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KARST MODELING AND HAZARD ASSESSMENT ON THE PENNYROYAL PLAIN AND WESTERN HIGHLAND RIM

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The Pennyroyal Plain of Kentucky and the Western Highland Rim of Tennessee provide a 25,000 karst-depression population for detailed study of karst landform evolution. Application of the contagion model and cogent logistic growth functions revealed fundamental principles governing the initiation and evolution of this complex, multifaceted karst geomorphic system. Accurate mapping of karst depressions is a complex process involving multiple data sets with high resolution and the development of a spatial database containing relevant geologic and geomorphic karst parameters. Implementation of spatial analysis and a geographic information system is necessary for spatial data presentation and developing karst hazards predictions.

Rates of urban development in the karst landscape of the Western Highland Rim are among the highest in the southeastern United States. Therefore, understanding karst evolution, mapping karst landforms and developing hazards maps are important goals for efficient land use and urban planning. This paper develops a link between quantitative assessment of karst terrane and application of spatial co-regionalization theory.

Key words: karst, doline, sinkhole, contagious model, logistic growth, environmental hazards, co-regionalization, cokriging

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INTRODUCTION

Karst is a diverse complex landform system characterized by soluble rocks, poor surface drainage, well-developed subsurface drainage, caves, disappearing streams, and an abundance of springs and well-defined, circular – to elliptical-shaped depressions. Soluble rocks include carbonates and evaporates (rock gypsum and rock salt). Karst landform development reflects control by geologic, geomorphic and hydrogeologic processes in a region. In the United States, the significant portion of karst is in carbonate bedrock principally occurring in central Kentucky, Western Highland Rim and Ridge and Valley provinces of Tennessee, Shenandoah Valley of Virginia, Dougherty Plain of Georgia, Salem Plateau of Missouri and much of central Florida. The karst region in West Texas and New Mexico developed largely in rock salt and rock gypsum rather than in carbonates (Fig. 1)

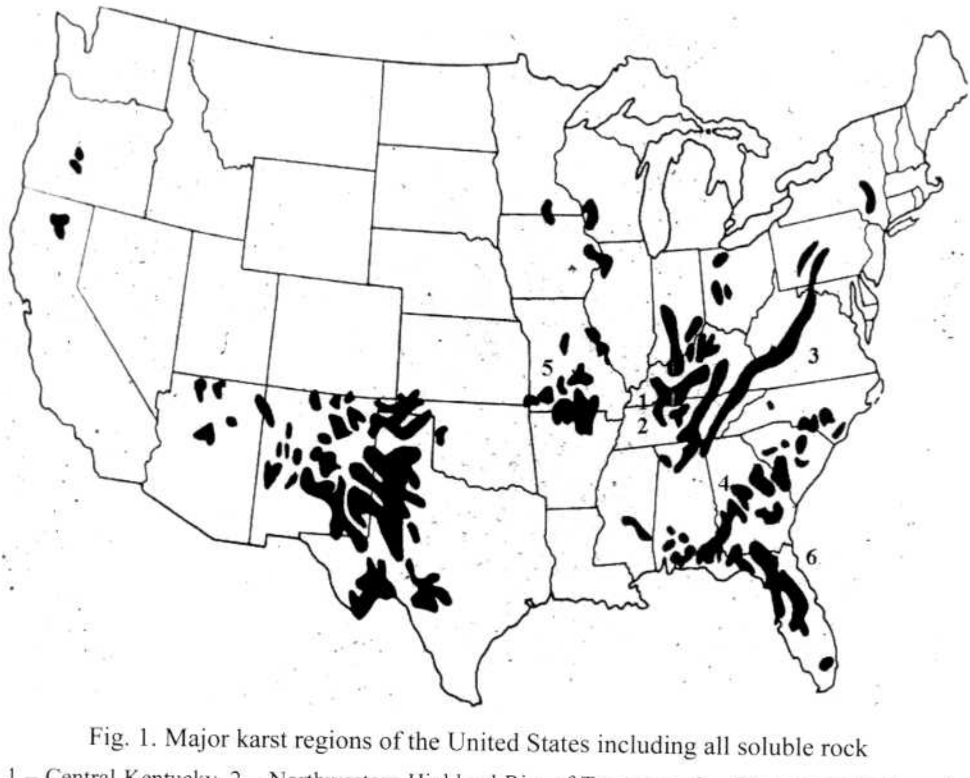

Fig. 1. Major karst regions of the United States including all soluble rock

1 – Central Kentucky, 2 – Northwestern Highland Rim of Tennessee, 3 – Shenandoah Valley of Virginia, 4 – Dougherty Plain of Georgia, 5 – Salem Plateau of Missouri, 6 – Central Florida (Modified after Palmer 1989).

This paper focuses on the karst of the Pennyroyal Plain (PP) of south-central Kentucky and its contiguous Western Highland Rim (WHR) of Tennessee (Fig. 2) that are described, analyzed and modeled in numerous works (Quinlan and Pohl 1967, White et al. 1970, Quinlan 1970, Miotke and Palmer 1972, Miotke and Papenberg 1972, Wells 1973 and 1976, Kemmerly 1976, 1981, 1982, 1986, 1989, 2006 and 2007, Kemmerly and Towe 1978, Palmer 1985). The purpose of this paper is to (1) provide a comprehensive analysis of the karst of the PP and WHR, including an update on karst research in the study area; (2) summarize the karst contagion model for karst landscape evolution; (3) evaluate karst hazards using geospatial methods and technology; and (4) lay the groundwork for future collaboration between American and Slavic karst geomorphologists. In this work, the term terrane encompasses the entire geologic setting including carbonate bedrock, its characteristics, surficial geology and distinctive karst topography.

One fundamental problem in karst is the lack of a world wide unified terminology. Others (Beck and Sinclair 1986, Lowe and Waltham 2002, Field 2002, Williams 2004, Waltham et al. 2005) have exhaustively treated differences in karst terminology among Anglo-American karst geomorphologists. This paper limits discussion of karst landform terminology to the two genetic types of karst depressions found in the PP and WHR. An attempt is made to identify the Slovak, Slovenian and Croatian karst equivalent terms for the two genetic depression types found in the study area, thus minimizing confusion.

GEOLOGY OF THE PENNYROYAL PLAIN AND WESTERN HIGHLAND RIM

The Pennyroyal Plain and Western Highland Rim karst in this study purposely excludes the Mammoth Cave Plateau for several reasons. Mammoth Cave Plateau is a sandstone-capped plateau while the PP and WHR are carbonate-capped plains. Cave development in the PP and WHR exhibits fewer well-developed cave systems than the Mammoth Cave. Geomorphic, hydrogeologic and geologic histories are also different (Quinlan and Pohl 1967, White 1969, White et al. 1970, Quinlan 1970, Wells 1973).

The PP and contiguous WHR comprise the western and northwestern flank of the Nashville Dome. Carbonate bedrock in the study area dips gently northwest averaging six meters/km into the Illinois Basin (Kemmerly 1982). Both the Cumberland River and Green River occupy deeply incised valleys in the Nashville Dome and the Pennyroyal Plain and played a significant role in karst development.

The study area consists of a 6,700 km^2 portion of the Pennyroyal Plain and Western Highland Rim underlain by the St. Louis and the Ste. Genevieve Limestones of upper Mississippian, Meramecian Series (upper Middle Carboniferous). Stratigraphic descriptions of the St. Louis and Ste. Genevieve Limestones are summarized below (Tab. 1). Both carbonate formations have high calcite-levels. The St. Louis Limestone averages between 91 % and 97 % calcite (Wilson et al. 1973). The Ste. Genevieve Limestone averages 95 % to 97 % calcite (McFarland 1943).

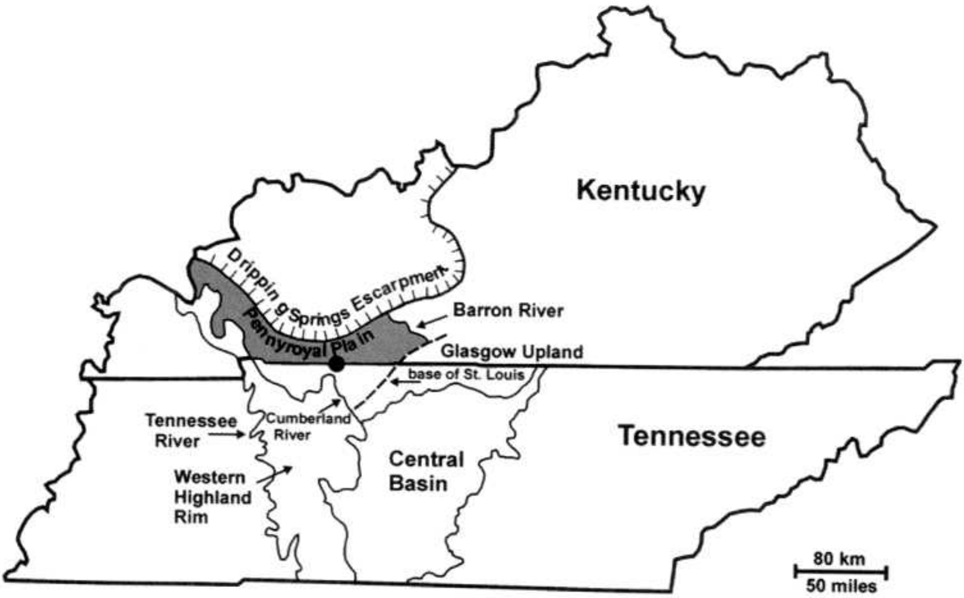

Fig. 2. Location of Pennyroyal Plain and Western Highland Rim

Tab. 1. Stratigraphic description of carbonates underlying the Pennyroyal Plain, Kentucky and Western Highland Rim, Tennessee +

Formation	Bedding Characteristics	Thickness Range (m)	Grain-size Distribution	Associated Lithology
Ste. Genevieve Limestone	thin- to thick- bedded	15-50	fine- to coarse-grained	prominent chert bed (0.5-2 m) at base of formation
St. Louis Limestone	thin-bedded to massive	40-90	fine- to coarse-grained	lens and bedded chert found near top (3-5 m) of formation; chert nodules common

+ Formations increase in thickness from southeast to northwest across the study area.

The multifaceted karst terrane of the PP and WHR exhibits extensive secondary permeability along three systematic joint sets which play a significant role in development of karst depressions and the hazards posed by them. The three systematic joint sets have the following azimuths: 20° to 40°, 70° to 80° and 330° to 340° in the southwest to 10° to 20°, 40° to 50°, and 320° to 330° in the northeast part of the area (Kemmerly 1982 and 2007). Azimuth is measured clockwise from north designated as 0°.

Surficial Geologic Setting

The surface of the karst terrane consists largely of a clayey, cherty residuum overlain by a silty colluviums and locally thin loess. Residuum derived from the St. Louis and the Ste. Genevieve typically consists of 0 to 20 meters of chert pebbles and cobbles incorporated in a strongly mottled clay matrix. Chert rubble in the residuum varies within and between formations. Residuum units of both formations are similar with respect to silt/clay ratios, gross particle-size distributions and plasticity characteristics (Royster 1967).

Depth to bedrock varies dramatically in the study area, particularly in the St. Louis Limestone. Commonly depth to bedrock ranges from 4 to 15 m in thickness. Soil borings show locally as much as 25 m differences in depth to bedrock on a 3 meters drill spacing (Kemmerly 1981). Overlying the residuum is a colluvial unit which consists of 0 to 5 meters of clayey silt within which occur minor quantities of pebble-sized chert derived from the underlying residuum.

The silty colluviums occupy most of the slopes that surround karst depressions and many of the depression bottoms. Loess up to 2 m occurs as a remnant capping many hilltops. Sheet-wash and channelized flow transported the loess down slope resulting in a mixing of loess and residuum to form the colluvial unit described above (Kemmerly 1982).

Hydrologic Setting

Initial exposure of the St. Louis and Ste. Genevieve Limestones occurred as a result of cap rock erosion of the Big Clifty Sandstone (May et al. 2005) followed by subsequent stream incision by the Cumberland River attendant with epirogenic uplift of the Nashville Dome (Stearns and Riesman 1984). The three systematic joint sets described earlier and their intersection loci provided the most efficient initial routes for surface water infiltration into the St. Louis and Ste. Genevieve, exhibiting little primary porosity and permeability. Infiltration concentrated at points of multiple joint intersections insured the greatest volume of water moving into the subsurface.

This infiltration of water through the planar joint sets is a result of chemically aggressive water that is under saturated with respect to calcite. Fluvial down-cutting of the Cumberland and Green Rivers gave rise to sufficient hydraulic gradient and the potential energy to produce solution-enlarged bedding planes and conduits. Ground-water flow regimes became increasingly turbulent with enlargement of the joint-intersection loci resulting in conduit development along the joint sets and some bedding planes in the carbonate bedrock. The three-dimensional and integrated ground-water flow network discharged through springs at the base of the incised valleys. Valley incision triggered initiation of karst depressions. Hydrogeologic mechanisms responsible for conduit development in the study area are described elsewhere (Kemmerly 2007).

As geochemical weathering proceeded, a limestone pavement cut by the three systematic joints became mantled by regolith. Regolith defines the entire weathered zone down to whatever serves as the parent material undergoing geochemical weathering. Soil may or may not develop within regolith depending upon climatic and biologic conditions. Regolith, generated contemporaneously with the solution enlargement of the multiple joint-intersection loci, subsided differentially into bedrock depressions that developed on the irregular limestone surface. A detailed discussion of karst depression development in the study area can be found elsewhere (Kemmerly 2007).

SLAVIC AND ANGLO-AMERICAN KARST DEPRESSION TERMINOLOGY

The characteristic landform which epitomizes karst terrane is the depression. A karst depression can be defined as a circular- to elliptical-shaped depression resulting from the movement of solutes and solids downward through one or more openings in the soluble bedrock below the surface. Rates of movement of solids and solutes into the subsurface vary from slow (subsidence) too rapid (collapse). This generic definition serves as the basis for discussion of depression genesis, nomenclature and language equivalency. Differences in languages, language translation, cultural and historic scientific traditions produce barriers to karst discourse. This being said, the following discussion attempts to bridge this gap.

Doline

Karst depressions characterize the fundamental landform in any karst terrane. Karst geomorphologists in North America and most of Europe use the generic term doline to describe a karst depression. Doline is derived from the Slavic word dolina first used to describe karst by Cvijić (1893). Originally dolina meant a valley in Slavic languages but in modern terms has come to mean any negative landform (Waltham et al. 2005). Current Slovak usage of dolina remains consistent with its original Slavic meaning and applies only to valleys of fluvial origin (Mazúr et al. 1989, Jakál 2001 and 2007) while term "závrt" corresponds to term "doline" in Anglosaxon context. Karstic depressions in Slovak are in general all deepened and closed karstic forms such as závrt, uvala and polje. A matrix for establishing term equivalence sensitive to these differences in karst terminology provides a basis for describing the karst of the PP and WHR (Tab. 2). For comparison purpose see also Gams (1973). Convergence of the terminology used by karst geomorphologists with that of the American engineering community resulted in the use of sinkhole being synonymous with doline. Unfortunately, sinkhole has also come to be used for any "sinking ground" much of which does not have a karst genesis (Waltham et al. 2005).

The use of the term doline does not imply that an opening into the subsurface must exist. Further, any opening in the doline flank or bottom does not necessarily leads to a cavern roof collapse. Most of the collapses observed in dolines in North America and the United Kingdom occur in the regolith mantling the soluble rock (Waltham and Fookes 2003). In contrast, most of the central and eastern European karst literature surveyed for this study suggests that collapse applied to doline must be as a result of cavern roof collapse (Šušteršič 2000 and 2002, Sauro 2003) including the largest collapse dolines in Slovenian karst called "kukava" with volumes exceeding on average 1,26 million m^3 (Šušteršič 1998).

Tab. 2. Matrix of language equivalence for selected karst terminology

Anglo-American	Slovenian	Croatian	Slovakian
Karst depression	Kraška depresija	Krška depresija (Krška uvala)	Krasová depresia
Doline	Vrtača, Kraška dolina	Ponikva (vrtača)	Závrt, Krasová jama
Collapse doline	Udorna vrtača, udornica	Urušna ponikva	Zrútený závrt
Subsidence (solution) doline	Aluvijalna vrtača	Aluvijalna ponikva	Subsidenčný (disolučný, korózny) závrt
Sinkhole	In the sense of doline: vrtača, In the sense of "sink" = ponor	In the sense of doline: ponikva, In the sense of "sink"= ponor	In the sense of doline: závrt, ponorový závrt, In the sense of "sink"= ponor
Doline karst	Vrtačasti kras	Ponikvasti krš	Závrtový kras
Karst	Kras	Krš	Kras

Collapse Doline

The terms collapse, solution and subsidence doline first appeared in the German karst literature (Cramer 1941). Acceptance of these terms occurred by the late 1960s throughout western Europe and North America. A collapse doline describes one in which dissolution of the soluble bedrock primarily occurs along one or more systematic joints or joint intersections beneath the regolith mantling the pinnacled bedrock. Instability in the regolith bridging the bedrock pinnacles triggers a near vertical, downward rapid movement of the depression bottom or flank, along a well-defined failure surface, into an underlying void of variable size (Fig. 3) Dimensions of the recently discovered collapse doline about 10 km northeast of Clarksville measured twenty meters in diameter and ten meters in depth.

The mechanism for development of a collapse doline involves the existence of a regolith-arch spanning two or more pinnacles along the regolith/bedrock surface as opposed to Slovenian karst where the origin of collapse dolines is directly related to bedrock collapse (Šusteršič 2002). A detailed discussion of regolith-arch mechanics and the hydrogeologic factors leading to a collapse doline is found elsewhere (Kemmerly 1980b and 1981). Collapse dolines typically exhibit a bowl-shaped, three-dimensional geometry because of the process for their development. Bowl-shape means that both doline length/depth and width/depth ratios are lower in collapse dolines compared to the three-dimensional geometry of subsidence or solution dolines.

In Slovenian karst, the shape of collapse dolines seems to be more appropriately described by an inverted cone with a scree on the bottom of the doline (Šušteršič 1998). Key distinctions between collapse and subsidence dolines include whether one principal solution-enlarged, vertical conduit exists beneath the depression bottom and whether the conduit is a component of a three-dimensional integrated conduit system. This central conduit located at the solution-enlarged, multiple joint intersection in collapse dolines exhibits the greater hydraulic conductivity and steeper hydraulic gradient. The direction of the hydraulic gradient, hydraulic conductivity and degree of integration of the three-dimensional conduit network beneath a collapse doline determine which local springs serve as ground-water discharge sites.

Fig. 3. Recently discovered collapse doline on Western Highland Rim

Subsidence (Solution) Doline

A subsidence doline forms by differential corrosion of randomly spatially-distributed fractures and non systematic joints in soluble bedrock (Ford and Williams 1989). Continued differential corrosion enlarges some fractures but does not result in a central conduit or an integrated conduit system like the collapse doline. This lack of a primary conduit beneath the doline feeding into an integrated conduit network retards ground-water flow, decreases solution rate, insures longer ground-water residence times and results in ground subsidence. Figures 4 and 5 show subsidence sinkhole on Western Highland Rim. The sinkhole has gentle slopes that were stabilized with vegetation and is surrounded by the buildings of Austin Peay State University; the high resolution aerial photographs were overlaid in GIS with two foot contour lines to increase shape definition of this sinkhole (Fig. 5). Figure 4 exhibits the northwest portion of the sinkhole. The two foot contour lines indicate the sinkhole asymmetry in east west direction. The slope on eastern side is steeper than the slope on the western side.

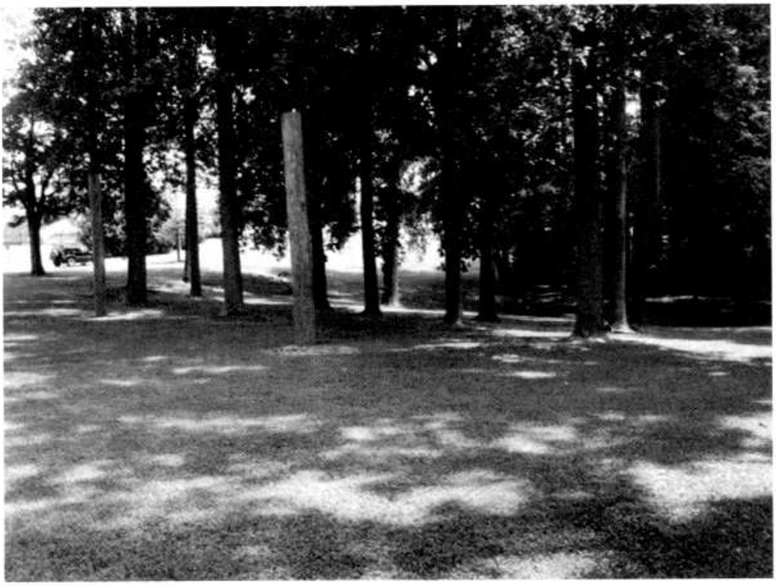

Fig. 4. Shallow subsidence (solution) doline on the Western Highland Rim

Fig. 5. Subsidence (solution) sinkhole depicted from aerial photograph and 2 ft contours

The absence of a well-defined central conduit results in subsidence of the ground surface into randomly distributed and poorly integrated corrosion channels developed in and along corrosion pits on the carbonate bedrock surface. Reduced rates of bedrock solution and the absence of efficient ground-water flow paths result in subsidence doline length/depth and doline width/depth ratios being significantly larger than the respective ratios in collapse dolines. These fundamental differences in doline genesis produce the bowl-shaped depression in collapse dolines and a near flat-bottomed, shallow depth, pan-shape depression in subsidence dolines.

CONTAGION MODEL OF KARST TERRANE EVOLUTION

In the previous work (Kemmerly 1982 and 1986) in the Pennyroyal Plain and Western Highland Rim the population of 25 000 karst depressions was analyzed. They were located on forty-two, 7 ½ -minute United States Geological Survey topographic maps of 1:24 000 scale. Based on depression density, two subpopulations of dolines were identified (Fig. 6).

The results reinforced previous studies in the Mendip Hills of England and in New Zealand (Ford 1964, Drake and Ford 1972, Williams 1972a and 1972b) and extended it by (1) quantifying the existence of two karst depression subpopulations within one large population; (2) identifying variables responsible for doline subpopulation initiation and enlargement; (3) establishing the existence of a doline-field infrastructure within which operates a karst-influence field; and (4) exploring the geomorphic and hydrogeologic mechanisms that determine the behavior of the contagion model of karst terrane evolution.

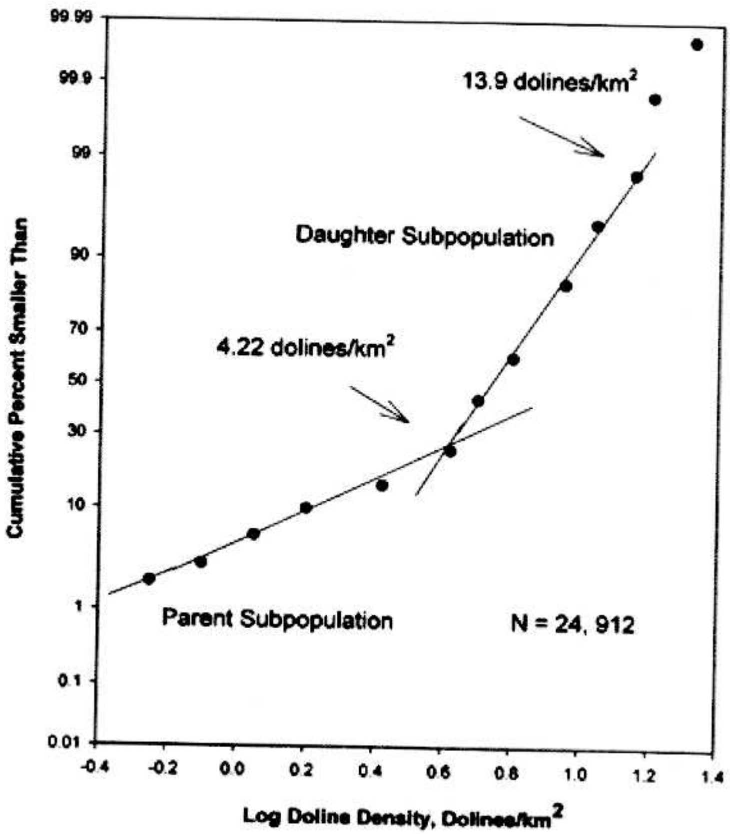

Fig. 6. Depression density distribution for dolines on the Pennyroyal Plain, Kentucky and the Western Highland Rim, Tennessee (Kemmerly 1982)

Major geologic controls on doline initiation and enlargement in the PP and WHR included ground-water recharge, hydraulic conductivity along solution-enlarged joints, hydraulic gradient and the degree to which depression long-axes were structurally aligned. Structural alignment of the doline is defined as the deviation of a doline long axis from the azimuth of any of the three systematic joint sets described previously.

The two doline subpopulations in the PP and WHR have distinctly different geomorphic characteristics. The primary (parent) doline subpopulation developed at triple-joint intersection loci where secondary permeability was maximized, is larger, deeper, with higher order swallet depressions and showed greater alignment of depression long axes with regional systematic joint sets than the secondary (daughter) dolines. Parent dolines developed first because the triple-joint intersection loci provided sites of maximum hydraulic conductivity resulting in not only sites of primary depression initiation but greater growth rates than the daughter dolines. The secondary (daughter) doline population that developed at joint intersections or single joints, was smaller, shallower, with lower order swallet depressions and showed decreased alignment of depression long axes. Daughter dolines developed after parent dolines at sites of lower hydraulic conductivity through geomorphic processes controlled largely by the hydrogeologic regime beneath the parent doline and within its karst-field of influence. This subsequent spreading of daughter dolines after the development of parent dolines in the karst area resembles to a large extent spreading of "contagious" diseases and in medical research were modeled extensively using mathematical equations.

The contagion model does provide a valid framework for further work in mantled karst terranes where lithologic differences are minimized and bedrock dip is low. The reader is referred elsewhere for detailed discussions of the contagion model and its implications for karst terrane evolution (Kemmerly 1982, 1986 and 2007).

Subsequent spatial analysis of the karst depressions in the study area revealed a depression-centered karst terrane with a defined doline-field infrastructure. Parent dolines tended to be near uniformly (regularly) spatially distributed at sites of multiple-joint intersection loci with the daughter dolines typically spatially clustered around their respective parent dolines. Elements of the doline-field infrastructure consist of depression density, depression size, swallet order and inter-doline spacing. Doline-field infrastructure evolved from the interaction of ground-water recharge, secondary bedrock permeability and local hydraulic gradient. Infrastructure consists of two genetically distinct but causally related karst depression subpopulations existing in a complex geologic framework of inter-doline competition for geomorphic resources, namely, catchment area and runoff. The two distinct doline subpopulations, defined as primary (parent) and secondary (daughter), exhibit density dependence (i.e., initiation of a parent doline affects the initiation and development of daughter dolines) and are independent of carbonate bedrock characteristics and are not a result of the mixture of subsidence and collapse dolines. Further, parent and daughter doline subpopulations are not time contemporaneous but genetically related in the complex karst geomorphic system. The two subpopulations represent different generations in which the parent doline influences the development of daughter dolines clustered around the parent. The implication is that each parent doline has an area surrounding it defined as the karst-influence field, in which daughter dolines may or may not develop.

Initiation and evolution of many karst terranes appear dependent upon the existence of a karst infrastructure constituted of several interdependent elements. Infrastructures, where they exist, vary in detail from one area of karst to another, but the same fundamental elements should be present. Major elements of the karst infrastructure include those that are hydrogeologic, structural and geomorphic.

Hydrogeologic elements in the evolving infrastructure are (1) fall in regional water levels within the carbonate platform undergoing karst development; and (2) well-developed cones of depression superimposed on the regional ground-water potentiometric surface at sites of multiple joint-intersection loci. Changes in the cones of depression dictate which depressions are initiated and which survive long enough to enlarge and trigger initiation of daughter depressions. The areal extent of cones of depression defines the karst-influence field around each surviving parent depression.

The structural geologic element occupies a pivotal role in a karst infrastructure. Solution-enlarged joints and bedding planes within the carbonate rock serve as pathways along which the karst contagion model spreads to initiate additional depressions. Parent depressions that survive are those that are larger, deeper and structurally more aligned. The primary depressions, less adapted geologically, do not survive (that is, filled with alluvial or colluvial sediments) owing to poorly developed karst-influence fields and the hydrogeologic inefficiency of their respective cones of depression during evolution of the karst terrane. Within daughter doline clusters around parent dolines, the inter-depression spacing between daughters reflects geomorphic competition for runoff and catchments area.

A solution-conduit network exists beneath each depression cluster that is to some extent vestigial from the Pleistocene. The solution-conduit network still serves as the current route for sediment and surface runoff entering the subsurface via depression swallets and infiltration through regolith mantling the carbonate bedrock. The major subsurface focus for collection of ground-water recharge is the solution-enlarged joint intersections located beneath parent depressions within each cluster.

Significant progress has occurred in the last two decades in understanding relationships between karst topography and carbonate hydrology. This progress makes it possible to model depression initiation and link it to subsurface and surface hydrology. Advancements include insights into detailed chemical kinetics of dissolution, modeling karst conduit development in a variety of geologic settings, ground-water flow regimes and spatial and time contexts (Dreybrodt 1988, White 1988, Ford and Williams 1989, Palmer 1991, Dreybrodt et al. 1999, Dreybrodt and Gabrovsek 2000). Lacking was a testable mathematical model for analyzing the initiation and evolution of a karst depression population.

LOGISTIC GROWTH MODEL

Logistic growth models provided the simplest yet robust approach to modeling the density-dependent growth mechanisms responsible for the doline subpopulations on the PP and WHR.

$$dN_p / dt = r\left(K - N_p\right), \tag{1}$$

where N_p is the number of parent dolines, K is the carrying capacity of the number of the parent dolines per square kilometer, t stands for time in units of 10^3 yrs. and r is the specific parent doline initiation rate. For PP and WHR this relationship is as follows:

$$N_p = 4.22 / \left[\left(1 + 3.22\exp\left(-4.28r\right)\right)\right] \tag{2}$$

Details concerning construction of the logistic growth model and the development of its geomorphic and mathematical framework can be found elsewhere (Kemmerly 2007). Initiation and development of the two doline subpopulations and the diffusion of the karst-influence field in the PP and WHR are all strongly related density-dependent geomorphic processes. Density-dependent doline development exists where number of dolines, size of individual dolines and depression subpopulations are in part determined by intraspecific competition for surface runoff and catchment area. Competition for surface runoff and catchment damps the exponential growth of doline populations by establishing a saturation limit or carrying capacity, K, defined by the resources available. The study of the PP and WHR karst terrane demonstrates the efficacy of logistic growth models to:

1) describe initiation and enlargement of parent dolines and the triggering of daughter dolines spatially clustered around parent dolines,
2) characterize development of the karst-influence field and the number of daughter dolines spatially clustered around parent dolines,
3) estimate the time required for the karst-influence field, once initiated, to reach steady-state conditions,
4) link the evolution of doline populations to quantitative modeling of a three-dimensional conduit system beneath a carbonate platform,
5) and analyze other karst terranes where hydraulically efficient, three-dimensional systems exist beneath a carbonate platform.

Even though karst landscapes represent a fascinating collection of diverse landforms and scenery visited by tourists, they can become significant hazards when they interfere with urban development. A hazard can be defined as a geologic process which interferes with or restricts certain human activities or poses a potential threat to lives, property and human health. Pragmatic solutions to such problems dictate the need to understand fully the geologic process causing the hazard and to translate the impact of the hazard into rational development guidelines that insure harmony between the dynamic karst processes and urban development.

The PP and WHR karst is a typical example of a geomorphic environment where fulfillment of both requirements becomes necessary for pragmatic solutions to karst hazards. This study is unique in that it draws from long-term study of two contiguous karst areas, outlines the principal hypotheses of the contagion model and establishes the framework for prediction of the evolutionary stages of karst terrane using the model. The second requirement for pragmatic solutions, as highlighted below, necessitates development of a scientifically-based and field-tested framework for not only assessing existing but future sinkhole/doline collapse and flooding hazards. The next section focuses on pragmatic solutions to problems of urban development in a dynamic karst terrane.

DEVELOPING A HAZARD PREDICTION MODEL

Increasingly, dolines/sinkholes are an urban planning problem in the 19 percent of the United States underlain by soluble rocks (Figs. 1 and 5). Studying karst hazards is important and economically determined due to the impact of collapse and chronic flooding. Hundreds of millions of dollars in damage have occurred in the last twenty years in the eastern United States from collapse alone (Newton 1987). Karst hazards pose similar problems throughout the world including karst areas in Slovakia (Jakál 2000). The main difference in the study area and the karst of central Europe appears to be a lower density of karst landforms.

Clarksville is the largest city in the karst region with a population of 125 000. Its population has more than tripled in the last thirty years, making it one of the fastest growing cities in Tennessee (Kemmerly 1993). Because of this rapid urbanization, karst has had a significant economic impact on Clarksville. Urban planners do not have the option of whether to avoid karst in the Clarksville and in the adjacent area but do have the option of mitigating the impact of karst. Numerous residential and commercial structures, highways and utility infrastructure experience architectural and structural damage and failure from differential movement of the ground surface associated with dolines and sinkholes (Figs. 7 and 8).

Chronic flooding of residential structures also occurs in depressions. Sinkholes pond water efficiently and increase risk of flooding. Flooding becomes a significant hazard when development occurs within or adjacent to sinkholes. Both collapse dolines and subsidence dolines experience chronic flooding. The most dangerous karst hazards are ground movements associated with collapse of dolines and sinkholes (Kemmerly 1993 and 2006). The urban area and highways are dominantly located in the southwestern portion of the study area (west of the Passenger Creek); there is significant amount of sinkholes in this area (Fig. 8). The sinkholes in the western part (north of Red River) tend to be larger (composite sinkholes) and less densely occurring while the eastern and northeastern side (north of Red River and Sulphur Creek) is heavily infested by sinkholes (Fig. 8).

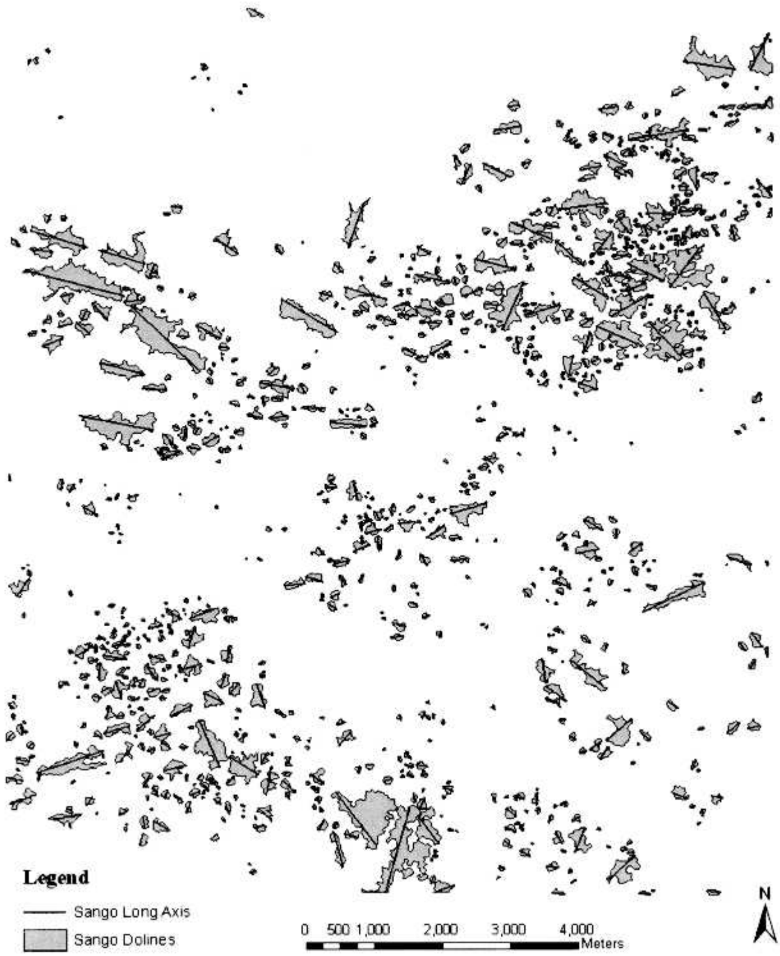

Fig. 7. Distribution of sinkholes and their structural orientation

Therefore it is imperative that a hazard prediction model be developed and the ground movements and flooding hazards be mapped and evaluated. The main goal in assessment of the previously mentioned two karst hazards requires the development of spatial models for accurate prediction. The comprehensive assessment process involves three steps:

1) Detailed and precise mapping of dolines/sinkholes in the karst area,
2) Development of a diagnostic set of sinkhole/doline parameters for each karst hazard,
3) Construction of a prediction model for assessing the probability of karst hazard (Fig. 9).

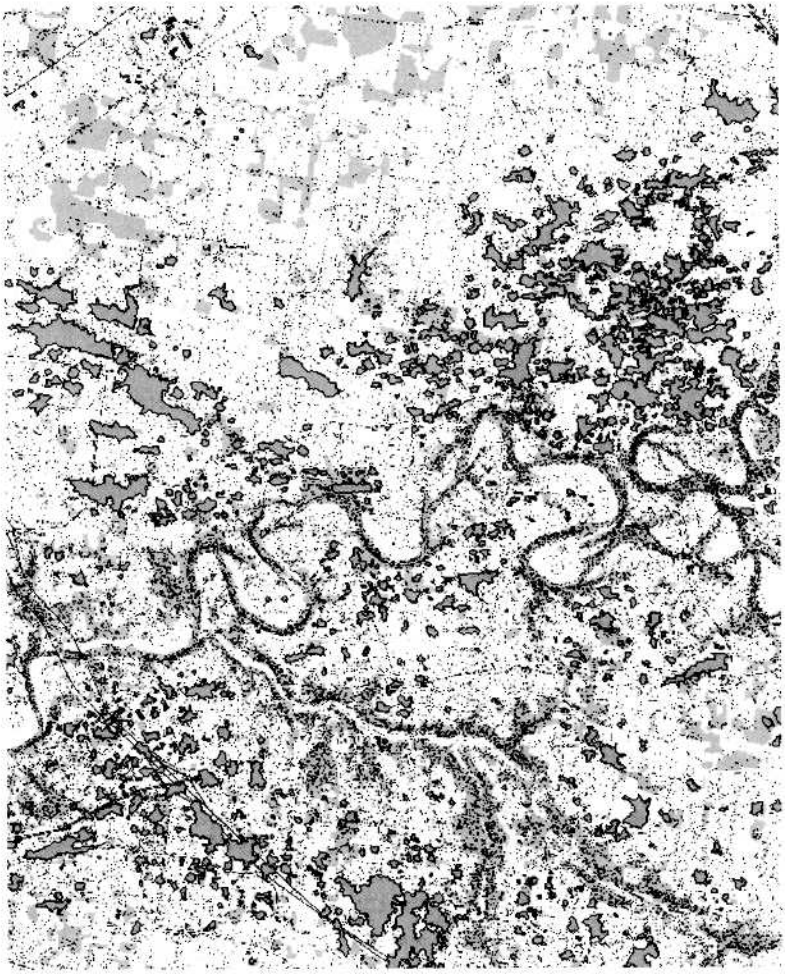

Fig. 8. Sinkhole distribution on topographic map 1:24 000

The majority of spatial data were collected in the field using topographic maps. Sinkholes/dolines were identified as closed contour lines with hachure marks. Implementation of modern geospatial technology (Geographic Information Systems, Global Positioning System and remote sensing) can increase horizontal and vertical precision. Closed, hachured contour lines shown on topographic maps coincide only with a portion of the bottom of sinkholes and are highly dependent upon the contour interval of the topographic map. Closed, hachured contour lines also do not show an entire depression including its drainage divide. The test mapping of sinkholes in the field using Global Positioning Systems (GPS) indicated some differences in positional accuracy. The two feet contour lines (Fig. 5) provide significant input for checking accuracy of topographic mapping and can be further used to construct sinkhole slope profiles and volume assessment. Numerous smaller sinkholes also were omitted or added as part of larger sinkholes due to the scale of the topographic map (1:24 000). Unfortunately, complete acquisition of GPS data is limited by the time, resources and permission to enter private property. Since the complete mapping of dolines/sinkholes is not feasible and technically possible to manage, remote sensing data such as high resolution aerial photos and two-foot digital contour maps would be sufficient to delineate more precise doline/sinkhole boundaries. Unfortunately, two-foot contour maps are not available for the entire study area making the use of lower resolution contour maps a necessity.

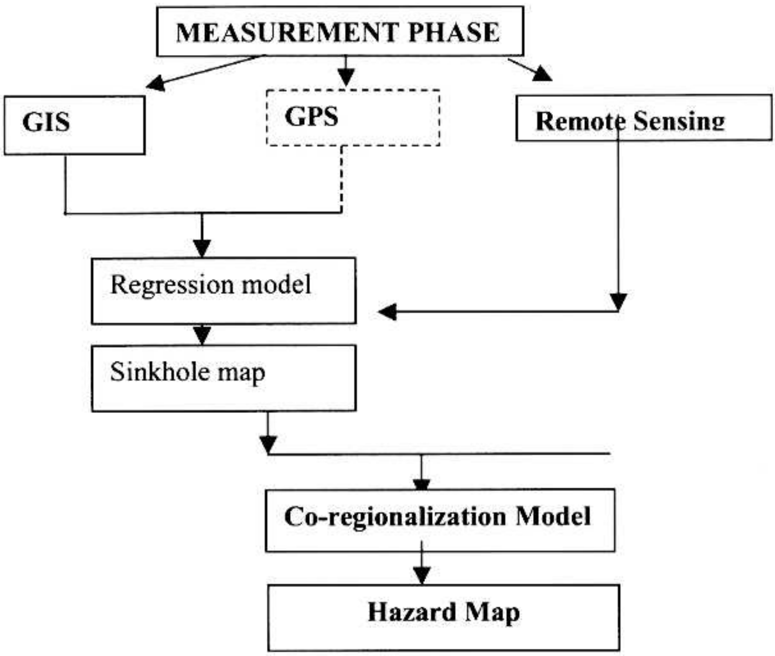

Fig. 9. Flow chart of hazard model for doline/sinkhole collapse in Middle Tennessee

Digitizing the entire sinkhole/doline produces several important parameters including sinkhole perimeter and area (projected to the plane). These data however have only limited application and were not sufficient to develop a comprehensive application and hazard model. The sinkhole long axis and its orientation with respect to the three systematic joints sets found in the study area become critical parameters in hazard model construction. Previous studies indicated that a karst depression length/width ratio ≤ 1.8 represents a geomorphic threshold for identifying dolines/sinkholes with a high probability of collapse (Kemmerly 1977, 1979 and 1980b). Using X-tools Pro extension for desktop GIS (http://www.xtoolspro.com), length/width ratios were computed and placed in a GIS attribute table along with the azimuth value of each sinkhole/doline long axis. The previously mentioned studies also confirm that two karst depression long-axis orientations play a significant role, 70-80° and 320-330°, because they parallel these two systematic joint sets.

The last parameter needed for assessing hazards is karst depression volume. For the Middle Tennessee region, the oblate spheroid model best fits the overall shape of sinkholes/dolines in the study area. Oblate spheroid assumes rotating a sphere around a known major-axis parameter stored in the GIS database. In order to complete this computation the ellipse equation must also be used to estimate b axis. Thus the final equation of sinkhole volume is in the following form:

$$V_{os} = \frac{4\pi a}{3}\left(\frac{A}{\pi a}\right)^2 \Rightarrow V_{snk} = \frac{4A^2}{3a\pi} \div 2 = \frac{2A^2}{3\pi a}, \tag{3}$$

where a is the length of long axis (known), A is the sinkhole area projected to the plane, V_{os} is the volume of oblate spheroid, V_{snk} *is* the volume of sinkhole and π is the mathematical constant (3.41459).

HAZARD PREDICTION MODEL AND CO-REGIONALIZATION

Kriging is an unbiased linear estimator from a family of so-called BLUE estimators (best linear unbiased estimator). Models of co-regionalization represent a group of sophisticated methods designed for high-level spatial analysis that utilize two spatial variables and their spatial continuity for more accurate prediction. One of the most significant features of spatial data is autocorrelation. One of the objectives of this study is to apply a co-regionalization model to estimate and predict the probability of sinkhole/doline collapse.

A karst depression length /width ratio ≤ 1.8, described earlier as a geomorphic threshold of higher collapse hazard, is then paired with the azimuth of the sinkhole/doline long-axis orientation. The azimuth of long-axis orientation with respect to systematic joint orientation and sinkhole/doline length/width ratio both play a role in collapse probability and hazard assessment, especially the N 70-80° E (70-80°) systematic joint set.

The central part of the co-regionalization model is cokriging:

$$\hat{z}(x_0) = \sum_{i=1}^{N} \lambda_i p_i(x_i) + \sum_{j=1}^{M} \omega_j a_j(x_j), \tag{4}$$

where $\hat{z}(x_0)$ is the estimate (prediction) of sinkhole/doline hazards at location (x_0), $p(x_i)$ are the N neighboring sample values of a primary variable that are weighted with λ_i, $a_j(x_j)$ are sample measurements (M) of secondary variable at locations x_j weighted with factors ω_j. The matrix form of cokriging equations is:

$$\begin{pmatrix} Cov_{pp} & Cov_{pa} & I \\ Cov_{ap} & Cov_{aa} & I \\ I & I & 0 \end{pmatrix} \begin{pmatrix} \Lambda_i \\ \Omega_j \\ \mu \end{pmatrix} = \begin{pmatrix} Cov_{p0} \\ Cov_{a0} \\ I \end{pmatrix}, \tag{5}$$

where Cov_{pp} is the spatial covariance of the primary variable, Cov_{aa} is the spatial covariance of the secondary variable and Cov_{ap} is the cross-covariance between the primary data and secondary variable. A_i, Ω_j are vectors of weights for each variable, μ is a matrix of LaGrange multipliers used to solve the cokriging system, I is the identity matrix and Cov_{p0}, Cov_{a0} are matrices of spatial covariance computed between locations being estimated and primary/secondary variables. In order to build a cokriging estimator, models of spatial variations are needed. Models of spatial variation will be determined from variogram and cross-variogram analysis (Pannatier 1996). Strict model limitations in co-regionalization are required because only positive definite variance can be used during the estimation procedures. Models of co-regionalization are potentially more accurate than regression models (Dungan 1998). The measurement error in the primary and secondary variable is captured with the nugget effect of variogram and cross-variograms (Cressie 1995).

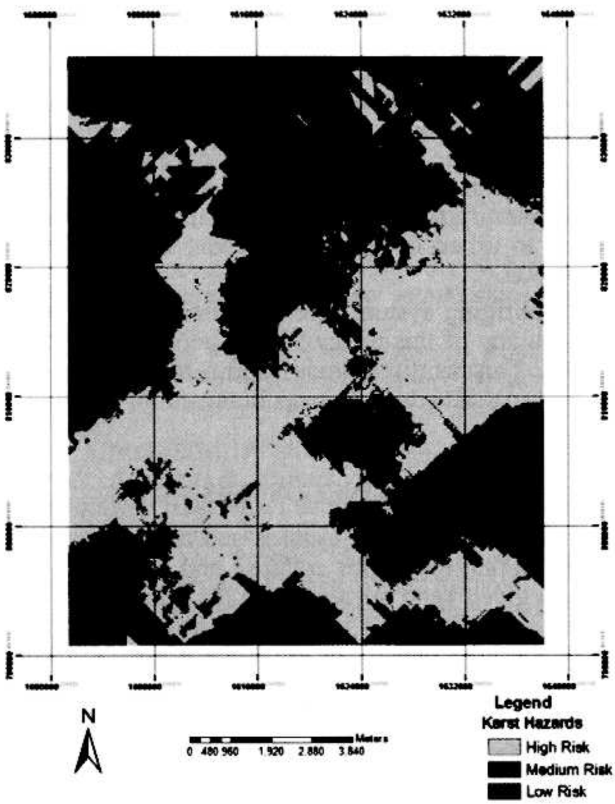

Fig. 10. Karst depression collapse hazards in Sango area

The nugget effect is spatially independent and can be filtered using proper procedures (Bourgault 1994). Filtering of the nugget effect guarantees the "exactness" of the cokriging estimator, (i.e., it will return the sample value at the sample locations). Accuracy of the co-regionalization model depends on the strength of the relationship between the primary and secondary data and the field measurements. Cokriging has the potential to generate more accurate predictions than linear regression especially when linear correlation coefficients are low. According to Dungan (1998) cokriging can increase the accuracy of prediction by 23 percent when correlation coefficients between field measurements and ground data decrease from 0.88 to 0.45. However, if the primary and secondary variables were measured at the same location, the use of cokriging does not significantly improve estimates in unsampled locations. In this project cokriging is recommended as a potential method for two variable system measurements provided that the secondary data came from a different location. Nevertheless, the small offset of variables due to GIS software requirements technically fulfills this condition and can improve the accuracy of final estimates.

The spatial distribution of collapse hazard for the Sango area (Fig. 8), Tennessee is based on the magnitude of the karst threshold values for depression length/width ratio and the azimuth of the depression long-axis. Karst depressions designated as high collapse hazard have long-axes orientations between 70-80^0 and a length/width ratio $\leq$ 1.80. Depressions designated as moderate collapse hazard have the same length/ratio threshold but have long-axis orientations paralleling the other two systematic joint sets (20-40^0 or 320-340^0). A low collapse hazard includes the remaining karst depressions in which the length/width ratio $\leq$ 1.80 regardless of the orientation of the depression long-axis. Collapse-hazard maps identify those karst areas exhibiting depressions which pose the greatest hazard to urban development before making detailed planning or site selection decisions.

A kriging and cokriging system offers several solutions to sinkhole hazard estimation. The accuracy of this technology depends on the quality of data that entered this system. This work assumes continued updating and refinement of the spatial data. As spatial-data accuracy increases so will the accuracy of the hazard model.

CONCLUSIONS

Quantitative assessment of karst hazards and subsequent development of an accurate hazard prediction model for collapse and flooding require comprehensive knowledge of a given karst terrane. Both the Pennyroyal Plain and Western Highland Rim are significant karst regions and deserve greater international attention because of the high density of epikarstic forms and rapid urbanization. Long term data collection and research of the PP and WHR resulted in the development of the contagion model for karst. Dynamics and evolution of the karst system were revealed using the contagion model and distinctive logistic growth functions. For the first time, the "genetic structure" that controls karst landscape evolution and its relationship to the hydrogeologic framework was understood. This understanding opened new avenues for spatial analysis using co-regionalization models and kriging. The results indicate that the assessment of karst hazards involves three hierarchical steps:

1) Detailed and precise mapping of karst depressions,
2) Development of diagnostic parameters for each hazard,

3) Construction of a hazard prediction model for determining the probability of both karst hazards.

The co-regionalization model linked attribute data in GIS format with the diagnostic field parameters (depression long-axis orientation, depression length/ width ratio) to produce an accurate collapse probability map. Kriging and co-kriging methods also lead to estimation of the probability of depression flooding.

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VYHODNOCOVANIE A MODELOVANIE KRASOVÉHO VÝVOJA NA PLANINE PENNYROYAL A OBRUBE ZÁPADNEJ VYSOČINY V ŠTÁTOCH KENTUCKY A TENNESSEE

Predložená práca je založená na štúdiu približne 25 000 krasových depresií, ktoré sa nachádzajú na Planine Pennyroyal v štáte Kentucky a na Obrube Západnej Vysočiny v štáte Tennessee. Uvedené krasové depresie boli pôvodne získané z topografických máp a overené terénnym výskumom. Dlhodobý výskum viedol k vytvoreniu modelu krasovej „kontaminácie" a ku konštrukcii špecifickej funkcie logistického vzrastu, ktorá vhodne modeluje počiatočné štádium vývoja krasových depresií. Odhalenie genetickej štruktúry vývoja krasového krajinného reliéfu a jeho vzťahu k hydrologickým pomerom v danej oblasti zohralo dôležitú úlohu pre porozumenie vývoja krasovej krajiny v tejto oblasti.

V druhej etape štúdia boli získane základné geometrické vlastnosti skúmaných depresií pomocou geografického informačného systému (GIS). Na základe spomenutých záverov prameniacich z aplikácie kontaminačného modelu a logistickej krivky sa vytvoril koregionálny model, ktorý umožňuje zhodnotiť stupeň potenciálneho nebezpečenstva spojeného s kolapsiou krasových útvarov. Geometrické patrametre merané pomocou GIS zahŕňali obvod depresie, hĺbku krasovej depresie, orientáciu hlavnej osi depresie a záchytnú plochu zrážok. Koregionálny model (cokriging) využíva uvedené dáta resp. kombináciu uvedených meraní na predikciu stupňa ohrozenia územia z prepadu krasových depresií v skúmanom území.