4.3.13. Subsidence, Sinkhole

4.3.13.1. Location and Extent

There are two common causes of subsidence in Pennsylvania: 1) dissolution of carbonate rock such as limestone or dolomite and 2) mining activity. In the first case, water passing through naturally occurring fractures and bedding planes dissolves bedrock leaving voids below the surface. Eventually, overburden on top of the voids collapses, leaving surface depressions resulting in karst topography. Characteristic structures associated with karst topography include sinkholes, linear depressions and caves. Often, sub-surface solution of limestone will not result in the immediate formation of karst features. Collapse sometimes occurs only after a large amount of activity, or when a heavy burden is placed on the overlying material.

Figure 4.3.13-1shows the distribution of limestone bedrock across Pennsylvania along with locations of known subsidence and sinkhole events as inventoried by DCNR. Thick sequences of structurally deformed carbonates comprise the surface bedrock of a sizable area in central, south-central and southeastern Pennsylvania. The carbonate rock formations, which are Cambrian through Devonian in age, have developed karst landforms, resulting in significant land-subsidence problems. Common sinkhole locations in Pennsylvania include the Saucon Valley of Lehigh County, the greater Harrisburg metropolitan area in Dauphin and Cumberland Counties, and the Nittany Valley in Blair, Centre, and Clinton Counties.

DCNR created a series of maps showing the density of identified karst features across south-central and eastern Pennsylvania (see Figure 4.3.13-2 for example). Karst features are defined as pockets of limestone or dolomite bedrock located within more stable geological formations that could cause subsidence or sinkholes. The density of karst features ranges from 0 to 600 features per square mile with wide variations in size. Fewer karst features have been mapped in existing urban areas; however, this is likely a result of development activities that disguise, cover, or fill existing features rather than an absence of the features themselves (PADCNR, 2003).

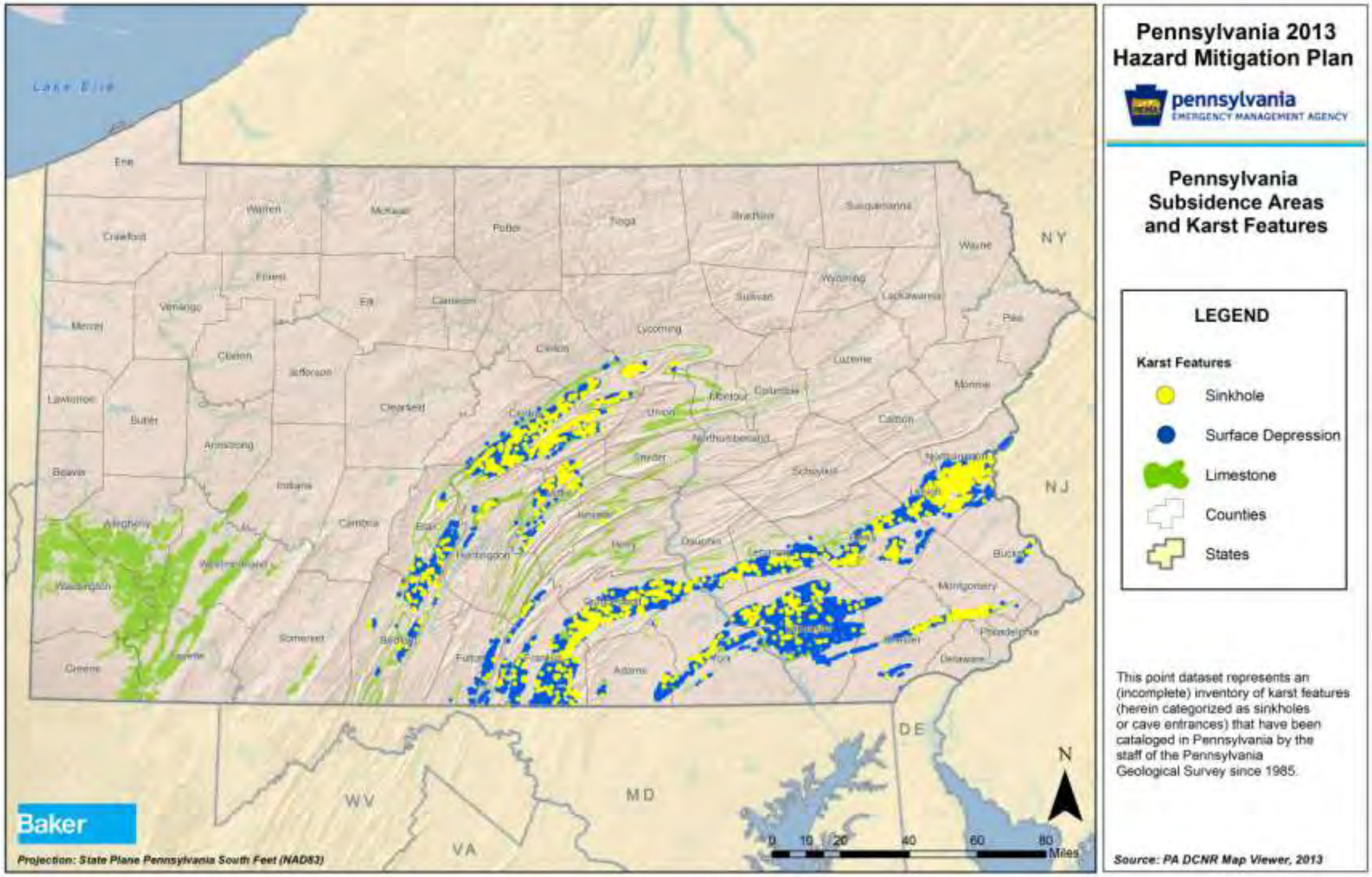
Human activity can also result in subsidence or sinkhole events. Leaking water pipes or structures that convey storm-water runoff may also result in areas of subsidence as the water dissolves substantial amounts of rock over time. Poorly managed stormwater has particularly been an exacerbating factor in subsidence events in Cumberland County, Lebanon County, and Palmyra. In some cases, construction, land grading or earthmoving activities that cause changes in stormwater flow can trigger sinkhole events.

Subsidence or sinkhole events may also occur in the presence of mining activity, even in areas where bedrock is not necessarily conducive to their formation. Sub-surface (i.e. underground) extraction of materials such as oil, gas, coal, metal ores (i.e. copper, iron, and zinc), clay, shale, limestone, or water may result in slow-moving or abrupt shifts in the ground surface.

Sinkholes generally develop where the cover above a mine is thin. Piggott and Eynon (1978) indicated that sinkhole development normally occurs where the interval to the ground surface is less than three to five times the thickness of the extracted seam and the maximum interval is up to ten times the thickness of the extracted seam. In western Pennsylvania, most sinkholes develop where the soil and rock above a mine are less than fifty feet thick (Bruhn et al., 1978).

A study of subsidence in the Pittsburgh area revealed that the majority of sinkholes, which constituted about 95% of all reported subsidence incidents, occurred on sites located less than sixty feet above mine level (Bruhn et al., 1981). This profile focuses most on karst-related subsidence and sinkholes; for more information on mine-related subsidence and sinkholes, see Section 4.3.19.

Figure 4.3.13-1 Map showing areas of Pennsylvania subject to natural subsidence due to the presence of limestone bedrock. Inventoried surface depression and sinkhole locations are also shown.

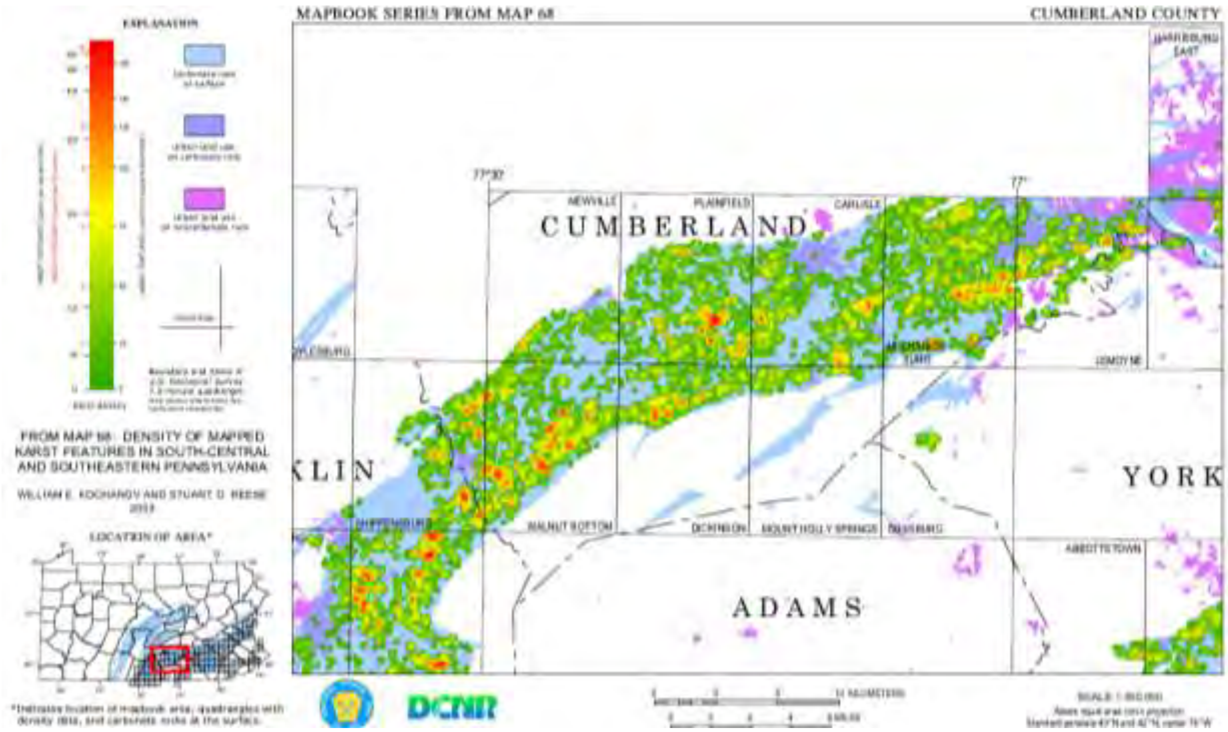


This point dataset represents an (incomplete) inventory of karst features (herein categorized as sinkholes or cave entrances) that have been cataloged in Pennsylvania by the staff of the Pennsylvania Geological Survey since 1985.

Projection: State Plane Pennsylvania South Feet (NAD83)

Source: PA DCNR Map Viewer, 2013

Figure 4.3.13-2 Example of map showing density of karst features in Cumberland County. An index map showing the coverage of the inventory is also provided.



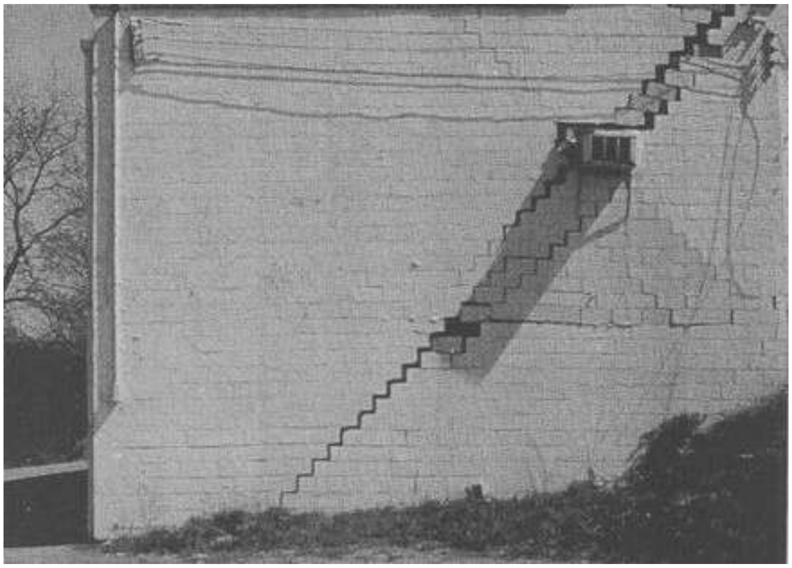
4.3.13.2. Range of Magnitude

No two subsidence areas or sinkholes are exactly alike. Variations in size and shape, time period under which they occur (i.e. gradually or abruptly), and their proximity to development ultimately determines the magnitude of damage incurred. Events could result in minor elevation changes or deep, gaping holes in the ground surface. Subsidence and sinkhole events can cause severe damage in urban environments, although gradual events can be addressed before significant damage occurs. Primarily, problems related to subsidence include the disruption of utility services and damages to private and public property including buildings, roads, and underground infrastructure. Figure 4.3.12-3 provides examples of the damage that can occur as a result of these events. If long-term subsidence or sinkhole formation is not recognized and mitigation measures are not implemented, fractures or complete collapse of building foundations and roadways may result. If mitigation measures are not taken, the cost to fill in and stabilize sinkholes can be significant although sinkholes are limited in extent. The 1994 event in Allentown (see top-left image in Figure 4.3.13-3) is one of the worst-case known events in Pennsylvania. Damage to the Corporate Plaza Building was significant, but dollar information is unknown.

Figure 4.3.13-3 Example of damage which can occur as a result of abrupt sinkhole and long-term subsidence events.

Sinkhole at Corporate Plaza Building in Allentown, Lehigh County, PA in February, 1994 (Photograph by *William E. Kochanov*. PADCNR, 2009).

Sinkhole in Dauphin County has exposed a utility pipeline (Kochanov, 1999).



Building damage as a result of subsidence in western Pennsylvania. An abandoned mine is located approximately 175 feet below the ground surface. The source of this photograph is unknown.

4.3.13.3. Past Occurrence

DCNR provides an online inventory of sinkholes which lists 3,619 sinkholes which have been identified across Pennsylvania – a 26% increase in sinkholes from what was reported in the 2010 SSAHMP. The distribution of these sinkholes by county is provided in Table 4.3.13-1. Note that some of these sinkholes have been filled. This inventory represents best available information at the state-wide level. The fact that no sinkholes are identified does not necessarily mean there are no sinkholes or historical subsidence hazards in a given county. For instance, Westmoreland County has 5 sinkholes identified in their County HMP, even though they do not have any sinkholes identified by DCNR. Additionally, PA DEP staff indicated that small sinkholes occur several times per week and cause limited damage; many of these are related to failing infrastructure like water main breaks or collapsed pipes.

Table 4.3.13-1 Summary of sinkholes identified in the Pennsylvania (PA DCNR, 2013)

COUNTY	NO. OF SINKHOLES	COUNTY	NO. OF SINKHOLES
Adams	31	Lackawanna	none identified
Allegheny	none identified	Lancaster	159
Armstrong	none identified	Lawrence	none identified
Beaver	none identified	Lebanon	129
Bedford	55	Lehigh	470
Berks	211	Luzerne	none identified
Blair	55	Lycoming	70
Bradford	none identified	McKean	none identified
Bucks	9	Mercer	none identified
Butler	none identified	Mifflin	176
Cambria	none identified	Monroe	none identified
Cameron	none identified	Montgomery	131
Carbon	none identified	Montour	*not provided*
Centre	546	Northampton	677
Chester	50	Northumberland	none identified
Clarion	none identified	Perry	none identified
Clearfield	none identified	Philadelphia	none identified
Clinton	75	Pike	none identified
Columbia	none identified	Potter	none identified
Crawford	none identified	Schuylkill	none identified
Cumberland	366	Snyder	none identified
Dauphin	48	Somerset	none identified
Delaware	none identified	Sullivan	none identified
Elk	none identified	Susquehanna	none identified
Erie	none identified	Tioga	none identified
Fayette	none identified	Union	none identified
Forest	*not provided*	Venango	none identified
Franklin	260	Warren	none identified
Fulton	5	Washington	none identified
Greene	none identified	Wayne	none identified
Huntingdon	27	Westmoreland	none identified
Indiana	none identified	Wyoming	none identified
Jefferson	none identified	York	60
Juniata	9	***TOTAL***	***3,619***

4.3.13.4. Future Occurrence

Based on geological conditions and current mining activity in Pennsylvania, the annual occurrence of subsidence and sinkhole events in areas of the Commonwealth underlain by carbonate rock or where mining occurs is considered *likely* as defined by the Risk Factor Methodology (see Section 4.1).

4.3.13.5. Environmental Impacts

The presence of sinkholes can result in increased potential for groundwater contamination. Due to their porous nature, sinkholes are sometimes used as instruments for enhancing groundwater recharge. However, if hazardous materials are spilled at a recharge point, groundwater can quickly be contaminated due to the lack of soil substrate which normally would slow migrating contaminants. Vegetation is usually damaged during abrupt subsidence events. However, re-growth takes place over time.

4.3.13.6. Jurisdictional Vulnerability Assessment

The northeast-trending valleys of the Ridge and Valley province are more desirable than adjacent ridges as sites for homes, farms, industry, and transportation routes. The residual soil in these valleys is excellent for agriculture, and, in many places, the carbonate rock is a valuable mineral resource and is a host rock for some metallic ore deposits. However, these areas are where most subsidence events occur.

Municipal governments determine guidelines for construction in high-subsidence areas. A community can reduce its vulnerability to subsidence or sinkholes by implementing solutions such as land use controls, insurance programs, subsidence-resistant designs, or in the case of mine-related subsidence, conduct selective support or mine filling. If a sinkhole occurs on private property, it is normally the responsibility of the property owner to initiate repairs. Homeowners’ insurance often does not cover damages attributed to sinkholes. Since 1987, sinkhole insurance has been available within Pennsylvania and may serve to eliminate the financial burdens placed on the homeowner.

Careful planning is the least-costly and most effective method for reducing vulnerability to subsidence hazards. Municipalities could minimize the potential for sinkhole development through proper maintenance and updating of water utility lines. Zoning laws can also be enacted to regulate development within highly karst areas.

The Surface Mining Control and Reclamation Act of 1977 imposes land use controls on active mines. This law requires an evaluation of whether subsidence could occur and cause material damage or diminution of use of structures or renewable resource lands. If there is potential for damage, a plan to prevent or mitigate the damage is required.

As stated in Section 4.2.2, jurisdictional and state critical facility vulnerability assessments were completed by spatially overlaying hazards with census tracts and state critical facility layers in GIS. When spatial analysis determined that the hazard would impact a census tracts within a county or the location of state critical facilities these locations where deemed vulnerable to the hazard. Loss estimates were prepared based on the value of the facilities impacted by census tract and by state critical facility. Each hazard uses a methodology that is specific to the type of risk it may cause; Table 4.2.2-2 includes a complete methodology description for vulnerability assessments and loss estimates for each hazard.

Since natural subsidence and sinkhole events occur when the predominant bedrock type is limestone, the 37 Pennsylvania counties that that are located on top of these limestone areas are vulnerable to subsidence and sinkhole occurrences. Risk to mining-related subsidence are discussed in Section 4.3.19: Environmental Hazards. Additionally, subsidence and sinkholes are an identified hazard in 38 county hazard mitigation plans, shown in Table 4.3.13-2. As stated in Section 4.1, the decision by a county to profile a hazard is one indicator of the presence of risk from that hazard. This indicator should be viewed complementary to other analysis in this section. Together this analysis from reputable sources addresses different aspects of risk for a full risk profile.

Of the 19 counties which currently have calculated risk factor values for Subsidence/Sinkholes, the average value is 1.7; this average does not include Lebanon, Montour, Perry, and Philadelphia, who use an alternate Risk Factor/Ranking system. The State Risk Factor for Subsidence/Sinkhole is 1.7, and the Pennsylvania THIRA does not evaluate this hazard. For more details on the State Risk Factor and THIRA rankings, please see Section 4.1.

Table 4.3.13-2 Counties profiling subsidence/sinkhole hazards with hazard ranking and risk factor (if available).

COUNTY	PROFILED HAZARD	DID NOT PROFILE HAZARD	RANKING (IF AVAILABLE)	RISK FACTOR (IF AVAILABLE)
Adams		X		
Allegheny	X		Medium	2.1
Armstrong	X		Not Ranked	No RF
Beaver		X		
Bedford	X		Low	1.3
Berks	X		Not Ranked	No RF
Blair		X		
Bradford		X		
Bucks	X		Low	1.3
Butler	X		Low	1.3
Cambria	X		Low	1.3
Cameron	X		Medium	2.2
Carbon		X		
Centre	X		Low	1.8
Chester		X		
Clarion	X		Not Ranked	No RF
Clearfield		X		
Clinton		X		
Columbia		X		
Crawford		X		

Table 4.3.13-2 Counties profiling subsidence/sinkhole hazards with hazard ranking and risk factor (if available).

COUNTY	PROFILED HAZARD	DID NOT PROFILE HAZARD	RANKING (IF AVAILABLE)	RISK FACTOR (IF AVAILABLE)
Cumberland	X		High	2.6
Dauphin	X		Not Ranked	No RF
Delaware	X		Low	1.6
Elk		X		
Erie		X		
Fayette	X		High	2.5
Forest		X		
Franklin	X		Not Ranked	No RF
Fulton		X		
Greene	X		Low	1.3
Huntingdon		X		
Indiana		X		
Jefferson	X		Low	1.8
Juniata		X		
Lackawanna	X		Not Ranked	No RF
Lancaster	X		Low	1.8
Lawrence	X		Low	1.3
Lebanon*	X		Not Ranked	2.8
Lehigh	X		Low	1.4
Luzerne	X		Not Ranked	No RF
Lycoming		X		
McKean	X		Low	1.8
Mercer	X		Low	1.3
Mifflin		X		
Monroe		X		
Montgomery	X		Medium	2.0
Montour*	X		Not Ranked	8.8
Northampton	X		Low	1.4
Northumberland	X		Low	1.6
Perry*	X		Not Ranked	8.4
Philadelphia**		X		
Pike		X		
Potter	X		Not Ranked	No RF

Table 4.3.13-2 Counties profiling subsidence/sinkhole hazards with hazard ranking and risk factor (if available).

COUNTY	PROFILED HAZARD	DID NOT PROFILE HAZARD	RANKING (IF AVAILABLE)	RISK FACTOR (IF AVAILABLE)
Schuylkill	X		Not Ranked	No RF
Snyder	X		Low	1.3
Somerset		X		
Sullivan	X		Not Ranked	No RF
Susquehanna		X		
Tioga	X		Medium	2.1
Union		X		
Venango		X		
Warren		X		
Washington	X		Not Ranked	No RF
Wayne		X		
Westmoreland	X		Not Ranked	No RF
Wyoming	X		Not Ranked	No RF
York	X		Low	1.8

* Lebanon, Montour, and Perry use an alternate weighted ranking where Risk Factor = Frequency x [(0.25 x Critical facilities) + (0.40 x Social) + (0.25 x Economic) + (0.10 x Environmental)]. While this risk factor was used to comparatively rank hazards, the number does not correspond to a high-medium-low rating.

**Philadelphia uses an A, B, C rating system where A is high, B is medium, and C is low.

As seen in Table 4.3.13-3, Allegheny, Lancaster, and Westmoreland Counties have the most critical facilities potentially impacted by subsidence and sinkhole events. Of the vulnerable counties, Somerset, Montour, and Indiana Counties have the fewest vulnerable critical facilities. These counties have localized limestone and thus are not likely to experience widespread subsidence and sinkhole incidents.

Table 4.3.13-3 Number of State Critical Facilities impacted by subsidence and sinkholes in each county

COUNTY	NUMBER OF CRITICAL FACILITIES	COUNTY	NUMBER OF CRITICAL FACILITIES
Adams	5	Lancaster	65
Allegheny	166	Lebanon	41
Bedford	10	Lehigh	19
Berks	24	Luzerne	3
Blair	8	Lycoming	6
Centre	24	Mifflin	11
Chester	13	Montgomery	9

Table 4.3.13-3 Number of State Critical Facilities impacted by subsidence and sinkholes in each county

COUNTY	NUMBER OF CRITICAL FACILITIES	COUNTY	NUMBER OF CRITICAL FACILITIES
Clinton	12	Montour	2
Columbia	3	Northampton	3
Cumberland	31	Northumberland	4
Dauphin	33	Perry	3
Fayette	46	Snyder	9
Franklin	23	Somerset	2
Greene	8	Union	11
Huntingdon	7	Washington	57
Indiana	2	Westmoreland	106
Juniata	14	York	23

4.3.13.7. *State Facility Vulnerability Assessment*

As is the case with jurisdictional vulnerability, the state critical facilities that are vulnerable to subsidence and sinkholes are those that are located on top of limestone features. A total of 803 state critical facilities are vulnerable to subsidence and sinkhole events. Table 4.3.13-5 shows number of impacted state critical facilities by facility type.

Table 4.3.13-4 State Critical Facilities vulnerable to subsidence and sinkholes by critical facility type

STATE CRITICAL FACILITY TYPE	NUMBER OF IMPACTED FACILITIES
Agriculture	25
Banking	5
Chemical	1
Commercial Facilities	5
Defense Industrial Base	3
Education	13
Emergency Services	14
Energy	4
Fire Departments (Non-HSIP)	315
Government Facilities	3
Healthcare & Public Health	7
Hospital (Non-HSIP)	31
Nuclear Reactors, Materials & Waste	2
Police (Non-HSIP)	141
Postal & Shipping	1
School (Non-HSIP)	224
Transportation	7
Water	2
Grand Total	**803**

4.3.13.8. Jurisdictional Loss Estimation

As stated in Section 4.3.9.6, loss estimates were prepared based on the sum of the number and value of buildings in Census tracts located over limestone bedrock features, aggregated to the county level. Subsidence and sinkholes have the potential to affect 811,610 structures in the Commonwealth with over $195 billion in exposed buildings and contents (Table 4.3.13-5). Of course, not every one of the buildings in a given Census tract or jurisdiction is situated above limestone feature, but those that are could face serious damage. Of the jurisdictions vulnerable to subsidence and sinkholes, Allegheny is the most threatened with over $45 billion in building and contents in vulnerable areas.

Table 4.3.13-5 Estimated jurisdictional losses due to subsidence and sinkholes.

COUNTY	NUMBER OF IMPACTED BUILDINGS	DOLLAR VALUE OF EXPOSURE, BUILDING AND CONTENTS (THOUSANDS $)
Adams	11,030	$2,796,552.00
Allegheny	199,520	$45,739,650.00
Armstrong	2,988	$544,578.00
Beaver	3,541	$1,006,299.00
Bedford	4,143	$753,288.00
Berks	20,698	$5,130,937.00
Blair	8,666	$1,776,558.00
Bucks	4,240	$1,723,745.00
Centre	22,407	$4,377,024.00
Chester	3,762	$839,760.00
Clinton	5,664	$1,149,047.00
Cumberland	52,800	$13,972,904.00
Dauphin	13,181	$3,030,111.00
Fayette	23,705	$4,629,062.00
Franklin	39,166	$8,776,732.00
Greene	8,163	$1,470,011.00
Huntingdon	5,044	$1,199,487.00
Indiana	2,542	$440,090.00
Lancaster	98,965	$24,671,808.00
Lebanon	20,091	$4,561,648.00
Lehigh	15,786	$4,704,857.00
Luzerne	2,936	$625,198.00
Lycoming	3,774	$826,940.00
Mifflin	9,285	$1,811,008.00
Montgomery	15,776	$5,160,135.00
Northampton	26,513	$8,959,584.00
Northumberland	5,409	$1,210,663.00
Perry	1,954	$325,491.00
Snyder	5,053	$1,273,737.00
Union	11,639	$2,749,797.00
Washington	59,930	$14,110,389.00
Westmoreland	67,947	$16,314,747.00
York	35,292	$8,531,820.00

Subsidence repair or preemptive mitigation can be quite costly for local communities. Areas that have already undergone development have special problems in re-design and re-construction. After-the-fact methods of subsidence repair are often expensive and offer no guarantee that the problem will not re-occur. Sinkhole repair for Vera Cruz Road in Lehigh County cost nearly $80,000, and a new sinkhole opened, just outside the repair area, within six months.

Bruhn et al. (1978) reported in a study of the Pittsburgh coal, that annual costs for remedial measures and repairs were $438,000. This estimate does not include the cost of damage to commercial structures, utilities, or transportation rights-of-way, and the cost of engineering and construction measures undertaken to prevent or minimize subsidence damage.

In a study of damage from active mining in western Pennsylvania, Bruhn et al. (1982) reported that home repair costs (measured in 1981 dollar values) ranged from a few hundred dollars to more than $100,000. The median repair cost was $6,000 to $10,000 per home.

4.3.13.9. State Facility Loss Estimation

Of the 1,263 vulnerable critical facilities, 83 do not have replacement values; these facilities are largely private entities. The estimated replacement cost of all state critical facilities with replacement values located in areas susceptible to natural subsidence and sinkhole hazard zones is $6,262,828,204. Actual losses may be lower because special regulations have been established at the state level for the construction of certain facilities (e.g. sanitary landfills).

4.3.14. Tornado, Windstorm

4.3.14.1. Location and Extent

Both tornado and windstorm events can occur throughout Pennsylvania. Tornado events are usually localized. However, severe thunderstorms may result in conditions favorable to the formation of numerous or long-lived tornadoes. Tornadoes can occur at any time during the day or night, but are most frequent during late afternoon into early evening, the warmest hours of the day, and most likely to occur during the spring and early summer months of March through June. Tornado movement is characterized in two ways: direction and speed of spinning winds and forward movement of the tornado, also known as the storm track. Most tornadoes have wind speeds of 110 mph (175 km/h) or less, are approximately 250 feet (75 m) across, and travel a few miles (several kilometers) before dissipating. Some attain wind speeds of more than 300 mph (480 km/h), stretch more than a mile (1.6 km) across, and stay on the ground for dozens of miles (more than 100 km). Some tornadoes never touch the ground and are short-lived, while others may touch the ground several times.

Straight-line winds and windstorms are experienced on a region-wide scale. While such winds usually accompany tornadoes, straight-lined winds are caused by the movement of air from areas of higher pressure to areas of lower pressure. Stronger winds are the result of greater differences in pressure. Windstorms are generally defined with sustained wind speeds of 40 mph or greater lasting for one hour or longer, or winds of 58 mph or greater for any duration. Wind events can vary in spatial size from small microscale events which take place over only a few hundred meters to large-scale synoptic wind events often associated with warm or cold fronts.