

Hydrogeologic-Framework Mapping of Shallow, Conduit-Dominated Karst—Components of a Regional GIS-Based Approach

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INTRODUCTION

Recent advancements in geographic information system (GIS) technology, coupled with the increased availability of Internet-accessible geospatial datasets such as Digital Elevation Models (DEMs), Digital Orthophoto Quadrangles (DOQs), and Digital Raster Graphic Maps (DRGs), have greatly improved the compilation, interpretation, and visualization of information needed to address water-resources management and protection issues. As applied to karst hydrogeologic studies, GIS is an exceptionally useful way to assemble and process the complex datasets needed to map karst hydrogeologic features (Florea and others, 2002; Gao, 2002) and also provides an effective means of identifying important but sometimes obscure relations between surface and subsurface components of karst aquifer systems (Veni, 1999, 2003).

This Abstract briefly describes the GIS-based approach being applied to synthesize available hydrogeologic mapping data as part of a regional karst study being conducted by the U.S. Geological Survey (USGS) Ground-Water Resources Program. The focus of the regional study is the shallow, conduit-dominated karst aquifers of the Interior Low Plateaus physiographic region of the United States (fig. 1). These aquifers are located in seven geographically distinctive karst terranes (fig. 1) that exhibit similar hydrogeologic characteristics. The framework for the karst aquifers in each of the seven terranes consists of contiguous karst drainage basins. Each karst drainage basin is defined by a specific geographic area where surface and ground water are highly interconnected and contribute to the flow within a dendritic conduit drainage network (fig. 2). Typically, each karst drainage basin dis-

charges to a large perennial karst spring that functions as the primary drainage element of a high-flow distributary (Quinlan and Ewers, 1989). The hydrologic behavior of the karst drainage basins and the springs is greatly affected, and often dominated, by concentrated recharge that originates as stormwater runoff drained rapidly to the subsurface by way of sinkholes and sinking streams. However, the bulk of the annual recharge to the karst drainage basins occurs by dispersed infiltration of precipitation through the soil and by water stored and released from a leaky epikarst zone (Ray, 2001).

COMPONENTS OF THE GIS-BASED APPROACH

Much of the first year of the study has been devoted to gathering available data and to developing GIS methods and datasets needed to map major karst hydrogeologic features at local to regional scale. Components of the GIS-based mapping approach include (1) sinkhole locations and catchment areas defined by processing of DEMs, (2) springs identified in the USGS National Water Information System (NWIS) database, (3) topographic drainage divides derived from DEMs, (4) identified sinking or losing streams and relic stream valleys (karst paleovalleys), (5) other hydrographic features such as perennial “blue line” streams and ponds or lakes, (6) 8- and 10-digit hydrologic unit (HU) boundaries, (7) vectors representing subsurface flow paths inferred from reported dye-tracer test results, and (8) boundaries of karst drainage basins inferred by dye-tracer tests and other hydrogeologic-mapping techniques.

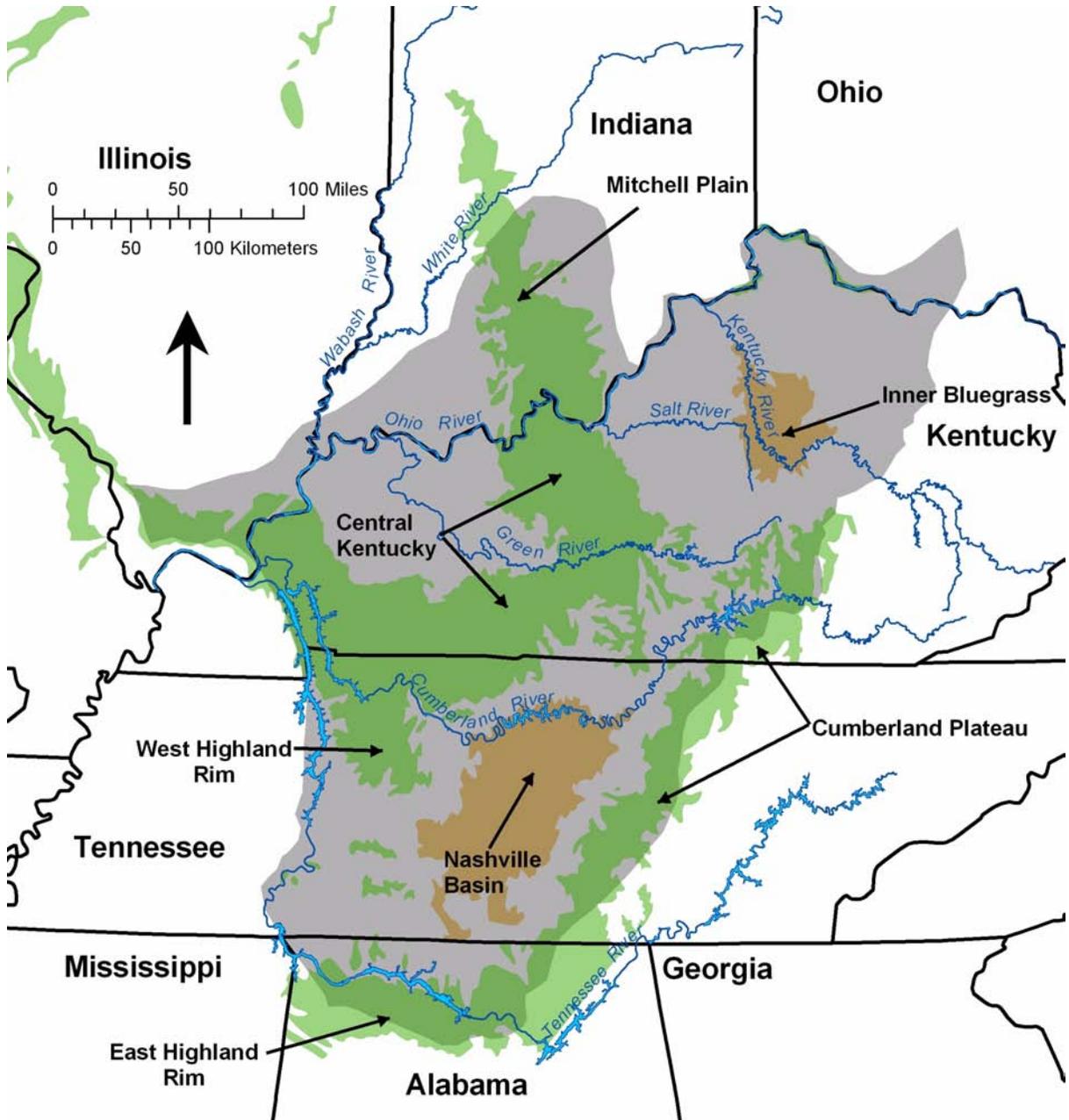


Figure 1. Interior Low Plateaus regional study area and its seven major karst terranes: (1) Mitchell Plain; (2) Central Kentucky; (3) Inner Bluegrass; (4) West Highland Rim; (5) Nashville Basin; (6) Cumberland Plateau; and (7) East Highland Rim.

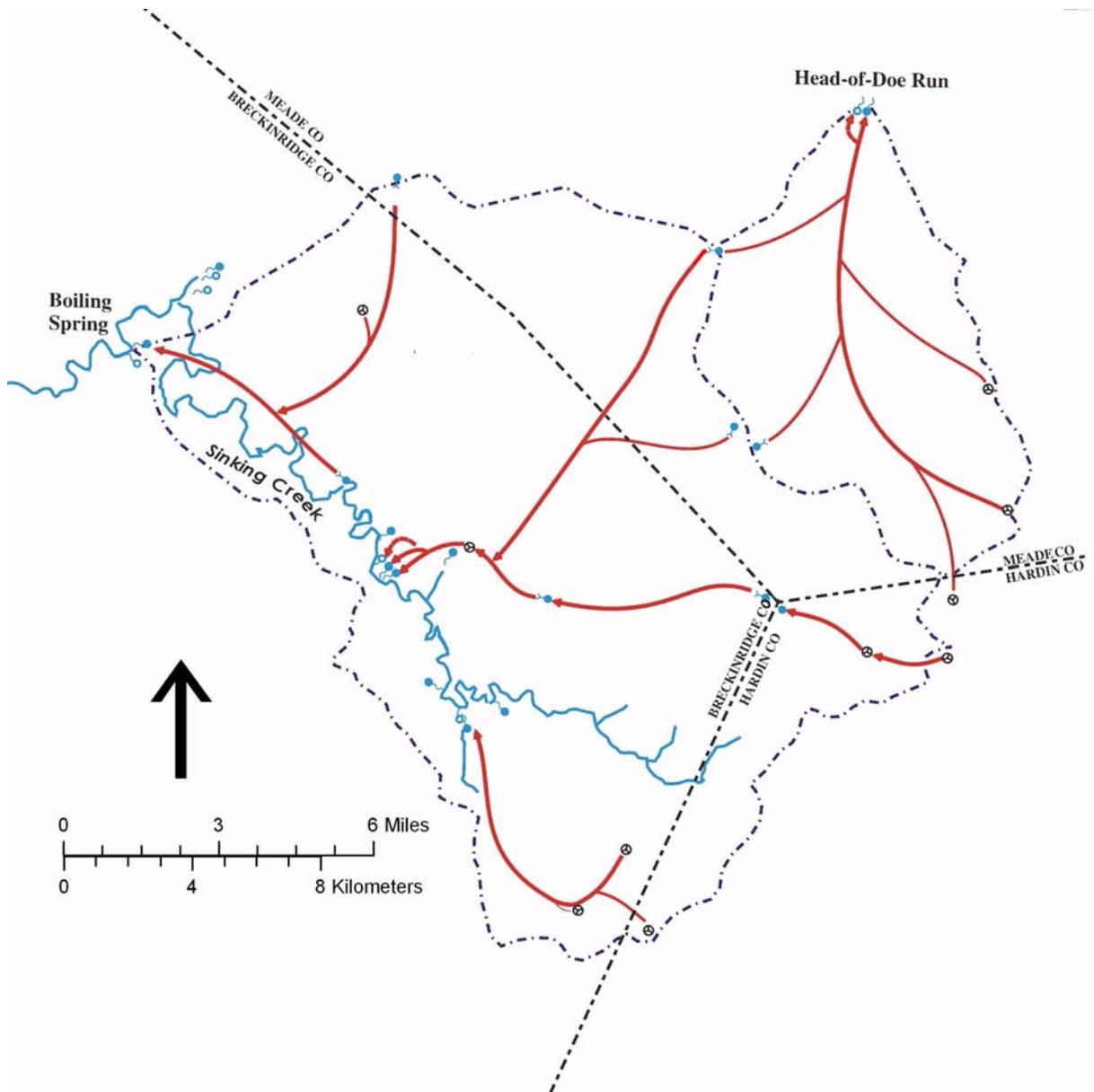


Figure 2. Dendritic conduit flow paths, inferred by dye-tracer test results (curvilinear arrows), are typical of karst drainage basins in the regional study area. This example illustrates the flow paths and basin boundaries (dashed lines) delineated for Boiling Spring and Head-of-Doe Run Spring in the Central Kentucky karst terrane. (Modified from Joe Ray, Kentucky Division of Water, unpub. data, 2005).

Of the eight components listed above, dye-tracer test data are the most crucial and difficult to obtain. A considerable effort has been made to identify sources of, and obtain, all available (i.e., publicly accessible) dye-tracer test data in the region. However, with the exception of Kentucky, where a systematic effort is being made by State agencies to map karst flow paths and drainage basin boundaries (Currens and Ray, 1999), the availability and quality of dye-tracer test data vary greatly. In general, dye-tracer test data are clustered in certain geographic areas within each of the seven karst terranes delineated in figure 1. Where dye-tracer test data are too sparse or lacking, GIS mapping of subsurface flow paths and karst drainage basin boundaries is not possible. Nevertheless, in these areas, as elsewhere in the region, the surficial karst features are being mapped, analyzed, and compared.

One goal of this work is to obtain a regional karst features database—composed of the eight hydrogeologic mapping components listed above—sembled as print-publishable map files (PMFs) that can be viewed and manipulated using ArcMap¹ or ArcReader GIS software. To emphasize the direct interconnection between ground and surface water in karst terranes, a watershed cataloguing scheme is being used to index the PMFs: first, by 8-digit HU codes; second, by 10-digit HU codes. An example of the watershed cataloguing scheme is shown in figure 3, which presents DEM data processed with GIS to delineate the 10-digit HUs, or topographic subbasins, included in the 8-digit Upper Green River HU (watershed) in the Central Kentucky karst terrane. This cataloguing scheme will facilitate evaluation and comparison of karst features within and among regional surface watersheds

and will aid the transfer of karst hydrologic data to the USGS National Hydrography Dataset (NHD) (<http://nhd.usgs.gov/>) and The National Map project (<http://nationalmap.gov/>).

The synthesis of data by watersheds also provides a useful means to easily correct or refine HU boundaries, which are used as basic water-accounting units by the NHD and are needed for a variety of Federal and State environmental and water-use regulatory programs. If HU boundaries, which are mapped using topographic drainage divides, are not corrected in karst areas to account for subsurface conduit routing of flow into or out of surface watersheds, appreciable errors may be introduced to the delineation of the contributing areas of surface streams, karst aquifer boundaries, and hydrologic calculations or models (Currens and Ray, 1999). Examples of this potential problem are shown in figure 3, where the inserts (figs. 3A and 3B) illustrate two locations in the Upper Green River watershed that the boundaries mapped for constituent 10-digit HUs do not coincide with the boundaries of the actual contributing area as determined by dye-tracing tests. The errors potentially introduced by assigning and using HU boundaries without correcting for karst drainage can be appreciable. In this case, approximately 75 percent of the Upper Green River's drainage area is misattributed to the Barren River—an adjacent 10-digit HU (Ray, 2001). In a preliminary assessment, using available dye-tracer test data, Ray and others (2000) estimated that approximately 15 to 20 percent of the Central Kentucky karst terrane may exhibit such "misbehaved" drainage. The extent of this potential problem in the other karst terranes in the regional study area has not been determined.

¹Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

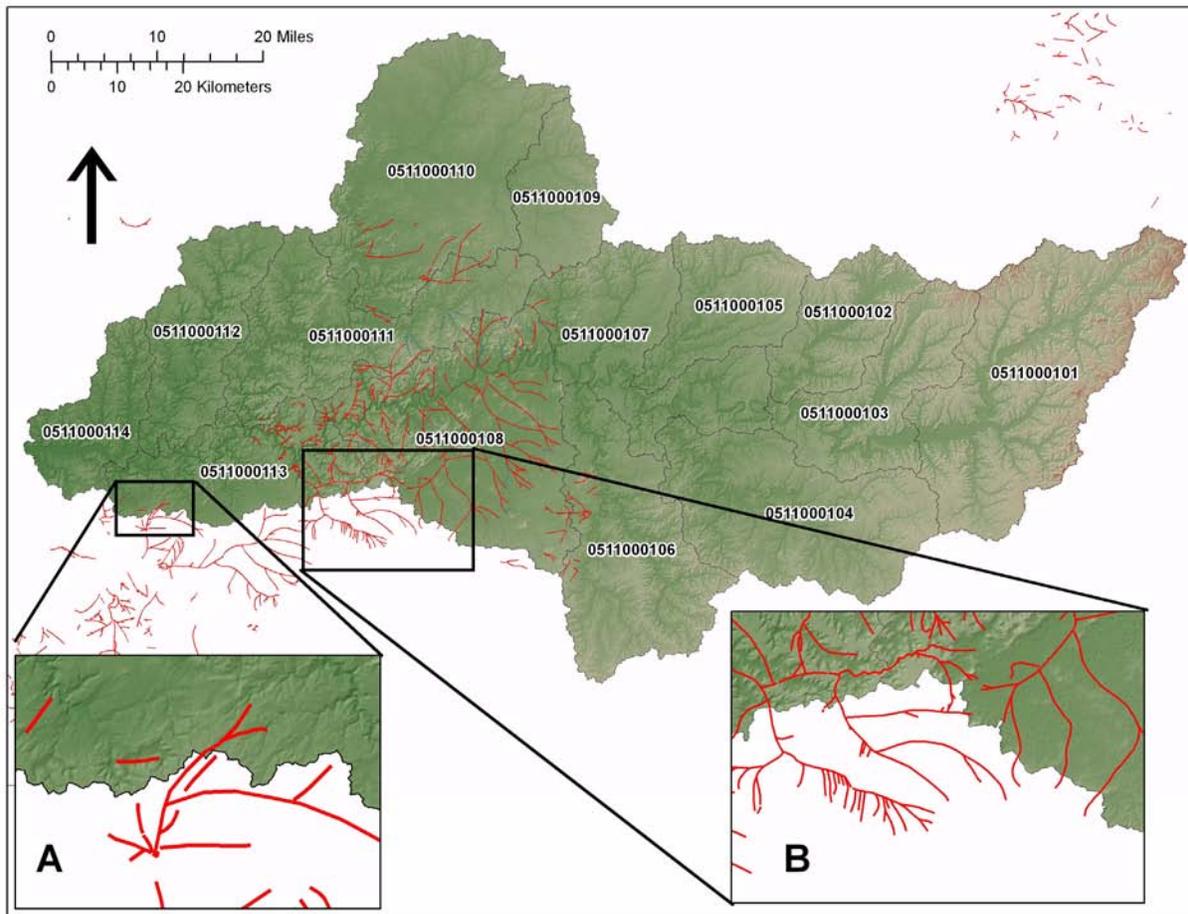


Figure 3. Processed DEM of the Upper Green River watershed (8-digit HUC 05110001), Kentucky, showing 10-digit HUs (sub-watersheds) and overlaid dye-tracer flow paths. Dye-tracer flow paths in (A) identify sinkhole drainage areas in a 10-digit HU (0511000113) mapped within the boundaries of the Upper Green River watershed that actually contribute to an adjacent 10-digit HU (not shown) located outside of the Upper Green River watershed. In contrast, dye-tracer flow paths in (B) identify a large area (approximately 85 square miles.) of sinkhole drainage mapped outside the boundaries of the Upper Green River watershed that, in fact, contribute to the watershed.

DEM PROCESSING TO MAP SINKHOLE CATCHMENTS

Sinkhole location maps have been, or are being, prepared by various State agencies in the regional study area; however, different sinkhole identification and mapping criteria are being used and the catchment areas of the sinkholes are usually not delineated. In karst terranes, delineation of sinkhole catchment areas is equally if not more important to hydrologic or water-quality studies and assessments as delineation of surface-stream watersheds. For this regional study, individual sinkhole catchment areas define useful “subbasins” within the 10-digit HUs. Therefore, a method of GIS processing of DEM data sets was developed to standardize and partly automate the mapping of sinkhole catchment areas. Topographic depressions in the DEMs are identified and artificially filled using GIS-processing tools, and a grid of the difference between the filled and unfilled depressions is developed. “Throats,” or locations within the depressions that are internally drained, are identified using a GIS “SINK” tool. Grid cells associated with these throats are grouped together by assigning them unique numeric values that lump throats together into clusters and tie the clusters to an associated topographic depression. Grouped topographic depressions and throats are then used as input data to define sinkhole catchment areas using a GIS “WATERSHED” delineation tool (fig. 4A). The grouping process helps eliminate over-tessellation (subdivision) of catchment areas for depressions identified in the raster grid (fig. 4B) and helps to produce more physically realistic delineations of sinkhole catchments, complex sinkholes, and the watersheds of sinking streams that terminate in a sinkhole depression. Additional processing techniques, such as setting filters on depression size (area) and buffers near surface streams and performing cross-checks with sinkholes identified on available State maps, are needed to eliminate depressions in the raster grid that are not likely to be actual dissolution-generated sinkhole features.

RELIC STREAM VALLEYS

One unique component of the GIS processing being done for the regional study is the delineation of relic stream valleys, which are also called paleovalleys (Thraikill, 1985). Relic stream valleys are karst geomorphic features identifiable as alignments or “trains” of sinkholes sometimes co-located within shallow topographic valleys and often appear to be the downstream extensions of sinking or losing stream reaches. Relic stream valleys represent former surface-stream channels in which flow was abandoned as a result of subsurface conduit piracy. In this study, relic stream valleys are being delineated using a GIS approach similar to that described by Glennon and Groves (2002) in which the DEMs are processed so that traces of the former surface-flow routes develop as sinkhole depressions are artificially filled to their spillover points (figs. 5A and 5B).

The identification and mapping of relic stream valleys using GIS is a potentially important outcome of this regional study because these features are often associated with the locations of major karst conduits and karst drainage basins (Thraikill, 1985). The trends and geomorphic characteristics of the relic stream valleys also provide clues that are helpful in conceptualizing the pre-karst drainage history and in understanding the development of conduit networks and the directions of subsurface flow revealed by dye-tracer tests (fig. 6). In addition, identification and mapping of relic stream valleys may help to identify potential flood hazard areas in the region’s karst terranes. Flooding of relic stream valleys—as with sinking or losing streams—occurs when the drainage capacity of sinkholes, swallets, or karst conduits cannot accommodate the volume of stormwater runoff generated within the surface catchment area (Ray, 2001). This mechanism has been identified in at least one location in the regional study area where flooding of a relic stream valley has resulted in substantial property damage (Bayless and others, 1994), and it may be an important, but poorly recognized, potential karst hazard elsewhere.

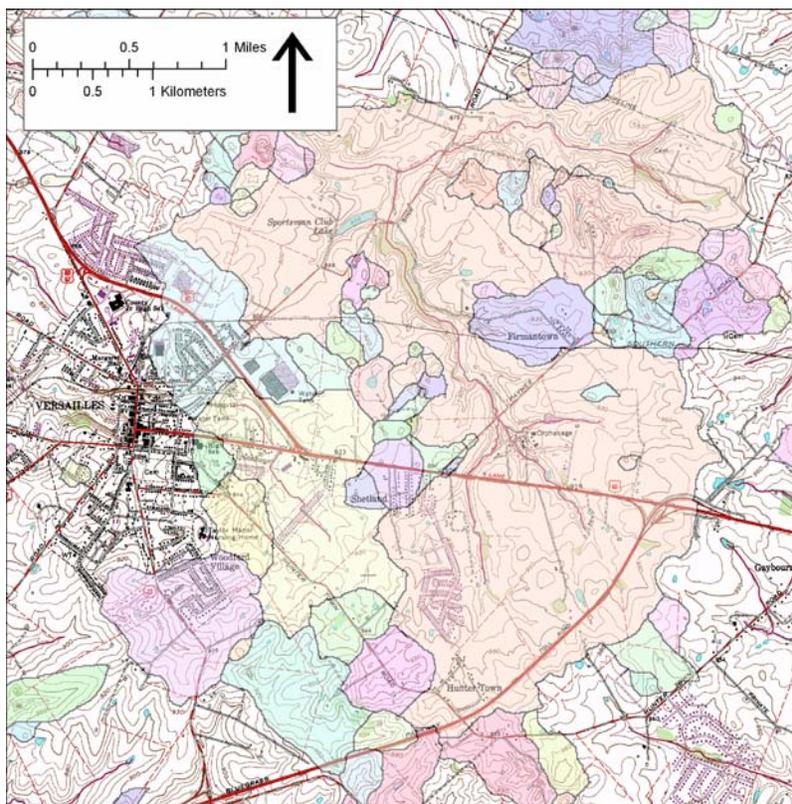


Figure 4A. Delineation of sinkhole catchments (shaded or colored polygons) near Versailles, Kentucky, (Inner Bluegrass karst terrane) using GIS-processed DEM data. The image shows the more realistic delineation of sinkhole catchments achieved by grouping “throats” (grid cells with internal drainage) within topographic depressions prior to applying the “WATERSHED” delineation tool.

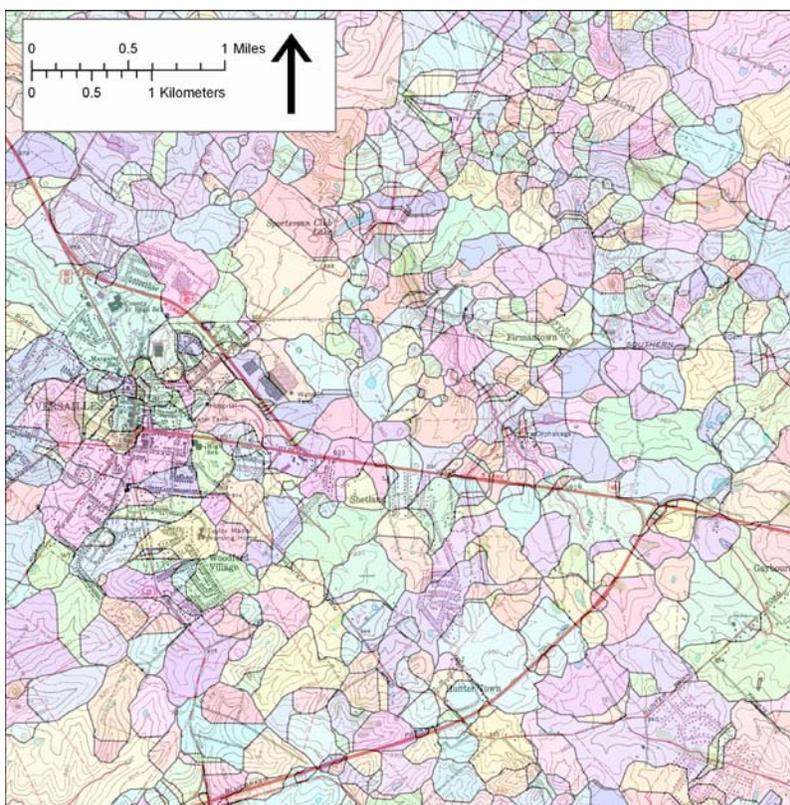


Figure 4B. Delineation of sinkhole catchments in the same area as that shown in figure 4A, illustrating the over-tessellation obtained by applying the “WATERSHED” delineation tool without grouping “throats.”

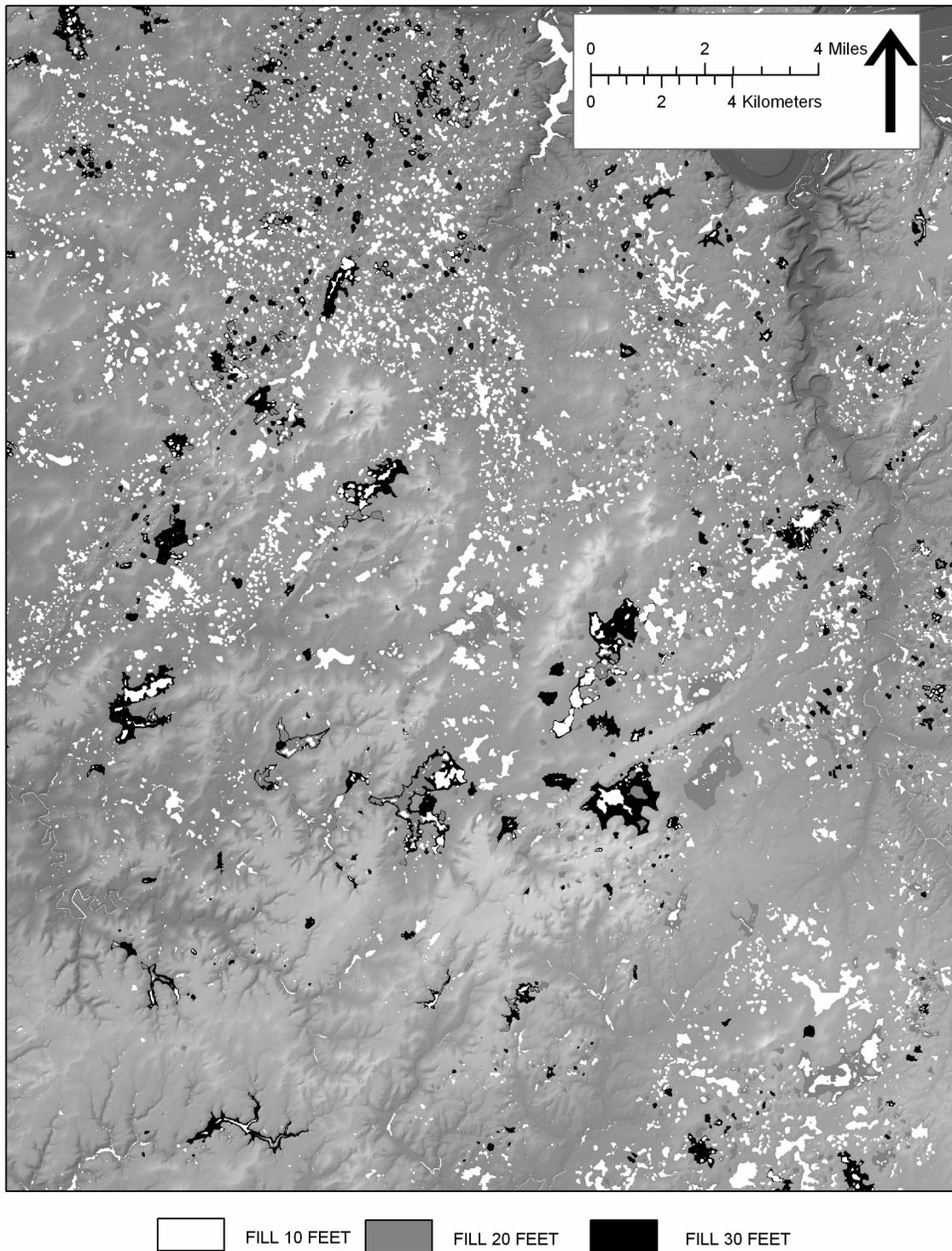


Figure 5A. Example of DEM processing used to delineate relic stream valleys in part of the Central Kentucky karst terrane. The image shows the geomorphologic patterns obtained by artificially filling identified sinkhole depressions to three different depths (indicated by shading).

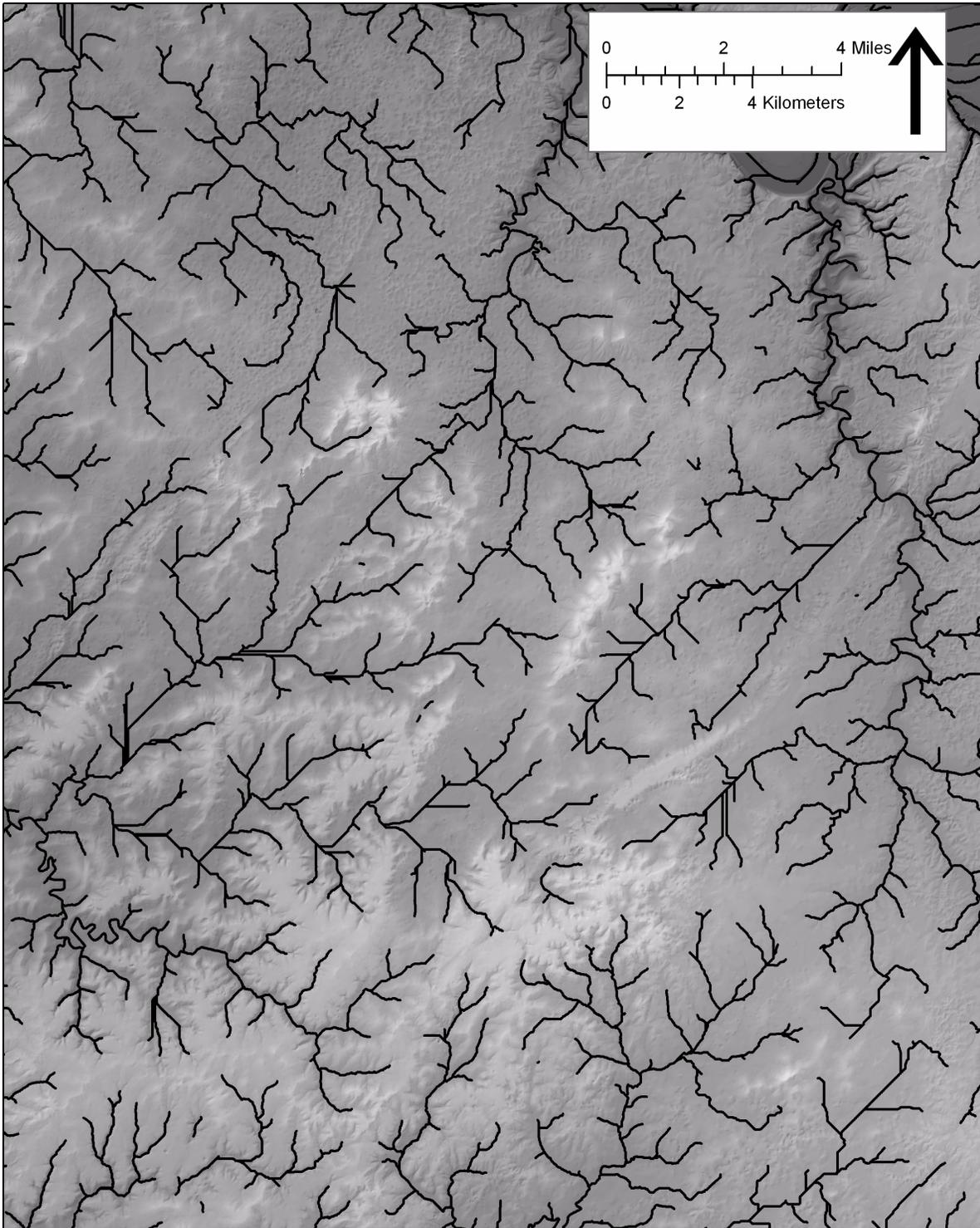


Figure 5B. Example of DEM processing used to delineate relic stream valleys in part of the Central Kentucky karst terrane. The image shows the surface-flow routes generated by artificially filling all sinkhole depressions depicted in figure 5A to their spillover points. In GIS, these flow routes—which delineate potential relic stream valleys—are overlaid and compared with the “blue-line” streams data coverage to discriminate them from present-day valleys having actively flowing surface streams.

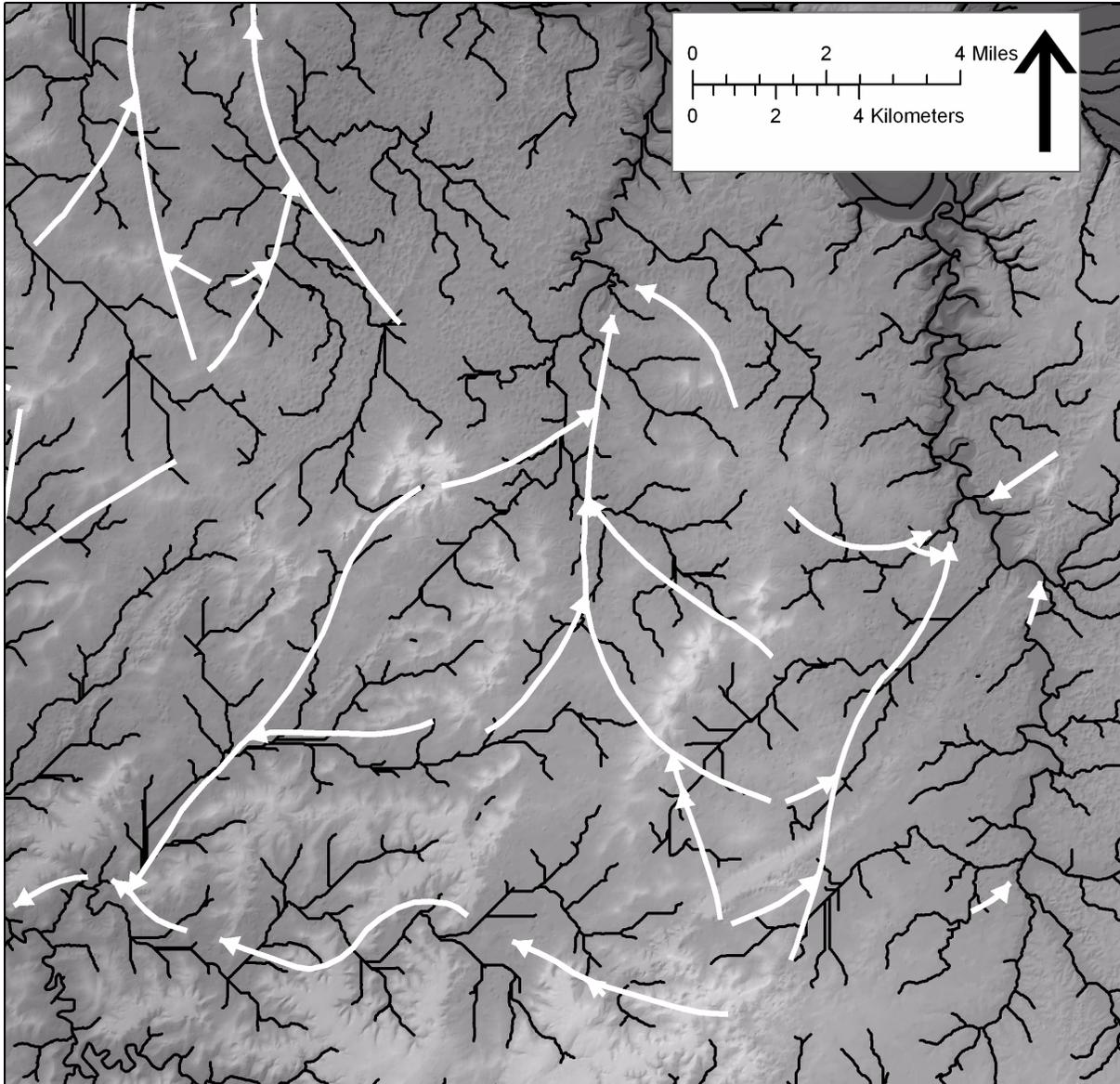


Figure 6. GIS-processed image showing the apparent relation between relic stream valleys shown in figure 5B and subsurface-flow routes inferred from results of previously published dye-tracer tests (Taylor and McCombs, 1998). The curvilinear arrows that represent the dye-tracer flow paths were drawn to follow the configuration of the potentiometric surface mapped in 1997-98 and were not altered to follow the GIS-generated trends for the relic stream valleys.

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