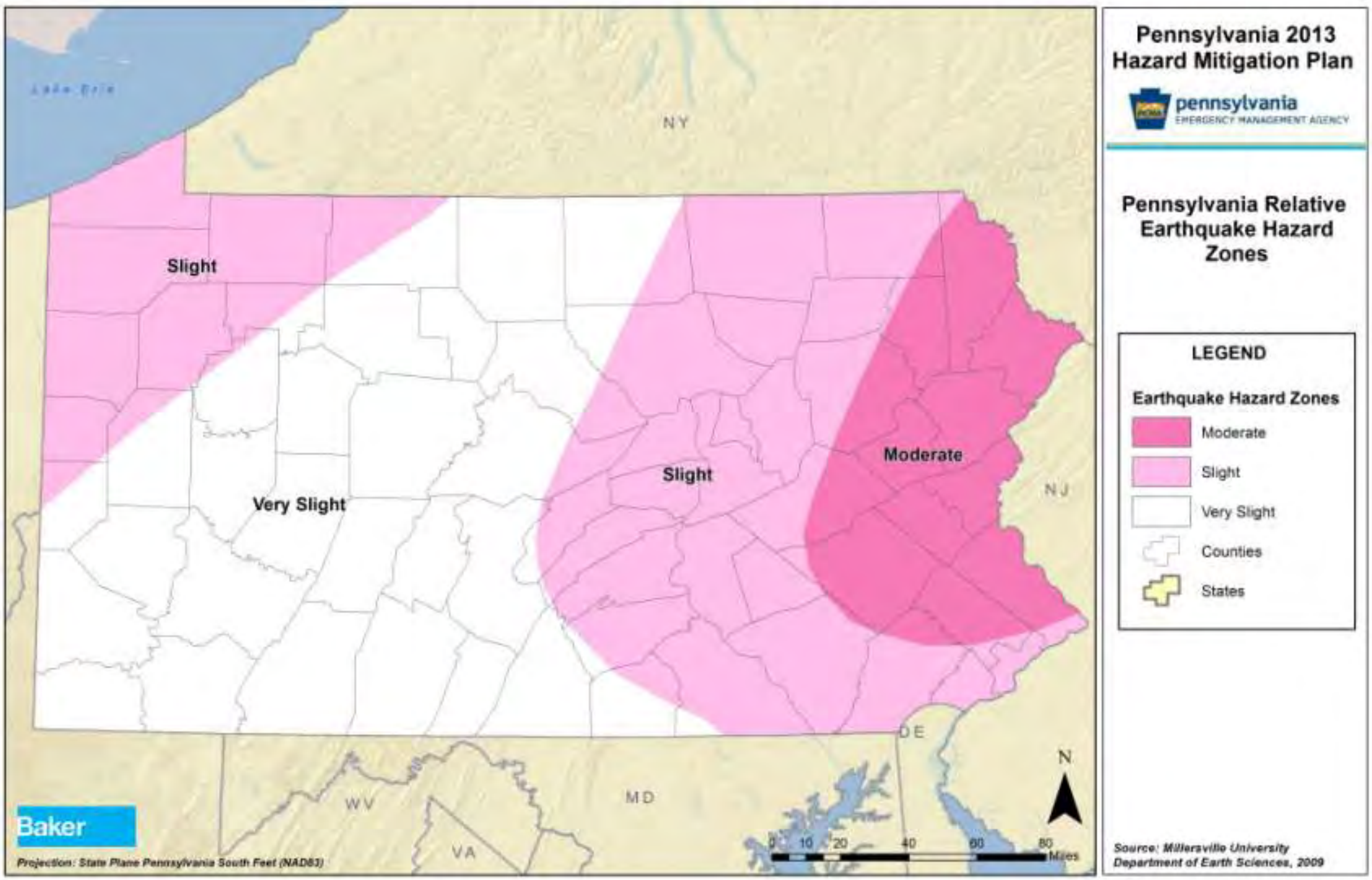
4.3.3. Earthquake

4.3.3.1. Location and Extent

Earthquake events in Pennsylvania typically do not impact areas greater than 100 km from the epicenter. Pennsylvania's strongest earthquakes with in-state epicenters have persistently occurred in an area near Lancaster, PA (Armbruster and Scharnberger, 1986; Armbruster and Seeber, 1987). Earthquakes originating from outside Pennsylvania, can also impact the Commonwealth, as was the case with a magnitude 5.8 earthquake in Virginia in August 2011 (see Section 4.3.3.3). Figure 4.3.3-1 shows the relative earthquake hazard zones in Pennsylvania identified by the Department of Earth Sciences at Millersville University. According to this map, earthquake hazards are "very slight" for most of the central to western portions of the Commonwealth. Eastern sections of Pennsylvania are in a moderate earthquake hazard zone.

Figure 4.3.3-1 Relative earthquake hazard zones of Pennsylvania (Millersville University Department of Earth Sciences, 2009).



Few precise data exist with regard to the focal depths of Pennsylvania earthquakes. The only reliable instrumental data, which comes from close-in studies of aftershocks in Lancaster County, indicate an average focal depth of about 3 miles. In Figure 4.3.3-2, some of the shocks that have relatively high epicentral intensities were felt over anomalously small areas, suggesting that these events were very shallow.

4.3.3.2. Range of Magnitude

Earthquake magnitude is often measured using the Richter Scale, an open-ended logarithmic scale that describes the energy release of an earthquake. Table 4.3.3-1 summarizes Richter Scale magnitudes as they relate to the spatial extent of impacted areas. Based on historical events, earthquakes in the Pennsylvania region have not exceeded magnitudes greater than 6.0.

Table 4.3.3-1 Richter scale magnitudes and associated earthquake size effects.

RICHTER MAGNITUDES	EARTHQUAKE EFFECTS
Less than 3.5	Generally not felt, but recorded.
3.5-5.4	Often felt, but rarely causes damage.
Under 6.0	At most, slight damage to well-designed buildings; can cause major damage to poorly constructed buildings over small regions.
6.1-6.9	Can be destructive up to about 100 kilometers from epicenter.
7.0-7.9	Major earthquake; can cause serious damage over large areas.
8.0 or greater	Great earthquake; can cause serious damage in areas several hundred kilometers across.

The impact an earthquake event has on an area is typically measured in terms of earthquake intensity. Intensity is most commonly measured using the Modified Mercalli Intensity (MMI) Scale based on direct and indirect measurements of seismic effects. A detailed description of the Modified Mercalli Intensity Scale is shown in Table 4.3.3-2. The earthquakes that occur in Pennsylvania originate deep with the Earth's crust; not on an active fault. Therefore, little or no damage is typically expected.

Table 4.3.3-2 Modified Mercalli Intensity Scale with associated impacts.

SCALE	INTENSITY	DESCRIPTION OF EFFECTS	CORRESPONDING RICHTER SCALE MAGNITUDE
I	**Instrumental**	Usually detected only on seismographs.	<4.2
II	**Feeble**	Felt only by a few persons at rest, especially on upper floors of buildings.	
III	**Slight**	Felt quite noticeably indoors, especially on upper floors. Most people don't recognize it as an earthquake (i.e. a truck rumbling).	
IV	**Moderate**	Can be felt by people walking; dishes, windows, and doors are disturbed.	
V	**Slightly Strong**	Sleepers are awoken; unstable objects are overturned.	<4.8

Table 4.3.3-2 Modified Mercalli Intensity Scale with associated impacts.

SCALE	INTENSITY	DESCRIPTION OF EFFECTS	CORRESPONDING RICHTER SCALE MAGNITUDE
VI	**Strong**	Trees sway; suspended objects swing; objects fall off shelves; damage is slight.	<5.4
VII	**Very Strong**	Damage is negligible in buildings of good design and construction, slight to moderate in well-built ordinary structures, and considerable in poorly built or badly designed structures; some chimneys are broken.	<6.1
VIII	**Destructive**	Damage is slight in specially designed structures; considerable in ordinary, substantial buildings. Moving cars become uncontrollable; masonry fractures, poorly constructed buildings damaged.	<6.9
IX	**Ruinous**	Some houses collapse, ground cracks, pipes break open; damage is considerable in specially designed structures; buildings are shifted off foundations.	
X	**Disastrous**	Some well-built wooden structures are destroyed; most masonry and frame structures are destroyed along with foundations. Ground cracks profusely; liquefaction and landslides widespread.	<7.3
XI	**Very Disastrous**	Most buildings and bridges collapse, roads, railways, pipes and cables destroyed.	<8.1
XII	**Catastrophic**	Total destruction; trees fall; lines of sight and level are distorted; ground rises and falls in waves; objects are thrown upward into the air.	>8.1

The worst-case earthquake event to have occurred in Pennsylvania was the Pymatuning Earthquake in 1998 (see Section4.3.3.3 for event summary). However, a potential worst-case scenario would be if a magnitude 6.1 or stronger earthquake occurred near one of Pennsylvania's nuclear facilities, as was the case in the Fukushima Earthquake in Japan in April 2011. This earthquake triggered a tsunami and multiple fires, and it also triggered a major nuclear disaster at the Fukushima Daiichi Nuclear Facility. The nuclear disaster caused permanent damage to some of the facility's reactors and disabled the reactor cooling system, which led to releases of radioactivity and triggered a 30 km evacuation zone displacing 100,000 people (World Nuclear Association, 2011).

4.3.3.3. Past Occurrence

About 35 earthquakes have caused light damage in Pennsylvania since the beginning of the Colonial period. Occasional broken windows, cracked plaster, and glassware toppled from shelves have characterized this damage. Nearly one half of these damaging events had out-of-state epicenters. Foremost among the class of distant shocks that were felt strongly in Pennsylvania were a trio of major earthquakes near New Madrid, Mo., in 1811-12, and the Charleston, S. C., earthquake of 1886. More recently, a magnitude 5.8 earthquake with an epicenter in rural Louisa County, VA was felt throughout Pennsylvania, triggering evacuations, emergency bridge and tunnel inspections, and minor damage to buildings. This shallow earthquake occurring along the Spotsylvania Fault, was felt as far north as Ontario, Canada and as far south as Alabama.

Most earthquakes with epicenters inside Pennsylvania have been located in southeastern areas of the Commonwealth. However, the largest earthquake ever recorded in Pennsylvania was Pymatuning Earthquake which occurred on September 25, 1998. This earthquake had an epicenter in Jamestown, PA, near Pymatuning Lake, and measured a magnitude of 5.2 on the Richter Scale. Early damage reports suggested a maximum intensity of VI.

Figure 4.3.3-2 Map of earthquake epicenters in Pennsylvania (DCNR, 2004).

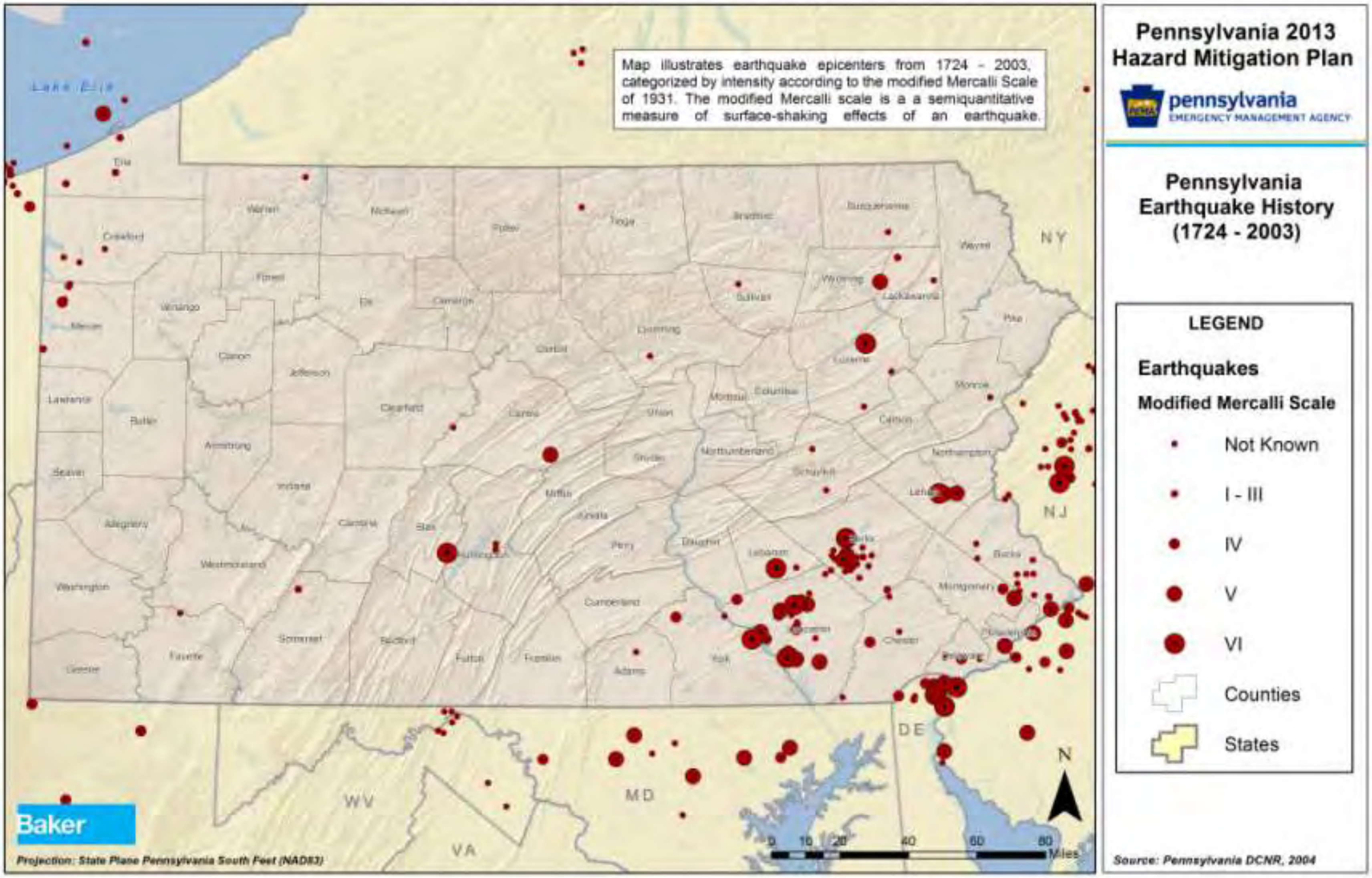


Table 4.3.3-3 Catalog of earthquakes with epicenters in Pennsylvania (DCNR, 2004).

DATE	NORTH LATITUDE (degrees)	WEST LONGITUDE (degrees)	MAGNITUDE	MAXIMUM INTENSITY	AREA (km^2)
08/16/1724	40.00	75.10	*unknown*	IV	*unknown*
12/19/1737	40.80	74.00	5.0	VII	200,000
12/17/1752	39.98	75.90	3.6	IV	*unknown*
11/27/1755	39.95	75.16	*unknown*	III	*unknown*
03/23/1758	39.95	75.16	*unknown*	III	*unknown*
03/22/1763	39.90	75.30	*unknown*	III	*unknown*
10/30/1763	40.00	75.10	*unknown*	IV	*unknown*
04/25/1772	39.95	75.16	*unknown*	II	*unknown*
11/22/1777	39.95	75.16	*unknown*	III	*unknown*
11/23/1777*	39.90	75.30	*unknown*	III	*unknown*
11/29/1780	39.95	75.16	*unknown*	III	*unknown*
01/11/1798	40.02	76.32	*unknown*	IV	*unknown*
03/17/1800	39.95	75.16	*unknown*	V	*unknown*
11/20/1800	40.12	76.39	4.1	V	*unknown*
11/29/1800	39.95	75.16	*unknown*	IV	*unknown*
01/27/1801	40.02	76.32	*unknown*	IV	*unknown*
11/12/1801	39.95	75.16	*unknown*	III	*unknown*
12/09/1811	39.95	75.16	*unknown*	III	*unknown*
12/16/1811*	39.95	75.16	*unknown*	III	*unknown*
03/19/1818	40.04	76.31	*unknown*	III	*unknown*
08/21/1820	40.03	76.50	3.4	V	*unknown*
05/04/1822	40.04	76.31	*unknown*	*unknown*	*unknown*
09/06/1829	40.04	76.31	*unknown*	III	*unknown*
02/05/1834	39.90	76.18	4.0	V	*unknown*
11/11/1840	40.00	75.10	*unknown*	V	*unknown*
11/14/1840*	39.95	75.16	*unknown*	*unknown*	*unknown*
09/15/1852	41.63	80.17	3.7	*unknown*	*unknown*
09/17/1865	39.90	76.30	*unknown*	*unknown*	*unknown*
11/07/1866	40.04	76.31	*unknown*	*unknown*	*unknown*
08/17/1873	41.20	80.50	*unknown*	III	*unknown*
05/31/1884	40.60	75.50	*unknown*	V	*unknown*
01/15/1885	40.30	76.30	*unknown*	*unknown*	*unknown*
03/09/1885	40.02	76.32	*unknown*	IV	*unknown*
09/27/1886	40.00	76.47	*unknown*	IV	*unknown*
09/29/1886*	40.17	76.63	*unknown*	IV	*unknown*
03/08/1889	40.00	76.55	4.3	VI	*unknown*
12/15/1890	41.41	80.39	2.9	II	*unknown*
05/28/1906	40.20	75.80	*unknown*	III	*unknown*
01/10/1907	41.20	77.10	*unknown*	*unknown*	*unknown*
05/31/1908	40.60	75.50	3.1	VI	*unknown*
09/27/1921	42.10	80.10	2.9	III	*unknown*
06/22/1928	40.60	75.50	*unknown*	III	*unknown*
11/05/1934	41.90	80.40	*unknown*	III	*unknown*
08/26/1936	41.40	80.40	2.9	IV	*unknown*

Table 4.3.3-3 Catalog of earthquakes with epicenters in Pennsylvania (DCNR, 2004).

DATE	NORTH LATITUDE (degrees)	WEST LONGITUDE (degrees)	MAGNITUDE	MAXIMUM INTENSITY	AREA (km^2)
03/25/1937	40.90	78.20	*unknown*	*unknown*	*unknown*
06/09/1937	40.34	75.93	*unknown*	II	*unknown*
07/15/1938	40.37	78.23	3.3	VI	*unknown*
09/27/1940	41.60	75.70	*unknown*	II	*unknown*
10/24/1942	41.00	75.20	3.4	*unknown*	*unknown*
02/05/1944	40.80	76.20	3.7	*unknown*	*unknown*
10/28/1946	41.50	76.60	3.6	*unknown*	*unknown*
03/20/1950	41.50	75.80	3.3	*unknown*	*unknown*
11/23/1951	40.60	75.50	3.3	IV	*unknown*
01/07/1954	40.42	76.02	3.2	VI	*unknown*
01/07/1954*	40.3	76	*unknown*	II	*unknown*
01/07/1954*	40.42	76.02	*unknown*	V	*unknown*
01/24/1954*	40.28	76.03	*unknown*	*unknown*	*unknown*
02/21/1954**	41.20	75.89	*unknown*	VII	*unknown*
02/24/1954**	41.20	75.89	*unknown*	VII	*unknown*
08/11/1954	40.33	76.02	3.3	IV	*unknown*
09/24/1954*	40.33	76.02	*unknown*	IV	*unknown*
01/20/1955*	40.33	76.02	*unknown*	IV	*unknown*
01/22/1960	41.50	75.50	3.4	*unknown*	*unknown*
09/15/1961	40.60	75.40	4.3	V	*unknown*
12/27/1961	40.50	74.75	3.3	V	*unknown*
03/02/1963**	41.50	75.80	3.4	V	*unknown*
02/13/1964**	40.38	77.96	3.3	*unknown*	*unknown*
05/12/1964	40.30	76.41	3.2	VI	*unknown*
10/08/1965	40.10	79.70	3.3	*unknown*	*unknown*
06/25/1972	40.30	75.90	*unknown*	*unknown*	*unknown*
12/08/1972	40.14	76.24	3.5	V	2,400
08/12/1973	40.30	75.90	*unknown*	*unknown*	*unknown*
04/27/1974**	40.97	75.91	3.2	*unknown*	*unknown*
07/16/1978	39.91	76.31	3.1	V	2,300
10/06/1978	42.14	76.32	3.0	VI	*unknown*
03/02/1980*	40.21	75.08	2.8	*unknown*	*unknown*
03/05/1980	40.19	75.16	3.5	IV	*unknown*
03/05/1980*	40.18	75.07	3.1	*unknown*	*unknown*
03/05/1980*	40.25	75.08	2.5	*unknown*	*unknown*
03/11/1980*	40.15	75.10	3.3	V	2,600
03/11/1980*	40.25	74.99	2.8	*unknown*	*unknown*
05/02/1980*	40.16	74.99	2.8	*unknown*	*unknown*
05/02/1980*	40.25	75.03	3.0	*unknown*	*unknown*
02/03/1982	40.21	79.05	2.6	III	*unknown*
05/12/1982	40.15	74.91	2.4	II	*unknown*
05/12/1982**	40.41	77.96	3.0	*unknown*	*unknown*
08/14/1982	41.71	75.75	1.8	*unknown*	*unknown*
04/19/1984*	39.94	76.36	2.9	*unknown*	*unknown*

Table 4.3.3-3 Catalog of earthquakes with epicenters in Pennsylvania (DCNR, 2004).

DATE	NORTH LATITUDE (degrees)	WEST LONGITUDE (degrees)	MAGNITUDE	MAXIMUM INTENSITY	AREA (km^2)
04/23/1984	39.92	76.36	4.1	V	77,000
04/23/1984*	39.95	76.32	4.1	*unknown*	*unknown*
05/10/1984	40.32	75.30	2.2	*unknown*	*unknown*
05/17/1984*	39.95	76.32	2.3	*unknown*	*unknown*
09/19/1984	40.06	76.30	*unknown*	III	*unknown*
04/14/1985	41.59	80.40	3.2	*unknown*	*unknown*
05/02/1986	39.92	76.36	2.5	IV	*unknown*
02/02/1989	40.38	75.30	*unknown*	*unknown*	*unknown*
03/30/1990	40.02	75.74	1.8	*unknown*	*unknown*
07/03/1990	40.29	76.12	1.7	*unknown*	*unknown*
12/14/1990	41.83	77.48	3.0	*unknown*	*unknown*
12/17/1990	41.95	80.12	2.5	III	*unknown*
04/17/1991**	40.39	77.96	2.5	*unknown*	*unknown*
08/15/1991	40.79	77.66	3.0	V	*unknown*
05/15/1992	40.57	75.13	1.6	*unknown*	*unknown*
05/10/1993	40.35	76.02	2.8	IV	*unknown*
05/11/1993*	40.35	76.02	2.0	*unknown*	*unknown*
05/11/1993*	40.35	76.02	2.3	V	*unknown*
05/11/1993*	40.35	76.02	1.6	*unknown*	*unknown*
05/11/1993*	40.35	76.02	2.2	*unknown*	*unknown*
05/13/1993*	40.35	76.02	*unknown*	*unknown*	*unknown*
05/18/1993*	40.28	76.00	2.0	*unknown*	*unknown*
05/18/1993*	40.35	76.02	2.1	IV	*unknown*
01/16/1994*	40.33	76.01	4.0	V	*unknown*
01/16/1994	40.33	76.04	4.6	VI	16,000
01/16/1994*	40.32	76.01	2.9	*unknown*	*unknown*
01/17/1994*	40.37	76.09	2.7	*unknown*	*unknown*
01/17/1994*	40.37	76.09	2.4	*unknown*	*unknown*
01/18/1994	40.19	76.23	2.6	*unknown*	*unknown*
03/24/1994	40.37	76.09	2.0	*unknown*	*unknown*
04/16/1994	40.31	75.96	2.3	*unknown*	*unknown*
05/07/1994*	40.31	76.04	2.5	*unknown*	*unknown*
05/18/1994	40.00	76.20	2.4	*unknown*	*unknown*
05/26/1994	39.95	77.19	2.8	*unknown*	*unknown*
05/31/1994*	40.34	76.00	2.4	*unknown*	*unknown*
07/03/1994*	40.35	75.88	2.0	*unknown*	*unknown*
07/03/1994*	40.33	76.09	2.3	*unknown*	*unknown*
01/08/1995	40.30	76.00	2.5	*unknown*	*unknown*
03/11/1995	40.10	76.40	2.7	IV	*unknown*
03/11/1995*	40.10	76.33	2.0	*unknown*	*unknown*
04/08/1995	40.35	76.10	2.6	*unknown*	*unknown*
06/04/1995	40.34	75.97	2.7	*unknown*	*unknown*
07/08/1995	41.95	79.04	2.4	*unknown*	*unknown*
08/17/1995	40.63	76.13	1.8	*unknown*	*unknown*

Table 4.3.3-3 Catalog of earthquakes with epicenters in Pennsylvania (DCNR, 2004).

DATE	NORTH LATITUDE (degrees)	WEST LONGITUDE (degrees)	MAGNITUDE	MAXIMUM INTENSITY	AREA (km^2)
02/03/1996	40.35	76.02	2.3	*unknown*	*unknown*
07/05/1996	39.91	76.49	2.6	*unknown*	*unknown*
07/07/1996	40.25	75.95	2.3	*unknown*	*unknown*
10/17/1996	39.75	76.06	2.2	*unknown*	*unknown*
10/28/1996	40.27	76.14	2.5	*unknown*	*unknown*
03/11/1997	40.31	74.99	1.6	*unknown*	*unknown*
06/16/1997	40.10	76.97	2.4	IV	*unknown*
06/17/1997*	40.10	76.97	1.6	*unknown*	*unknown*
11/14/1997	40.16	76.28	3.0	IV	*unknown*
11/16/1997*	40.17	76.29	1.8	*unknown*	*unknown*
09/25/1998	41.47	80.37	5.1	*unknown*	*unknown*
10/09/1998*	41.48	80.36	2.0	*unknown*	*unknown*
10/16/1998*	41.47	80.37	2.0	*unknown*	*unknown*
10/22/1998*	41.47	80.37	*unknown*	*unknown*	*unknown*
10/23/1998*	41.47	80.36	*unknown*	*unknown*	*unknown*
10/27/1998*	41.47	80.37	*unknown*	*unknown*	*unknown*
11/01/1998*	41.47	80.37	*unknown*	*unknown*	*unknown*
11/07/1998	41.57	80.31	2.3	*unknown*	*unknown*
04/18/1999	40.32	75.97	1.9	*unknown*	*unknown*
07/27/1999	40.17	75.79	*unknown*	*unknown*	*unknown*
10/22/1999	40.38	75.93	1.9	*unknown*	*unknown*
02/24/2000	41.12	75.75	2.3	*unknown*	*unknown*
03/22/2000	40.07	76.30	1.8	*unknown*	*unknown*
08/24/2000	40.10	76.70	1.9	*unknown*	*unknown*
10/05/2000	39.94	76.34	2.1	*unknown*	*unknown*
07/17/2001	39.94	76.34	1.8	*unknown*	*unknown*

Note: This table includes only earthquakes whose epicenters were located within Pennsylvania.

* Indicates a foreshock or aftershock event
** Indicates a mine collapse or quarry blast event

Table 4.3.3-3 was assembled from published and unpublished lists of historic earthquakes and from descriptions of earthquakes in professional journals and government reports. The rediscovery of ten previously forgotten Pennsylvania earthquakes by Armbruster and Seeber (1987) made a significant contribution to the catalog. Winkler's (1979, 1982) reviews of East Coast seismicity and the compilation of original newspaper accounts of Pennsylvania earthqu/akes by Abdypoor and Bischke (1982) were also helpful. The authors tabulated only those events having a maximum intensity of IV or more because the historic record is incomplete below this level, and because some of the shocks reported at level II or III are non-tectonic events such as quarry blasts or rock bursts (Scharnberger, 1988). Table 4.3.3-3 does not include strong local shocks experienced on February 21 and 24, 1954, which caused heavy damage in a five-block area of Wilkes-Barre, PA. Most seismologists now attribute these events to mine subsidence.

DCNR's earthquake records end in 2001, but a number of minor earthquakes have occurred in Pennsylvania and have been documented by USGS's Seismic Hazard Program, as shown in Table 4.3.3-4. This data indicates that recent earthquakes in Pennsylvania have generally been minor, with the highest magnitude being a 3.4. They have also been spatially concentrated in historically seismically active areas in south central Pennsylvania.

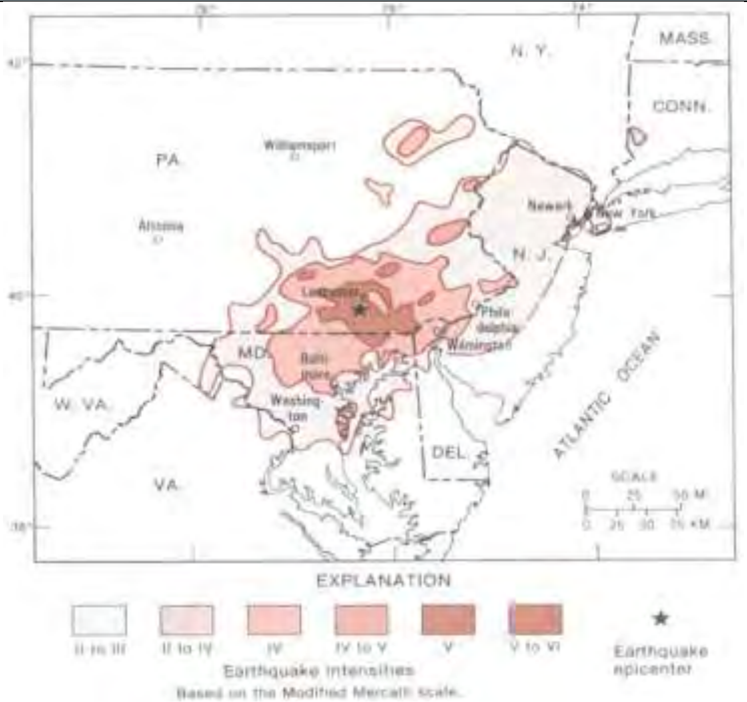
Table 4.3.3-4 Recent earthquakes with epicenters in Pennsylvania reported to USGS (USGS, 2013).

DATE	APPROXIMATE LOCATION	MAGNITUDE
11/4/2003	Reading	2.7
4/16/2006	Reading	1.0
4/17/2006	Reading	1.2
12/13/2006	Reading	2.5
1/3/2007	Meadville	2.5
4/20/2007	Reading	2.1
5/15/2007	Reading	2.1
10/05/2008	York	2.0
10/19/2008	Harrisburg	2.1
10/19/2008	Harrisburg	1.8
10/19/2008	Carlisle	1.7
10/20/2008	Carlisle	1.5
10/23/2008	York	1.2
12/27/2008	Lancaster	3.4
12/31/2008	Carlisle	0.0
4/22/2009	Carlisle	1.1
4/23/2009	Carlisle	2.4
4/24/2009	Carlisle	2.9
4/30/2009	Carlisle	2.0
5/11/2009	Carlisle	1.3
10/25/2009	Carlisle	2.6
10/25/2009	Carlisle	2.8
12/20/2009	Easton	2.3
6/3/2010	Harrisburg	2.9
12/10/2010	Meadville	2.7

Very few earthquakes having a maximum intensity of IV or higher have been centered in Pennsylvania outside the southeastern part of the Commonwealth. An earthquake shock on March 8, 1889 shook southeastern Pennsylvania, northern Maryland, and the northern tip of Delaware. Chimneys fell in Harrisburg and York, where the 1889 tremor was severe. Stover and others (1981) listed 10 historic earthquakes having maximum intensities of III or more and epicenters in the immediate vicinity of Philadelphia. The largest of these, a shock with a maximum intensity of approximately V, occurred on November 11, 1840. Small tremors in the Philadelphia area, such as the shocks on March 5 and March 11 in 1980, are often both felt and heard (Bischke, 1980). Witnesses usually describe the accompanying noise as a sonic boom or furnace explosion.

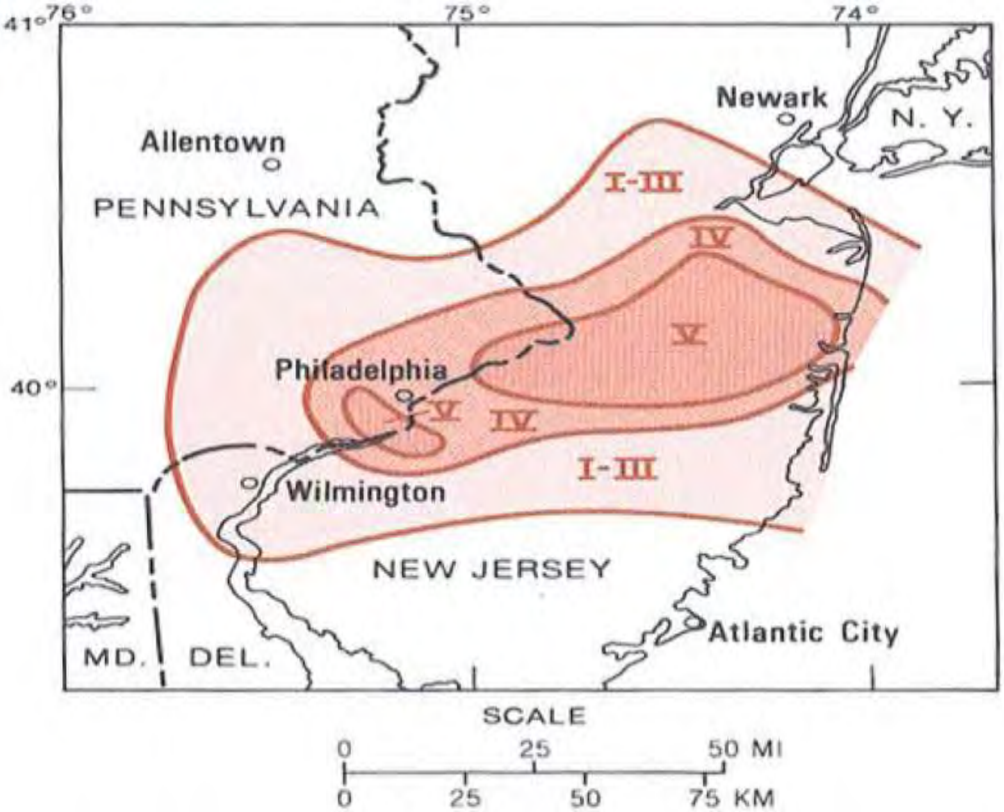
The most widely felt earthquake known to be centered in Pennsylvania occurred in the Lancaster area on April 23, 1984 (Armbruster and Seeber, 1987; Scharnberger and Howell, 1985). An isoseismal map for this event is included in Figure 4.3.3-3. More recently, an earthquake on January 16, 1994 measured 4.6 on the Richter Scale and caused damage exceeding two million dollars in the Reading area.

Figure 4.3.3-3 Isoseismal lines of the Lancaster, PA earthquake on April 23, 1984 (modified from Stover, 1988).



Earthquake whose epicenters fall outside of Pennsylvania can impact the Commonwealth as well. A cluster of historical epicenters in southeastern Pennsylvania is spatially associated with a seismic trend along the lower Delaware River, which continues northeasterly through New Jersey. One of the strongest shocks in this northeast-trending zone occurred on August 23, 1938 (see Figure 4.3.3-4). This tremor, which was centered in New Jersey about 31 miles northeast of Philadelphia, was the principal shock of a swarm of about a dozen tremors in the area that were felt in Philadelphia. The main shock of the swarm alarmed many people and broke a few windows in the Philadelphia area.

Figure 4.3.3-4 Isoseismal lines of the New Jersey earthquake on August 23, 1938 (modified from Neumann, 1940).



The strongest, most widely felt shock known to have originated in the region covered by Figure 4.3.3-5 was the earthquake of August 10, 1884, which was centered in New Jersey about 50 miles northeast of Philadelphia. Contemporary newspapers contained reports that this earthquake caused a few chimneys to fall and glassware and other small objects to be upset in greater Philadelphia. Waves on the Delaware River were reported to have swamped small boats. Figure 4.3.3-5 is an adaptation of Rockwood's (1885) isoseismal map; the original map is the oldest known published isoseismal plot of a North American earthquake. The isoseismal lines in the figure exhibit southwest-northeast elongation that is characteristic of shocks in the region.

Figure 4.3.3-5 Isoseismal lines of the New Jersey earthquake on August 10, 1884 (modified from a publication by C.G. Rockwood, Jr., 1885).

On October 9, 1871, an earthquake having a maximum intensity of VII struck Wilmington, Del., located about 25 miles southwest of Philadelphia. This shock, Wilmington's most famous earthquake, was felt in a northeast-trending, elliptically shaped area about 40 miles wide and 68 miles long; chimneys were thrown down in Oxford, PA and doors and windows were rattled in Philadelphia. Another relatively strong earthquake centered near Wilmington occurred on February 28, 1973. The area characterized by intensity V, the highest intensity associated with this shock, extended northeasterly along both sides of the Delaware River to the vicinity of Philadelphia, where the shock cracked plaster and toppled glassware.

4.3.3.4. Future Occurrence

One way to express an earthquake's severity is to compare its acceleration to the normal acceleration due to gravity. Peak horizontal ground acceleration (PHGA) measures the strength of ground movements in this manner. PHGA is the percent of *g* (acceleration due to gravity) experienced during the earthquake or the rate in change of motion of the earth's surface during an earthquake as a percent of the established rate of acceleration due to gravity. In general, an acceleration of 10- to 15-percent of gravity is associated with structural damage to ordinary buildings not specifically designed to resist earthquakes, although soil conditions at local sites are extremely important in controlling how much damage will occur as a consequence of a given amount of ground acceleration.

The first attempts to delineate seismic hazard in the United States were based on the historic records of the highest intensity earthquake ever experienced at individual localities. Using this concept, Algermissen (1969) placed Pennsylvania in a zone where relatively minor damage (intensity V to VI) is expected. Algermissen and others (1982) used probabilistic methods to map earthquake hazards in the United States. In southeastern Pennsylvania, the zone of highest seismic hazard in the state, they indicated that there is a 90-percent probability that maximum horizontal acceleration in rock of 10-percent of gravity will not be exceeded in a 50-year period. In comparison, for the same probability and exposure period, a maximum horizontal acceleration of about 60-percent of gravity characterizes high-risk areas along the San Andreas Fault in California.

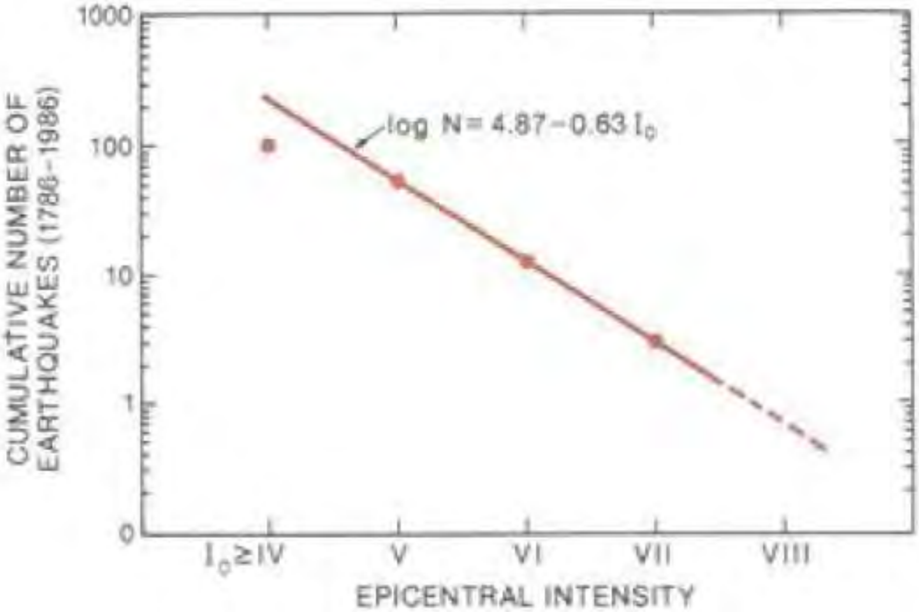
A probabilistic hazard map is provided by the DCNR (2007) in Figure 4.3.3-6. The map shows contours which represent earthquake ground motions that have a 10-percent probability of exceedance over a 50-year period. PHGA values ranging from 10-14-percent are shown in eastern Pennsylvania. These values correspond to intensities of VII; such earthquakes can cause significant building damage. PGHA values of between six and eight, found in the rest of Pennsylvania, correspond to an intensity of VI. On the whole, the future probability of earthquakes can be considered *possible.*

Figure 4.3.3-6 Pennsylvania probabilistic earthquake hazard map. Contours represent PHGA values that have a 2-percent probability of being experienced over a 50-year period (PADCNR, 2007).

Figure 4.3.3-7 is a plot of the cumulative number (N) of earthquakes versus epicentral intensity (I_0) for the period 1786-1986 in the study region. The straight line ($\log N=4.87-0.63\ I_0$) has been fitted to the observed frequencies at the V, VI, and VII intensity levels. In regions where earthquake records have been kept for a long time, log N versus I_0 relationships are nearly linear over the range of higher intensities. In regions that have short-term histories, a linear log N relation is commonly assumed to extrapolate the frequencies of shocks larger than those that have actually been observed. The calculated frequency derived from the linear expression shown in the figure is more than twice the observed frequency at the intensity IV level. This discrepancy, the fact that the observed frequency falls below the calculated frequency, is

probably due to the incomplete cataloging of intensity IV events in the eighteenth and nineteenth centuries.

Figure 4.3.3-7 Cumulative number (N) of earthquakes versus epicentral intensity (I_0) for the period 1786 – 1986 in Pennsylvania and adjacent areas.



Pennsylvania has not experienced an earthquake of intensity VIII, the threshold of serious damage to ordinary structures, or greater in historic time. Assuming that the expression for log N that has been derived may be extrapolated to higher intensities, it is estimated that, on average, three to four such events ($I_0 \geq$ VIII) will take place over 1,000 years. This result is similar to Algermissen's (1969) estimate of seismicity rates for the entire East Coast region (2.3 shocks per 100,000 km^2 [38,600 mi^2] with $I_0 \geq$ VIII over a 1,000-year period). In 1979, Benjamin Howell, Jr. of Pennsylvania State University used extreme-value theory and certain assumptions about the maximum size of earthquakes in the region to estimate an average return period of between 100 and 300 years for earthquakes in Pennsylvania having a maximum intensity of VIII.

Extrapolation from a record several centuries long of small and moderate Pennsylvania earthquakes to estimate the rate of occurrence of infrequent strong earthquakes will be improved by a better understanding of seismogenic faults in the Commonwealth and by a more complete cataloging of the historical shocks. Felt-area estimates, magnitudes, and approximate focal depths can probably be developed for more of the pre-instrumental earthquakes. A thorough search of original sources for the eighteenth and nineteenth centuries would probably result in the discovery of many additional, previously unlisted earthquakes.

4.3.3.5. *Environmental Impacts*

Environmental impacts of earthquakes can be numerous, widespread and devastating, particularly if indirect impacts are considered. Some examples are shown below, but such impacts are rare to Pennsylvania:

- Induced tsunamis and flooding or landslides and avalanches
- Poor water quality
- Damage to vegetation
- Breakage in sewage or toxic material containments
- Secondary impacts including: train derailments and spillage of hazardous materials and utility interruption

4.3.3.6. Jurisdictional Vulnerability Assessment

Historically, earthquakes have occurred in eighteen of Pennsylvania's 67 counties. Additionally, as illustrated Figure 4.3.3-2, earthquakes have historically been concentrated in the southeastern and south central areas of the Commonwealth. Pennsylvania has three zones of earthquake hazard; jurisdictions that fall into the "moderate" zone can be considered vulnerable to future earthquake events. Using this analysis parameter, 43 of Pennsylvania's 67 counties are vulnerable to earthquake events.

In addition to the jurisdictions identified via GIS analysis, 51 out of 67 counties in Pennsylvania identify earthquakes as a hazard, as seen in Table 4.3.3-5. 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. When counties ranked hazards in local HMPs 'H' is listed for high rankings, 'M ' for medium, and 'L' for low. This ranking information was prepared separately by counties using different methodologies and criteria.

Of the seven counties which currently have calculated risk factor values for earthquake hazards, the average value is 1.6. The State Risk Factor for earthquake is 1.9, while the Pennsylvania THIRA scored earthquake as a 5 out of 10. For more details on the State Risk Factor and THIRA rankings, please see Section 4.1.

Table 4.3.3-5 Counties profiling earthquakes 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		Low	1.3
Armstrong		X		
Beaver	X		Medium	2.4
Bedford	X		Low	1.3
Berks	X		Not Ranked	No RF
Blair		X		
Bradford	X		Not Ranked	No RF
Bucks	X		Low	1.7

Table 4.3.3-5 Counties profiling earthquakes with hazard ranking and risk factor (if available).

COUNTY	PROFILED HAZARD	DID NOT PROFILE HAZARD	RANKING (IF AVAILABLE)	RISK FACTOR (IF AVAILABLE)
Butler	X		Low	1.5
Cambria	X		Low	1.3
Cameron	X		Low	1.3
Carbon		X		
Centre		X		
Chester	X		Not Ranked	No RF
Clarion	X		Not Ranked	No RF
Clearfield	X		Low	1.3
Clinton		X		
Columbia	X		Low	1.3
Crawford		X		
Cumberland	X		Low	1.3
Dauphin		X		
Delaware	X		Low	1.5
Elk		X		
Erie	X		Medium	2.0
Fayette	X		Low	1.9
Forest	X		Not Ranked	No RF
Franklin		X		
Fulton		X		
Greene		X		
Huntingdon	X		Not Ranked	No RF
Indiana	X		Low	1.8
Jefferson	X		Low	1.9
Juniata		X		
Lackawanna	X		Not Ranked	No RF
Lancaster	X		Low	1.5
Lawrence		X		
Lebanon*	X		Not Ranked	1.0
Lehigh	X		Low	1.9
Luzerne	X		Not Ranked	No RF
Lycoming		X		
McKean	X		Low	1.3

Table 4.3.3-5 Counties profiling earthquakes with hazard ranking and risk factor (if available).

COUNTY	PROFILED HAZARD	DID NOT PROFILE HAZARD	RANKING (IF AVAILABLE)	RISK FACTOR (IF AVAILABLE)
Mercer	X		Low	1.5
Mifflin		X		
Monroe	X		Low	1.5
Montgomery	X		Low	2.3
Montour*	X		Not Ranked	1.0
Northampton	X		Low	1.9
Northumberland	X		Low	1.7
Perry*	X		Not Ranked	1.0
Philadelphia**	X		Low	C
Pike	X		Low	1.5
Potter	X		Not Ranked	No RF
Schuylkill		X		
Snyder	X		Low	1.7
Somerset		X		
Sullivan	X		Not Ranked	No RF
Susquehanna	X		Low	1.7
Tioga	X		Low	1.3
Union	X		Not Ranked	No RF
Venango	X		Low	1.5
Warren	X		Low	1.3
Washington	X		Not Ranked	No RF
Wayne	X		Not Ranked	No RF
Westmoreland	X		Not Ranked	No RF
Wyoming	X		Not Ranked	No RF
York	X		Low	1.6

* 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.

The aforementioned vulnerable jurisdictions host a number of state critical facilities. Most of these state critical facilities are located in southeastern Pennsylvania, particularly in Luzerne, Montgomery, Lancaster, Berks,Bucks, and Delaware Counties. Table 4.3.3-6 provides a complete accounting of the number of state critical facilities vulnerable to earthquakes in each vulnerable county.

Table 4.3.3-6 Number of State Critical Facilities impacted by earthquakes located in each county.

COUNTY	NUMBER OF CRITICAL FACILITIES	COUNTY	NUMBER OF CRITICAL FACILITIES
Adams	38	Lancaster	146
Bedford	7	Lawrence	39
Berks	148	Lebanon	106
Blair	75	Lehigh	77
Bucks	124	Luzerne	240
Cambria	62	Mercer	75
Carbon	66	Mifflin	25
Centre	57	Monroe	33
Chester	123	Montgomery	202
Clinton	1	Northampton	83
Crawford	2	Perry	3
Cumberland	38	Philadelphia	117
Dauphin	55	Pike	26
Delaware	157	Schuylkill	62
Erie	140	Somerset	54
Fayette	64	Susquehanna	52
Franklin	12	Wayne	16
Greene	2	Westmoreland	43
Huntingdon	13	Wyoming	28
Indiana	31	York	27
Lackawanna	6		

4.3.3.7. State Facility Vulnerability Assessment

The vulnerability of state critical facilities was evaluated as facilities that were either within 17.5 miles of a previous earthquake event or that were located in the “moderate” earthquake hazard zone identified by researchers at Millersville University. Using these criteria, a total of 2,924 vulnerable critical facilities have been identified. As illustrated in Table 4.3.3-7, 1,204 vulnerable facilities are fire departments, and a further 640 vulnerable facilities are designated as police facilities. At least one critical facility from each category is vulnerable to earthquake hazards; most notably, 34 government facilities are located within earthquake hazard zones.

Table 4.3.3-7 State Critical Facilities vulnerable to earthquakes by Critical Facility Type.

STATE CRITICAL FACILITY TYPE	NUMBER OF IMPACTED FACILITIES
Agriculture	75
Banking	18
Chemical	6
Commercial Facilities	42
Communications	3
Critical Manufacturing	3
Dams	13
Defense Industrial Base	15
Education	97
Emergency Services	45
Energy	22
Fire Departments (Non-HSIP)	1204
Government Facilities	34
Healthcare & Public Health	31
Hospital (Non-HSIP)	148
Information Technology	3
Manufacturing	1
National Monuments & Icons	6
Nuclear Reactors, Materials & Waste	3
Police (Non-HSIP)	640
Postal & Shipping	4
School (Non-HSIP)	462
Transportation	31
Water	18
TOTAL VULNERABLE CRITICAL FACILITIES	***2,924***

4.3.3.8. Jurisdictional Loss Estimation

Jurisdictional losses due to earthquakes will depend on the magnitude and intensity of the earthquake event. With higher magnitude earthquake events comes greater possibility for significant structural damage to buildings, roads, and other infrastructure. Philadelphia and Montgomery Counties are the most threatened jurisdictions with $201 and $160 billion in exposed buildings and contents, respectively. Jurisdictional loss estimates were identified at the tract level and aggregated at the county level to show the possible losses per county. The total dollar value of exposure in vulnerable jurisdictions tops $1.3 trillion. These potential losses are displayed in Table 4.3.3-8.

Table 4.3.3-8 Estimated jurisdictional losses due to earthquakes.

COUNTY	NUMBER OF IMPACTED BUILDINGS	DOLLAR VALUE OF EXPOSURE, BUILDING AND CONTENTS (THOUSANDS $)
Adams	53,826	$12,604,062
Bedford	12,883	$2,348,729
Berks	227,614	$59,210,259
Blair	66,561	$14,156,138
Bucks	321,764	$108,123,710
Cambria	50,612	$11,669,315
Carbon	79,071	$17,961,659
Centre	60,132	$14,861,568
Chester	261,350	$89,860,597
Clinton	2,479	$556,622
Crawford	40,481	$8,054,451
Cumberland	115,029	$30,363,013
Dauphin	135,742	$33,621,413
Delaware	281,319	$86,856,472
Erie	129,780	$30,454,807
Fayette	7,580	$1,327,978
Franklin	4,631	$984,863
Greene	8,054	$1,369,296
Huntingdon	30,513	$6,268,058
Indiana	12,330	$2,504,821
Juniata	7,820	$1,512,836
Lackawanna	147,658	$33,533,470
Lancaster	264,197	$68,045,591
Lawrence	31,519	$6,749,048
Lebanon	90,685	$22,046,975
Lehigh	218,320	$59,736,030
Luzerne	190,058	$42,702,861
Mercer	62,261	$13,464,728
Mifflin	30,033	$6,044,286
Monroe	134,818	$33,513,041
Montgomery	484,549	$160,866,480
Northampton	181,973	$50,378,288
Perry	20,194	$5,460,632
Philadelphia	778,715	$201,276,171
Pike	70,552	$16,534,398
Schuylkill	73,909	$16,673,756
Snyder	3,455	$596,574
Somerset	47,616	$10,156,910

Table 4.3.3-8 Estimated jurisdictional losses due to earthquakes.

COUNTY	NUMBER OF IMPACTED BUILDINGS	DOLLAR VALUE OF EXPOSURE, BUILDING AND CONTENTS (THOUSANDS $)
Susquehanna	22,676	$4,411,807
Union	2,139	$388,344
Wayne	75,557	$15,861,133
Westmoreland	29,653	$6,223,366
Wyoming	32,416	$7,098,854
York	214,709	$53,181,939
TOTAL	**5,117,233**	**$1,369,615,349**

In addition to the aforementioned analysis, FEMA's HAZUS-MH loss estimation model was used to explore the potential damage of earthquake hazards in the Commonwealth using a Level 2 analysis incorporating new 2010 Census data and updated general building stock information that better reflect the demographics and building stock in Pennsylvania. This level of analysis is a rough estimate of damage to buildings, essential facilities, transportation systems, utility systems, and high potential loss facilities based on national data included in the HAZUS software. This analysis assumes a uniform soil type of D for all of Pennsylvania. Soil type D, according to the National Earthquake Hazards Reduction Program, is characterized as having a stiff soil profile with a soil sheer wave velocity of between 600 and 1,200 feet per second. Since soil types across Pennsylvania are not uniform, it would be preferable to incorporate more specific soil classifications for the Commonwealth. However, as stated in the HAZUS technical manual for earthquakes, more specific soil site classifications should be developed by a soil science expert or geologist and then entered into the HAZUS model. Currently, specific soil site classifications have not been developed for Pennsylvania according to the USGS and DCNR's Bureau of Geologic and Topographic Survey. As a result, the results presented here should be considered a broad estimate of statewide risk and statewide loss estimates. Action 2-3d in the 2013 Mitigation Action Plan seeks to develop this dataset for the 2016 SSAHMP. For more information on the HAZUS data and methodology used in the SSAHMP, see 4.1.4.

The risk of a significant earthquake event is not evenly distributed across the Commonwealth. To accurately analyze earthquake risk, six events representing the earthquake hazard zones in the Commonwealth as well as two events based on significant historical events were examined. This was done in order to understand the range of earthquake events possible statewide. The parameters selected for the earthquake HAZUS models were extracted from the 2007 and 2010 Commonwealth Hazard Mitigation Plans. This was done in order to enable more effective comparison of the change in risk and loss estimation from 2007-2013. The parameters were selected in 2007 according to studies conducted by the Millersville University Center for Disaster Research and Education (see Figure 4.3.3-1). These same parameters were repeated using HAZUS version 2.1, Level 2 analysis for this plan update. The decision to run three scenarios in 2007 close to the Reading Lancaster border was likely chosen due to this area having the largest volume of previous occurrences in the Commonwealth.

All of the models were conducted as arbitrary earthquake events using the Central and Eastern United States (CEUS) attenuation function. This attenuation function defines the way in which a seismic wave loses strength as it moves through earth and is regionally defined based on predominant soil composition. All events modeled except the Mercer County event are considered arbitrary events, meaning they are based on user-defined parameters rather than historical event parameters. These arbitrary events were modeled with magnitudes ranging from 5 to 6.1 in order to provide results that are reasonable given the fact that Pennsylvania has had only one earthquake of a magnitude of over 6.0 in its history. Table 4.3.3-9 illustrates the parameters for each event modeled.

Table 4.3.3-9 HAZUS earthquake model event parameters.

EVENT NAME	LATITUDE	LONGITUDE	MAGNITUDE	DEPTH
Philadelphia	39.95	-75.16	5	12
Reading/Lancaster	40.23	-76.37	5	10
Mercer County (historical)	41.49	-80.39	5.3	10
Indiana County	40.64	-79.28	6.1	15
Spring Township	40.33	-76.04	5	10

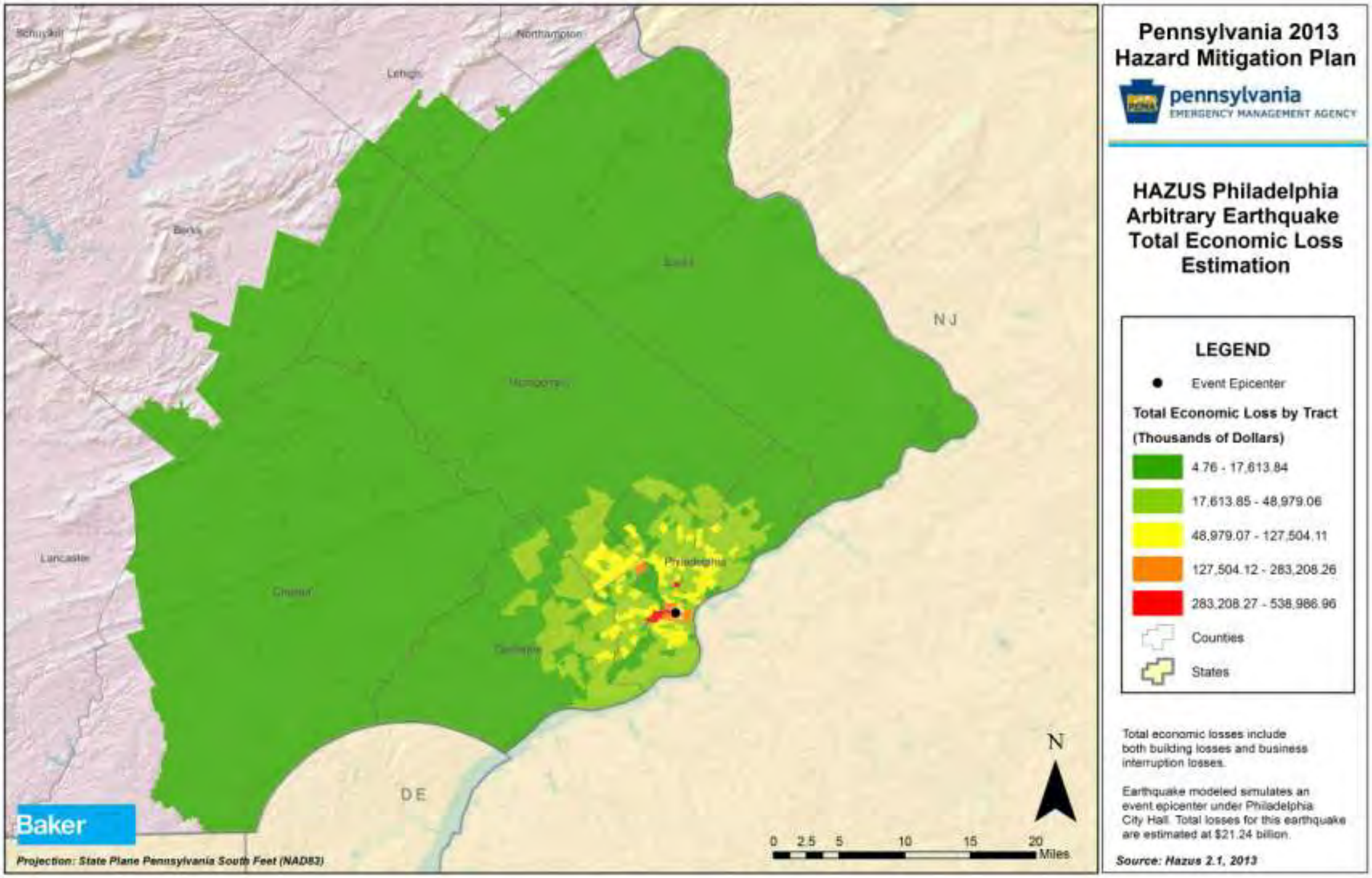
Minimum event magnitude for arbitrary events is 5; minimum event depth is 10 km.

HAZUS model results reveal that there was more building damage and overall economic loss in events whose epicenters are located in more densely populated areas and in higher magnitude events. For example, even though the arbitrary event in Philadelphia was only a magnitude 5 earthquake, the model indicates over $21 billion in economic loss and nearly 342,400 buildings with at least moderate damage. Table 4.3.3-10 displays the potential losses to life, property, and the economy predicted for each event modeled. Figures 4.3.3-8 through 4.3.3-13 show the distribution of potential total economic losses for each HAZUS scenario. See *Appendix H – HAZUS Results Reports* for the full report on the HAZUS model results.

Table 4.3.3-10 Summary of earthquake losses predicted by HAZUS.

EVENT NAME	BUILDINGS AT LEAST MODERATELY DAMAGED	BUILDINGS DAMAGED BEYOND REPAIR	TOTAL ECONOMIC LOSS (MILLIONS)	BUILDING-RELATED ECONOMIC LOSS (MILLIONS)	SHELTER REQUIREMENT	INJURY ESTIMATES (2AM)	CASUALTY ESTIMATES (2AM)
Philadelphia	157,484	7,428	$21,240.78	$20,547.92	9,695	25	1
Reading/Lancaster	22,127	613	$2,412.75	$1,901.89	541	28	1
Mercer County (historical)	8,320	365	$973.9	$651.73	186	3	0
Indiana County	77,884	6,439	$8,528.48	$7,057.96	3,963	778	27
Spring Township	28,777	1,078	$3,535.51	$3,080.42	1,162	643	27

Figure 4.3.3-8 HAZUS Earthquake map for the Philadelphia event.



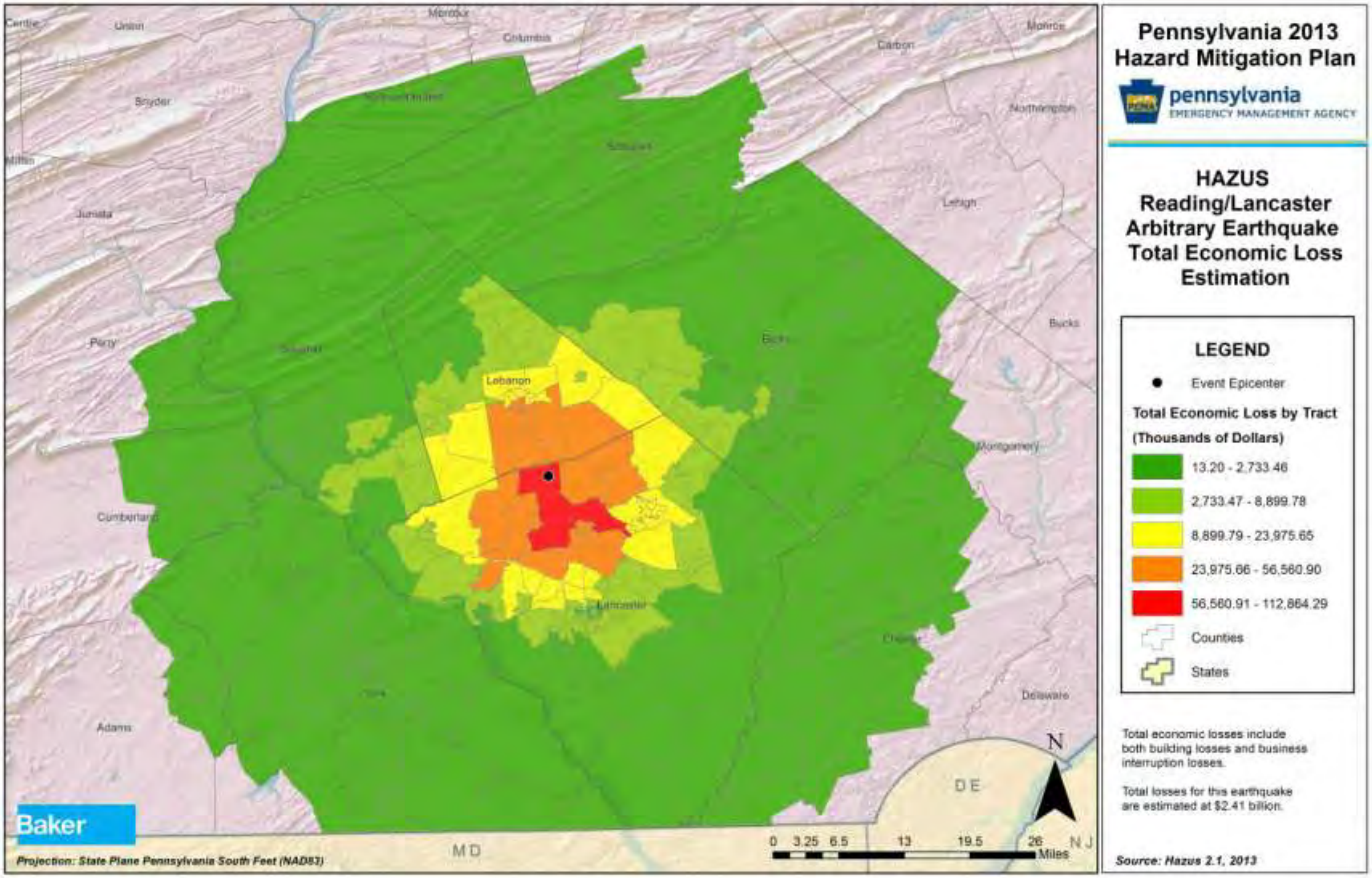
Total economic losses include both building losses and business interruption losses.

Earthquake modeled simulates an event epicenter under Philadelphia City Hall. Total losses for this earthquake are estimated at $21.24 billion.

Projection: State Plane Pennsylvania South Feet (NAD83)

Source: Hazus 2.1, 2013

Figure 4.3.3-9 HAZUS Earthquake map for the Reading/Lancaster event.

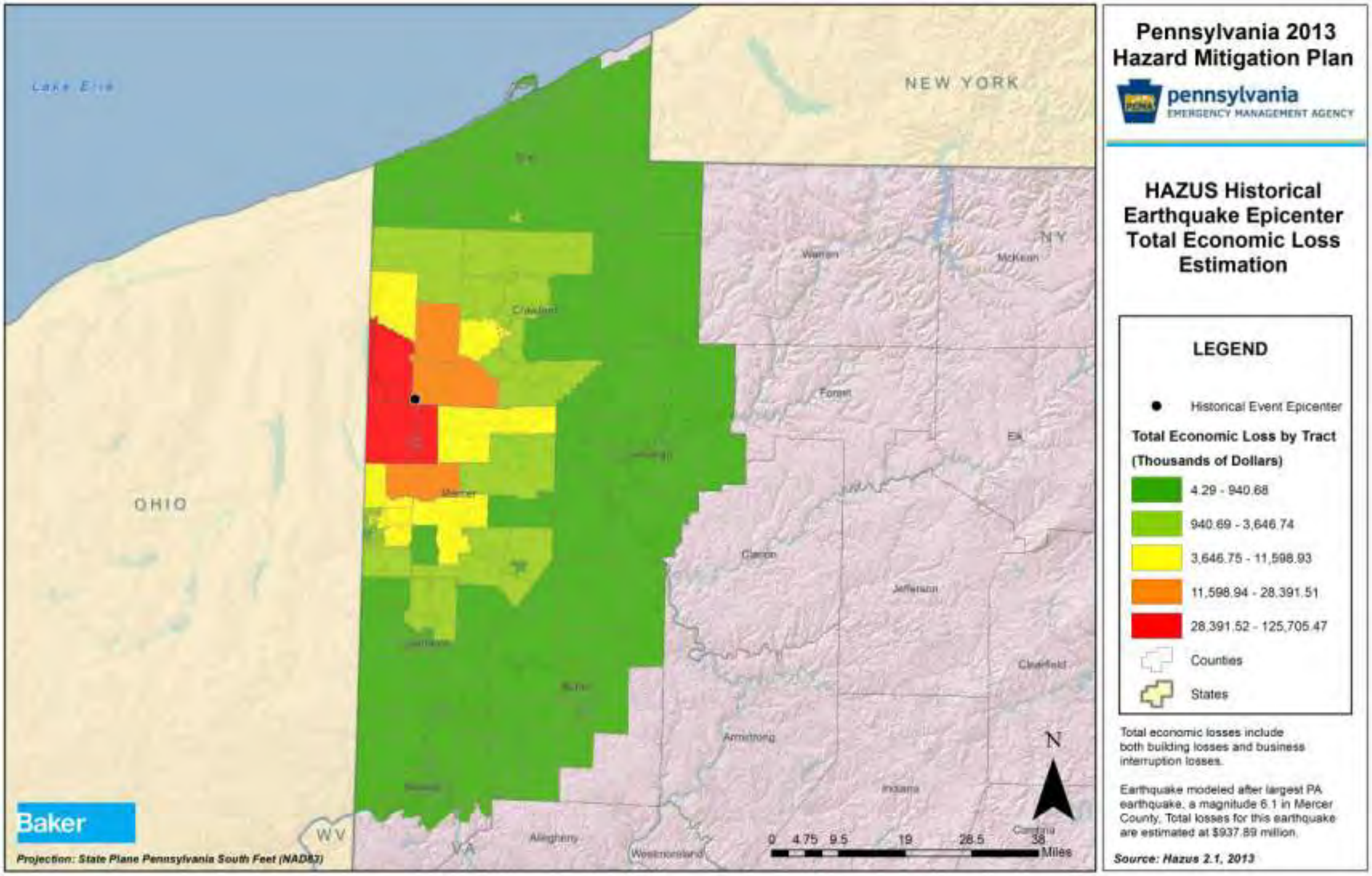


Total economic losses include both building losses and business interruption losses.

Total losses for this earthquake are estimated at $2.41 billion.

Source: Hazus 2.1, 2013

Figure 4.3.3-10 HAZUS Earthquake map for the Mercer County event (historical).

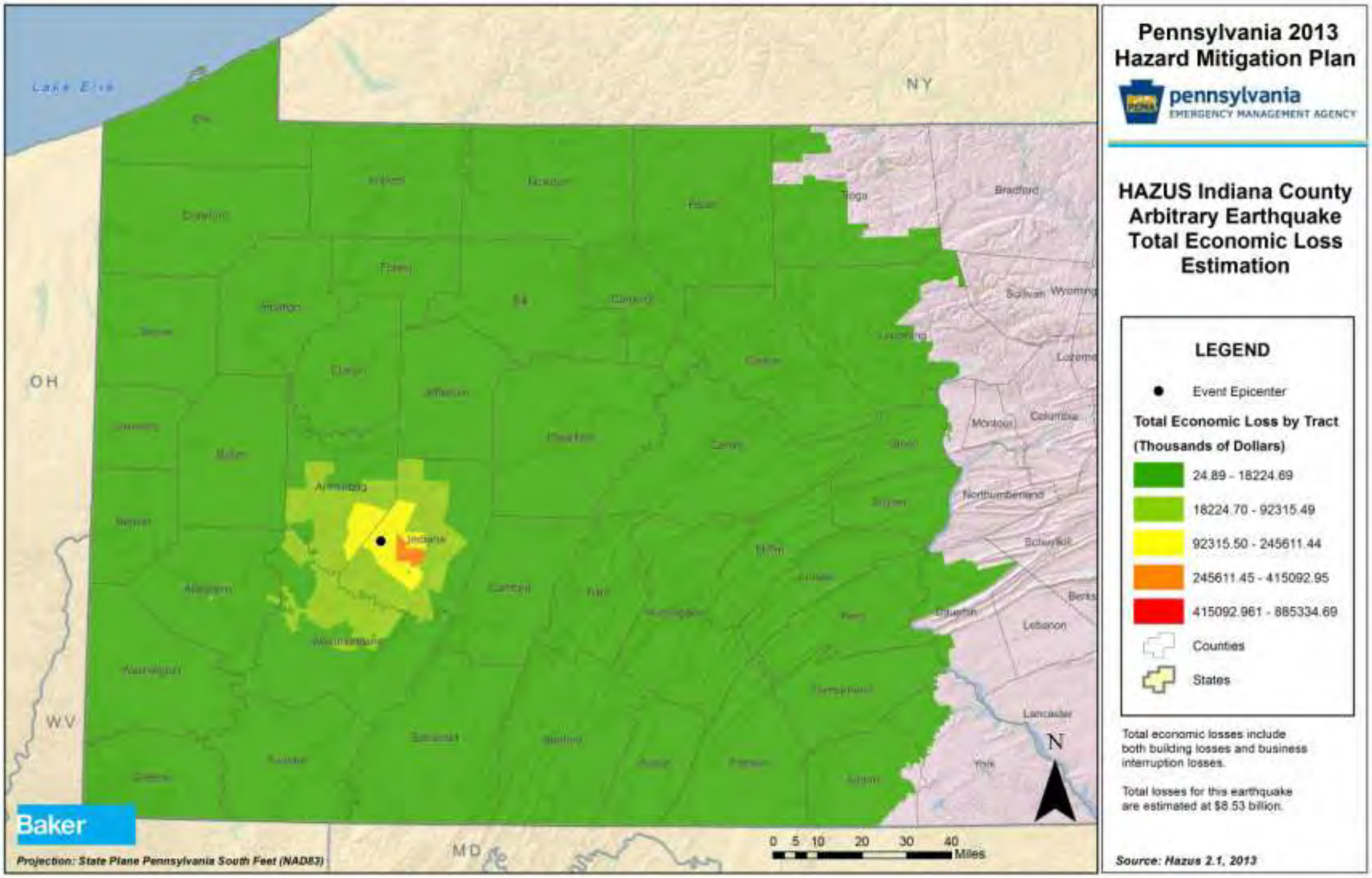


Total economic losses include both building losses and business interruption losses.

Earthquake modeled after largest PA earthquake, a magnitude 6.1 in Mercer County. Total losses for this earthquake are estimated at $937.89 million.

Source: Hazus 2.1, 2013

Figure 4.3.3-11 HAZUS Earthquake map for the Indiana County event.

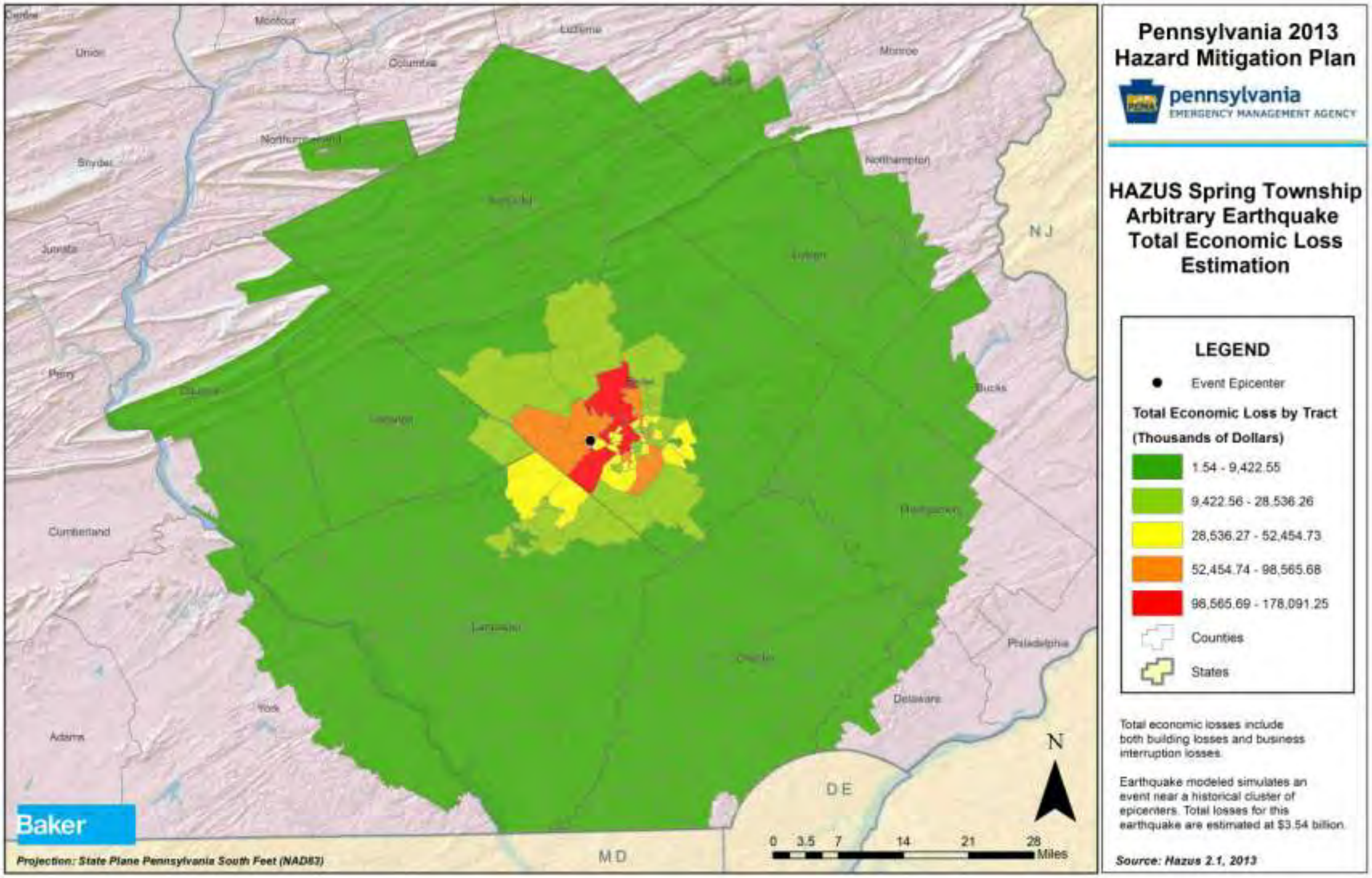


Total economic losses include both building losses and business interruption losses.

Total losses for this earthquake are estimated at $8.53 billion.

Source: Hazus 2.1, 2013

Figure 4.3.3-12 HAZUS Earthquake map for the Spring Township event.



Total economic losses include both building losses and business interruption losses.

Earthquake modeled simulates an event near a historical cluster of epicenters. Total losses for this earthquake are estimated at $3.54 billion.

Source: Hazus 2.1, 2013

4.3.3.9. State Facility Loss Estimation

State facilities will not experience uniform losses in earthquake events. The losses will depend on the level of damage to the facility, from cosmetic damage to total destruction of a structure. Additionally, replacement values are not available for all critical facilities. With the values available, the estimated replacement cost of all state critical facilities located in earthquake hazard zones is $19,762,562,079.00.

4.3.4. Extreme Temperature

4.3.4.1. Location and Extent

Pennsylvania can experience many different temperature extremes. Temperatures across the Commonwealth normally remain between 0°F and 100°F and average from 43°F in the north-central mountains to 55°F in the southeast. High temperatures of 90°F or above occur about ten days per year at any one location, but southeastern localities may experience more than twice this number. Ranges of daily temperature from maximum to minimum are commonly around 20°F during the summer and are a few degrees less during the winter. Freezing temperatures occur on an average of 100 or more days per year, and the greatest number of occurrences is in the Appalachian Plateaus province in north-central Pennsylvania. The southeast (near sea level) and northwest (adjacent to Lake Erie) portions of the Commonwealth have the longest freeze-free period. Extreme temperature hazards are not tied to a specific temperature threshold; instead, these hazards occur when the temperature is extremely high or extremely low.

Figure 4.3.4-1 and Figure 4.3.4-2 show annual mean maximum and minimum temperatures throughout Pennsylvania. During July, the warmest month, high temperatures normally range from the upper-70s in northern areas of the Commonwealth to the mid-80s in southern areas. Minimum temperatures for this month range from the upper-60s in the southeast to the lower 50s in the north-central mountains. During January, the coldest month, most of the Commonwealth experiences low temperatures in the teens and high temperatures in the 30s. High temperatures usually remain near or below the freezing point during this month in northern sections of the Commonwealth. In southern sections, high temperatures hover in the mid- to upper-30s.