics. Semivariograms of the different study areas could be produced for comparative analysis and as inputs for kriging interpolation of the data.

Once DEMs were created, the primary topographic attributes, such as mean elevation, slope, aspect, and curvature, could all be computed. Neighborhood analyses of DEMs also allowed extraction of additional information from the DEMs. The range of elevation at different neighborhood sizes revealed key differences between cockpit karst and noncockpit karst areas. As a result, cockpit karst areas could be readily identified—especially in areas of mixed topography—on the basis of their unique characteristics, and a semiautomated method of mapping cockpit karst could be developed.

Digital landform analysis involved the added complication of delimiting karst features from the overall landscape. Sinks and summits in the terrain were identified from the DEMs using hydrological modeling techniques that allowed the patterns and distributions of these features to be described. Delimiting the hills and depressions was a greater challenge. Isolating these features, using manual digitizing and supervised image classification proved unsatisfactory, so the Compound Topographic Index was used. This method involves determination of the slope and catchment areas from the original DEMs. Areas of steep slope and small catchment areas were positive relief features (hills), and areas of gentle slope and large catchment areas were negative relief features (depressions). The digital identification of sinks, summits, hills, and depressions was were all verified by ground-truthing.

The morphometric properties of the delimited landforms could then be determined. Attributes, such as area, height of hill/depth of depression, elongation, degree of circularity, surface area, and slope, were all ascertained. Additionally, the degree of isolation of each set of features could also be calculated. Again, unique properties of cockpit karst areas could be described using the terrain's constituent landforms.

The quantification of such landscapes using GIS enabled further research in determining the origins of such places and can be used in other fields such as investigating the connection between the high biodiversity of this area, its geomorphology, and the application of this information to karst terrain management. Many key assumptions about the nature of such places can be reevaluated on the basis of thorough GIS-based morphometric analysis. Other spectacular karst landscapes exist in southeast China and in other parts of the Caribbean from Belize to Barbados. The extent to which these landscapes are geomorphologically similar to each other can now be assessed.

GIS was an invaluable tool in conducting this research. With GIS, a wide-ranging database could be assembled that included topographic data and its associated derivatives, vector geology maps, and Space Imaging's IKONOS imagery. While many specialized software packages exist, GIS allowed software customization for performing detailed analyses while retaining other aspects of functionality. The GIS methodology can be easily exported elsewhere without the need to develop entirely new software and would enable comparative analyses of different areas based on the same analytical framework.

The use of GIS in this research went beyond analysis of topographic data and DEMs. GIS was also constructively used to plan the logistics of fieldwork and the sampling design for the geological portion of the research in Cockpit Country, taking into account issues of accessibility to the study areas by using satellite imagery, georeferenced topographic sheets, digitized maps, and terrain roughness. Fieldwork information could be recorded on a GPS instrument and readily transferred to the GIS for subsequent analysis. The versatility of GIS for prefieldwork planning and postfieldwork analysis, as well as detailed morphometric investigation of the area, enabled a comprehensive study of Cockpit Country to be carried out efficiently.

The entire GIS portion of the research was conducted using ArcView 3.2 and ArcGIS 8.2 software packages, which were able to integrate GPS data collected in the field as well as IKONOS satellite imagery with the rest of the dataset. Key software extensions used were ArcView Spatial Analyst, ArcView 3D Analyst, and ArcGIS Geostatistical Analyst.

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Since 1969, ESRI has been giving customers around
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