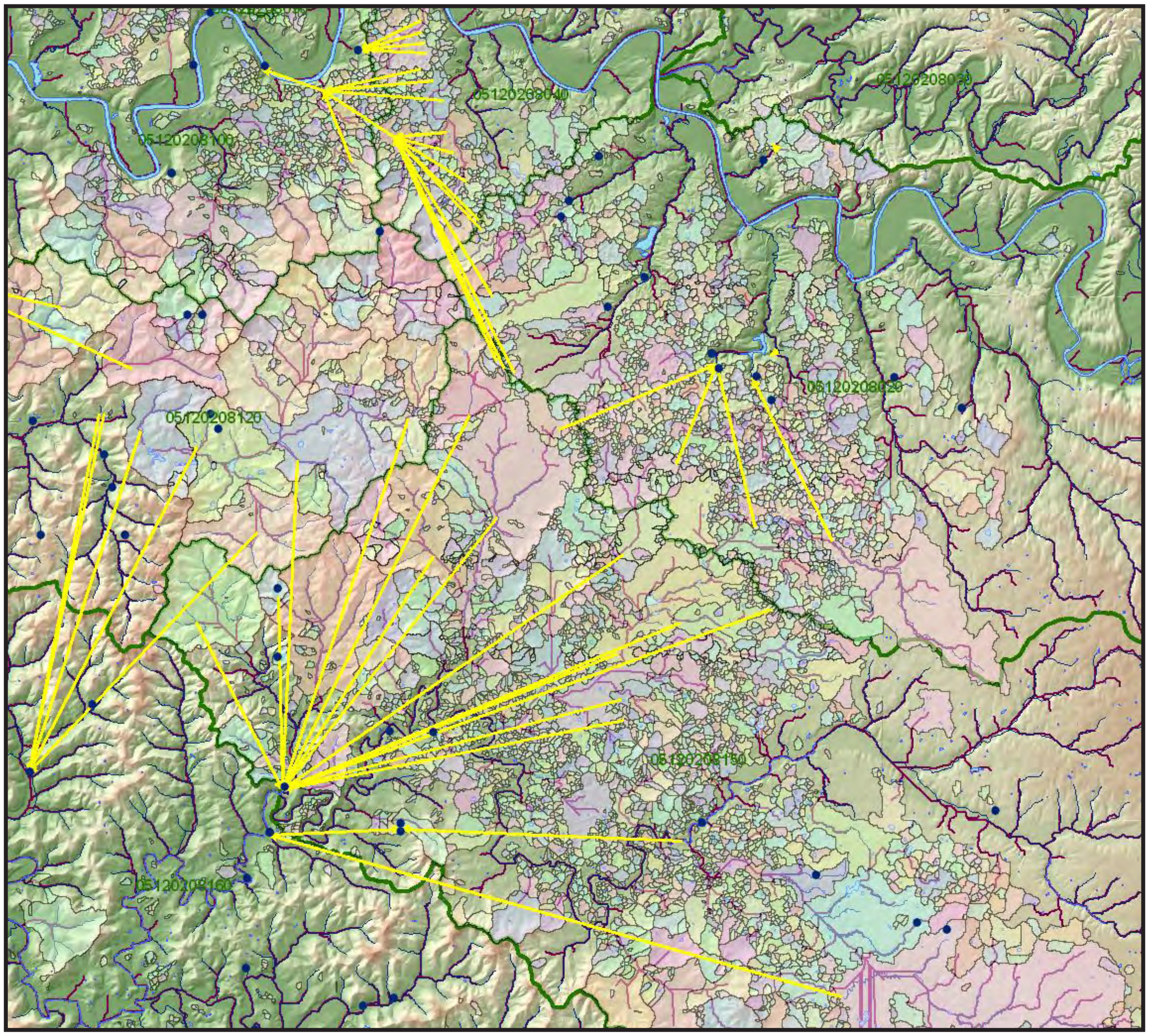
Ground-Water Resources Program

A Compilation of Provisional Karst Geospatial Data for the Interior Low Plateaus Physiographic Region, Central United States



Data Series 339

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Cover. Screen-capture image showing example of plotted dye-tracer flow paths (yellow), internally drained catchments (multi-colored polygons), and locations of inventoried karst springs (blue dots) in a portion of the White River Hydrologic Unit (05140104IN) in south-central Indiana.

A Compilation of Provisional Karst Geospatial Data for the Interior Low Plateaus Physiographic Region, Central United States

By Charles J. Taylor and Hugh L. Nelson Jr.

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U.S. Department of the Interior
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Conversion Factors

Multiply	By	To obtain
	Length	
meter	3.281	foot
foot	0.3048	meter
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)

A Compilation of Provisional Karst Geospatial Data for the Interior Low Plateaus Physiographic Region, Central United States

By Charles J. Taylor and Hugh L. Nelson Jr.

Abstract

Geospatial data needed to visualize and evaluate the hydrogeologic framework and distribution of karst features in the Interior Low Plateaus physiographic region of the central United States were compiled during 2004–2007 as part of the Ground-Water Resources Program Karst Hydrology Initiative (KHI) project. Because of the potential usefulness to environmental and water-resources regulators, private consultants, academic researchers, and others, the geospatial data files created during the KHI project are being made available to the public as a provisional regional karst dataset. To enhance accessibility and visualization, the geospatial data files have been compiled as ESRI ArcReader data folders and user-interactive Published Map Files (*.pmf* files), all of which are catalogued by the boundaries of surface watersheds using U.S. Geological Survey (USGS) eight-digit hydrologic unit codes (HUC-8s). Specific karst features included in the dataset include mapped sinkhole locations, sinking (or disappearing) streams, internally drained catchments, karst springs inventoried in the USGS National Water Information System (NWIS) database, relic stream valleys, and karst flow paths obtained from results of previously reported water-tracer tests.

Introduction

The U.S. Geological Survey (USGS) Ground-Water Resources Program (GWRP) supports regional studies of ground-water flow systems, enhanced access to ground-water data, and research into improved methods of hydrogeologic data analysis. Better regional characterization of the Nation's karst aquifers is one of several objectives included under the GWRP mission statement ("Strategic Directions for the U.S. Geological Survey Ground-Water Resources Program: A Report to Congress" dated November 30, 1998). One aspect of this objective is improving access to basic geospatial data needed to effectively map and visualize the distribution of regional karst features, and to evaluate the relation of these features to regional-to-local scale hydrogeology. Recent advances in Geographic Information System (GIS) technology and the increased accessibility of geospatial data such as Digital Elevation Model (DEM) datasets have greatly simplified the tasks required for hydrogeologic framework mapping, and GIS methods have been successfully applied in a variety of studies as an effective means of mapping the distribution of sinkholes, caves, and springs, and examining the relationships between karst features and other physical environmental characteristics (Florea and others, 2002; Gao and others, 2005; Veni, 1999, 2003; Weinreich and others, 2005). However, geospatial data needed to map and examine the distribution of, and relationship between, karst features and their hydrogeologic settings are lacking in much of the United States because much of the existing data are scattered among various State and Federal agencies, reside in unpublished or poorly distributed paper documents and publicly inaccessible files, or have simply not been previously compiled in GIS-compatible formats or as regional-to-national scale databases (Palmer, 2006).

To help redress this need, a geospatial dataset of karst features in the Interior Low Plateaus physiographic region of the central United States was compiled as part of the GWRP Karst Hydrology Initiative (KHI) project during 2004–2007. The regional dataset incorporates existing karst hydrogeologic data compiled from digital and non-digital sources published or released previously by various State and Federal agencies, universities, and private consultants, as well as new geospatial data generated during the KHI project. The compiled geospatial data provide a means of mapping and examining the distribution and interrelation of the following karst features: (1) sinkhole locations, (2) sinking (or disappearing) streams, (3) internally drained surface catchments, (4) karst springs inventoried in the USGS National Water Information System (NWIS) database, (5) special geomorphic features termed relic stream valleys, and (6) karst flow paths derived from available reports of karst water-tracer tests. Because of the potential usefulness of this information to Federal, State, and local environmental regulators, water-resources managers, and other interested parties, the karst geospatial data files are being released as a provisional dataset to the general public. For ease of viewing and evaluation, the geospatial data have been compiled using ESRI ArcReader and pre-processed as user-interactive Published Map Files (*.pmf* files). This report describes the karst geospatial data, the contents of the ArcReader data folders, and the viewing and manipulation of data compiled as the .pmf files. Instructions for acquiring the geospatial data files are posted at the USGS Kentucky Water Science Center webpage (*http://ky.water.usgs.gov/index.htm*) and the USGS GWRP webpage (*http://water.usgs.gov/ogw/gwrp/*).

Some data and information contained in the data files, or accessed through the Internet websites listed above may, out of necessity, be preliminary in nature and presented prior to final review and approval by the Director of the USGS. These data and information are provided with the understanding that they are not guaranteed to be correct or complete. In addition, the ArcReader files may contain geospatial data compiled using new or modified GIS techniques and may include data originally collected or reported by sources outside the USGS. Users are cautioned to carefully consider the provisional nature of these data before using them for decisions that concern regulatory issues, personal or public safety, or in the conduct of public or private business matters. Conclusions, or actions undertaken, based on these data are the sole responsibilities of the user.

Regional Study Area

The Interior Low Plateaus physiographic region (Fenneman, 1938) encompasses more than 69,000 mi^2 of the central United States, including much of Alabama, Indiana, Kentucky, and Tennessee (fig. 1). Most of the region is underlain by soluble carbonate rocks and exhibits moderately to well-developed karst topography (Davies and LeGrand, 1972). Karst features are particularly well developed in six major regional *karst terranes* (fig. 1, table 1) which are defined by geographic or stratigraphic boundaries and possess similar hydrogeologic characteristics that govern the occurrence and movement of ground water (Brahana and others, 1988). Four of the karst terranes—the Central Kentucky karst, Cumberland Plateau karst, Mitchell Plain karst, and Highland Rim karst—are developed in Early-Middle Mississippian-age limestones and dolostones. Two of the karst terranes—the Inner Bluegrass karst and the Nashville Basin karst—are developed in Early-Middle Ordovician-age limestones. The karst aquifers in each of these terranes may be conceptualized as consisting of multiple discrete *karst basins*, each of which drains a specific geographic area and contributes water to a subsurface conduit network that discharges to one or more karst springs (White and White, 1989; Ray, 2001).

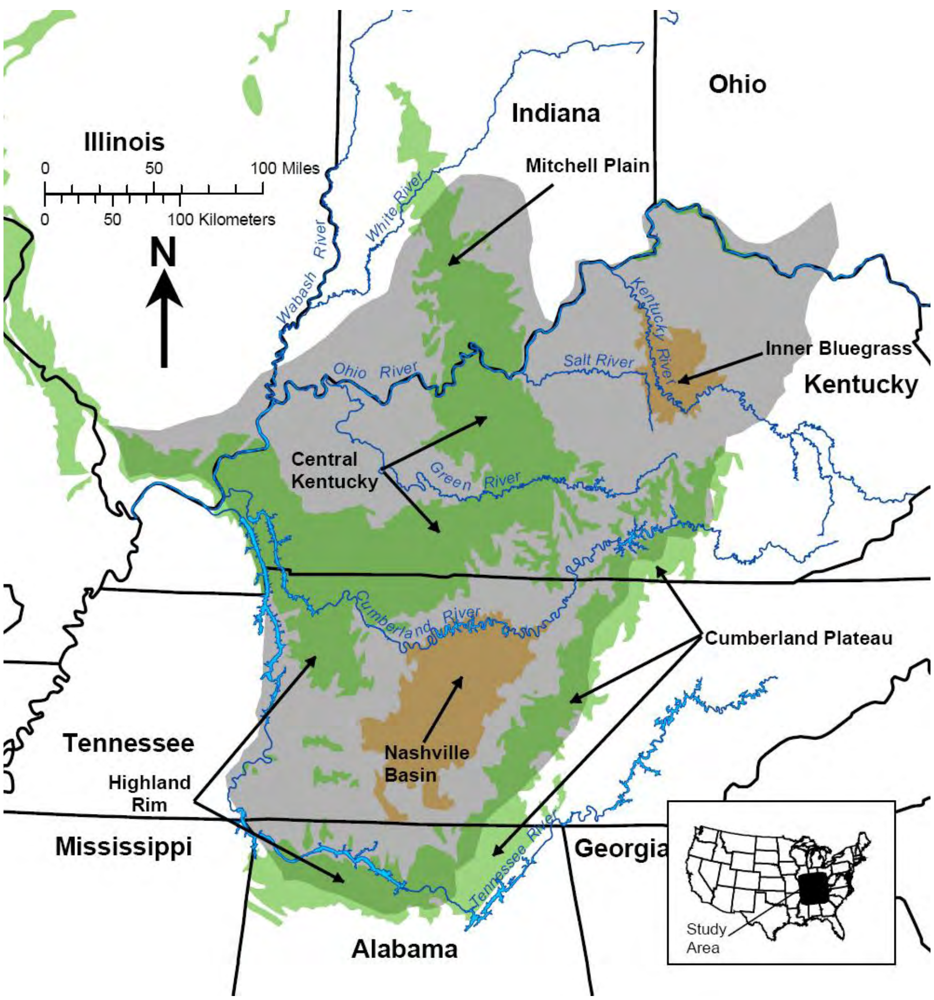


Figure 1. Geographic boundaries of the Interior Low Plateaus regional study area and major regional karst terranes (Explanation: tan areas underlain by Ordovician-age carbonates; green areas underlain by Mississippian-age carbonates; and grey areas underlain by relatively less karstified Ordovician-Mississippian-age carbonates, or non-karstic sedimentary rocks).

Table 1. List of major regional karst terranes and their general hydrogeologic features (modified from Brahana and others, 1988).

[km², square kilometer; O, Ordovician Period; M, Mississippian Period]

Karst terrane	Approximate area (km²)	Bedrock age	Hydrologic characteristics	Major controls	References
Central Kentucky	7,585	M	Extensive shallow aquifer; highly anisotropic with well-developed conduit networks. Broad sinkhole plains, often bordered with sinking streams. Topographic escarpments delineate cap rock retreat along northwestern boundary. Springs, caves, karst windows abundant and well formed.	Gently dipping geologic structure. Thick bedded limestones, well fractured. Chert beds act as leaky confining zones. Base level of streams is important and multiple conduit levels reflect periods of entrenchment and aggradation.	Quinlan and others (1983); White and White (1989); Ray (1999, 2001)
Cumberland Plateau	2,715	M	Shallow, disjointed aquifer having separate conduit networks developed in valley bottoms and beneath retreating edge of major topographic escarpments. Sinking streams and pit caves are common along edge of caprock escarpments. Numerous springs emerge where confining units crop out along the face of the escarpments and the valley walls.	Near-horizontal bedding for most of the area. Stress-relief fractures are important. Stratigraphic controls include recurring sequence of cavernous limestone alternating with shaly or cherty confining units. Minor confinement throughout stratigraphic sequences.	Crawford (1984, 1987); Ewers (1985); Smart and Campbell (2003)
Inner Bluegrass	1,171	O	Shallow aquifer with highly variable character. Surface streams act as drains for isolated karst basins separated by interbasin areas having less conduit development. Sinkholes abundant, often clustered; losing streams, springs, and caves common.	Nearly flat-lying geologic structure. Anisotropic development of porosity and permeability due to shales and thin shaly limestones. Regional joint sets may be locally important. Base level of local streams is a significant control.	Dougherty (1985); Thrailkill (1985)
Mitchell Plain	3,107	M	Shallow aquifer with surface features that funnel recharge into major subsurface streams. Active anisotropic flow system present. Scattered sinkhole plains with mixed shallow depressions and large complex sinkholes or karst windows. Numerous springs and caves. Some perennial surface streams, many partly or completely pirated by subsurface conduits.	Relatively flat-lying geologic structure with thick-bedded limestones and some evaporites at shallow depths. Other lithologic controls such as chert beds acting as confining zones. Base level of local streams is a significant control.	Bassett (1976); Malott (1981); Bayless and others (1994)

Table 1. List of major regional karst terranes and their general hydrogeologic features (modified from Brahana and others, 1988).—Continued

[km^2, square kilometer; O, Ordovician Period; M, Mississippian Period]

Karst terrane	Approximate area (km^2)	Bedrock age	Hydrologic characteristics	Major controls	References
Nashville Basin	3,778	O	Similar to Inner Bluegrass karst region of Kentucky. Shallow aquifer with highly variable character. Surface streams act as drains for isolated karst basins separated by interbasin areas having less conduit development. Sinkholes abundant, often clustered; losing streams, springs, and caves common.	Nearly flat-lying geologic structure. Anisotropic development of porosity and permeability due to shales and thin shaly limestones. Regional joint sets may be locally important. Base level of local streams is a significant control.	Brahana and Bradley (1986a)
West Highland Rim and South Highland Rim	3,660	M	Extensive shallow aquifers; highly anisotropic with well-developed conduit networks. Well-developed, scattered sinkhole plains. Sinkholes, caves, and springs are abundant and well developed in near-surface limestone units. Thick residuum and soils are significant sources of recharge. Topographic relief is extremely variable. Some perennial surface streams, many partly or completely pirated by subsurface conduits.	Gently dipping geologic structure. Thick bedded limestones, well fractured. Upper bedding units of thick, relatively pure limestones with many large openings; lower units increasingly impure limestones grading to chert and shale with relatively weak dissolution porosity; major confinement at base. Chert beds act as leaky confining zones. Base level of streams is significant.	Quinlan and others (1983); White and White (1999); Brahana and Bradley (1986b)

The physiography of much of the regional study area is characterized as well-developed fluviokarst, that is, a karst landscape where the dominant landforms are valleys initially cut by surface streams that have been subsequently pirated by underground solutional conduits. Surficial karst features such as sinkholes, sinking (or disappearing) streams, and karst springs are common, as are subsurface conduits or caves; however, the occurrence, density, and physical characteristics of these features are quite variable. Karst springs are headwaters or contributing tributaries to many regional surface streams. Regional surface drainage is controlled by the Ohio River and its major tributaries, which include the White River in Indiana; the Kentucky, Salt, and Green Rivers in Kentucky; the Cumberland River in Kentucky and Tennessee; and the Tennessee River in Alabama, Kentucky, and Tennessee. Much of the history and pattern of regional surface and subsurface drainage development are directly related to periodic changes in base level that occurred throughout the lower Ohio River valley during Quaternary glacial and interglacial stages (Palmer, 1989; Granger and others, 2001).

Methods of Data Compilation

During the initial phase of the KHI project, a comprehensive search was conducted for existing sources of karst hydrogeologic mapping data, including previously published papers or maps, electronic or paper databases maintained by various State and Federal agencies, and academic research papers or student theses that document results of karst mapping studies conducted in the regional study area. Efforts also were made to obtain data from reports prepared for local site-specific environmental studies in karst areas and dye-tracer test results conducted by private consultants; however, this effort was largely unsuccessful because much of these data are proprietary and are held under legally binding restrictions regarding public distribution and use.

Environmental Systems Research Institute (ESRI) ArcGIS version 9.1 software was used to compile or synthesize all geospatial data and to generate digital data files that contain feature classes (such as lines, points, and polygons) used to represent the various identified and mapped karst features.

Digital data files created as base maps needed to represent the topography and surface hydrology of the regional study area were compiled using conventional GIS terrain-processing techniques and geospatial data obtained from Digital Elevation Models (DEMs), Digital Raster Graphics (DRGs) files, Digital Orthophoto Quadrangles (DOQs), and the National Hydrography Dataset (NHD). Special geospatial data files were created using customized GIS-processing techniques to delineate karst features such as internally drained catchments for sinkholes and sinking streams, relic streams, and tracer-inferred subsurface flow paths. These features, and other aspects of the database compilation effort, are described in more detail in the following sections.

ArcReader Data Folders and Files

The ArcReader .pmf files, and all input data files, are stored in data folders catalogued by USGS eight-digit Hydrologic Unit Codes (HUC-8s) that correspond to the boundaries of major surface watersheds mapped within each State in the regional study area (fig. 2, table 2). This method of data cataloging allows the user to easily map and visualize the distribution of karst features within the context of surface topography and drainage, and applies the watershed-management approach recommended by the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency, 1996, 2001) to the issue of karst geospatial data management. In addition, this method of data compilation will facilitate the transfer of the data to other national geospatial databases including the USGS NHD (*http://nhd.usgs.gov/*) and The National Map project (*http://nationalmap.gov/*). It should be noted that some of the HUC-8 watersheds in the regional study area include areas underlain by both karstic and non-karstic rocks, and many of the watersheds included in the regional study area are located outside the boundaries of the major regional karst terranes shown in figure 1.

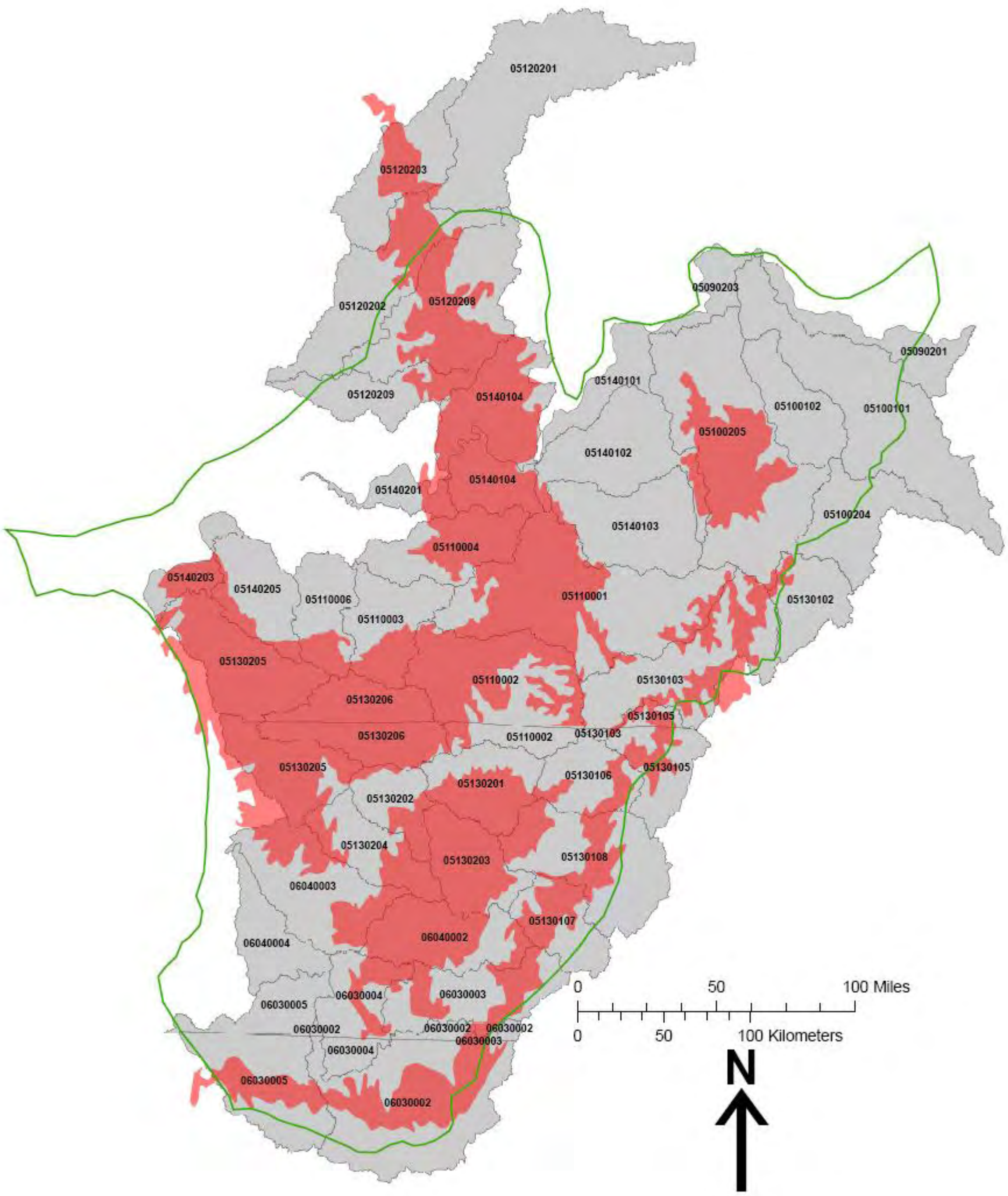


Figure 2. Locations and boundaries of eight-digit Hydrologic Units (HUs, indicated by black-bounded polygons) and their identifying codes (HUC-8s) within the regional study area (green boundary line). (The red-shaded polygons indicate approximate geographic boundaries of major regional karst terranes shown in figure 1.)

Table 2. List of eight-digit Hydrologic Units in the regional study area, major named streams, States, and karst terranes.

[km^2, square kilometer; KY, Kentucky; CKK, Central Kentucky karst; CPK, Cumberland Plateau karst; IBK, Inner Bluegrass karst; TN, Tennessee; IN, Indiana; MPK, Mitchell Plain karst; NBK, Nashville Basin karst; HRK, Highland Rim karst; ND, not defined]

ArcReader folder	Eight-digit Hydrologic Unit	Drainage area (km^2)	State(s)	Karst terrane
05090201KY	Ohio-Brush-Whiteoak	1,995.36	KY	ND
05090203KY	Middle Ohio-Laughery	1,004.52	KY	ND
05100101	Licking	7,195.63	KY	ND
05100102	South Fork Licking	2,401.18	KY	ND
05100204	Upper Kentucky	2,832.30	KY	ND
05100205	Lower Kentucky	8,392.70	KY	IBK
05110001	Upper Green	8,133.26	KY	CKK, CPK
05110002	Barren	5,866.79	KY, TN	CKK, CPK
05110003	Middle Green	2,661.41	KY	CKK
05110004	Rough	2,799.18	KY	CKK
05110006	Pond	2,064.65	KY	CKK
05120202	Lower White	4,335.11	IN	MPK
05120208	Lower East Fork White	5,254.79	IN	MPK
05120209	Patoka	2,231.4	IN	MPK
05130102	Rockcastle	1,977.35	KY	CPK
05130103	Upper Cumberland-Lake Cumberland	4,875.24	KY, TN	CPK
05130104	South Fork Cumberland	3,582.24	KY, TN	CPK
05130105	Obey	2,453.53	KY, TN	CPK
05130106	Upper Cumberland-Cordell Hull	2,065.15	TN	CPK, NBK
05130107	Collins	2,042.24	TN	CPK
05130108	Caney Fork	4,658.25	TN	CPK, NBK
05130201	Lower Cumberland-Old Hickory Lake	2,554.22	TN	NBK
05130202	Lower Cumberland-Sycamore	1,677.37	TN	NBK
05130203	Stones	2,426.12	TN	NBK
05130204	Harpeth	2,248.35	TN	NBK, HRK
05130205	Lower Cumberland	6,045.95	KY, TN	HRK
05130206	Red	3,765.40	KY, TN	CKK, HRK
05140101KY	Silver-Little Kentucky	1,513.33	KY	ND
05140102	Salt	3,804.63	KY	ND
05140103	Rolling Fork	3,753.56	KY	ND
05140104IN	Blue-Sinking	3,245.89	IN	MPK
05140104KY	Blue-Sinking	1,669.75	KY	CKK
05140201IN	Lower Ohio-Little Pigeon	2,563.03	IN	MPK
05140201KY	Lower Ohio-Little Pigeon	1,050.02	KY	CKK

Table 2. List of eight-digit Hydrologic Units in the regional study area, major named streams, States, and karst terranes. —Continued

[km^2, square kilometer; KY, Kentucky; CKK, Central Kentucky karst; CPK, Cumberland Plateau karst; IBK, Inner Bluegrass karst; TN, Tennessee; IN, Indiana; MPK, Mitchell Plain karst; NBK, Nashville Basin karst; HRK, Highland Rim karst; ND, not defined]

ArcReader folder	Eight-digit Hydrologic Unit	Drainage area (km^2)	State(s)	Karst terrane
05140203KY	Ohio-Bay	1,156.35	KY	CKK
05140205	Tradewater	2,441.84	KY	CKK
06030002	Wheeler Lake	7,512.26	TN, AL	HRK
06030003	Upper Elk	3,331.18	TN, AL	CPK, NBK
06030004	Lower Elk	2,502.51	TN, AL	NBK
06030005	Pickwick Lake	5,318.72	TN, AL	HRK
06040002	Upper Duck	3,063.42	TN	ND
06040003	Lower Duck	4,010.73	TN	HRK, NBK
06040004	Buffalo	4,567.78	TN	ND

To view the karst features mapped within a particular HUC-8 watershed, the desired ArcReader data folder, identified by the HUC-8, is selected and opened and the enclosed ArcReader *.pmf* file is then also selected and automatically opened by double-clicking on its file name (also designated by the HUC-8). This action launches the user-interactive ArcReader interface which consists of a window with two halves or frames (fig. 3). The table-of-contents frame, displayed on the left-hand side, is a data-tree list of GIS files that can be selected for display by the user. The data frame, displayed on the right-hand side, is the area on the computer screen in which digital map images of selected GIS files are plotted. To generate a digital map of the watershed area, the user must select and open the top-level GIS data file by double-clicking on the designated HUC-8 file listed in the table-of-contents frame.

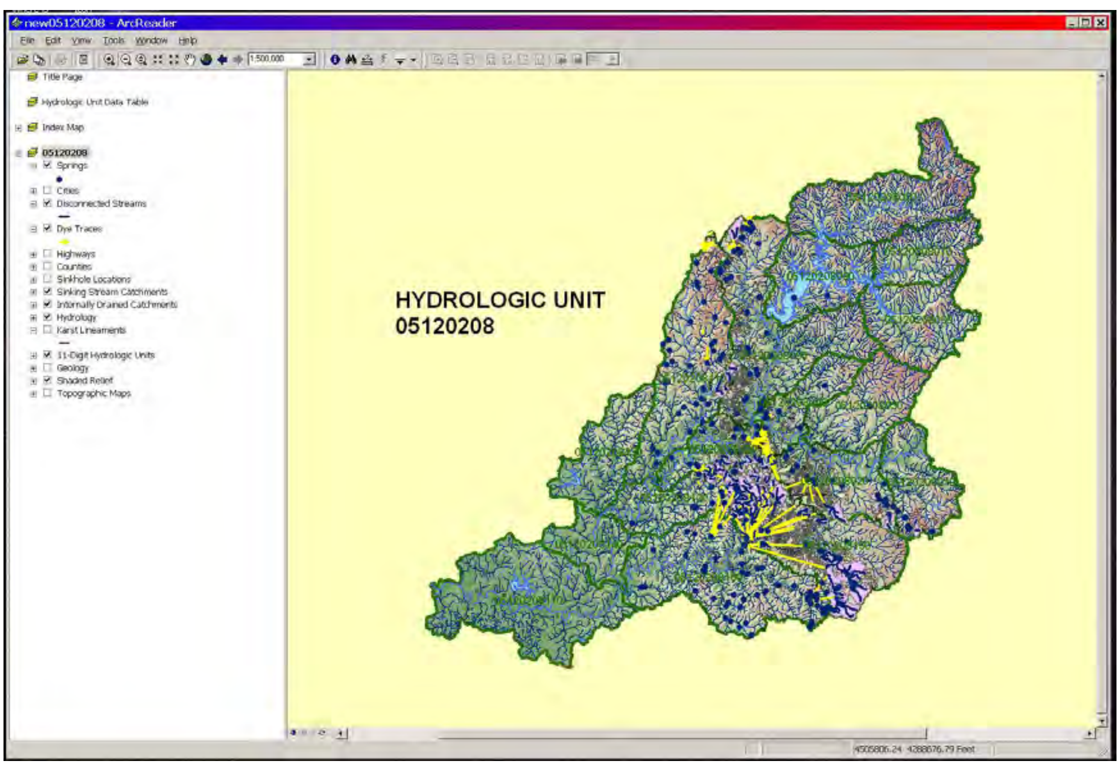
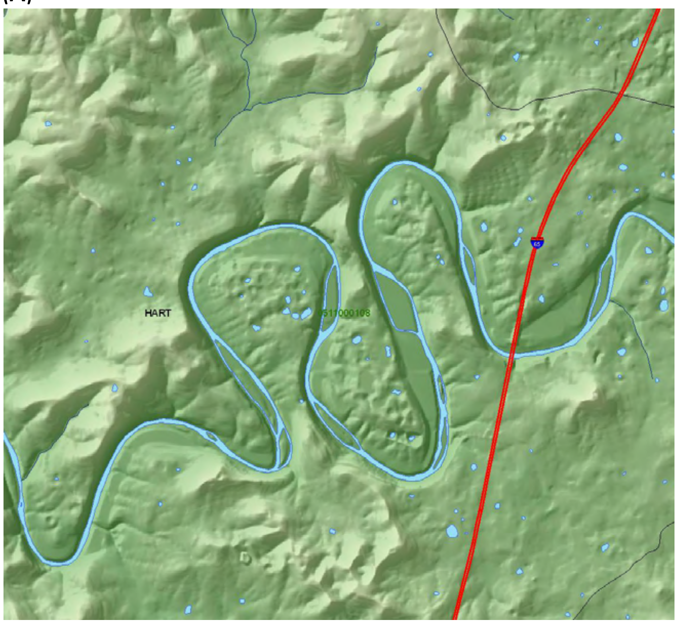


Figure 3. Screen-capture image showing the ArcReader user interface used for viewing and manipulating karst geospatial data files. (The table-of-contents frame, showing list of available Geographic Information System (GIS) data files, is to the left; digital-map images are displayed in the data frame to the right. Green lines and numbers on the map image indicate boundaries of ten-digit Hydrologic Unit contributing areas (sub-watersheds) within the selected eight-digit Hydrologic Unit.)

Once loaded in the ArcReader data frame, the digital map image of the watershed area displays basic geographic information such as roads, cities, and towns, and the boundaries of all HUC-10 sub-basin areas delineated within the larger HUC-8 watershed. At this point, the digital map image can be manipulated using the available ArcReader tools, and any combination of topographic, hydrographic, geologic, or karst-feature data can be displayed as desired by using the computer cursor to check or uncheck the appropriate boxes for the GIS files listed in the table-of-contents frame. Two options for a topographic base map are provided for the user (fig. 4).

(A)



(B)

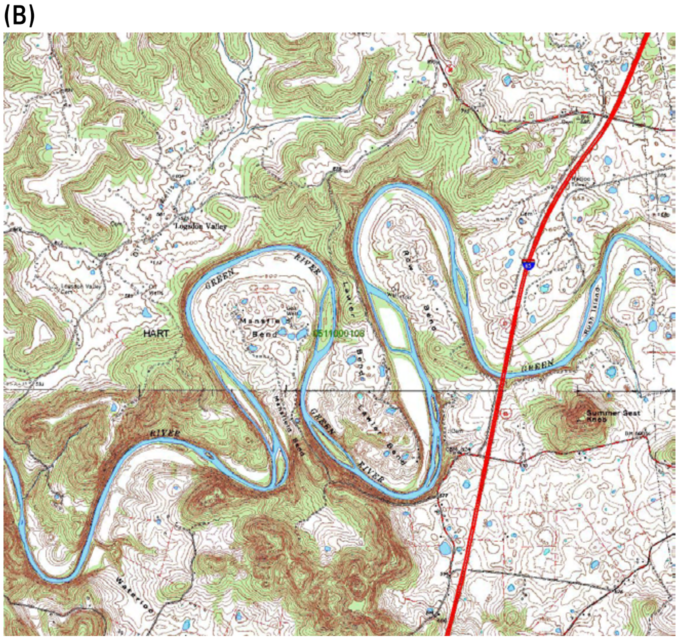


Figure 4. Screen-capture images showing the two topographic base maps available with the ArcReader datasets: (**A**) shaded-relief topography (default), and (**B**) contoured-map topography derived from digital U.S. Geological Survey 1:24,000 topographic quadrangles (alternative).

The default base map is a shaded-relief topographic format generated by ArcGIS using input 10-meter or 30-meter DEMs. The alternative base map is a traditional contoured-topography format created from published USGS 1:24,000 digital topographic map files. Each topographic base displayed is clipped to the boundaries of the HUC-8 watershed. To display the alternative contoured-topography base, the data file for the shaded-relief topographic base map must first be deselected by unchecking the file name and then checking the file for the contoured-topography base map. The user should be aware that as files listed in the table-of-contents frame are selected or deselected, the ArcReader digital map image shown in the data frame is automatically refreshed and updated to incorporate the indicated data file changes. This may take a few moments as the topographic data files are large.

To manipulate the digital map image, the ArcReader user interface provides a toolbar along the top with various buttons that can be used to change the scale of the digital map (zoom in or zoom out), pan laterally or longitudinally, and identify individual features being displayed. Detailed instructions available in the ArcReader help files (see top menu bar on reader) describe various ways the digital images visible in the data frame can be manipulated according to the user's particular needs. It is usually necessary to adjust the digital map image using these tools to obtain an image suitable for viewing at the desired scale. As a rule-of-thumb, the digital map images are best viewed at scales of 1:100,000 to 1:24,000. Slight misalignments may occur between some displayed features plotted at the same locations, particularly when viewing the digital map image at larger scales (about 1:24,000). These misalignments usually occur because of registration errors introduced by the superposition of two or more GIS files created originally at different scales, particularly where features were digitized by hand.

In addition to the ArcReader *.pmf* file, each data folder for a particular HUC-8 watershed contains various other files used as input data or to store metadata (table 3). If needed, the contents of these files can be extracted using the appropriate text-file readers, spreadsheet programs, or ArcGIS application software. Three other specially created files are also included in the folders that are meant to be accessed using the ArcReader table-of-contents frame and are provided as an aid to the user while examining digital map images. These files include (1) a Hydrologic Unit Data table, which summarizes selected watershed statistics such as the density of sinkholes or internal drainage for the HUC-8 watershed and its ten-digit sub-basins; (2) an Index Map image file, showing the location and boundaries of the selected watershed area and its location relative to other HUC-8 watersheds in the State; and (3) a Springs Data Table image file, which provides a summary of available information for karst springs inventoried within the boundaries of the watershed. Clicking on the file name from the table-of-contents frame causes the digital map image to be automatically replaced with a table or map, depending on the file, that provides the indicated information. These images can be manipulated, for example, magnified, for better viewing using the appropriate ArcReader tools.

Table 3. General contents of ArcReader geospatial data folders.

[HU, hydrologic unit; DEM, Digital Elevation Model; {HUcode}, eight-digit HU code entered for that part of the data file name; .aux, ArcGIS auxillary file; .drg, digital raster graphics file; .htm / .html, Hypertext Markup Language files; .mdb, Microsoft Access database file; .pmf, ArcReader Published Map file; .rrd, Reduced Resolution Dataset file; .tfw, ESRI World file; .tif, tagged image format file; .txt, ArcInfo text file; .xls, Microsoft Excel spreadsheet file; KHI, Karst Hydrology Initiative; NWIS, National Water Information System]

Subfolders containing geospatial data obtained from Internet-accessible digital databases:	(1) **Digital raster graphics ("drg") files:**	(a) One **.tif** file for each topo map in the eight-digit HU. (b) One **.tfw** file for each topo map in the eight-digit HU. (c) One **.aux** file for each topo map in the eight-digit HU.
	(2) **DEM grids ("grids"):**	(a) DEMs for the area enclosed by the eight-digit HU. (b) Hillshade (indicating range of topographic relief) for same. (c) One **.aux** file for each grid. (d) One **.rrd** file for each grid.
	(3) **metadatafiles:**	(a) One **.txt**, **.htm**, or **.html** file for each data file with internal metadata.
Project-specific geodatabase files:	(1) **basedata.mdb**	(a) Geospatial data used to generate roads, hydrography, counties, etc. The contents may vary for each 8-digit HU.
	(2) **karstdata.mdb**	Contents may vary according to individual eight-digit HUs and include: **(a) sinkpoly**–sinkhole locations represented as polygons mapped specifically in Kentucky as provided by digital data file prepared by Paylor and others (2003). **(b) sinkpoint**–sinkhole locations represented as points mapped in Alabama, Indiana, and Tennessee as mapped during the KHI project. **(c) catchment**–digitally mapped area of internally drained catchments. **(d) disconnected streams**–represents sinking or disappearing karst streams. Features may not be present in all eight-digit HUs. **(e) sscatchments**–represents catchment areas mapped for identified sinking or disappearing streams. May not be present in all eight-digit HUs. **(f) relic streams**–specially defined surficial geomorphic features (see text). **(g) springs**–May not be present in all eight-digit HUs. There may be more than one dataset present in an eight-digit HU. **(h) dyetraces**–vectors that may not be present in all eight-digit HUs. There may be more than one dataset in an eight-digit HU. **(i) geology**–mapped surficial carbonate bedrock units compiled from various State geologic maps.
	(3) **springtable{HUcode}.xls**	(a) Contains location and ancillary data for karst springs inventoried in NWIS.
ArcReader executable file:	(1) **{HUcode}.pmf**	(a) One file for each eight-digit HU. Automatically opens ArcReader user interface and compiles base-map data files.

When the Index Map image is displayed, the area of the selected HUC-8 watershed is highlighted and its boundaries are displayed along with the boundaries of all other HUC-8 watersheds in the State. If needed, the user can identify the HUC-8 of any of these other watersheds by moving the computer cursor into the indicated boundaries of each. Thus, if a user has accidentally opened the ArcReader folder for the wrong HUC-8 watershed, the Index Map can be used to locate the correct or desired HUC-8, and also can be used to identify other possible HUC-8s of interest.

Mapped Karst Features

One of the primary input data files in each ArcReader data folder is the *karstdata.mdb* geodatabase file which contains geospatial information compiled for specific classes of karst features mapped in the regional study area (table 3). These include (1) locations of sinkhole depressions; (2) sinking surface streams; (3) internally drained catchment areas, delineated for both sinkholes and sinking streams; (4) karst springs inventoried in the USGS NWIS database; (5) special geomorphic features termed relic streams; and (6) subsurface flow paths inferred from reported dye-tracer tests. The *karstdata.mdb* file also contains a geology feature class, which generates an image of the stratigraphic boundaries of surficial carbonate bedrock units extracted from the various State geologic maps. For further explanation of the geologic unit labels, refer to the individual source references: Alabama (Geological Survey of Alabama, 2006), Indiana (Gray and others, 1987), Kentucky (Carey, 2002), and Tennessee (Greene and Wolfe, 2000).

Using the table-of-contents frame in the ArcReader user interface, these feature classes can be selected, as desired, and viewed individually or in various combinations. This functionality provides a means to examine possible correlations in the distribution of different features and the spatial relations between them. For example, the data files for mapped sinkhole locations and geology may be selected by the user to examine the relation between the occurrence of sinkholes and stratigraphic units in a portion of the Blue River HU (05140104IN) in south-central Indiana (fig. 5).
Similarly, data files for dye-tracer tests, internally drained catchments, and karst springs could be selected to examine tracer-inferred directions of ground-water flow and the relation between specific points of karst recharge and discharge in the White River HU in south-central Indiana (fig. 6). The user should note that symbols and shading used to represent certain karst features may occasionally overlap and partly or completely obscure other features plotted in the same locations. For example, the shaded polygons that represent sinking stream catchments typically overplot and obscure polygons used for the more generic internally drained catchments feature class. Wherever this occurs, the user may have to alternately toggle off and toggle on the overplotted data file(s) in order to visually examine any underlying obscured features.

Sinkholes and Internally Drained Catchments

Sinkholes (dolines) are among the most abundant and recognizable visible karst features in the regional study area, and the geospatial data files created to depict these features were created using a combination of pre-existing and newly compiled geospatial data. Sinkhole mapping projects were underway at the State level throughout the regional study area (Alabama, Indiana, Kentucky, and Tennessee) at the time the KHI project was being conducted. However, the status of these projects, their products, and the availability of geospatial sinkhole data, varied considerably from State-to-State and even within States. In Kentucky, a Statewide digital data file of sinkhole locations has been prepared by Paylor and others (2003), which depicts sinkhole locations as polygons drawn to represent the area contained within the uppermost depression contour visible on 1:24,000 scale topographic maps. In Indiana, available data are limited to a published map and accompanying digital data file prepared by Powell and others (2002a, b), showing the locations of larger sinkhole depressions and valley-like solutional depressions locally known as "gulfs" (Malott, 1981) in the Mitchell Plain karst. In Tennessee and Alabama, sinkhole-mapping projects are in the early stages of progress, and no published maps or digital data files of sinkhole locations are presently (2008) available.

A number of inherent technical difficulties are involved in identifying and mapping sinkhole depressions using automated terrain-processing techniques with DEM datasets (Kochanov and Reese, 2003; Weinreich and others, 2005). Therefore, to eliminate gaps in the geographic coverage of sinkholes in the HUC-8 data files, new data were collected on sinkhole locations by visually inspecting DOQ and DRG files to identify naturally occurring closed topographic depressions and then digitizing the location coordinates of the apparent centroid of each. Much of these new data were compiled in Indiana, Tennessee, and Alabama, where both newly identified and previously mapped sinkhole locations are represented in the ArcReader data files using filled-dot symbols. In Kentucky, the symbols used for mapped sinkhole depressions differ; there, the symbols used to mark sinkhole locations are the shaded polygons transferred to the ArcReader data files directly from the digital data file prepared by Paylor and others (2003). As a consequence, a combination of shaded dots and polygon symbols will be observed to represent sinkhole depressions mapped in several HUC-8 watersheds whose boundaries cross the Kentucky–Tennessee State line (fig. 7).

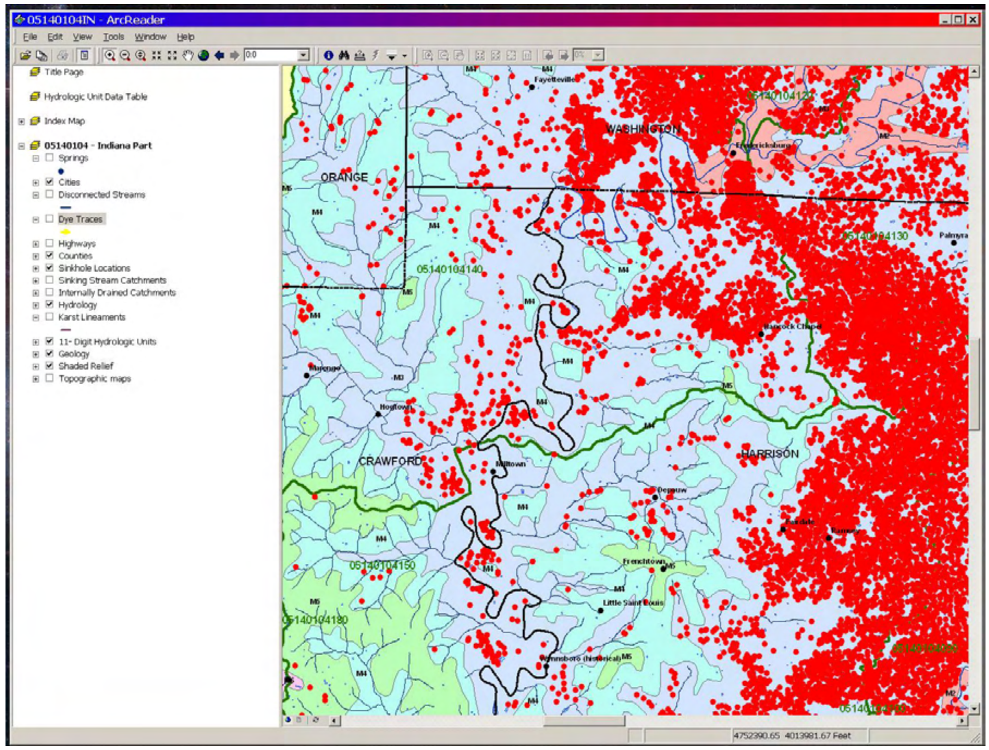


Figure 5. Screen-capture image showing example of digital-map image plotted in ArcReader data frame, including locations of identified sinkhole depressions (red dots) and surficial bedrock units (variously colored polygons) in a portion of the Blue River Hydrologic Unit (05140104IN) in south-central Indiana.

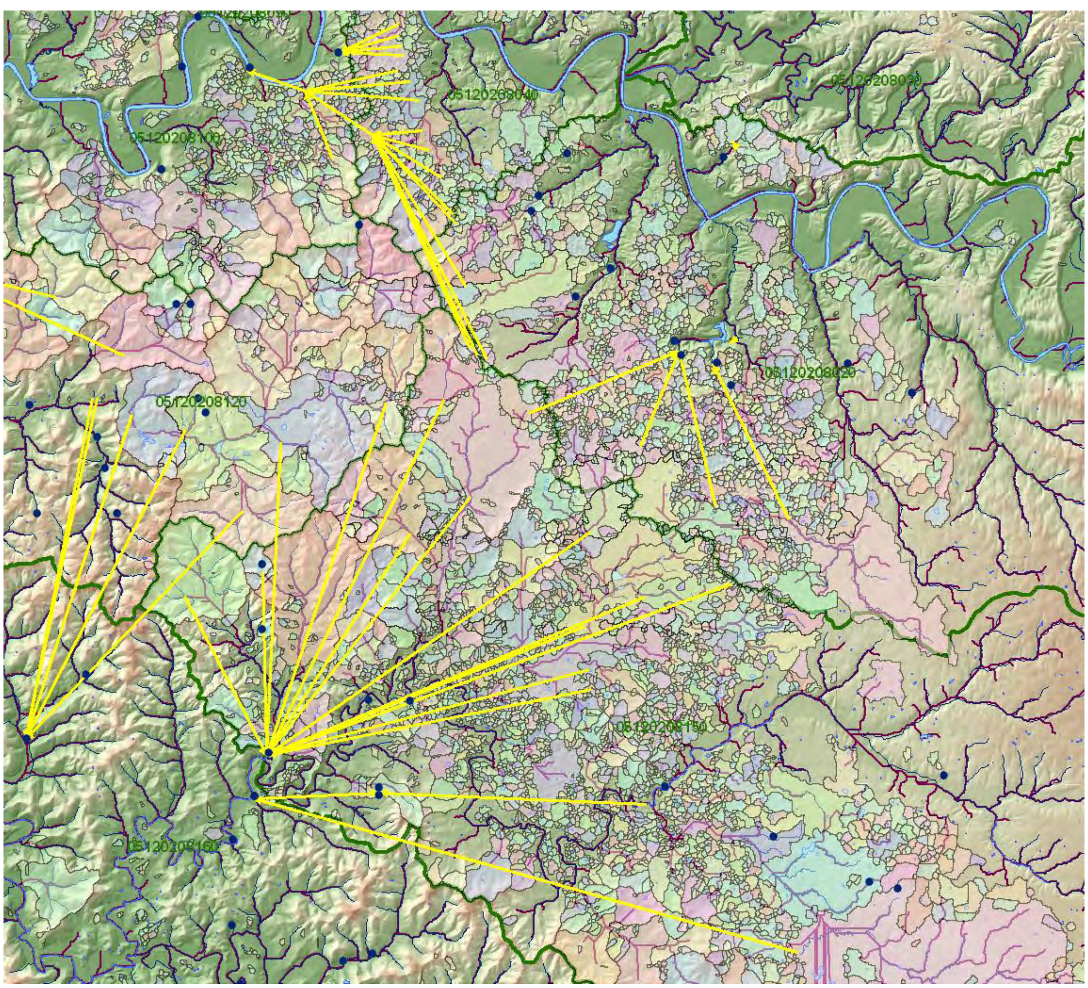


Figure 6. Screen-capture image showing example of plotted dye-tracer flow paths (yellow), internally drained catchments (multi-colored polygons), and locations of inventoried karst springs (blue dots) in a portion of the White River Hydrologic Unit (05140104IN) in south-central Indiana.

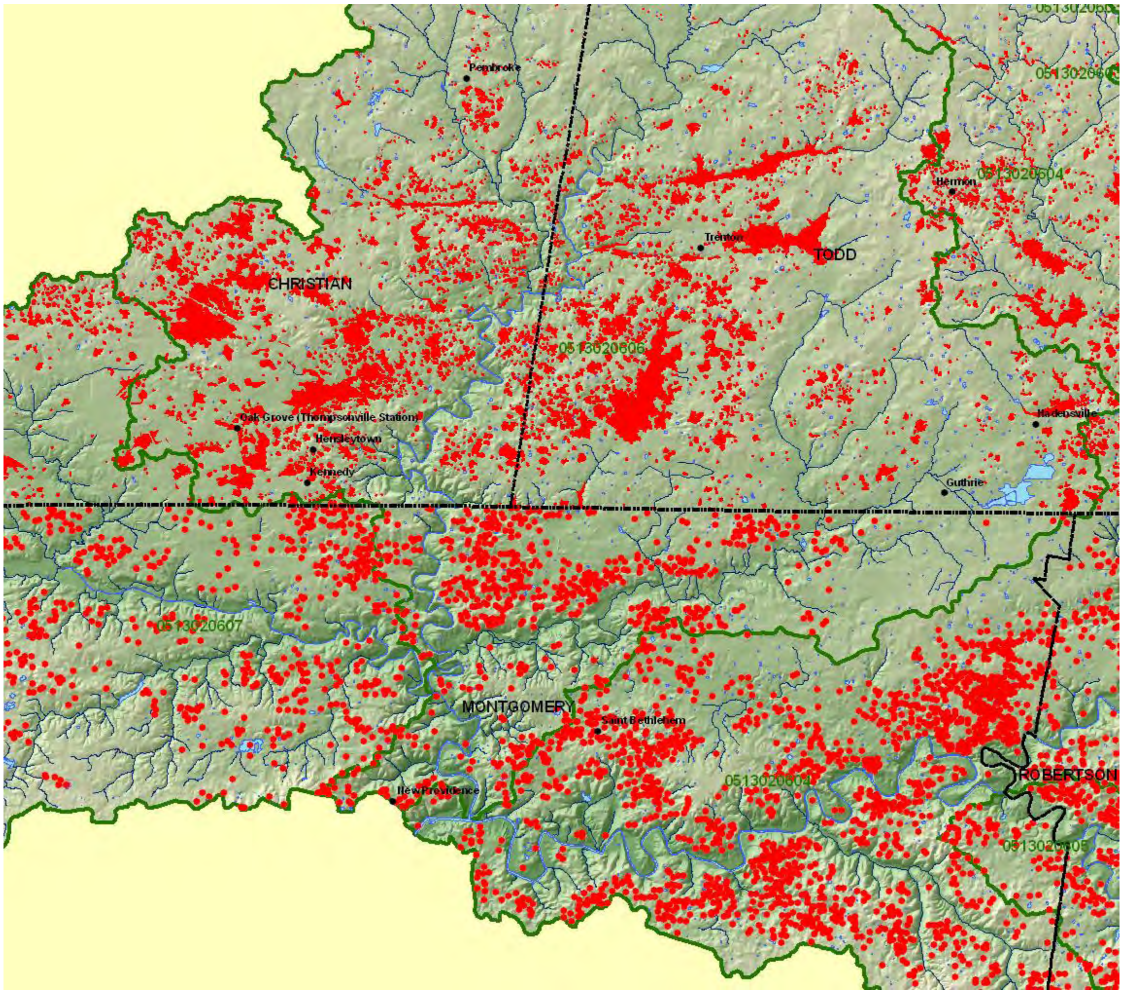


Figure 7. Screen-capture image showing the difference in symbols used to denote sinkhole-depression locations in Kentucky (red-shaded polygons) and Tennessee (red-shaded dots), in a portion of the Red River eight-digit Hydrologic Unit (05130206), Kentucky–Tennessee. (The Kentucky–Tennessee boundary line approximately bisects the map figure.)

One unique product of the KHI project is the creation of geospatial data files to identify and map internally drained catchment areas (fig. 8). Collectively, the term applies to the surface drainage areas of all identified sinkholes and sinking or disappearing streams as these are topographic catchments that have no apparent surface outlet (or "pour point") for runoff or streamflow. The locations of these karst features may be particularly useful to investigators wishing to identify potential source areas of pollutants and the recharge areas of karst springs and aquifers. Separate data files can be selected in the ArcReader table-of-contents frame to display all internally drained catchments, only the catchments for mapped sinkhole depressions, or only the catchments for mapped sinking streams. The compilation of the geospatial data files for these features required the development and use of special GIS processing techniques (appendix 1). As a first step in this process, the GIS data files created for sinkhole locations were applied as a mask to preserve sinkhole-depression locations while additional terrain-processing methods were employed on the DEM datasets. Then the closed topographic depression associated with each mapped sinkhole depression was artificially filled, and a grid of the difference in elevation between the filled and unfilled depression was developed using ArcGIS tools. Finally, the boundaries of the catchment area for each depression were delineated using a raster file of gridded numerical values and the ArcGIS "WATERSHED" delineation tool. For the ArcReader data folders, boundaries of the grid file were clipped to the specific geographic area enclosed by the particular HUC-8 watershed.

Prior to applying the ArcGIS watershed-delineation tool, any multiple sink points identified on the DEM within each depression were identified using the ArcGIS "SINK" identification tool, and the grid cells associated with these spots are assigned unique numeric values used to group or tie them to their host depressions. This processing step helps to eliminate over-tessellation and results in the delineation of more

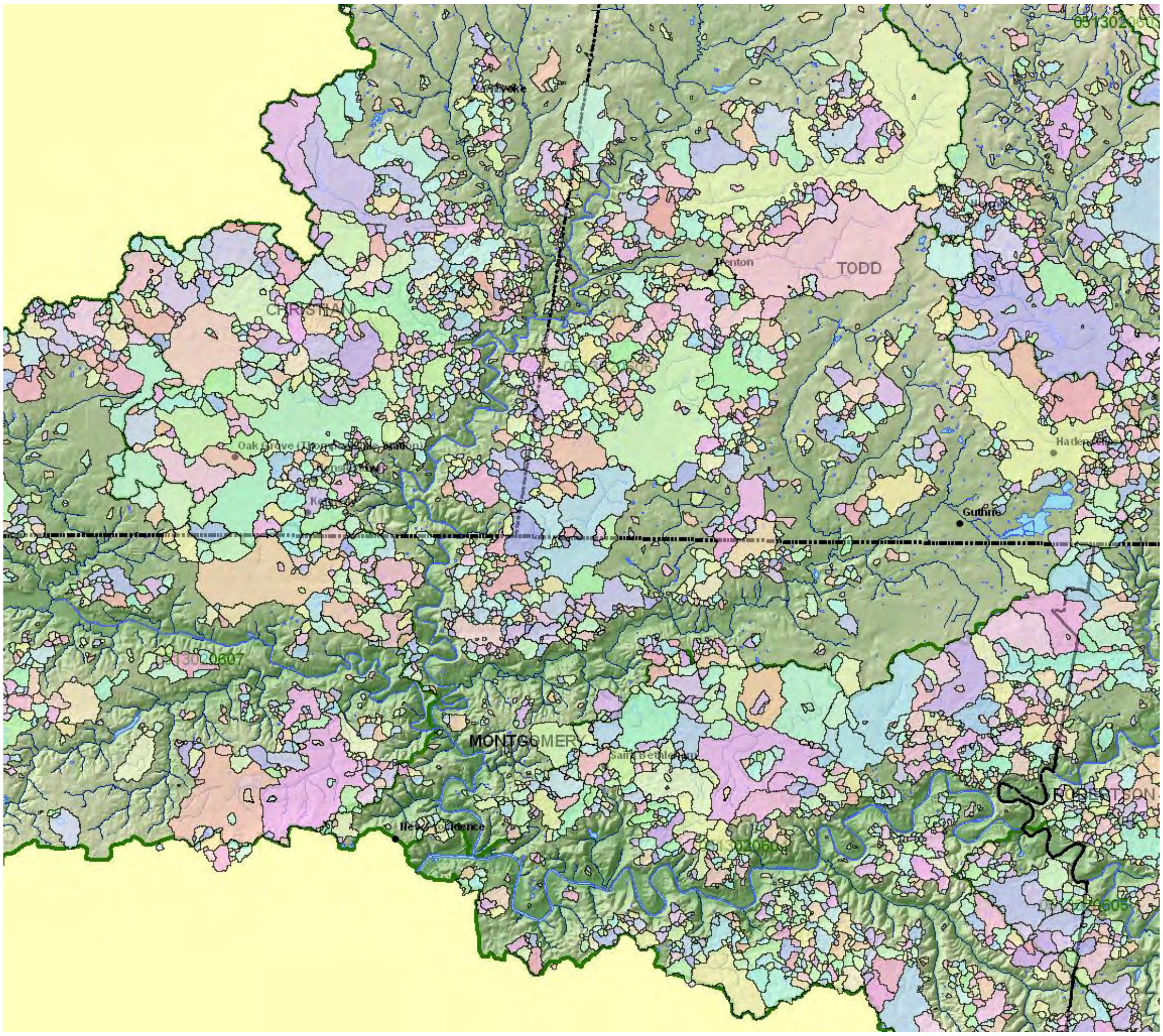


Figure 8. Screen-capture image showing example of plotted internally drained catchments (multi-colored polygons) in the same portion of the Red River eight-digit Hydrologic Unit (05130206), Kentucky–Tennessee, shown in figure 7.

physically realistic internally drained catchment areas in areas dominated by sinkhole-plain topography. Even after using these processing techniques, the delineation of catchment-boundary lines may be seen in some locations to be improperly drawn across apparent closed depressions, and others may encompass several apparent closed depressions because of the scale limitations imposed by the input DEM data and difficulty in applying the watershed-mapping tool where topographic relief is particularly low, the sinkhole topography is particularly complex, and drainage divides separating individual sinkhole depressions are not well defined. In these areas, multiple sinkhole depressions may be enclosed within a single catchment polygon, and catchment boundaries for the smaller individual sinkholes (whose diameters are less than or equal to the minimal resolution of the input DEMs) may not be delineated at all.

Karst Springs

The input data used by ArcReader to plot the locations of karst springs consists of latitude and longitude coordinates obtained for springs inventoried in the USGS NWIS or Ground-Water Site Inventory (GWSI) databases. The NWIS/GWSI site id number and (or) location coordinates for an individual spring may be identified by clicking on the ArcReader identification tool button, moving the computer cursor to point at the plotted spring symbol. The spring location coordinates, and ancillary data such as the county name and code number, and selected discharge measurements and specific-conductance data, are stored in the Excel spreadsheet file contained in each ArcHydro data folder, and for added convenience, is summarized in the "Spring Data Table" file listed near the top of the ArcHydro table-of-contents frame.

Spring inventories in the various States in the study area are typically conducted as part of site-specific ground-water investigations, or in response to environmental incident investigations, and therefore the information obtained is reported and maintained in various ways by different State and Federal agencies. As a consequence, there is a lack of uniformity in data reporting which makes a regional compilation effort such as this one difficult to achieve. Much of the spring inventory data collected in years past resides outside NWIS in electronic databases maintained by State agencies or in unpublished paper reports prepared by regulators or private consultants that are difficult to identify and access. As of the date of this report (2008), only the Commonwealth of Kentucky maintains a publicly accessible electronic database which enables users to search for spring-inventory data on the Internet, although similar efforts are planned or are being undertaken by State geological surveys or water-resources agencies elsewhere in the region. Project resource limitations precluded a comprehensive effort of searching for spring inventory data outside of NWIS and cross-checking of spring inventory data stored in databases maintained by State geological surveys or water-resource agencies. Users are advised, when searching the ArcReader data files for springs in a particular locality, to record the station identification number and location coordinates of mapped springs of interest and to contact the appropriate State agencies to confirm these data or obtain comprehensive, up-to-date data. Users also should be aware that information searches based on assumed spring names may be problematic as springs located in widely divergent geographic areas often possess the same given name, for example, “Big Spring”, and individual springs are often known locally by more than one name.

Sinking Streams

In the KHI dataset, the identification of sinking or disappearing streams is based on the identification of disconnected stream reaches imported from the NHD, which have corresponding internally drained catchments. Two GIS data files, one labeled “disconnected streams” and one labeled “sinking stream catchments,” must be selected (toggled on) in the ArcReader table-of-contents frame to enable digital mapping of these karst features. When the disconnected streams data file is selected, all NHD stream reaches that have no surface connection to the outlet or pour point of the watershed delineated by the eight-digit HU are highlighted. In karst areas, these disconnected reaches are the streams in which surface flows are likely terminated by diversion into one or more swallow holes and then routed underground through subsurface conduits. The ArcGIS process that was used to identify such streams and create the disconnected streams data files is relatively straightforward and requires only the use of the network tools available in ArcMap. For the ArcReader data files, 1:24,000-scale NHD stream reaches were imported and turned into a network using ArcCatalog commands, and the “find disconnected” tool was applied. Streams identified as disconnected were matched to polygons created for internally drained catchments, and a new data file for these features was created. Manual editing was used where required, to edit out any stream reaches identified as disconnected because of minor digitizing errors in the NHD input files. Additional minor GIS processing was done on some line segments to enhance visual depiction of the sinking streams in the digital maps generated by ArcReader.

Examples of sinking streams identified by this process and delineation of their catchments are shown in figures 9 and 10, respectively. Note that the catchments of sinking streams overplot those delineated for internally drained catchments; therefore when these two data files are selected, the catchments delineated for sinkholes can be easily distinguished from those for the sinking streams by the shading of the polygons used to represent each of these two features in the digital map image generated by ArcReader. It should be noted that this GIS processing method was not capable of identifying classic losing streams, that is, surface streams that lose only part of their flow to subsurface-conduit piracy but which continue to flow on the surface for all or part of the year. In the latter case, surface flow may cease completely seasonally or during periods when the water table is lowered below the elevation of the stream bed so that the stream may at times be characterized by a dry surface channel. These so-called “dry bed streams” (Brahana and Hollyday, 1988) are typical of overflow-allogenic karst basins (Ray, 2001), where the hydrologic capacity of a conduit network is large enough to capture the base flow of a surface stream, but not great enough to fully pirate the maximum storm flow discharged by the stream. These types of karst-modified streams may be present in many parts of the regional study area and are not always properly identified as losing or sinking streams in the NHD reach files. One particularly notable example is the Lost River in south-central Indiana, which seasonally loses all surface flow to subsurface conduits discharging at a large karst spring known as the Lost River Rise (Malott, 1981; Bayless and others, 1994). The GIS-mapping process applied to delineate sinking streams was effective at identifying several sinking tributary reaches of the Lost River in the upper part of its surface watershed, but did not identify the seasonally dry main stem of the river as a disconnected stream because its reach segment is identified within the NHD as a perennial stream.

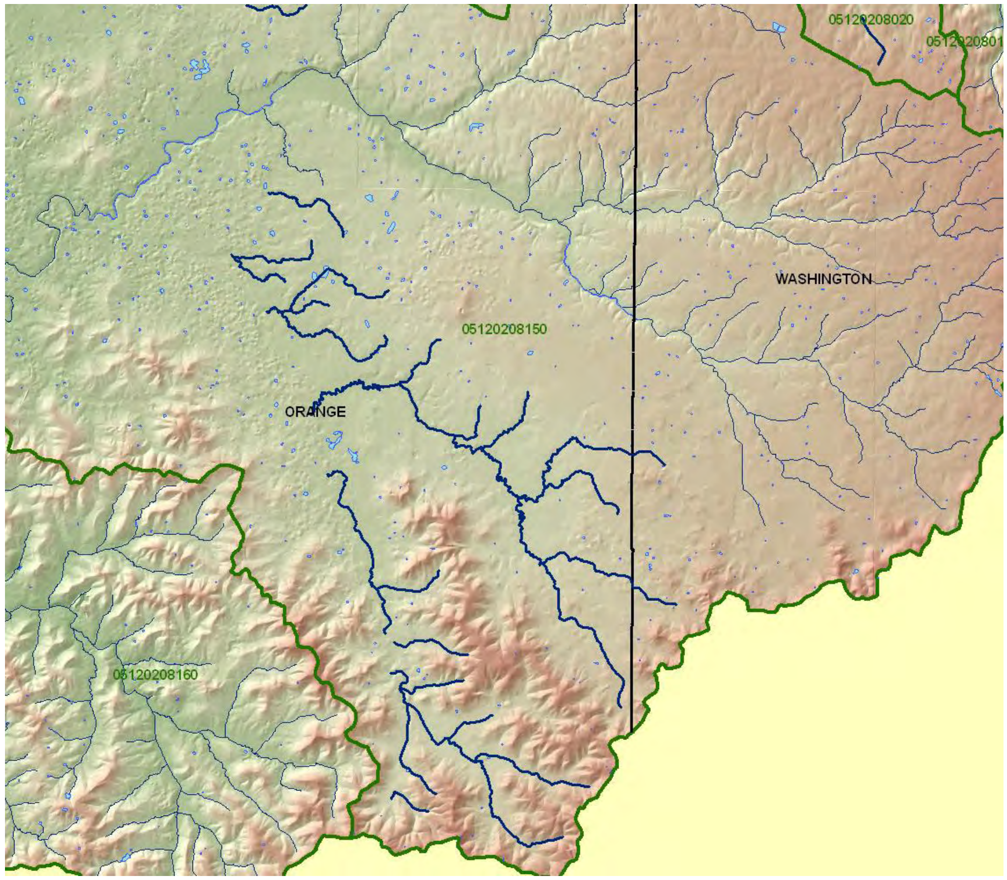


Figure 9. Screen-capture image showing example of sinking streams delineated by highlighting disconnected stream reaches identified in part of the Lower East Fork White River eight-digit Hydrologic Unit (05120208), in south-central Indiana.

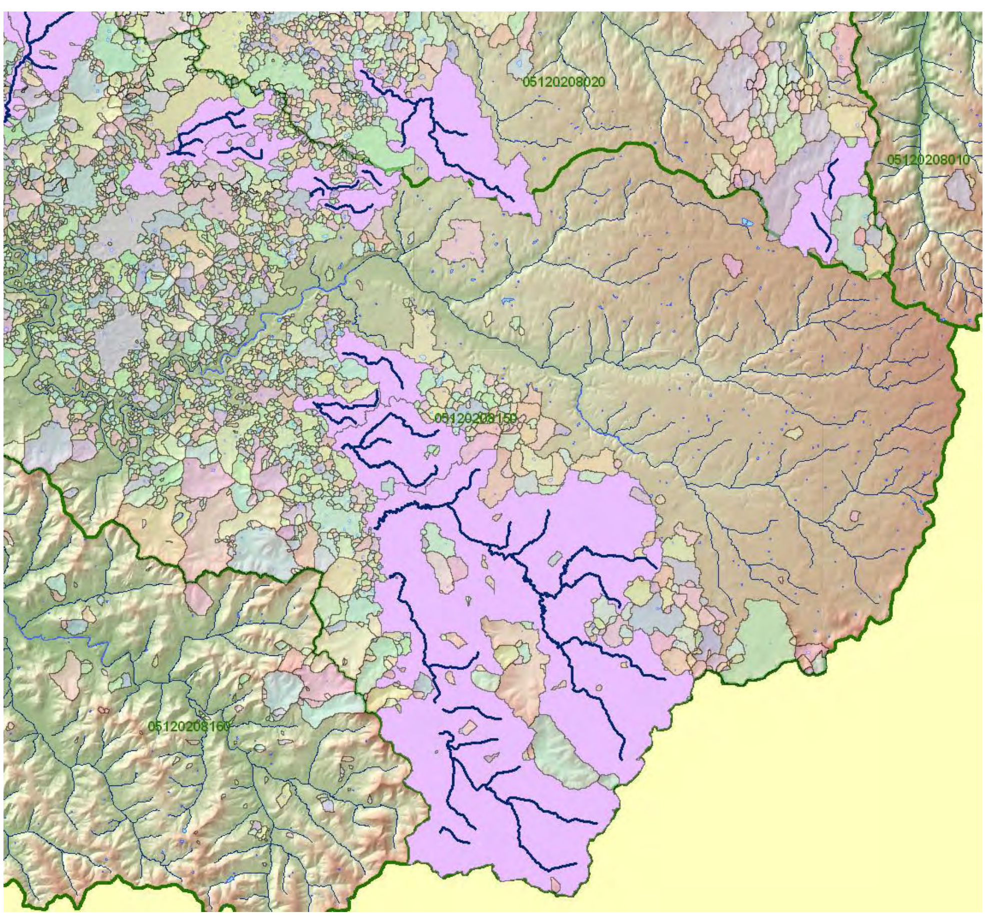


Figure 10. Screen-capture image showing catchments for sinking streams delineated in the same portion of the Lower East Fork White River eight-digit Hydrologic Unit (05120208), south-central Indiana, shown in figure 9. (Note the multi-colored polygons that represent the internally drained catchment areas of sinkholes.)

Karst Flow Paths

In the ArcReader data files the vectors used to represent the trends of tracer-inferred karst flow paths were obtained from available digital data files or were derived by digitizing maps and other illustrations contained in available published and unpublished reports of water-tracer tests usually conducted with fluorescent dyes. During data compilation, no efforts were made to redraw, reinterpret, or correct the karst flow paths as plotted or illustrated in the original source materials. Therefore, in some locations, tracer-inferred flow paths are depicted as straight lines, representing the inferred hydrologic connections between specific points of tracer-input and tracer-recovery and the general direction of flow, and in other locations vectors are represented as curvilinear lines that attempt to provide a more natural depiction of the pattern of conduit drainage which typifies most of the region's karst flow systems (Ray, 2001). The later method is used exclusively for depiction of karst flow paths derived from the Kentucky karst atlas series (Currens and Ray, 1999). In most cases, the trajectories and interconnections of these curvilinear vectors are conjectural and are not meant to represent actual ground-water flow paths except where subsurface mapping has confirmed the presence of actual solutional conduits (Ray, 2001). In addition, while most of the karst flow paths depict subsurface flow through conduits, many also include segments of surface flow, for example, at sinking streams or at karst geomorphic features known as *karst windows*, which are topographic depressions that reveal a part of an active subsurface conduit or an unroofed part of a cave stream passage (Field, 2002).

In general, the geographic coverage of water-tracer data is quite sparse within the regional study area and karst flow paths have not been delineated in most of the HUC-8 watersheds due to either a lack of water-tracer tests or a lack of publicly accessible data. Differing approaches are taken by State agencies with regard to karst field mapping efforts and the reporting requirements placed on water-tracer tests conducted for academic, environmental assessment, contaminant response, and hazardous-waste site studies. A considerable number of water-tracer tests have been undertaken in each State in the regional study area as part of site-specific hydrogeologic investigations or environmental-assessment studies done for regulatory purposes; however, much of these data are presently (2008) designated as proprietary and cannot be released or reported to the general public. Otherwise, large gaps in the geographic coverage of existing karst flow path data highlights the relative lack of resources, funding, and effort being provided to support basic karst field mapping studies in the regional study area.

Presently (2008), the greatest amount of available water-tracer test data and the greatest area of geographic coverage of data are found in Kentucky where State water-resources agencies have conducted a long-term effort of cooperative karst mapping, resulting in a series of published karst atlas maps (Currens and Ray, 1999). Other State agencies in the regional study area are in the early stages of implementing karst-mapping programs of various kinds, with the overall goal of making more water-tracer test data available to the public. For example, the State of Tennessee is in the process of creating an Internet-accessible database of dye-tracer test results (Ogden and others, 2005). Efforts to compile a water-tracer test database also are being planned and implemented to various degrees in Alabama. In Indiana, some available data also have been compiled as printed and digital-map products (Frushour and others, 2000).

The metadata contained in the ArcReader datasets for each karst flow path delineated is generally limited to the location coordinates of the plotted tracer-input and tracer-detection site, and the originating source of the tracer-test data. While documentation of field and analytical methods used to conduct a particular water-tracing test are critically important to the interpretation of the results, it is beyond the scope of this project to obtain, report, or independently verify this information for each tracer-inferred karst flow path included in the ArcReader datasets. Therefore, no assurances can be made regarding the accuracy or validity of the plotted karst flow paths nor any interpretations made on the indicated water-tracer-test results. Caution should be applied to the use and interpretation of any karst flow paths presented here. Users of the KHI project geodatabase are encouraged to contact appropriate State agencies to obtain information needed for site-specific studies or applications.

Relic Streams

One unique product of the KHI project is the delineation of relic streams, also known as karst paleovalleys (Thrailkill, 1985). These are geomorphic features that indicate the presence and trend of former surface streams which have ceased flowing because of subsurface conduit piracy and whose valleys have undergone subsequent solution-enhanced modification and erosion. As a consequence, the former channels of relic streams may be largely unrecognizable in the field, especially where there has been significant modification of the local topography by sinkholes. The mapping of relic streams is a particularly useful capability provided by the KHI project dataset because the locations of these features are often correlated with, and influenced by, the development of subsurface karst conduits. The trends and geomorphic characteristics of relic streams may provide clues that are helpful in conceptualizing the pre-karst drainage history and the subsequent development of subsurface conduit drainage routes and networks.

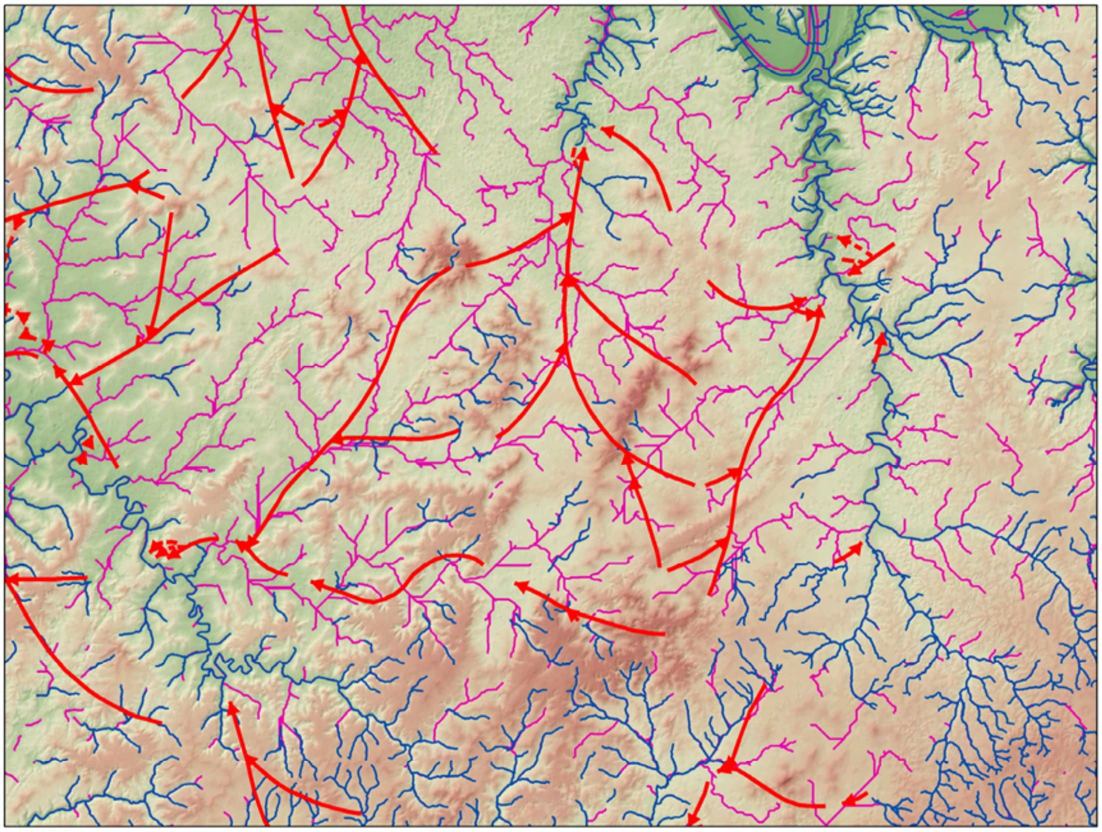
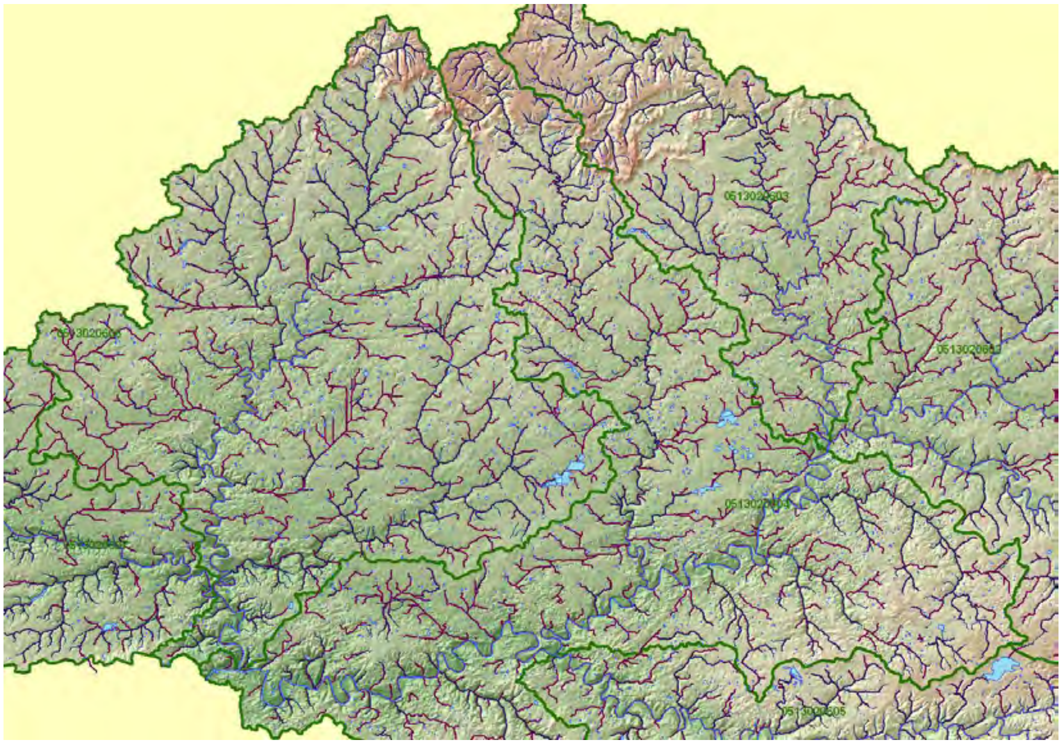


Figure 11. Screen-capture image showing the apparent close correlation between relic streams (purple lines) and tracer-inferred subsurface flow paths (red arrows) in a portion of the Sinking Creek/Otter Creek Hydrologic Unit (05140104KY), in north-central Kentucky (from Taylor and others, 2005).

They may therefore be useful in understanding the directions of subsurface flow revealed by dye-tracer tests (fig. 11) or serve as useful indicators of the presence of major subsurface conduits or as favorable locations for drilling observation or water-supply wells (Taylor and others, 2005). In addition, recognition of relic streams may assist in the identification of karst flooding hazards in locations where former surface flow routes are reactivated during storm events in which the hydraulic capacities of subsurface conduit drainage networks are exceeded (Ray, 2001; Currens and Graham, 1993; Bayless and others, 1994).

To properly visualize relic stream features using the ArcReader datasets, both the “hydrology” and “relic stream” data files must be toggled on in the ArcReader table-of-contents frame. Doing this enables the traces of relict streams to be distinguished from the channels of perennial and intermittent surface streams. The traces of the relic streams were delineated using a relatively simple GIS-terrain-processing technique similar to that described by Glennon and Groves (2002). In general, the technique (appendix 2) involves using ArcGIS tools to artificially fill sinkholes, valley traces, and other topographic depressions in the DEMs to their spillover points until the traces of the formerly active surface drainage routes begin to emerge (figs. 12 a and b). One critical step in the data processing is to apply the ArcGIS GRID command FILL by defining a particular Z_LIMIT value for depth of fill. The Z_LIMIT value is initially selected based on the general range of topographic relief between base-level stream channels and adjacent uplands or sinkhole plains. It can be adjusted by trial and error as needed to enhance the delineation of the traces of the relic stream valleys. If the fill depth is too great, the traces delineated for the relic streams may expand laterally beyond the spatial limits of the sinkholes and topographic features that delineate them. In most locations in the regional study area, Z_LIMIT values of 10 to 20 meters (30 to 60 feet) seemed to best delineate the traces of relic streams. In some locations, unnaturally linear traces may be observed (fig. 13). These features are an uncorrected plotting artifact of the GIS-terrain-processing algorithm and typically occur where the traces of a relic stream extend across a lake or along the floor of certain broad, flat topographic valleys.

(A)



(B)

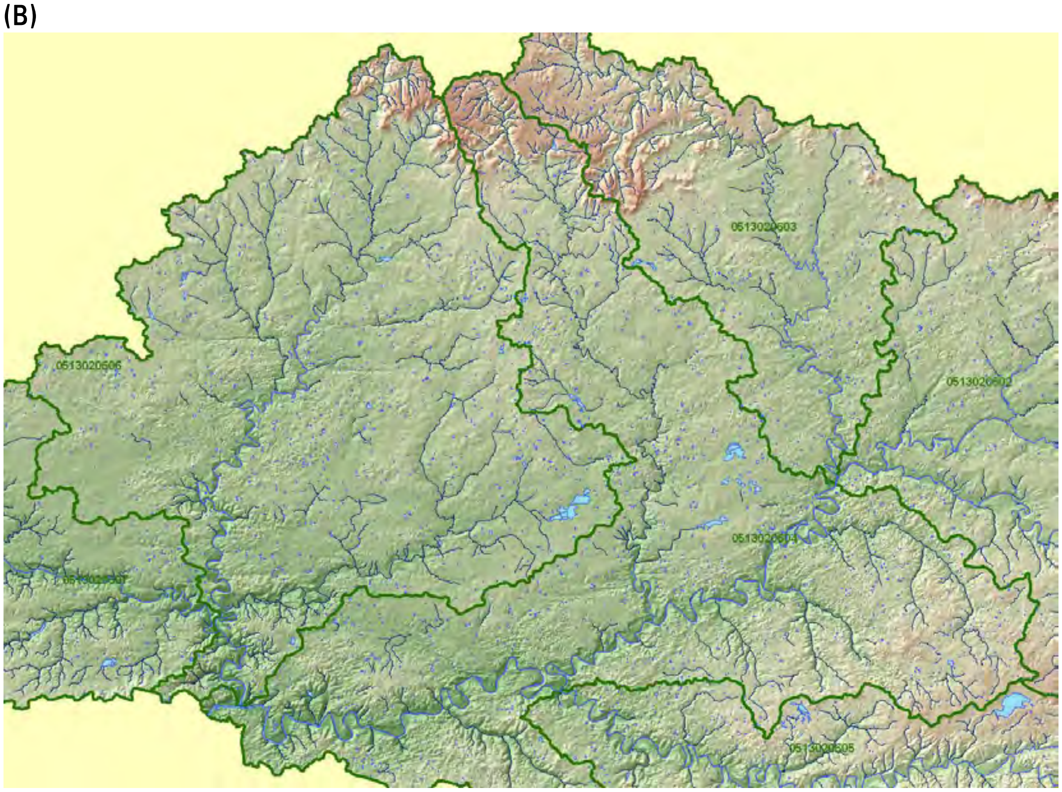


Figure 12. Screen-capture images showing catchments for a portion of the Red River Hydrologic Unit (05130206), Kentucky–Tennessee, with traces of relic streams delineated by Geographic Information System (GIS)-terrain-processing methods: (**A**) relic streams “on” and (**B**) same area shown with relic streams “off.” (Note extensive areas of sinkhole-pitted topography lacking surface streams.)

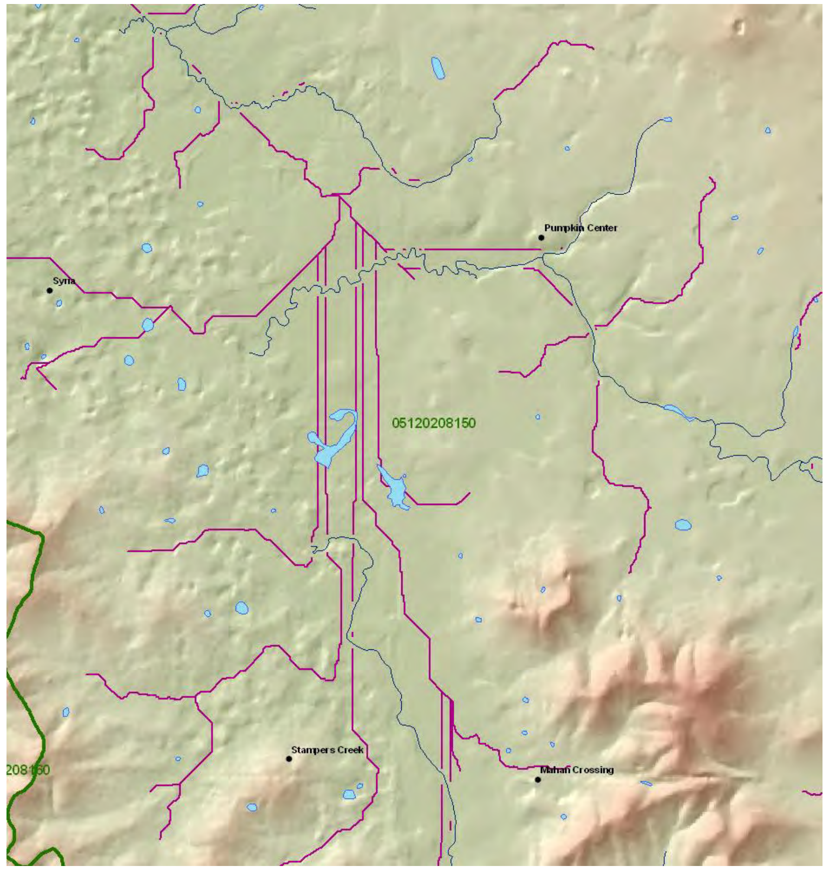


Figure 13. Screen-capture image showing an unnatural linear delineation of relic streams. (This is a plotting artifact created in certain topographic locations by the Geographic Information System (GIS)-terrain-processing algorithm.)

Summary

The release of provisional karst geospatial data compiled during 2004–2007 for the Karst Hydrology Initiative (KHI) project is intended to improve the public's accessibility to karst hydrogeologic mapping data in the Interior Low Plateaus region, aid or supplement State and Federal karst mapping programs, and promote additional work in mapping and investigation of regional karst hydrogeologic frameworks. The ArcReader datasets and Printable Map Files (*.pmf* files) described in this report serve as a pre-processed source of karst geospatial data that can be easily used to visualize features such as sinkholes, sinking streams, karst springs, and internally drained surface catchments, as well as karst flow paths inferred from water-tracer test data, and to evaluate the distribution of these features in the context of other regional topographic, surface hydrologic, and geologic characteristics which constitute the hydrogeologic framework for the karst. Newly derived geospatial data that are unique to this regional dataset include internally drained catchment areas for sinkholes and sinking streams and karst geomorphic features termed relic streams.

Instructions for obtaining the ArcReader data folders can be obtained from the Internet web page of the U.S. Geological Survey (USGS) Kentucky Water Science Center (*http://ky.water.usgs.gov/index.htm*) or the USGS Ground-Water Resources Program (*http://water.usgs.gov/ogw/gwrp/*). It is anticipated that this provisional regional karst dataset will be most beneficial to State and Federal environmental regulators, water-resources managers, consultants, and others involved in karst hydrologic studies or having responsibilities that address emergency response to hazardous spills, water use and source-water protection, assessments of total maximum daily contaminant loads (TMDLs) and other wastewater-discharge issues, mitigation of point- and nonpoint-source pollution, identification of potential karst geohazards, and protection of sensitive karst ecosystems.

The compilation of these data, that is, the cataloguing of ArcReader data folders according to HUC-8 codes designated for major regional watersheds, is consistent with the watershed-management framework recommended by the U.S. Environmental Protection Agency (USEPA) and will facilitate the transfer of regional karst data to other national geospatial databases such as the USGS National Hydrography Dataset (NHD) (*http://nhd.usgs.gov/*) and The National Map project (*http://nationalmap.gov/*). In addition, this method of data compilation emphasizes the direct interconnection between surface-water and ground-water regimes in the well-developed karst areas of the regional study area, and provides a template for compilation of regional karst geospatial data that may be beneficially applied to other karst areas throughout the United States.

Acknowledgments

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Appendixes 1 and 2

Appendix 1. Process for delineation of internally drained catchments using ArcGIS

Method applied in the present study requires ESRI ArcMap software with the Spatial Analyst extension. Required geospatial datasets include (1) DEM (Digital Elevation Model) as a raster file; (2) National Hydrography Dataset (NHD) stream reaches compiled as vector lines into Hydrology and Reach files; (3) a "Notsink file," subset of connected or non-sinking streams; (4) disconnected or sinking stream reaches; and (5) sinkhole locations compiled as vector polygons or points.

The GIS processing steps are as follows:

1. In the Spatial Analyst toolbar use the **Convert–Feature to Raster** tool to convert the reach vectors to a raster with the same size cells and the same origin as the DEM. The cell values are obtained from an item in the attribute table set for each feature, in this case, all values are set to 1. Result is a raster with stream-cell values equal to 1 and all other cells as nodata (null).
2. Use the Spatial Analyst Tools–Math–Logical–**Is Null** tool to change the null values in the reach raster to zero. Then use the Spatial Analyst Tools–Math–Trigonometric–**Minus tool to** multiply the reach raster by a large value (1,000 is good for this study area; value should be larger than the maximum elevation in the DEM).
3. Use the Spatial Analyst Tools–Math–Trigonometric–**Minus** tool to subtract the reach raster from the DEM. This "burns in" the streams to ensure proper flow.
4. Use the Spatial Analyst Tools–Hydrology–**Flow Direction** tool to create a flow-direction raster from the burned-in raster.
5. Use the Spatial Analyst Tools–Hydrology–**Sink** tool to create a sink raster from the flow-direction raster. Result is a raster with unique numeric values for the cells that do not flow to any other cell and nodata values everywhere else.
6. Use the Spatial Analyst Tools–Hydrology–**Fill** tool to fill the burned-in raster to remove all sinks (cells that do not flow to another cell). This raises the elevation of sink cells through several iterations until every cell flows to another cell or off the edge of the raster.
7. Use the Spatial Analyst toolbar–**Raster Calculator** to create a raster of the difference between the burned-in raster and the filled raster. The result is a raster of all the locations of depressions in the DEM whether they are true sinkholes or not. Example: Diffgrid = [fillgrid] diff [burngrid].
8. Use the **Raster Calculator** to change the values of 0 in the difference raster to nodata (null). Example: diffnodata = con([diffgrid] > 0, [diffgrid].
9. Use the **Raster Calculator** to convert the difference raster with nodata values to an integer raster by truncation. Example: intdiff = int([diffnodata]).
10. Use the Spatial Analyst tools–Generalization–**Region Group** tool to create a region raster by grouping the contiguous cells in the integer-difference raster and giving each group a common unique value.
11. Use the Spatial Analyst toolbar–Convert–**Raster to Feature** tool to convert the region raster to polygons.
12. Use the main ArcMap–Selection–**Select by Location** tool to select the region polygons that are true sinkholes by using the sinkhole-location data layer and the "Notsink" streams layer. Region polygons intersecting the sinkhole-location layer and not intersecting the notsink layer are kept as spillway polygons and the rest are eliminated.
13. Use the Spatial Analyst toolbar–Convert–**Feature to Raster** tool to convert the spillway polygons to a spillway raster.
14. Use the Spatial Analyst toolbar–**Raster Calculator** to create a raster of throats, which are only the cells which have a non-null value in both the sink raster and the spillway raster. Example: throat grid = con(is null([spillway grid]), [spillway grid], [sinkfdr]).
15. Use the Spatial Analyst toolbar–Convert–**Raster to Feature** tool to convert the throat raster to polygons.
16. Use the main ArcMap–Selection–**Select by Location** tool to select the spillway polygons that intersect the throat polygons and eliminate the rest.
17. Use the Spatial Analyst toolbar–Convert–**Feature to Raster** tool to create a spillsink raster from the remaining spillway polygons.
18. Use the **Raster Calculator** to create a raster of throatlinks by giving the non-null cells in the throat raster the values from the spillsink raster and the rest of the cells a value of nodata. Example: thrtlink = con([throatgrid], [spillsinkgrid]).
19. Use the **Is Null** tool (from step 2) to create a raster that has values of 0 for the non-null cells in the throatlink raster and values of 1 everywhere else.

20. Use the **Raster Calculator** to create a raster that has the values from the burned-in raster from step 3 wherever the value of the raster from step 19 is 1 and nodata values everywhere else. Example: thrtnddem = con([throatnodata] = = 1, [burngrid]).

21. Use the **Fill** tool on the raster from step 20, creating a version of the DEM with filled false sinkholes and nodata where the true sinkholes are located.

22. Use the **Raster Calculator** to create a raster that fills in the nodata values in the raster from step 21 with the values from the burned-in raster in step 3. Example: finaldem = con(isnull([thrtdemfil]), [burngrid], [thrtdemfil]).

23. Use the Spatial Analyst Tools–Hydrology–**Flow Direction** tool to create a new flow direction raster from the raster in step 22.

24. Use the Spatial Analyst Tools–Hydrology–**Watershed** tool to create a raster of the sinkhole-drainage areas using the flow direction raster from step 24 with the throatlink raster as the pour points.

25. Use the **Raster to Feature** tool to convert the drainage-area raster to polygons.

Appendix 2. Process for delineation of relic stream valleys using ArcGIS

1. Used Kentucky’s 10-meter Digital Elevation Model (DEM) as base data for this process.
2. Filled the sinks in the DEM using the GRID command FILL with the SINK option and a Z_LIMIT of 30 feet.
3. Created a flow-direction grid from the filled DEM by using the GRID command FLOWDIRECTION.
4. Created a flow-accumulation grid from the flow-direction grid by using the GRID command FLOWACCUMULATION.
5. Created a synthetic-streams grid by truncating the flow-accumulation grid to a value of 5,000 cells by using the GRID function SETNULL.
6. Converted the synthetic-streams grid to an integer grid by using the GRID function INT.
7. Converted the synthetic-streams-integer grid to an ARC/INFO line coverage by using the GRID command STREAMLINE with a weed tolerance of 40.
8. Applied a buffer to the NHD streams data file to eliminate the line segments within 100 feet of the NHD streams.

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