

Karst and Sinkhole Hazards

Definitions and Description

Derived from a Slavic word meaning “barren, stony ground,” the term *karst* has been variously used to describe a landscape (terrain), a geologic setting (terrane), and a type of aquifer (or hydrology) characterized by features formed by the dissolution of soluble bedrock:

“A terrain, generally underlain by limestone or dolomite, in which the topography is chiefly formed by the dissolving of rock and which may be characterized by sinkholes, sinking streams, closed depressions, subterranean drainage, and caves (Monroe, 1970).

A terrane underlain by soluble rock in which the topography is chiefly formed by dissolving of rock ... and may be characterized by sinkholes, sinking streams, closed depressions, subterranean drainage, and caves ... (Field, 1999).

“Karst is a unique hydrogeologic terrane in which the surface water and ground water regimes are highly interconnected and often constitute a single, dynamic flow system.” (Taylor and Greene, 2008).

“An aquifer in which the flow of water is or can be appreciable through one or more of the following: joints, faults, bedding-plane partings, and cavities — any or all of which have been enlarged by dissolution (Quinlan and others, 1991).

Karst has a wide geographic distribution, covering approximately 13 percent of Earth’s land surface, and is present on almost every continent underlain by carbonate rocks of various geologic age (Ford and Williams, 2007). In the United States, approximately 18 percent of all exposed or shallow bedrock exhibits, or has the potential for forming, karst or karst-like features (Weary and Doctor, 2014). Many geologic, topographic, and climatologic factors influence the development of karst, and not all karst features—such as sinkholes, caves, and springs—are present to the same extent or develop in the same way in every karst area. For example, although the occurrence and formation of sinkholes in Florida are often used for conceptual and comparative purposes, karst features there have formed in bedrock and under very different geologic and hydrogeologic conditions from karst features in Kentucky. Although comparing karst characteristics in the various states can be useful and informative, karst features are also locally to regionally unique, so that karst features in one state may not be completely analogous to those in another (Fig. 3-1).

In Kentucky, approximately 50 to 60 percent of the state has karst or potential for karst, as indicated by maps showing areas where limestone crops out. About 38 percent of the state has at least some karst development that can be recognized on topographic maps, and 25 percent of the state is known to have well-developed karst features. Data obtained from the 2010 U.S. Census indicate that 2,894,115 people, or about 67 percent of the state’s population, live in a karst region (Cecil, 2015). Some of the larger Kentucky cities and towns located on karst are Frankfort, Louisville, Lexington, Lawrenceburg, Georgetown, Winchester, Paris, Versailles, and Nicholasville (all located in the Inner Bluegrass Region); Fort Knox, Bowling Green,

Elizabethtown, Munfordville, Russellville, Hopkinsville, and Princeton (in the Western Pennyroyal Region); and Somerset, Monticello, and Mount Vernon (in the Eastern Pennyroyal Region).

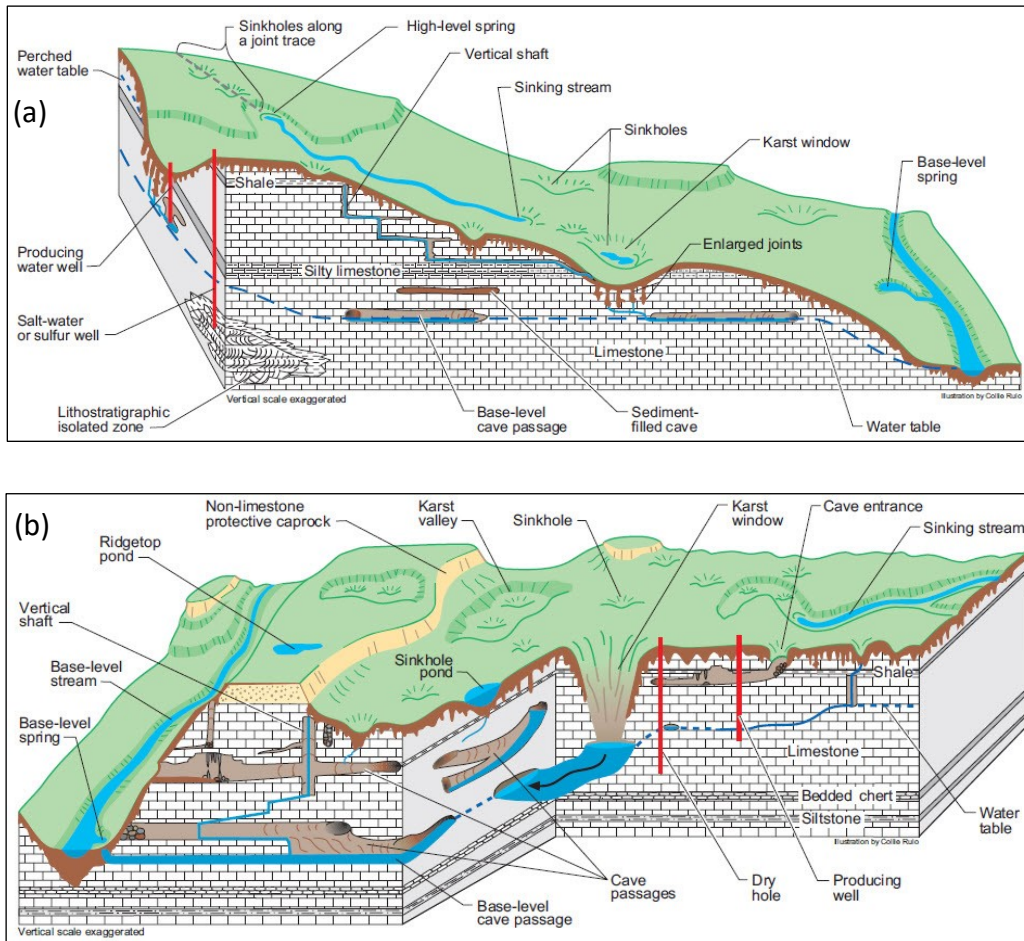


Figure 3-1. Comparison of typical surface and subsurface karst features in the Inner Bluegrass (a) and Western Kentucky Pennyroyal (b) karst regions of Kentucky.

Facts

- Approximately 20 percent of the conterminous United States and 50 percent of the U.S. east of the Mississippi River is underlain by soluble and potentially karstic bedrock (Weary and Doctor, 2014).
- Much of Kentucky’s prime farmland is underlain by karst, as is a substantial amount of the Daniel Boone National Forest, with its important recreational and timber resources.
- Caves are important karst features, providing recreation and unique ecosystems. Mammoth Cave is the longest surveyed cave in the world, with more than 400 miles of passages. Two other caves in the state are known to extend more than 30 miles, and seven mapped Kentucky caves are among the 50 longest in the United States (Gulden, 2018).
- Kentucky is ranked fifth nationally among states affected by sinkhole hazards.

- Karst aquifers and springs supply drinking water and water used for agricultural, industrial, and recreational purposes to an estimated 20 to 25 percent of the global population (Ford and Williams, 2007). Karst aquifers and karst springs provide much of the base flow to surface streams worldwide, and the caves, aquifers, and springs present in karst areas provide critical habitat for a variety of rare, threatened, or endangered aquatic and terrestrial organisms (Culver and White, 2004).
- About 40 percent of groundwater used for drinking water in the U.S. comes from karst aquifers.
- According to the Kentucky Division of Water, springs and wells in karst areas supply water to tens of thousands of private homes, and are also used by five public water suppliers serving more than 164,000 citizens in total: Hardin County Water District No. 1, Hardin County Water District No. 2, Georgetown Municipal, Cadiz Municipal, and Green River Valley Water District (Rob Blair, Source Water Protection Program, Kentucky Division of Water, written communication, April 9, 2018).

Karst hazards that could have an impact on Kentucky’s citizens and infrastructure include sinkholes, flooding, and groundwater and surface-water contamination. Sinkholes are by far the largest and most frequently encountered karst hazards.

Sinkholes

Subsidence—a natural or human-induced process that results in progressive lowering of local or regional land-surface elevations—is a consequence of karst development and may occur over long-term (including geologic) and short-term timescales. Sinkholes, also called *dolines* in the scientific literature, are arguably the most distinctive and abundant type of subsidence-related feature (Ford and Williams, 1989). Sinkholes are physically manifested as closed and internally drained topographic depressions, of generally circular shape, that develop where soil or other overburden material subsides or collapses into subsurface voids. Sinkholes can form as a result of both natural (karst-related) processes and as a direct or indirect consequence of human activities. Human activities that can cause sinkholes include groundwater withdrawals, alteration or diversion of surface runoff, subsurface mining; subsurface erosion, piping, or compaction of unconsolidated soils or sediments along buried pipelines or beneath highways and roads; and decaying buried organic debris (e.g., tree roots, buried trash, and other debris). Sinkholes also form in nonkarst areas where leaking water or sewer pipes and other human activities create or result in subsidence, compaction, or subsurface erosion (i.e., piping) of soil, gravel, or other fill materials. Pipeline leakage and flooding affect highway roadbeds, pipelines, and other utility trenches, and often confuse nongeologists because the “sinkholes” created by these localized collapses may not be, and often are not, related in any way to karst or karst processes (Kuniansky and others, 2016).

Sinkholes are classified by geologists using numerous descriptive terms depending on the types of geologic materials and processes or sequence of processes involved in their formation. Waltham and others (2005), for example, defined six classes of karst-related sinkholes. For simplicity, sinkholes may be grouped into two broad categories: subsidence and collapse. Subsidence and collapse sinkholes often occur together in the same karst area, and many sinkholes form as a combination of the two processes. Subsidence sinkholes form by the relatively slow and gradual subsurface dissolution of soluble bedrock and piping of unconsolidated cover materials (soil, alluvium) into fractures and conduits enlarged by solution in the *epikarst*, a zone of intensified weathering and dissolution at the soil-bedrock interface. Subsidence sinkholes in Kentucky are generally recognizable as broad, shallow, bowl-shaped depressions (Fig. 3-2a, b). These sinkholes are largely responsible for the rolling topography that characterizes much

of the Bluegrass and Western Pennyroyal Regions. Diameters can range from several tens to hundreds of feet, and shapes can be circular, elongate or irregular and complex.



Figure 3-2. Examples of common subsidence sinkholes formed in a rural agricultural setting (a) and a suburban setting (b).

Collapse sinkholes form suddenly by failure of the roof or arch of soil, bedrock, or other surface and subsurface materials located above subsurface karst voids and caves (Waltham and others, 2005). Their seemingly unpredictable occurrence makes them a hazard of particular concern in karst areas. Collapse sinkholes that form over voids in unconsolidated materials—soil, sediment, or brecciated bedrock—are common and are referred to as *cover-collapse* sinkholes (Currrens, 2012). Cover-collapse sinkholes are typically steep-walled circular or funnel-shaped depressions (Fig. 3-3) having diameters that range from a few feet to hundreds of feet. Depths may vary, and may be somewhat dependent on the thickness of soil or unconsolidated material above karstified bedrock. The Kentucky Geological Survey began developing a catalog of case histories of cover-collapse occurrences in 1997 and has documented 354 occurrences throughout the state; an average of 24 new reports are received each year (Currrens, in

press). Statistical evaluation of the data in the catalog indicate that cover-collapse sinkholes in Kentucky are on average 9 feet long, 6 feet wide, and 8 feet deep (Currens, in press). Many of them can be substantially larger in size, however. One of the largest documented cover-collapse sinkholes in the state—the Dishman Lane sinkhole in Bowling Green—was about 150 feet in diameter and more than 16 feet deep (Kambesis and others, 2003). Historically, most cover-collapse sinkholes are reported between April and June (Currens, 2012). Factors that may influence the natural formation of cover-collapse sinkholes include freeze-to-thaw weather cycles and rainfall, particularly intense or prolonged storms occurring after relatively dry conditions (Waltham and others, 2005).



Figure 3-3. Cover-collapse sinkholes like those seen here are typical of the kind that occur most frequently in Kentucky.

Impacts of Sinkhole Hazards

Karst-related subsidence, and particularly catastrophic sinkhole collapse, is a wide-spread, nationally recognized hazard (Weary, 2015). The extent of the problem and the cumulative economic impacts are difficult to assess for many states, however, because of under-reporting, the lack of a centralized database managed by appropriate state or federal authorities, inconsistent or insufficiently detailed documentation about sinkhole damage, and lack of follow-through regarding remediation costs (Weary, 2015; Kuniansky and others, 2016). The available data indicate that sinkhole-related damage is greatest, in order, in Florida, Texas, Alabama, Missouri, Kentucky, Tennessee, and Pennsylvania, although these rankings are somewhat anecdotally based (Weary, 2015). Human fatalities and injuries as a result of sinkholes are rare, but damage to homes, buildings, highways, and other infrastructure results in many millions of dollars in repair and remediation costs each year, and acts to devalue property values and raise insurance costs (Weary, 2015). Best estimates derived from reviews of available state-by-state data indicate that annual costs related to sinkhole damage nationwide range from \$125 to \$300 million per year (Kuniansky and others, 2016).

Most damage and injuries resulting from karst-related subsidence in the U.S. are caused by cover-collapse sinkholes, because these types of sinkholes are extremely common and they typically occur without warning as sudden ground failures (Weary, 2015). Unlike other natural hazards, cover-collapse sinkholes generally do not depend on extreme weather events. In many cases, visible indicators of subsidence and sinkhole development are simply overlooked or misinterpreted. These indicators include

curvilinear cracks developing in soil, asphalt, and concrete; development of swales, gullies, or other shallow surface depressions that may result in surface ponding of water; slumping, sagging, or tilting of trees, roads, rails, fences, pipes, poles, signs, and other vertical or horizontal structures; and step-like fractures developing in the foundations and walls of houses or buildings.

Because of a scarcity of well-documented data, the impact of sinkholes on the economy of Kentucky is difficult to quantify. Dinger and others (2007) estimated the annual costs of repairs of cover-collapse damage to be in the range of \$20 to \$24 million. Two of the most spectacular and best-documented cases of damage caused by sinkholes in Kentucky are the 2002 Dishman Lane event, which cost \$1.2 million to remediate, and the more recent Feb. 12, 2014, National Corvette Museum event, also in Bowling Green, which cost more than \$3.2 million to repair, not including the loss of the cars themselves, estimated by the museum to be an additional \$3.1 million (Polk and others, 2015). The National Corvette Museum and Dishman Lane sinkholes represent extreme and worst-case scenarios of damage caused by collapse sinkholes in Kentucky (Fig. 3-4a, b). Fortunately, such large and especially damaging sinkholes as these are relatively rare in this state. Damage from the more typical cover-collapse sinkholes varies over a very wide range, but may be generally less than a few thousand to tens of thousands of dollars per event. Currens (in press) reported that two of the more expensive known cover collapses that involved private residences resulted in damage costs of \$12,000 and \$40,000, and suggested that an average cost of about \$16,000 is a reasonable estimate of damage caused by a typical cover-collapse event that involves a structure such as a house or building.



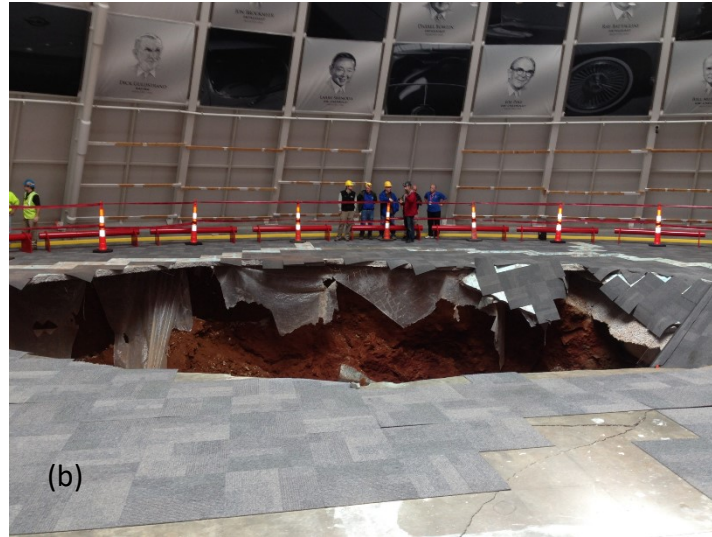


Figure 3-4. Damage associated with collapse sinkhole events at Dishman Lane in 2003 (a) and the National Corvette Museum in 2014 (b), both in Bowling Green, is some of the largest ever reported in Kentucky. (Photo (a) courtesy Western Kentucky University Department of Geography and Geology; used with permission).

Other Potential Impacts and Hazards

Three other potential karst hazards are worthy of consideration: sinkhole flooding, dam construction and maintenance, and groundwater/surface-water contamination. With the exception of flooding, these hazards are relatively rare and are mostly localized in scope and impact. Depending on the specific location, severity, and circumstances of occurrence, however, they have the potential to have an adverse impact on large numbers of citizens and local and regional economies. Available data are insufficient to attempt a quantitative risk assessment about any of the three. The following information is provided to raise awareness of the issues and provide food for thought about the need for additional investigation, analysis, and emergency preparedness.

Sinkhole flooding

Karst-related flooding is perhaps an unrecognized hazard in much of the United States, including in Kentucky. In addition to being a topographic feature, sinkholes and karst valleys (valleys that may be formed by multiple sinkholes coalescing and that contain sinking or losing streams) have the hydrologic function of acting as catchment basins in which storm runoff is collected and diverted underground into the enlarged fractures, cave streams, and solutional openings that comprise the conduit drainage network of a karst aquifer (Taylor and Greene, 2008). Runoff accumulating in a sinkhole may infiltrate slowly through soil or sediment or may be drained rapidly underground through throat-like openings called *swallets*. Individually and collectively, karst conduits have fixed upper limits on cross-sectional areas and volumes; therefore, inflows during storms result in increasing flow velocities and hydraulic head. Whenever the elevation of hydraulic heads in conduits or the larger karst aquifer increase to the point at which the heads equal or exceed-land surface elevations in sinkhole depressions, flooding occurs. In the central and western parts of Kentucky where the karst is characterized by expansive

sinkhole plains and larger karst basins tens to hundreds of square miles in area, conditions are favorable for extensive sinkhole flooding that has the potential to greatly impact local and regional roads, farmlands, economic activity, and houses and other infrastructure.

Sinkholes and karst valleys may also flood whenever the hydraulic drainage capacities of swallets or underlying conduits are exceeded by the inflow of storm runoff. This can be exacerbated by land-development practices (increased impervious surfaces, surface routing of stormwater drainage) and by swallets being clogged by washed-in sediment, trash, and other debris. An unusually severe and well-documented case of this type of flood occurred in February 1989 and affected citizens living in the Tashamingo subdivision and the Delaneys Ferry Road area of Jessamine County (Currens and Graham, 1993). Several homes were isolated by blocked roads, and two homes were flooded; one was damaged extensively.

Two other mechanisms that are common causes of karst-related flooding are restricted drainage from sinkholes and the presence of lower-permeability epikarst and bedrock. Unlike in Florida, most sinkholes in Kentucky do not intersect a base-level (perennial) water table. Instead, relatively thick, clayey residual soils that form in the bottoms of many sinkholes throughout the state impede downward infiltration and percolation, especially during intense storms, resulting in intermittent ponding. Development of a seasonal or intermittent water table perched on lower-permeability carbonate bedrock in the epikarst zone is another common mechanism that causes or exacerbates flooding of sinkholes and basements, particularly in urban and suburban areas. Sinkhole- and epikarst-related flooding in Bowling Green and other parts of Warren County is relatively frequent and has prompted the county to enact strict zoning regulations and building codes. The City of Versailles has spent more than \$500,000 to purchase flood-damaged property in order to take remedial action. In Lexington, repeated impacts to homes and roads in several neighborhoods, especially in the Stonewall–Cindy Blair development in southwest Fayette County, created by epikarst- and sinkhole-related flooding, has cost the Lexington-Fayette Urban County Government at least \$1.5 million in remediation and led to a municipal ordinance on urban development in and near sinkholes and their associated floodprone areas (Dinger and Rebmann, 1991).

Flood recurrence data and flood inundation maps are unavailable for most of Kentucky's karst areas at present. Various approaches for delineating and mapping sinkhole floodplains have been proposed and implemented, at least experimentally or at local scale, in other states (Kemmerly, 1981; Hart and others, 2009). These mapping attempts lack sufficient data and have certain technical deficiencies.

Development of a suitable methodology for assessing the potential severity and risks associated with sinkhole flooding in Kentucky, especially in the state's urban areas, would be extremely beneficial.

Dam Construction and Maintenance

Potential impacts of karst on dam construction and maintenance is another relatively under-recognized and unassessed potential hazard. A number of mostly low-head dams built for flood control, navigation, and public water supply are present throughout Kentucky's karst areas. Many of these are included in a list of dams with high hazard potential in the National Inventory of Dams compiled by the U.S. Army Corps of Engineers (www.damsafetyaction.org/KY/about-eaps/where.php; last accessed 4/11/2018). Issues having to do with construction and long-term maintenance similar to those encountered at Wolf Creek Dam, for example, could occur at many of these dams or at future dam sites located in the state's major karst areas. No study or evaluation has been conducted to date to evaluate the specific role that

the presence of karst plays in the assessment of the status of these dams. The Water Technology website (<https://www.water-technology.net/projects/wolf-creek-dam-remediation-kentucky-us/>; last accessed 4/11/2018) described the potential scope of the problem, remedial actions, and economic impacts at Wolf Creek Dam:

The US Army Corps of Engineers (USACE) completed foundation remediation works for the Wolf Creek Dam in March 2013 at total \$594 million. The project was carried out to prevent possible flooding from the dam, which experienced seepage issues for more than five decades. Property damage worth \$3bn is estimated on occurrence of a potential breaking of the dam. The dam was built on the Cumberland River located in south central Kentucky. The geology of the location is mainly composed of Karst formations, which lead to the breakup of the limestone in the dam's foundation. The dam first witnessed seepage in 1968. First efforts to avoid seepage were made from 1968 to 1970 by grouting the dam's foundation. A major construction project was carried out from 1975 to 1979, in which a reinforced concrete cut-off wall was constructed through the earth embankment into the rock foundation. The problem was still not solved, with seepage intensifying in 2005. The project comprised of constructing a new barrier wall upstream on the right side of the concrete monoliths, to stop seepage in the Karst geology of the rock. A protective concrete embankment wall (PCEW) was also constructed to protect the embankment during the construction of the main barrier wall. The construction of the main barrier was completed in March 2013, ahead of the estimated December 2013 schedule. The barrier wall utilized about 1,197 piles measuring three feet in diameter and extending up to 275ft deep into the bedrock below the foundation of the embankment, which is about 75ft deeper than the original wall. The barrier wall measures 4,200ft in length, which is about 61% longer than the existing wall. The protective embankment wall constructed of concrete is six foot wide and about 230ft deep. The extension of the wall along the embankment is about 3,600ft. The construction of the protective wall was completed in June 2012.

Groundwater and Surface-Water Contamination

In Kentucky, thousands of citizens obtain potable water from wells and springs in karst aquifers. Contaminant releases in karst areas can have rapid and catastrophic effects on drinking-water supplies (Field, 1992). Contaminants are easily injected into karst aquifers through sinkholes and sinking streams and through solution-enlarged fractures and shafts in karstified bedrock (Vesper and others, 2001). Water-tracer tests conducted in karst areas throughout the United States indicate that groundwater and injected stormwater flows at very rapid rates through conduit networks; contaminant transport times in karst aquifers commonly range from a few hours to less than a few days, providing little or no opportunity for contaminant filtration, sorption, or degradation, and little to no time for emergency response (Worthington, 2011).

Determining when, where, and at what concentration a pollutant will arrive is critical to assessing the potential impacts of a contaminant spill or release, and initiating a proper emergency response (Field, 1992). Some, but not all, of the data needed to make these assessments are available for parts of the state's karst areas. KGS, working collaboratively with the Kentucky Division of Water, has conducted hundreds of water-tracing tests throughout the state's karst areas and used this information to develop

a series of maps of karst-groundwater flow paths and basin boundaries. The information provided by these maps helps answer the question of where a potential contaminant spill will go and which downstream users may be affected. In many cases, tracer-test data maintained by KGS and the Division of Water are also available to at least roughly estimate when a contaminant may arrive. There are few data to adequately predict at what concentration a contaminant may arrive, nor how long concentrations will persist in the aquifer above safe drinking-water limits.

The Kentucky Division of Water has the mandated responsibility of protecting public drinking water and the state’s surface and groundwater resources, and maintains programs such as the Source Water Protection Assistance Program to help communities and municipal entities develop protection plans for wellheads and spring basins. Permitted public water suppliers located in karst areas are listed in Table 3-1. Although wellhead and spring basin protection plans are required for these suppliers, some are based on minimally adequate quantitative data. Thousands of other citizens in the state obtain drinking water from private water wells or springs, for which there are no protection plans and for which little is known about the potential vulnerability of the karst aquifer to contamination. An additional consideration that is often overlooked is that karst springs and groundwater discharging from karst aquifers contribute to the surface water of many of the Commonwealth’s streams—these surface-water resources, which are also the source of much of the public’s drinking water, are therefore also potentially affected by contaminant spills in karst. Quantitative water-tracing tests and additional mapping of karst aquifers are needed to provide this vital information and to ensure that the state’s drinking-water resources are protected and emergency preparedness is adequate.

Table 3-1. Permitted public water suppliers located in karst areas in Kentucky.

Public Water Supply	Estimated Population Served Directly
Hardin County Water District No. 1 (includes Fort Knox and Radcliffe)	27,033
Hardin County Water District No. 2 (includes Elizabethtown)	78,326
Georgetown Municipal	35,714
Cadiz Municipal	5,609
Green River Valley Water District	17,431
	Total: 164,113

Source: Rob Blair, Water Quantity Management Section, Watershed Management Branch, Kentucky Division of Water, written communication, April 9, 2018.

Table 2. Summary of sinkholes and karst-related hazards.

Karst/Sinkhole Profile Risk	
Extent	Karst-related hazards: Approximately 55 to 60 percent of the state, as indicated by areas underlain by carbonate bedrock and mapped Karst Potential Index ¹ .
Potential Hazard Impacts	Minor to severe structural damage to buildings; increased building or landscape repair and maintenance costs, decreased property values; damage to pipelines and other above- or below-ground utility infrastructure; seepage and underflow, structural undermining, and potential

	failure of dams on streams in karst areas; sinkhole and other karst-related flooding; groundwater or surface-water contamination in the event of a chemical spill or release, with the potential to affect private and public water supplies.
Period of Occurrence	Sinkholes only: At any time.
Number of Events in Kentucky	Sinkholes only: 101,632 mapped sinkhole depressions ² ; 354 documented cover-collapse sinkholes (1997–2017) ³
Annual Rate of Occurrence	Sinkholes only: Unknown; insufficient data available.
Warning Time	Sinkholes: Often cannot be determined; formation of subsidence sinkholes may provide early warning signs; cover-collapse sinkholes may or may not.
Recorded Losses	Not documented.
Annualized Loss	Undetermined, but estimated at \$20–\$24 million ⁴ .

1 Currens and others (2009)

2 Paylor and others (2003)

3 Currens (in press)

4 Dinger and others (2007)

Assessing Vulnerability by Jurisdiction

Grid-Level Risk Assessment Model

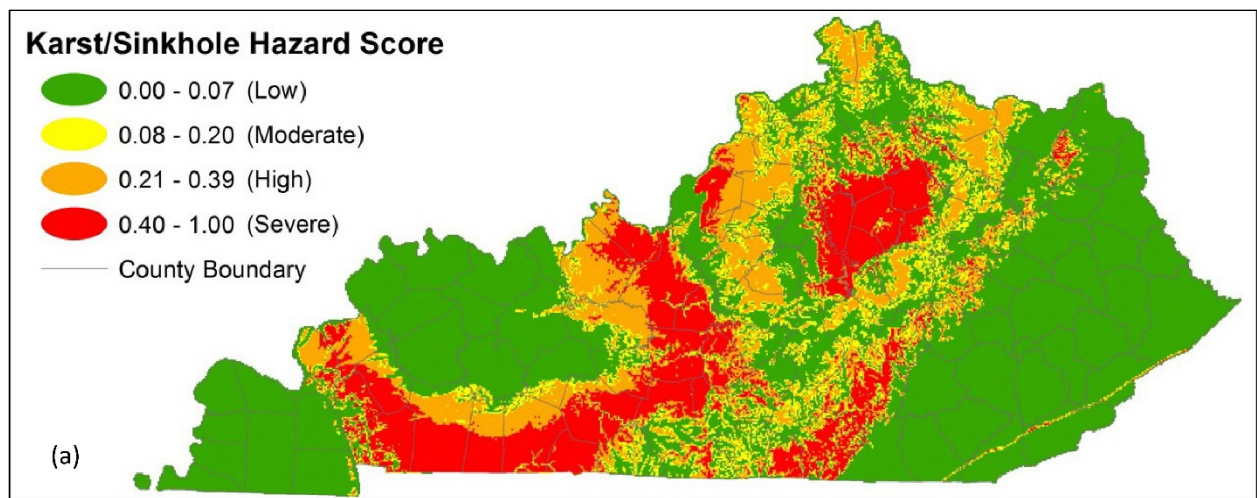
Evaluation of the assessment method in the 2013 Plan

Karst and sinkholes are well recognized as geologic hazards in Kentucky and were included for risk assessment in the 2013 State Hazard Mitigation Plan (Kentucky Emergency Management, 2013). To assess hazard by jurisdiction, the 2013 plan divided the state using the U.S. National 1-km² grid, and a hazard score was calculated for each grid cell. The scores statewide were subsequently divided into four categories using the natural breaks classification, which partitions data to minimize variation within each group while maximizing difference among groups. The four hazard categories were low, moderate, high, and severe, in ascending order of the scores (Fig. 3-5a). In the 2013 plan, the karst/sinkhole hazard score was calculated using a formula that sums the percentage of areas with potential for karst development and the percentage of areas of sinkhole occurrence.

The percentage of area with potential for karst was calculated from the Kentucky karst potential map (Currens and others, 2009), which delineates areas with high and moderate potential for karst development based on mapped outcrops of carbonate bedrock at or near

the land surface, using 1:500,000-scale geologic maps (Fig. 3-5b). The percentage of area of sinkhole occurrence was calculated from a sinkhole map (Paylor and others, 2003) derived from digitizing closed depressions on 1:24,000-scale topographic maps (Fig. 3-5c). The karst potential map identified a 19,981-km² area with high karst potential and a 17,968-km² area with moderate karst potential. The total area occupied by sinkholes was approximately 1,059 km², based on the sinkhole map. Because the area identified as having the potential for karst is much larger than the area of mapped sinkhole occurrence, the spatial distribution of the karst/sinkhole hazard scores is mostly influenced by karst-potential information and is little influenced by sinkhole occurrences.

Sinkhole occurrence is a proxy measurement of karstification, however; karstification is also influenced by additional important hydrogeologic factors such as soil thickness, bedrock porosity and permeability, topography, and surface and subsurface drainage. Because the formation of sinkholes is generally recognized as the most prominent karst-related hazard in Kentucky, we believe the method used to assess karst/sinkhole hazard should give more weight to the information on sinkhole occurrence.



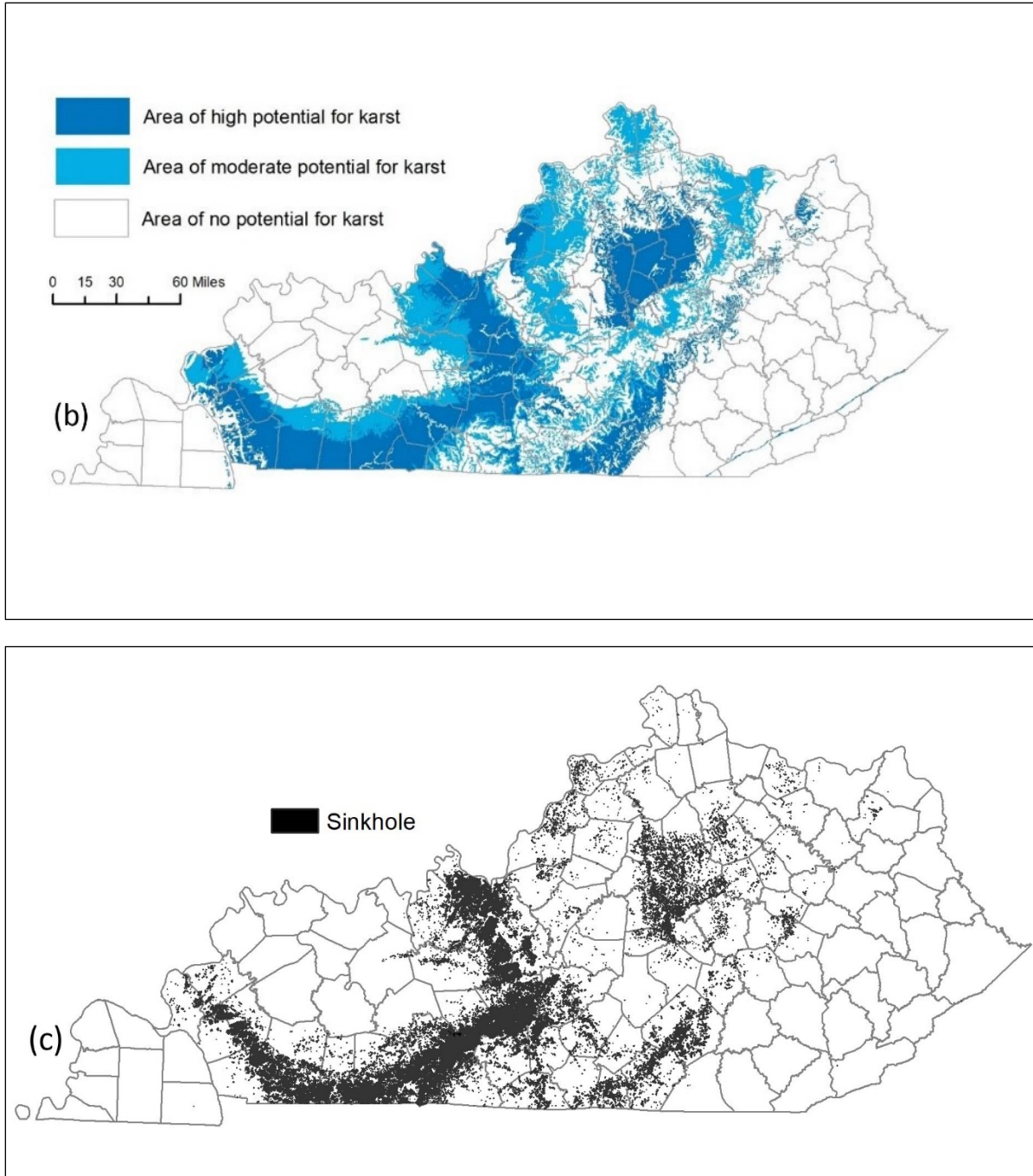


Figure 3-5. (a) The karst/sinkhole hazard map (from Kentucky Emergency Management, 2013) in the 2013 plan and the two source datasets: (b) karst potential map and (c) sinkhole map.

Modifications to the Karst/Sinkhole Hazard Assessment in the 2013 Plan

To better incorporate information about sinkhole occurrence, we tested two modifications to the karst/sinkhole hazard assessment method used in the 2013 plan. The first modification assigns a higher weight to area percentage of sinkhole occurrence than to area percentage with

karst potential. The second modification substitutes sinkhole density (number of sinkholes per square kilometer) for percentage area of sinkhole occurrence, and sums sinkhole density and karst potential area percentage. To compare the results from the two modifications with the scores in the 2013 plan, the same classification method (natural breaks) and the same four hazard categories (low, moderate, high, and severe) were used.

Increase Weight for Sinkhole Area Percentage

Calculation of the karst/sinkhole hazard score in the 2013 plan can be expressed as:

$$0.5 \times (\text{karst area percentage}) + 0.5 \times (\text{sinkhole area percentage}) \quad (1)$$

In equation 1, the weights for karst area percentage and for sinkhole area percentage are equal (0.5) and sum to 1. To increase the influence of sinkhole area percentage on the score, we tested several weight combinations of increased weight for sinkhole area percentage and decreased weight for karst area percentage, while keeping the sum of weights as 1. We found adjusting sinkhole-occurrence weights in a way that meaningfully improves upon the 2013 hazard scores to be difficult, however. For example, using a weight of 0.75 for sinkhole area percentage and a weight of 0.25 for karst area percentage, which can be expressed as

$$0.25 \times (\text{karst area percentage}) + 0.75 \times (\text{sinkhole area percentage}) \quad (2)$$

decreased the overall hazard scores, but barely changed the spatial distribution of hazard categories with natural breaks (Fig. 3-6a). Using a weight of 0.9 for sinkhole area percentage and a weight of 0.1 for karst area percentage, which can be expressed as

$$0.1 \times (\text{karst area percentage}) + 0.9 \times (\text{sinkhole area percentage}) \quad (3)$$

mostly shifted areas from higher hazard categories to lower hazard categories, whereas the spatial pattern of hazard remained similar to that in the hazard score in the 2013 plan (Fig. 3-6b).

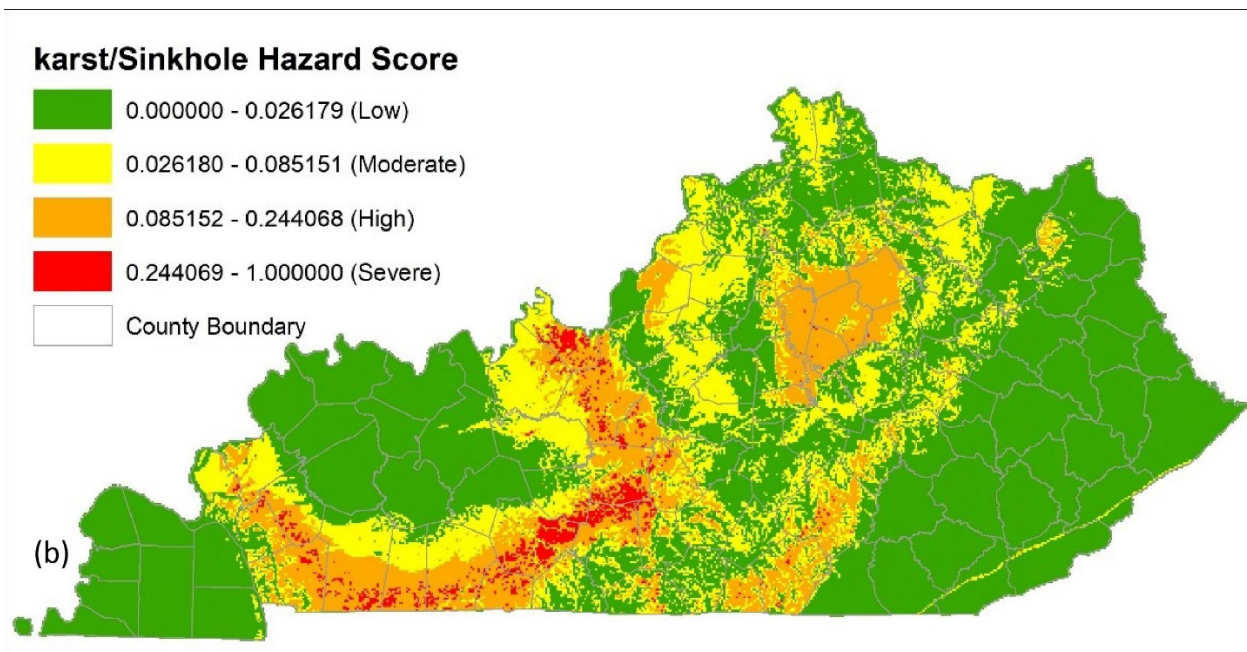
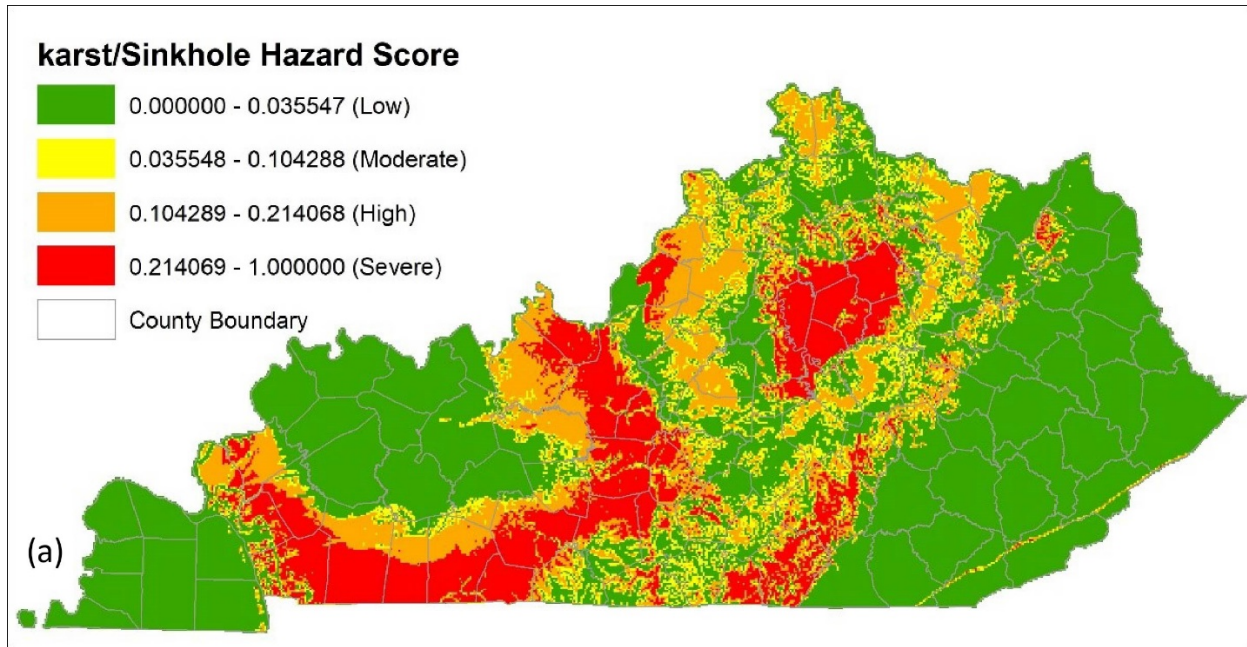


Figure 3-6. Spatial distribution of karst/sinkhole hazard scores with (a) a weight of 0.75 for sinkhole area percentage and a weight of 0.25 for karst area percentage and (b) a weight of 0.9 for sinkhole area percentage and a weight of 0.1 for karst area percentage.

Combining Sinkhole Density With Karst Area Percentage

Sinkhole density has been applied in conjunction with other data to assess sinkhole hazard in other karst regions. For example, Kaufmann and Quinif (2002) delineated three collapse hazard zones (low, moderate, and high) using sinkhole density and the relationship between the water

table and the top of the limestone bedrock for Tournaisis, Belgium. SSM (2018) defined zones of low, moderate, and high sinkhole risk based on sinkhole density and carbonate formations in Pennsylvania. Table 3-3 lists the sinkhole density values used to define hazard categories in the Kaufmann and Quinif (2002) and SSM (2018) studies, showing that sinkhole density values used for defining hazard categories are highly dependent on available data and field-specific conditions.

Table 3-3. Association of sinkhole hazard categories with sinkhole density values for Tournaisis, Belgium, and Pennsylvania.

Hazard Category	Sinkhole Density Used for Tournaisis, Belgium	Sinkhole Density Used for Pennsylvania
Low	< 1 per km ²	< 1 per mi ²
Moderate	1–15 per km ²	1–100 per mi ²
High	> 15 per km ²	> 100 per mi ²

Keeping the same four hazard categories used in the 2013 plan, we identified a combination of sinkhole density values (Table 3-4) that yields a reasonable spatial distribution of hazard score (Fig. 3-7).

Table 3-4. Definition of hazard categories in Kentucky in terms of karst area and sinkhole density.

Hazard Category	Definition
Low	Area of no potential for karst
Moderate	Karst area without sinkholes
High	Karst area with 1–9 sinkholes per km ²
Severe	Karst area with > 9 sinkholes per km ²

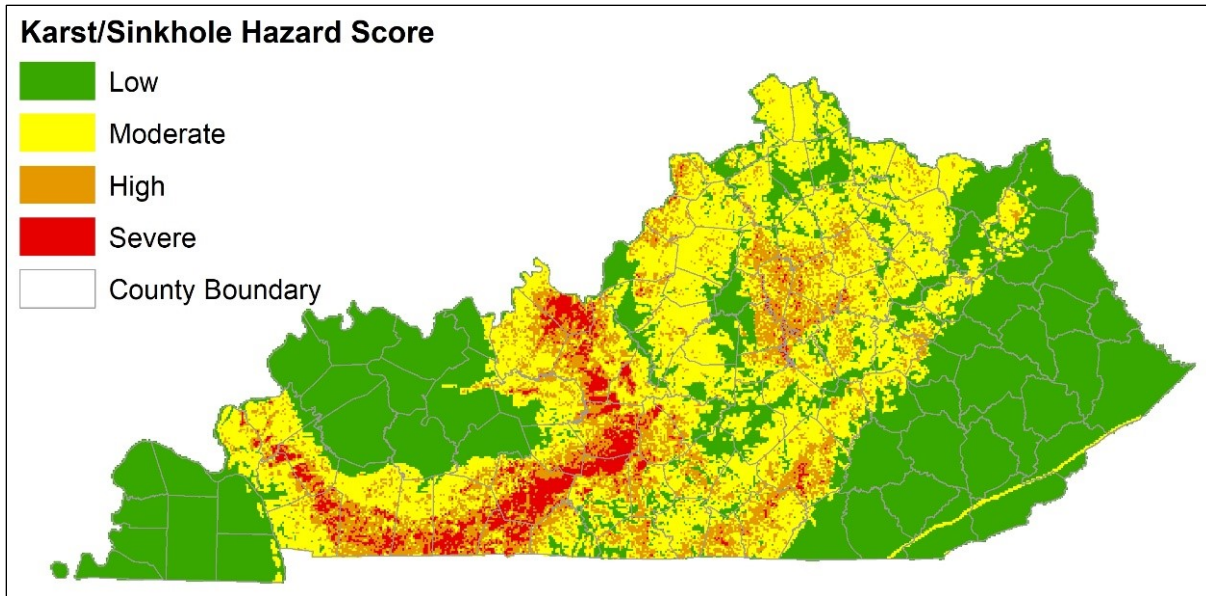


Figure 3-7. Karst/sinkhole hazard scores based on karst area and sinkhole density.

The hazard scores shown in Figure 3-7 have no associated numerical values. To make the hazard scores work directly with a numerical exposure score for assessing risk, we developed the following formula:

$$\text{karst/sinkhole score} = \log_{10}((\text{karst area percentage}) + (\text{sinkhole density}) + 1) \quad (4)$$

where \log_{10} is the base-10 logarithmic function. The number 1 on the right side of the equation was added to keep the score positive. The scores calculated from equation (4) are further normalized to the range 0–1. Figure 3-8 shows the resulting hazard scores.

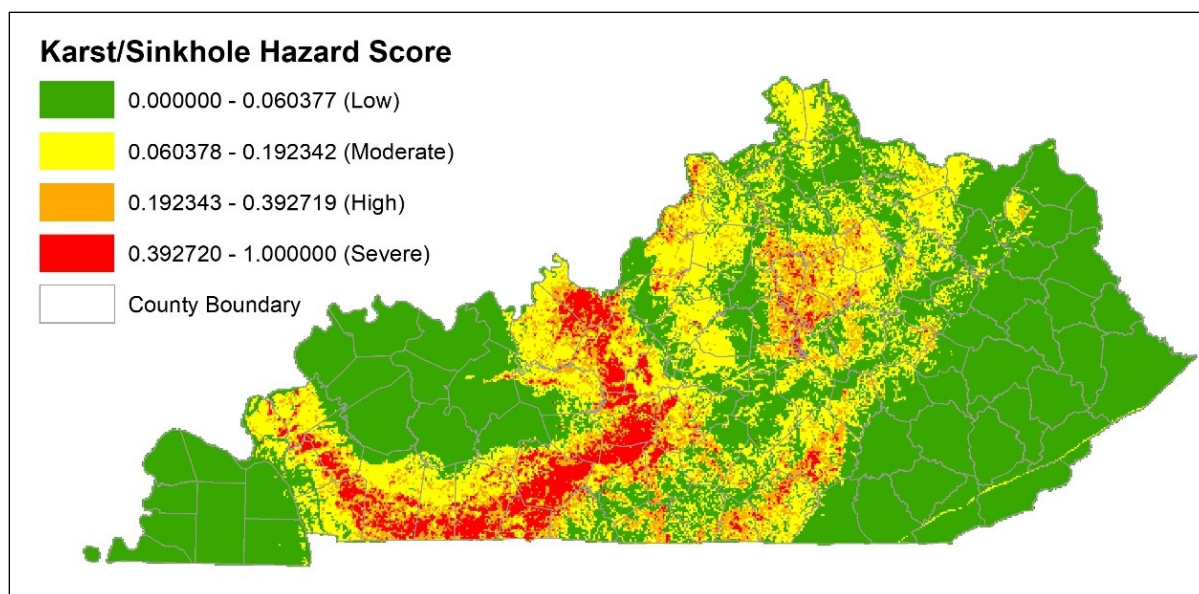


Figure 3-8. Numerical karst/sinkhole hazard scores based on karst area percentage and sinkhole density.

Figures 3-7 and 3-8 show that the karst/sinkhole hazard scores calculated from the combination of karst potential area and sinkhole density have increased spatial variability in hazard categories in areas with high and moderate karst potential, compared with hazard scores in the 2013 plan. The increased variability is a reflection of the sinkhole occurrences (Fig. 3-5c).

Conclusions

The spatial distribution of the karst/sinkhole hazard scores in the 2013 plan is heavily influenced by karst-potential information and little influenced by sinkhole occurrences. Because we believe sinkholes are the most prominent karst-related hazard in Kentucky, we tested two modifications while using the same data sources as in the 2013 plan. We found the modification that combines karst potential area and sinkhole density better reflects sinkhole occurrences and also considers information on karst potential areas.

Future Research Recommendations

Although appropriate assessment methods can improve hazard scores, the scores are ultimately the result of source data. The karst potential map and sinkhole map used for the current karst/sinkhole hazard assessment are outdated. The karst potential map is based on 1:500,000-scale geologic maps. A more detailed karst potential map based on 1:24,000-scale geologic maps is available and more accurately delineates carbonate formations (Currens and others, 2009). The sinkhole occurrence map used for the 2013 plan was derived from digitizing closed depressions from 1:24000-scale topographic maps. The topographic maps were mostly created prior to the 1970s, and many new sinkholes may have formed since then. In addition,

the sinkholes on the topographic maps were not field verified. Zhu and others (2014) demonstrated that many more sinkholes can be located with high accuracy by using airborne LiDAR (Light Detection and Ranging) data, and their study led to continued efforts at KGS to use LiDAR to locate sinkholes in Kentucky since 2014. Up to now, however, sinkholes have been mapped using LiDAR for only seven counties because of funding and resource constraints. Consequently, we recommend the following to improve karst/sinkhole hazard assessment in Kentucky:

1. In the near term, replace the karst potential map with the more detailed karst potential map (based on 1:24,000-scale geologic maps) in assessing karst area percentage.
2. Accelerate sinkhole mapping using LiDAR through collaboration between KGS, Kentucky Emergency Management, the Natural Resources Conservation Service, and FEMA, with the goal of having a statewide sinkhole map based on LiDAR data available for the 2023 mitigation plan update.

Waltham and others (2005) summarized parameters that should be considered when assessing karst/sinkhole hazard. The parameters applicable to Kentucky are bedrock (type, depth, fracturing, fault), type of cover soil, topography, and sinkholes (number, size, type). Although some information on bedrock and sinkholes is considered in the current assessment method, a future assessment method should test if adding more of the parameters listed above can improve hazard evaluation.

Although quantifying the karst/sinkhole hazard is important and necessary, as Waltham and others (2005, p211) noted, “It may be argued that hazard predictions must be inherently general because of the numerous variables involved, and that attempts to quantify the hazard or predict the time of collapse are usually inappropriate.”

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A Note on Future Conditions¹

The Commonwealth of Kentucky Enhanced Hazard Mitigation Plan for 2018 (CK-EHMP 2018) has relied on a recent study on climate conditions from modeling specific to Kentucky that was conducted by the United States Army Corps of Engineers (USACE) and the Ohio River Basin Alliance (ORB Alliance). This study is called *Ohio River Basin: Formulating Climate Change Mitigation/Adaptation Strategies through Regional Collaboration with the ORB Alliance*.

From this study, the Commonwealth of Kentucky assumes the following:

- There has been a gradual warming trend throughout the Ohio River Basin since the late 1970s.
- Precipitation has increased during the latter summer and early fall months since the late 1970s.
- Summer highs and winter lows between 2011 and 2040 will remain generally within what has been observed over that historic period. (But, record temperatures, rainfall, or drought cannot be ruled out.)
- The influence of the jet stream across the Ohio River Basin latitudes increases the *variability* of the weather (and further complicates forecasting future climatic conditions).
- Significant changes in river flow discharges and mean annual air temperatures will not be occurring before 2040. The climate will not vary substantially from what has been experienced between 1952 and 2001.

In other words, there has been gradual warming since the late 1970s. This gradual warming will continue without much significant change until 2040. (After 2040, the modeling in the study predicts temperatures may rise one (1) degree every decade through 2099.) Further, part of this gradual warming since the late 1970s involves precipitation increases. Precipitation increases affects nearly every hazard identified in this hazard mitigation plan: Landslides are triggered by precipitation; sinkholes flood with increased precipitation; flash flooding increases from severe storms; and winter storms either increase or become more severe.

The variability interpretation also is interesting and applicable to expected future conditions for Kentucky's identified hazards:

With gradual warming and its effects on summer highs and winter lows, with increased precipitation, and with increased variability of the weather, it is expected that the probability (or, rather, the frequency and/or severity) of sinkhole events, particularly sinkhole flooding events, will increase.

¹ The below statement is made by the University of Kentucky Hazard Mitigation Grants Program Office (UK-HMGP) and by Kentucky Emergency Management (KYEM) and does not necessarily reflect the views of the Kentucky Geological Survey (KGS).