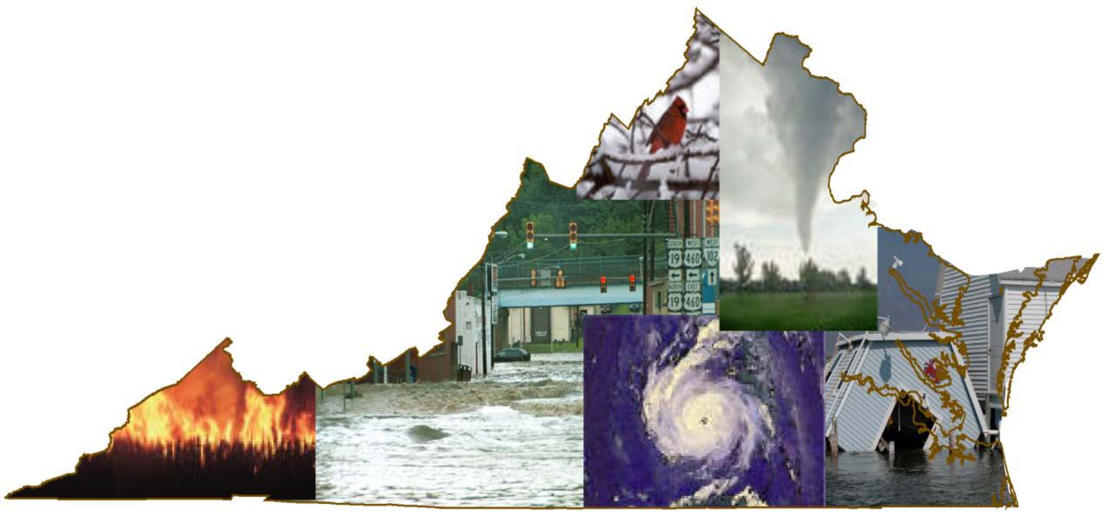
COMMONWEALTH OF VIRGINIA

Hazard Mitigation Plan



Chapter 3
Hazard Identification and Risk Assessment (HIRA)

Section 3.14 – Land Subsidence (Karst)

SECTION 3.14

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Section 3.14: Land Subsidence (Karst)

Description

August 2004 Tropical Depression Gaston
City of Richmond, Virginia
Source: Sign of the Times www.sott.net

Land subsidence is a gradual settling or sudden sinking of the Earth's surface owing to subsurface movement of earth materials. Subsidence is a global problem, and in the United States, more than 17,000 square miles in 45 States, an area roughly the size of New Hampshire and Vermont combined, have been directly affected by subsidence. The principal causes are aquifer-system compaction, drainage of organic soils, underground mining, hydrocompaction, natural compaction, sinkholes, and thawing permafrost. Three distinct processes account for most of the water-related subsidence--compaction of aquifer systems, drainage and subsequent oxidation of organic soils, and dissolution and collapse of susceptible rocks.[1]

"Karst" is the term commonly used to describe areas containing distinctive surficial and subterranean features, such as fissures, tubes, and caves, developed by solution of carbonate and other rocks. Karst areas are characterized by closed depressions, sinking streams, and cavern openings. When used in its broadest sense, the term karst encompasses many surface and subsurface conditions that give rise to problems in engineering geology. In Virginia, most karst lands are underlain by soluble limestone and dolomite, collectively referred to as "carbonate rock. The limestone and dolomite valleys west of the Blue Ridge Mountains are separated by narrow ridges largely composed of sandstone and shale. Lower ridges are often composed of sandy dolomites and limestones. Both of these terrains can exhibit extreme karst topography, with first and second order streams that abruptly, or gradually lose drainage to the cavernous subsurface, temporal streams with large subsurface drainage areas, "blind valleys" (i.e., large linear sinkholes that are often mistaken for adequate drainage ways), and *estavelles* or hydrologically-active sinkholes that normally receive drainage from surrounding areas, but also discharge water in time of flood.[2] While karst is not the only cause of land subsidence, it tends to receive more attention in Virginia than the other causes, due to its potential for sudden and catastrophic events.

[1] Land Subsidence in the United States. USGS Fact Sheet 165-00. December 200.
[2] Technical Bulletin No.2. VA DCR Hydrological Modeling and Design in Karst

In addition to karst terrain, Virginia also has a number of known active and abandoned underground mines. These are present primarily in the southwestern part of the state, in including the counties of Lee, Scott, Wise, Dickenson, Russell, Buchanan, Tazewell, and the City of Norton.[3] Like karst terrain, underground mines may pose a hazard to certain types of land use.

Historic Occurrence

To date, there have been no Federal Declared Disasters or NCDC recorded events for karst related events. Land subsidence is very site-specific. Currently there is no comprehensive long-term record of past events in Virginia. Several documented occurrences have been included in Table 3.14-1. For future revisions of this section, it is recommended that the Virginia Department of Transportation be involved to determine areas where roads experience sinkholes to improve on the incidence reporting.

[3] Virginia Department of Mines Minerals and Energy. "Mines." Retrieved from https://maps.dmme.virginia.gov/flexviewer/DM/ on March 4, 2013.

Table 3.14-1: Historical land subsidence events

Year	Location of Sinkhole	Description
1910	City of Staunton	Three sinkholes opened up on Lewis and Baldwin Street and Central Avenue in Staunton. One of the sinkholes was so large that it swallowed a 35-foot maple tree and a house. One worker was killed when he fell into one of the chasms caused by the sinkhole as it was being repaired
1977	Smyth County	A sinkhole 50 feet in diameter caused a section of State Route 91 to collapse in Smyth County. The incident took place in front of U.S. Gypsum Company offices
1992	Clarke County	A house collapsed inside of a sinkhole after the drilling of a new well on the property in Clarke County.
2000	City of Staunton	Thirty-two sinkholes were reported after 7" of rain fell in April after a long dry spell in the City of Staunton.
2001	Augusta County	Interstate 81 was closed for a nine-mile stretch in Augusta County because of the sudden appearance of three sinkholes. The largest of the three sinkholes was measured at 20 feet long, 11 feet wide and 22 feet deep and costing over $100,000 to repair.
2004	City of Richmond	Heavy rain from Tropical Depression Gaston led to a 30ft sinkhole in the City of Richmond that swallowed an intersection.
2005	Botetourt County	A sinkhole 40 feet deep and 25 feet wide was discovered on Trinity Road (Virginia 670) in Botetourt County[4].
2006	City of Staunton	A sinkhole 18 feet deep on Interstate 64 closed one lane and shoulder in the City of Staunton.
2008	Prince William County	A sinkhole 20 feet deep and 25 feet wide closed down Dale Boulevard west of Mapledale Avenue, about four miles from Interstate 95 in Prince William County.
2011	Town of Strasburg	A sinkhole 50 feet deep and 75 feet wide shut down Oranda road in both directions in the Town of Strasburg. The Virginia Department of Transportation believed this to be one of the larger sinkholes they had seen. The road was closed for several days for repairs[5].
2011	Stafford County	A sinkhole approximately 30 feet deep and 100 feet wide swallowed the backyards and back decks of two homes in Stafford County. The two homes were condemned and the owners forced to leave for fear that the encroaching sinkhole will eventually destroy their homes[6].
2011	Rockbridge County	Near mile marker 170, the northbound lanes of Interstate 81 had to be closed because of a sinkhole[7].

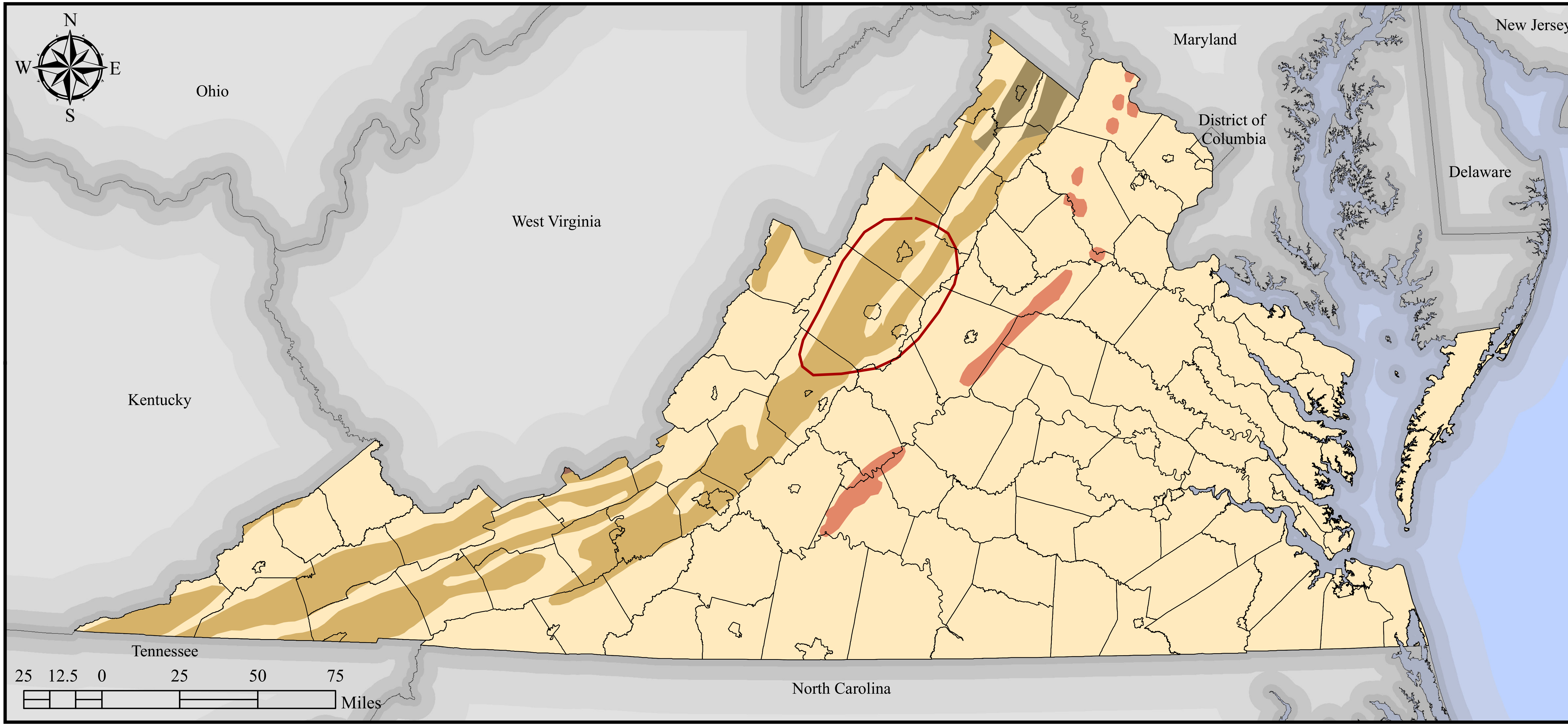
[4] Roanoke Times. "Sinkhole crew cooks up 'rock lasagna.'" Retrieved from http://www.roanoke.com/news/roanoke/wb/xp-21921 on November 20, 2012.
[5] Knight, Preston. "Oranda Road Sinkhole Patched up Anew." April 28, 2011. http://www.nvdaily.com/news/2011/04/oranda-road-sinkhole-patched-up-anew.php
[6] NBC Washington. "Growing Sinkhole Threatens Home Destruction in Stafford." October 13, 2011. http://www.nbcwashington.com/news/local/Growing-Sinkhole-Threatens-Home-Destruction-in-Stafford-131582513.html
[7] Roanoke Times. "Sinkhole is found on part of I-81." Retrieved from http://www.roanoke.com/news/roanoke/wb/285503 on November 20, 2012.

Risk Assessment

The Engineering Aspects of Karst data set shows areas of karst in the United States. This data set is a digital representation of USGS Open-File Report 2004-1352, which is a PDF version of the 1984 USGS Engineering Aspects of Karst map (scale 1:7,500,000). Figure 3.14-1 shows the areas containing distinctive surficial and subterranean features developed by solution of carbonate and other rocks and characterized by closed depressions, sinking streams, and cavern openings.

David Hubbard, geologist with the Virginia Department of Mines Minerals and Energy (DMME) developed 1:24,000 scale sinkhole boundary maps during 1980 and 1988 for the state. Sinkhole distribution is shown in three main regions along the Valley and Ridge province. A total of 51,455 sinkholes have been mapped in a digital GIS format provided by Dave Hubbard (DMME), based on DMME Publications 44, 83, 167 (see Figure 3.14-2). Note that this data was compiled only for those jurisdictions with the largest areas of karst terrain.

Figure 3.14-1: Karst Regions and Historical Subsidence



Center for Geospatial Information Technology

VIRGINIA DEPARTMENT OF EMERGENCY MANAGEMENT

PROJECTION: *VA Lambert Conformal Conic North American Datum 1983*

DISCLAIMER: Majority of available hazard data is intended to be used at national or regional scales. The purpose of the data sets are to give general indication of areas that may be susceptible to hazards. In order to identify potential risk in the Commonwealth available data has been used beyond the original intent.

DATA SOURCES:

USGS Engineering Aspects of Karst
VGIN Jurisdictional Boundaries
ESRI State Boundaries

LEGEND:

Historical Subsidence

Karst Type (Long)
- In moderately to steeply dipping beds of carbonate rock
- In gently dipping to flat- lying beds of carbonate rock

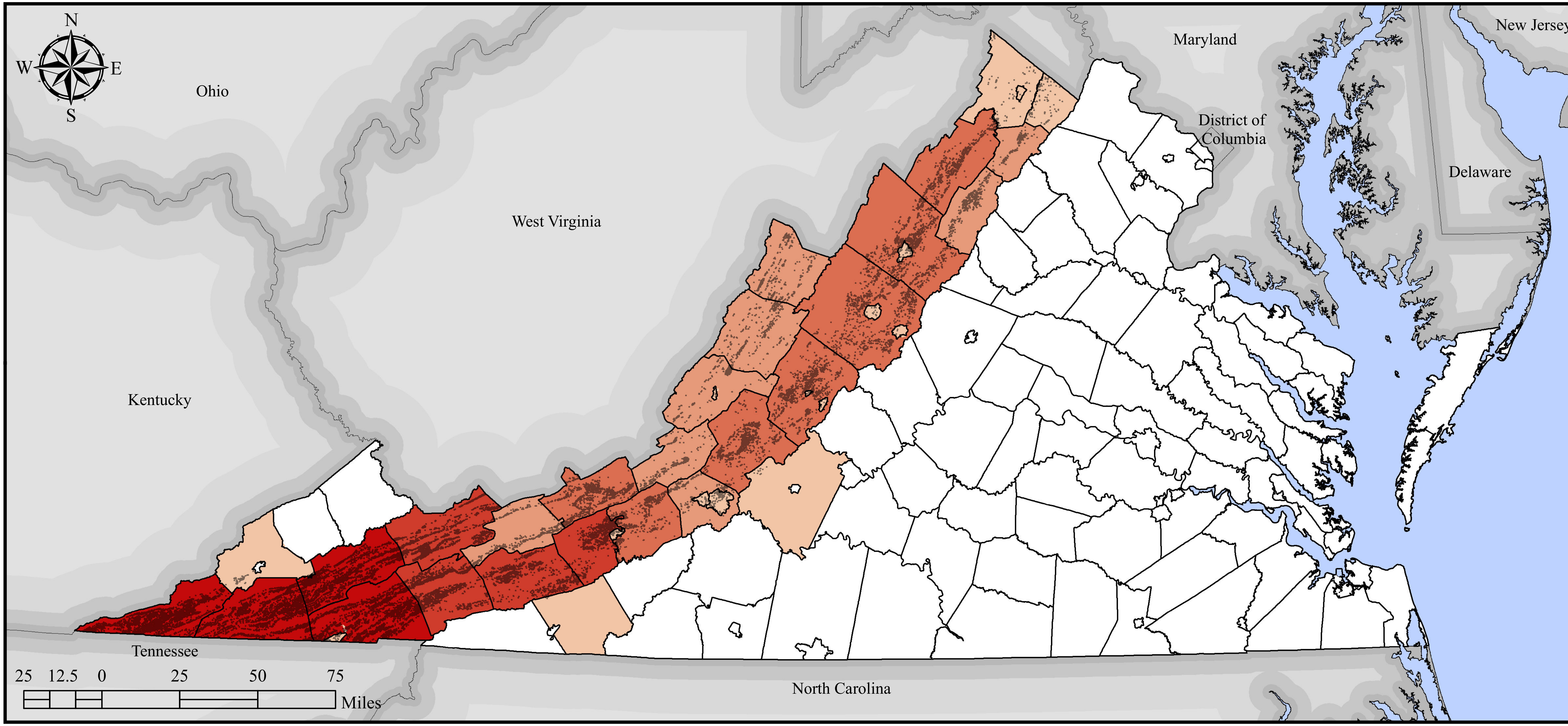
Karst Type (Short)
- In metamorphosed limestone, dolostone, and marble
- In moderately to steeply dipping beds of carbonate rock

HAZARD IDENTIFICATION:

Long Karst Type: Fissures, tubes, and caves over 1,000 ft long; 50 ft to over 250 ft vertical extent
Short Karst Type: Fissures, tubes and caves generally less than 1,000 ft long; 50 ft or less vertical extent

Historical subsidence represents areas of extensive sinkhole development.

Figure 3.14-2: Mapped Sinkholes in Virginia



Center for Geospatial Information Technology

VIRGINIA DEPARTMENT OF EMERGENCY MANAGEMENT

PROJECTION: *VA Lambert Conformal Conic North American Datum 1983*

DATA SOURCES:

Dave Hubbard, Virginia DMME
VGIN Jurisdictional Boundaries
ESRI State Boundaries

LEGEND:

Mapped sinkhole

Number of Sinkholes by Jurisdiction

- 0
- 1 - 200
- 201 - 1000
- 1001 - 2000
- 2001 - 4000
- 4001 - 6676

DATA IDENTIFICATION:

This map shows the number of sinkholes in high risk jurisdictions mapped by Dave Hubbard in Virginia DMME Publications 44, 83, 167. While sinkholes may occur in other jurisdictions, these were not mapped as a part of the aforementioned publications.

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Probability

Karst formations develop in specific ways that are influenced by unique local conditions. Sinkholes can be induced through natural or human causes. Sinkholes that occur naturally usually form by the slow downward dissolution of carbonate rock though bedrock collapse in areas that overlie caverns.[8] Human induced sinkholes can be triggered by simple alteration in the local hydrology. Inadequate drainage along highways and increased runoff from pavements can also be sources of sinkhole development.

The probability of land subsidence cannot be expressed in terms of specific return periods or recurrence intervals as easily as it can be for other hazards. As a result, the probability analysis consists of delineating those regions experience relatively more karst, based on the USGS Engineering Aspects of Karst (Figure 3.14-1).

Impact and Vulnerability

The most important environmental issue with respect to karst is the sensitivity of karst aquifers to groundwater contamination. This problem is universal among all karst regions in the United States that underlie populated areas.

The USGS recognizes four major impacts caused by land subsidence:

- Changes in elevation and slope of streams, canals, and drains
- Damage to bridges, roads, railroads, storm drains, sanitary sewers, canals and levees
- Damage to private and public buildings
- Failure of well casings from forces generated by compaction of fine-grained materials in aquifer systems

Risk

Risk, strictly defined as probability multiplied by impact, cannot be fully estimated for land subsidence due to the lack of historical data and detailed mapping. To assess risk, mapping by the USGS of karst regions in Virginia was used as the probability of future occurrence. A high percentage of karst geology in a jurisdiction does not necessarily mean that the whole locality is at high risk for land subsidence. Without well established occurrence probabilities true risk cannot be calculated.

The principal area affected by sinkholes is the Valley and Ridge province, an extensive karst terrain underlain by limestone and dolomite, but the narrow marble belts in the Piedmont and some shelly beds in the Coastal Plain are also pocked with sinkholes[9]. This assessment focuses

[8] Langer, W. H. "Potential environmental impacts of quarrying stone in karst—a literature review." U.S. Geological Survey Open-File Report 0F-01-0484, (2001).
[9] Division of Geology and Mineral Resources, Virginia Department of Mines, Minerals and Energy. Sinkholes and Karst Terrain. http://www.dmme.virginia.gov/DMR3/sinkholes.shtml

on areas vulnerable to collapse resulting from geologic formations prone to dissolution. It does not include areas underlain by coal which can be subject to abandoned mine collapse, or urban areas where failed underground infrastructure can lead to sinkholes

State Facility Risk

In order to determine which facilities are at risk for land subsidence, the state facilities were intersected with the USGS karst geology layer. The results of this analysis indicate 2,651 buildings at risk for subsidence with a combined building value at risk of over $4.1 trillion. Table 3.14-2 shows the distribution based on karst type and the building value at risk for state facilities. Annualized loss estimates were not calculated for state facilities due to the scale of available karst mapping and lack of probabilities of future occurrences.

Table 3.14-2: State facilities at risk for land subsidence

Karst Type	Number of State Facilities	Building Value at Risk
Fissures, tubes, and caves over 1,000 ft. (300 m) long; 50 ft. (15 m) to over 250 ft. (75 m) vertical extent; in moderately to steeply dipping beds of carbonate rock.	2,367	$3,756,674,693
Fissures, tubes and caves generally less than 1,000 ft. (300 m) long; 50 ft. (15 m) or less vertical extent; in metamorphosed limestone, dolostone, and marble	194	$333,756,612
Fissures, tubes and caves generally less than 1,000 ft. (300 m) long; 50 ft. (15 m) or less vertical extent; in moderately to steeply dipping beds of carbonate rock.	90	$64,750,018
Total	**2,651**	**$4,155,181,323**

The 2,651 buildings that are at risk for subsidence can be divided between 94 different agencies in Virginia. The top five of those agencies have been listed in Table 3.14-3, by building value. The agencies listed represent approximately 30% of the buildings and 79% of total building value that is within a land subsidence zone.

Table 3.14-3: Top five state agencies in a karst zone

Agency	Number of Buildings in Karst Zone	Building Value in Karst Zone
James Madison University	216	$1,270,740,898
Virginia Polytechnic Inst. and State University	328	$1,004,275,694
Radford University	81	$502,949,429
Central Virginia Training Center	87	$289,477,157
Virginia Military Institute	71	$225,240,869
Total	**783**	**$3,292,684,047**

Critical Facility Risk

Risk for critical facilities was calculated in the same fashion as mentioned above for state facilities. Approximately 27% of critical facilities are in regions with some karst geology. Table 3.14-4 shows the distribution of risk, by karst type. Schools and emergency response represent the majority of critical facilities in potential land subsidence areas. Annualized loss estimates were not calculated for critical facilities due to the scale of available karst mapping, limited information on mapped critical facilities, and the lack of probabilities of future occurrences.

Table 3.14-4: Critical facilities by karst zone

Karst Type	Law Enforcement	Transportation	Public Health	Emergency Response	Education	Total
Fissures, tubes, and caves over 1,000 ft. (300 m) long; 50 ft. (15 m) to over 250 ft. (75 m) vertical extent; in moderately to steeply dipping beds of carbonate rock.	123	6	178	395	384	**1,086**
Fissures, tubes and caves generally less than 1,000 ft. (300 m) long; 50 ft. (15 m) or less vertical extent; in metamorphosed limestone, dolostone, and marble	7	3	16	38	34	**98**
Fissures, tubes and caves generally less than 1,000 ft. (300 m) long; 50 ft. (15 m) or less vertical extent; in moderately to steeply dipping beds of carbonate rock.	12	1	20	43	40	**116**
Total	**142**	**10**	**214**	**476**	**458**	**1,300**

Karst Risk to Energy Pipelines

Pipeline infrastructure, underlain by karst terrain, can be damaged by a collapse in the supporting soil.

Jurisdictional Risk

In order to compare different hazards based on a common system, inputs for karst were very limited as a result of no recorded NCDC events for historical land subsidence. To be able to include karst in the risk assessment some general assumptions were made. Geographical Extent, using USGS Karst Topography maps, was the primary basis for establishing risk and was calculated as a percent of the jurisdictional area. In lieu of probability of future occurrence areas with more karst were assumed to be at greater risk.

The hazard ranking for karst is based on events reported in the NCDC Storm Events database and a generalized geographic extent. These parameters in the karst risk assessment are illustrated in Figure 3.14-2, along with the total ranking. There are currently no karst related records in NCDC; as a result, the lowest ranking score (1) was assigned to the annualized data for events, damages, and deaths and injuries to be able to compare karst to the other hazards, as described in section 3.5.

Jurisdictions ranked as high risk for Virginia include:

- City of Harrisonburg
- City of Winchester
- City of Roanoke
- Roanoke County

Communities in the Valley and Ridge province have a large percent of karst geology and therefore have a higher risk associated with them. Many of these areas also have an extensive history of sinkhole development. The jurisdictions identified at higher risk are urbanized areas in the Western, more mountainous parts of the state.

Local Plan Risk Assessment

Local plans were reviewed for spatial data sources used, historical occurrences, hazard probabilities, vulnerability, loss estimations, and land use and development trends. When available, this information supplements the text and figures of each of the sections in this revision.

One of the twenty-five local plans estimated loss due to land subsidence as negligible (less than $1,000). The remaining twenty-four local plans did not provide loss estimates for land subsidence. Of the plans that provided a general description of karst, some of them intersected U.S. Census data with the USGS karst zones to estimate the population located within a karst zone. The overall consensus in the local plan is that there is no way to estimate potential damages.

Comparison with Local Ranking

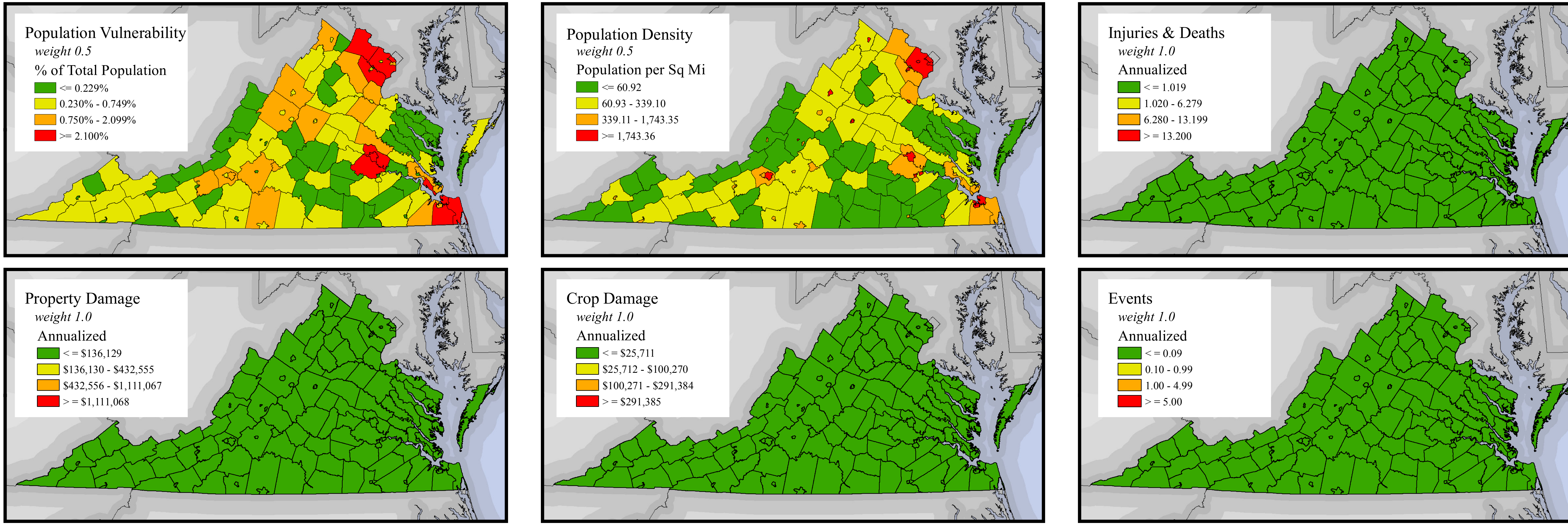
No local plans ranked karst as a high hazard. Central Shenandoah Valley PDC (made up of Augusta County, Bath County, Highland County, Rockbridge County, Rockingham County, City of Buena Vista, Lexington City, Harrisonburg City, Staunton City, and Waynesboro City) ranked karst as a medium hazard for their region.

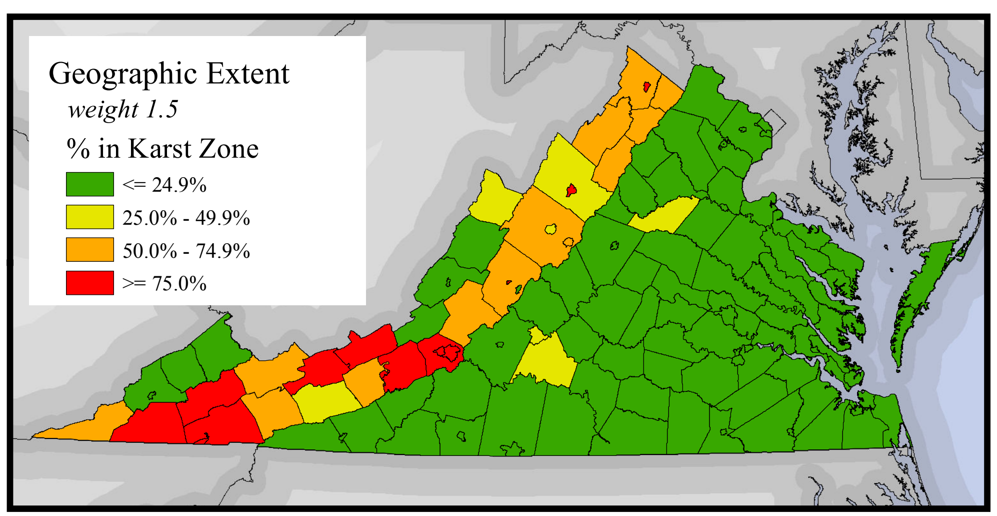
Two plans ranked karst as a medium-low hazard and ten additional plans ranked karst as a low hazard, resulting in a local plan average of low for karst (section 3.6). Eleven plans did not consider karst in their risk assessment. The 2013 statewide analysis also has ranked karst as low and is consistent in that regard with the local plans. Section 3.6 (Table 3.6-2) includes the complete ranking of all the local plans.

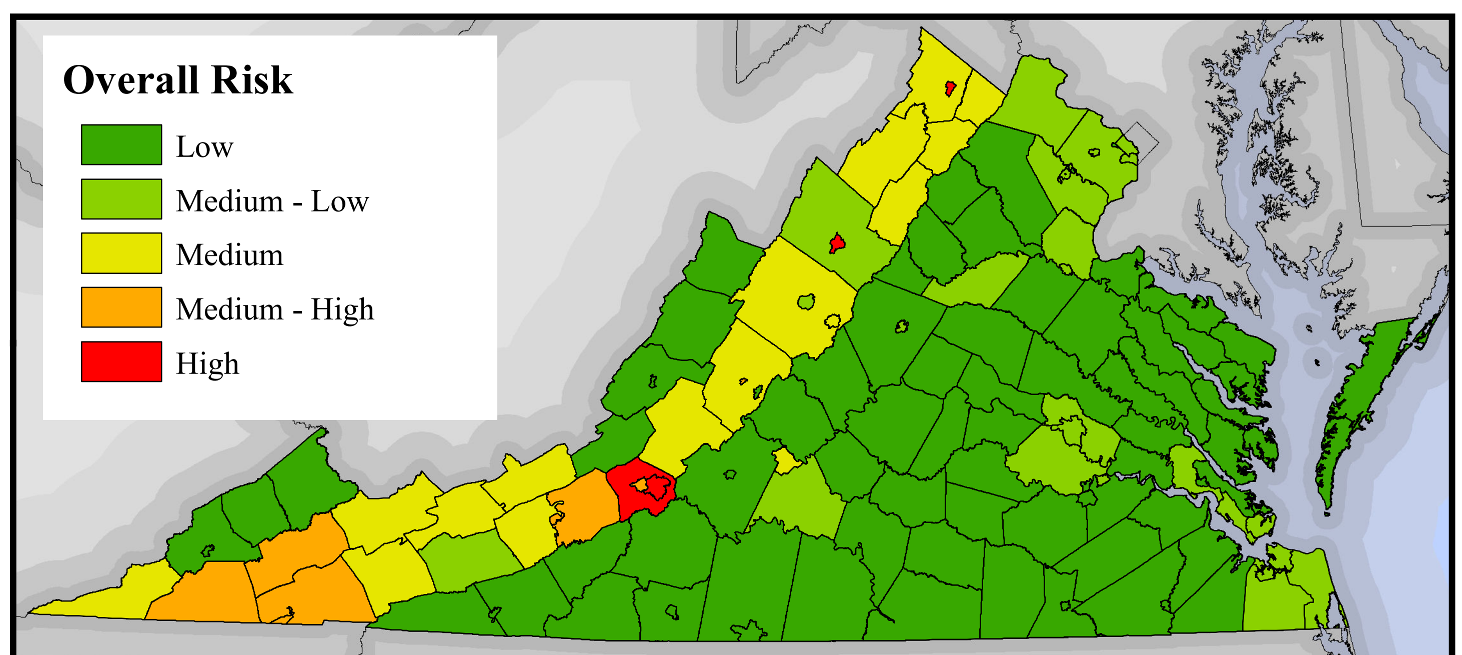
Changes in Development

The majority of local plans did not specifically address changes in development for each hazard or the effects of changes in development on loss estimates. In most cases overall development patterns were discussed in general. Sixteen of the twenty-five local plans cite their comprehensive plans for current and future land use changes (section 3.2). A few plans exclusively noted that they have zoning ordinances related to sinkhole development or they have mitigation actions to address these in the future.

Figure 3.14-3: Karst Hazard Ranking Parameters and Risk Map







HAZARD RANKING:

A number of factors have been considered in this risk assessment to be able to compare between jurisdictions and hazards. The factors have been added together to come up with the overall total ranking for each hazard.
Some factors were weighted based on imput from the HIRA sub-committee.
Section 3.5 explains each of the factors in detail.

Factors & Weighting Include:
- Population Vulnerability & Density 0.5 weighting
- Injuries & Deaths 1.0 weighting
- Crop & Property Damage 1.0 weighting
- Annualized Events 1.0 weighting
- Geographic Extent 1.5 weighting

DATA SOURCES:

CGIT Ranking Methodology
VGIN Jurisdictional Boundaries
ESRI State Boundaries

PROJECTION: *VA Lambert Conformal Conic*
North American Datum 1983

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Table 3.14-5: EMAP Analysis

Subject	Detrimental Impacts
Health and Safety of Public	Localized impacts are expected to be moderate to severe in the impact area.
Health and Safety of Response Personnel	Limited unless sinkhole involves broken utility lines.
Continuity of Operations	Limited, unless a facility is impacted
Property, Facilities, and Infrastructure	Depending on the magnitude of the event, localized impact to facilities, residential properties, and infrastructure in the area of the event could be severe.
Delivery of Services	Localized disruption of roads, facilities, communications and/or utilities caused by the event may postpone the delivery of some services.
The Environment	Localized impacts expected to be moderate for the impacted areas. Always a potential for utility line breaks.
Economic and Financial Condition	Limited. Depending on the magnitude of the event, local economy and finances may be impacted.
Public Confidence in the Jurisdiction's Governance	Localized impacts expected to cause property owners confidence in state and local land use/development policies to waiver.

*****_Table was modeled from the Missouri State Hazard Mitigation Plan_