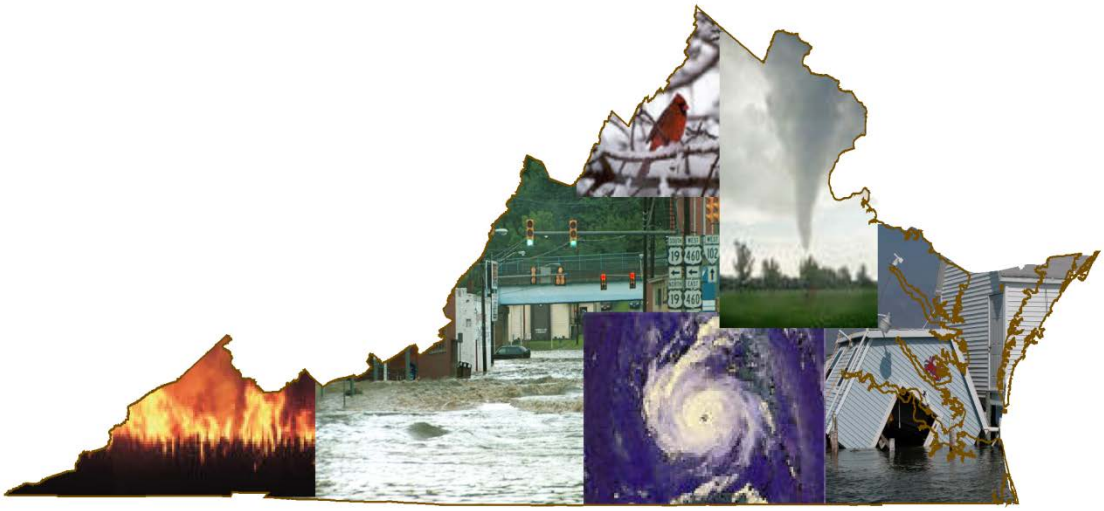
COMMONWEALTH OF VIRGINIA

Hazard Mitigation Plan



Chapter 3
Hazard Identification and Risk Assessment (HIRA)

Appendix 3.8b – Tornado

SECTION 3.8b

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Section 3.8b: Tornado

Washington County
April 2011
Source: Virginia State Police

Description

Tornadoes are rotating columns of air extending from a thunderstorm cloud to the ground; while most tornadoes measure less than 200 feet wide and have wind speeds less than 100 mph, severe tornadoes sometimes occur with much broader swath widths and wind speeds approaching 200 mph, or even higher. Tornadoes with winds in excess of 75 mph begin to cause significant structural damage to most buildings, but tornadoes with lower wind speeds can also cause secondary damage, for example, by causing a tree to fall into a house. In the United States, tornadoes have been classified on the Fujita Scale, assigning numeric scores from zero to five (or higher) based on the severity of observed damages. The traditional Fujita scale, introduced in 1971, was used to rate the intensity of tornadoes thereafter, and was also applied to previously documented tornadoes (Table 3.8b-1). Starting in February of 2007, an "enhanced" Fujita scale was implemented, with somewhat lower wind speeds at the higher F-numbers, and more thoroughly-refined structural damage indicator definitions. Table 3.8b-2 shows the differences between the old and new tornado intensity scales.

In Virginia, tornadoes primarily occur from April through September, although tornadoes have been observed in every month. Low-intensity tornadoes occur most frequently; tornadoes rated F2 or higher are very rare in Virginia, although F2, F3, and a few F4 storms have been observed. In comparison to other states, Virginia ranks 28th in terms of the number of tornado touchdowns reported between 1950 and 2006; Midwestern and Southern states ranked significantly higher.[1]

[1] Determined from CGIT analysis of SVRGIS tornado database, discussed in the Probability section

Table 3.8b-1: Original Fujita Scale (F Scale) classifications[2]

F #	Est. Wind (mph)	Typical Damage
F0	< 73	Light: chimneys damaged, shallow-rooted trees pushed over
F1	73-112	Moderate: mobile homes pushed off foundations, cars blown
F2	113-157	Considerable: mobile homes demolished, trees uprooted, roofs torn off frame houses
F3	158-206	Severe: roof and walls torn down, trains overturned, cars thrown
F4	207-260	Devastating: well-constructed walls leveled, large objects thrown
F5	261-318	Incredible: homes lifted and carried, cars thrown 300 ft, trees de-barked

Table 3.8b-2: Operational EF scale classifications in relation to original F Scale[3]

Fujita Scale			Derived EF Scale		Operational EF Scale	
F #	Fastest ¼ mile (mph)	3 Second Gust (mph)	EF #	3 Second Gust (mph)	EF #	3 Second Gust (mph)
0	40-72	45-78	0	65-85	0	65-85
1	73-112	79-117	1	86-109	1	86-110
2	113-157	118-161	2	110-137	2	111-135
3	158-207	162-209	3	138-167	3	136-165
4	208-260	210-261	4	168-199	4	166-200
5	261-318	262-317	5	200-234	5	Over 200

Historic Occurrence

Numerous low-intensity tornadoes are reported almost every year in Virginia. Figure 3.8b-1 shows the historic tornado touchdowns and tracks. Of the more intense tornadoes which have occurred, a few recent incidents stand out from the rest:[4]

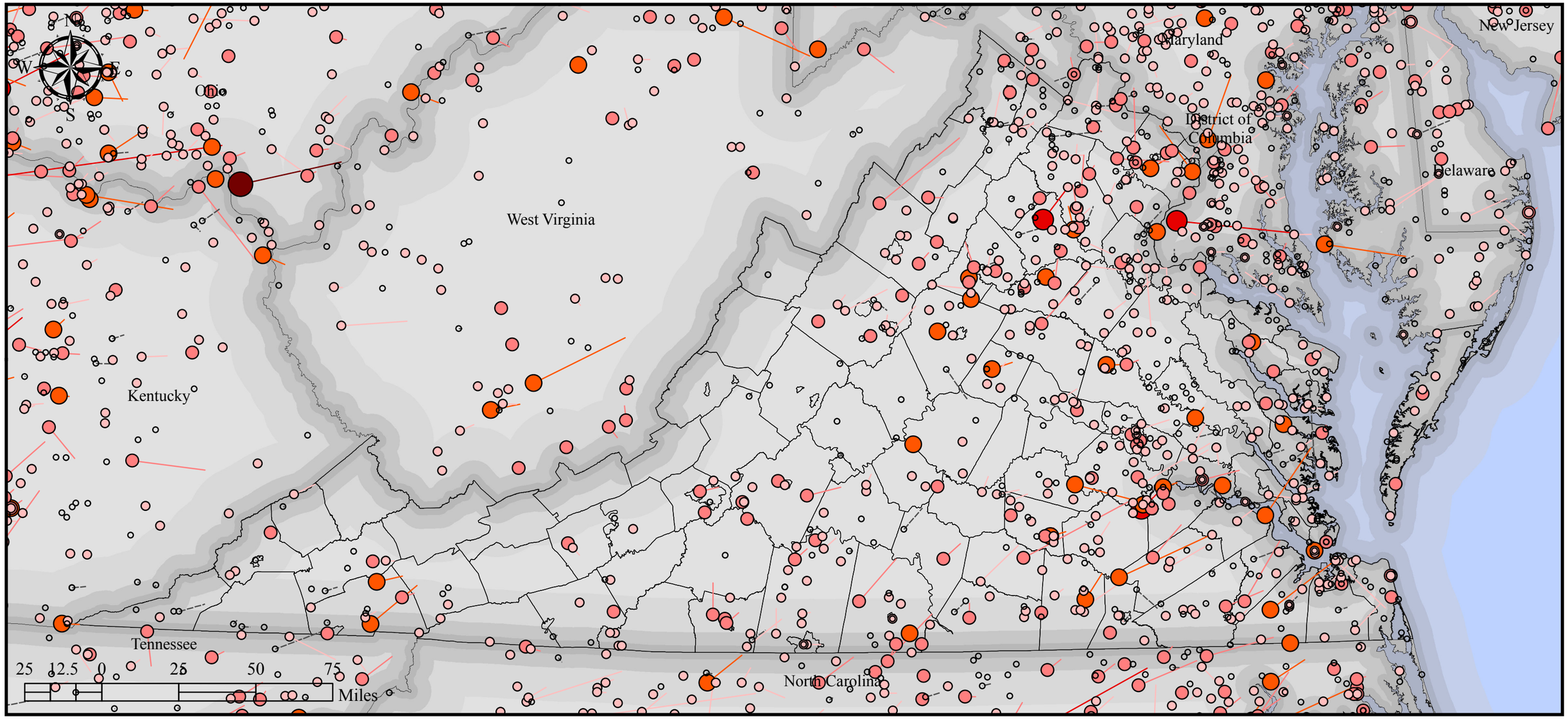
- On May 2, 1929 five tornadoes were reported in southwest Virginia, killing 22 people and injuring over 150 more. These tornadoes caused at least a half a million dollars in damages as four schools were destroyed[5].
- On March 4, 1944, what is thought to have been an F3 tornado tracked 30 miles through Lee, Wise, and Scott counties and injuring 32 people. Another tornado struck Washington County, injuring seven people and causing approximately $500,000 in total losses[6].

[2] Adapted from http://www.spc.noaa.gov/faq/tornado/f-scale.html
[3] http://www.spc.noaa.gov/faq/tornado/ef-scale.html, http://www.spc.noaa.gov/faq/tornado/ef-ttu.pdf
[4] Source: National Climatic Data Center (NCDC) Storm Events Database
[5] Virginia Department of Emergency Management. "Tornado History: Virginia Tornadoes." http://www.vaemergency.gov/news/history/tornado
[6] Ibid.

- On June 13, 1951, an F3 tornado went through the heart of Richmond creating a four mile path and over one million in damages. Reports suggest that it was a multi-vortex tornado with four visible vortices.

- On August 6, 1993, four tornadoes were reported across southeast Virginia, ranging in intensity from F2 to F4. The F4 tornado impacted commercial and residential areas in Petersburg, Colonial Heights, and Hopewell, killing 4 people, injuring 246, and causing about $50 million in damages.
- On September 4, 1999, an F2 tornado caused about $7.7 million in damages in Hampton, as well as many injuries.
- On the afternoon of September 17, 2004, thunderstorms produced twelve tornadoes across the state, causing over $65 million in damages, with $54 million of the damages occurring at a factory in Fieldale.
- On April 28, 2008, an F3 tornado traveled from north of Suffolk to the Norfolk Naval Air Station, causing a total of $30 million in commercial and residential damage, with at least a dozen homes completely destroyed.
- On May 8, 2008, an EF2 tornado caused $10 million in damages in Berea (North of Fredericksburg); 160 homes damaged, with 25 rendered uninhabitable.
- On October 8, 2011 an EF2 tornado caused $3.9 million in damages in Pulaski County, resulting in 9 injuries. More than 200 homes reported having some damage with approximately 30 of those homes damaged beyond repair. On that same day, a tornado in Drapers Valley caused $1.4 million in damages.
- On April 16, 2011, fifteen tornados were reported in Virginia, ranging in intensity from an EF0 to an EF3. Of these tornadoes, 4 caused over a million dollars in property damages: Gloucester County $7.7 million, Augusta County $2.2 million, Dinwiddie County $1.5 million and Middlesex County $6 million. As a result of these storms, there were 2 deaths and 34 injuries.
- On April 28, 2011, twelve tornadoes were reported in Virginia, ranging in intensity from an EF0 to an EF3. Of these tornadoes, two caused over a million dollars in property damages and 5 deaths: Washington County $3 million and Smyth County $2.25 million.
- On October 13, 2011, eight tornadoes were reported in Virginia, ranging in intensity from an EF0 to an EF1. One of the EF1 tornadoes caused $1 million in property damages in New Kent, as this tornado damaged more than 30 homes in the Woodhaven Shores Subdivision.
- On March 2, 2012, an EF1 tornado caused $1.65 million in damages in Lee County of which $350,000 constitutes residential property loss, while $1.3 million is the estimated loss for agricultural property.

Figure 3.8b-1: Historic Tornado Touchdowns and Tracks: 1950 - 2011



DATA SOURCES:

SVRGIS
VGIN Jurisdictional Boundaries
ESRI State Boundaries

LEGEND:

Tornado F-Scale

- 0
- 1
- 2
- 3
- 4
- 5

HAZARD IDENTIFICATION:

Historic tornado touchdowns and tracks are symbolized for visual effect and are not drawn to scale. Actual tornado swath widths vary considerably, although more intense tornadoes are generally wider.

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.

Risk Assessment

Probability

Tornado formation is a complex process for which it is difficult to develop a physically-based model. The simplest way to estimate the probability of future tornadoes is to analyze historical tornado incidence data and generate descriptive statistics, such as the frequency of occurrence. Records of historical tornadoes are maintained by the National Climatic Data Center (NCDC) and by the National Weather Service's Storm Prediction Center. Tornado incidence is rare, especially in Virginia, and the available historic data is insufficient to estimate tornado probability conclusively. Therefore, while the data can be used to show the geographic variation in tornado frequency, such data should not be taken as an exact determination of tornado probability.

John Hart, at the National Weather Service Storm Prediction Center in Norman Oklahoma, has developed a graphical program, SeverePlot[7], to display a database of tornado occurrence that was derived from the NCDC Storm Events Database. This database dates from 1950 to 2006, and also contains data on hail and high wind. Bryan Smith, as an intern with the National Weather Service in Indianapolis, has converted the SeverePlot program data into shapefiles which are ready to use in GIS software; these files are collectively referred to as SVRGIS.[8] Other researchers have developed tornado databases extending further back into history, or which contain additional attributes. However the SVRGIS dataset, based on SeverePlot data, was sufficient for the purpose of this analysis.

In reviewing the historic tornado database, a few important points must be noted. First, although tornadoes are reported back to the year 1950, there are vastly higher numbers of low-intensity (F0 and F1) tornadoes reported in recent decades. The general consensus among climatologists is not that there are more low-intensity tornadoes occurring in recent years; rather, that with increased population and advanced technology such as weather radar, more of these low-intensity tornadoes are observed and documented than were historically. Second, while tornadoes are reported throughout the state, there are more tornadoes reported in areas of higher population. This may be due in part to the fact that many population centers are located in areas where tornadoes are likely to occur, but the correlation is probably also indicative of human bias in reporting. Conversely, the mountainous counties in the western part of the state have lower populations and in some cases, no reported historical tornadoes, but tornado occurrence is still theoretically possible, albeit less probable.

The frequency analysis conducted on the SVRGIS tornado data is described in the Tornado Hazard Frequency Analysis Appendix 3.8c. In brief, this analysis consisted of tabulating the area impacted by tornadoes for individual cells in a grid overlaid on the state of Virginia. The tornado hazard frequency is calculated as the total area impacted by each tornado in the grid

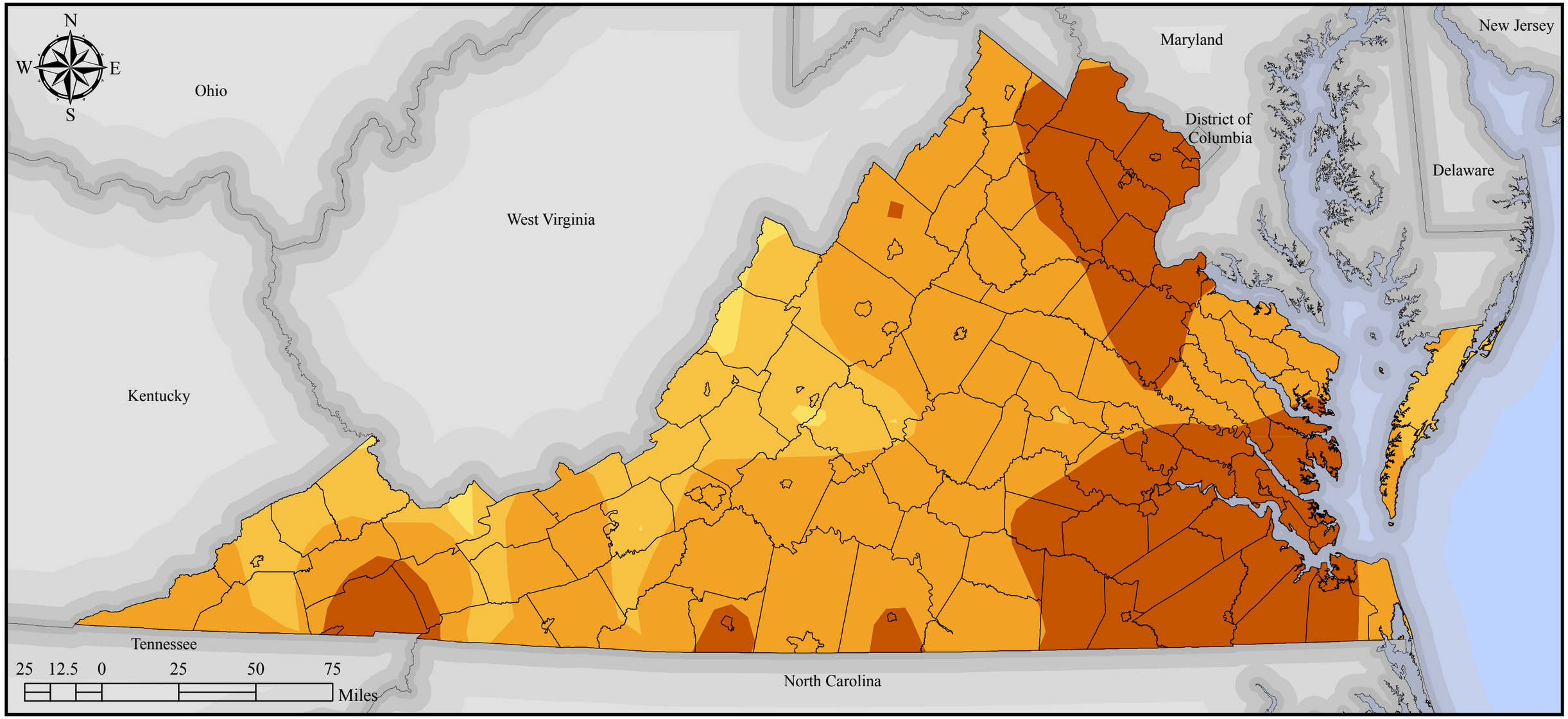
[7] The current version of this software is available online at: http://www.spc.noaa.gov/software/svrplot2/
[8] The current collection of SVRGIS data is available online at: http://www.crh.noaa.gov/ind/?n=svrgis

divided by the area of the grid cell and the number of years in the period of record. Virginia annual tornado hazard frequencies were calculated in each analysis grid cell, for tornado intensities F0, F1, F2, and F3+. The annual hazard frequency of each tornado intensity class was calculated separately; these results are added together to depict the overall tornado hazard frequency as shown in Figure 3.8b-3. In calculating the F0 and F1 intensity hazard frequencies, the 1985 – 2011 subset of the SVRGIS dataset was used, as this period was estimated to be more representative of the true frequency of these low-intensity tornadoes. In calculating the F2 and F3+ intensity hazard frequencies, the entire period of record (1950 – 2011) was used, as the reported frequency of occurrence has not changed noticeably over time. Figure 3.8b-4 shows the Significant Tornado Hazard Frequencies (for F2 and larger tornadoes).

In calculating these annual hazard frequencies, a multiplier of one million was added to make the results easier to read. When interpreting these results, for example, a value of 1 actually means that the annual tornado hazard frequency at a point is 1 divided by 1 million, or 0.000001 – essentially, assuming that past trends prove true, that there would be a 1 in 1 million chance that a given point would experience a tornado in a given year.

The results of the tornado frequency analysis show a much higher incidence of tornadoes in the eastern parts of the state, and a much lower incidence of tornadoes in the mountainous western parts of the state. Despite concerns about biases in the historical data, the results of the probability analysis provide a reasonable depiction of the relative tornado risk in different regions of the state. Finally, while the overall statewide probability of tornadoes is low relative to many other states, the probability of tornadoes in Virginia should not be overlooked, especially in the eastern parts of the state.

Figure 3.8b-2: Historical Tornado Hazard Frequency



DATA SOURCES:

SVRGIS
VGIN Jurisdictional Boundaries
ESRI State Boundaries

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

LEGEND:

Annual Tornado Hazard Frequency
Times One Million

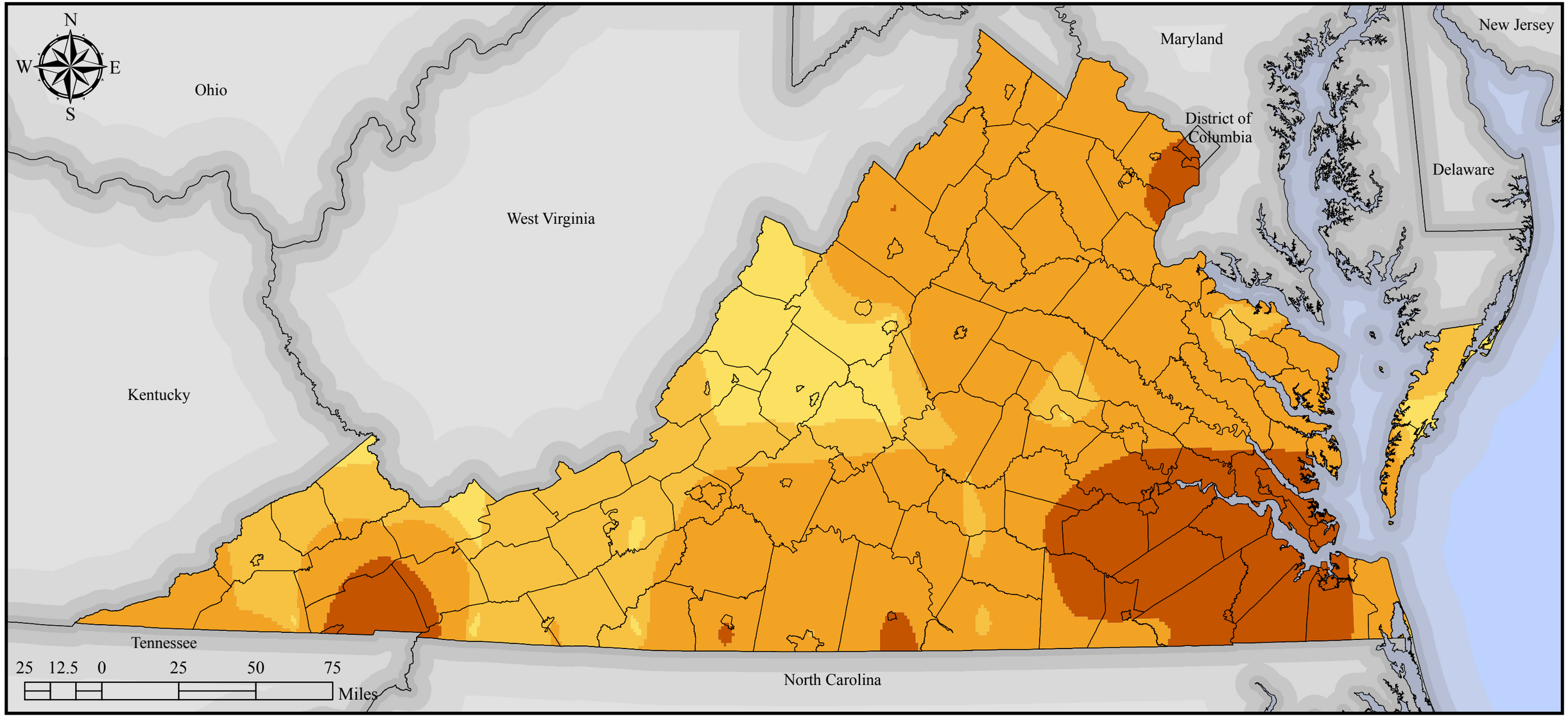
0 - 1.25	Low
1.251 - 10	Medium-Low
10.1 - 100	Medium-High
100.1 - 316	High

HAZARD IDENTIFICATION:

Annual tornado hazard frequency is an estimate of the frequency with which a point will experience a tornado, interpolating from neighboring tornado impact areas over the historical period of record. This map shows hazard frequency of any intensity of tornado. Note that "high" frequency in the state of Virginia is still rather low in comparison to many midwestern and southern states.

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.

Figure 3.8b-3: Historical Significant Tornado Hazard Frequency (F2+)



Center for Geospatial Information Technology

VIRGINIA DEPARTMENT OF EMERGENCY MANAGEMENT

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

DATA SOURCES:

SVRGIS
VGIN Jurisdictional Boundaries
ESRI State Boundaries

LEGEND:

Annual Tornado Hazard Frequency
Times One Million

0 - 1.25	Low
1.251 - 10	Medium-Low
10.1 - 100	Medium-High
100.1 - 252	High

HAZARD IDENTIFICATION:

Annual tornado hazard frequency is an estimate of the frequency with which a point will experience a tornado, interpolating from neighboring tornado impact areas over the historical period of record. This map shows hazard frequency of "significant" tornadoes, defined as F2 or greater. Note that "high" frequency in the state of Virginia is still rather low in comparison to many midwestern and southern states.

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.

Impact and Vulnerability

Tornado vulnerability is based on building construction materials and standards, availability of safe rooms, and advanced warning system capabilities. Low-intensity tornadoes may not completely destroy a well-constructed building, although even the most well-constructed buildings are vulnerable to the effects of a more intense (F2 or higher) tornado. In cases involving intense tornadoes, the best defense against injury or death is a properly engineered safe room or tornado shelter.

Tornadoes are high-impact, low-probability hazards. The net impact of a tornado depends on the storm intensity and the vulnerability of development in its path. An intensity-damage relationship for tornadoes would need to consider a variety of variables, and such a relationship has not been established for Virginia. Theoretically, an intensity-damage relationship could be estimated based on an analysis of reported damages, but such an analysis was beyond the scope of this planning process. In FEMA's Benefit Cost Toolkit the calculations to determine whether tornado shelter construction is justified are based on injuries and deaths prevented, not total economic loss[9]. This approach was based on relationships between injuries/deaths, tornado F-scale, and basic building construction type.

Risk

A formal calculation of annualized tornado risk, as a function of probability and impact, has not been performed for this analysis. Tornado probability has been quantified in terms of historical hazard frequency, and despite concerns regarding population bias in the original reporting, the results of the tornado hazard frequency analysis provide a reasonable estimation of the relative tornado hazard probability across the state. However, tornado impact has not been quantified in the form of an intensity-damage relationship that could be used for tornado damage prediction.

Rough estimates of annualized losses due to tornadoes can be generated based on the NCDC Storm Events database, which documents the damage costs associated with many tornadoes. In the 19 years from 1993 through 2011, NCDC reports an annual average of about $21 million per year (all dollars expressed in inflation-adjusted 2011 dollars).

Tornado hazard zones were developed from the annual tornado hazard frequency results. This scoring system, as shown in Table 3.8b-3, is used to identify facilities "at risk", and to identify the jurisdictions exposed to the greatest tornado hazards.

[9] FEMA. "Supplement to the Benefit-Cost Analysis Reference Guide. June 2011. http://www.fema.gov/benefit-cost-analysis

Table 3.8b-3: Tornado hazard frequency scores

Tornado Hazard Zone	Annual Tornado Hazard Frequency (times 1 million)
Low	<1.25
Medium-Low	1.25-10
Medium-High	10-100
High	100-316

State Facility Risk

State facility risk was determined by intersecting the VAPS facilities with the Annual Tornado Hazard Frequency layer. Risk for building polygons was determined by taking the area weighted average for the building and assigning a risk category based on the results. Intensity-damage information due to tornadoes has not been quantified at this time; as a result annualized loss estimates have not been calculated for state facilities.

As shown in Table 3.8b-4, when these categories are applied to the Virginia state-owned/operated facilities database (VAPS), a large number of facilities are identified as being in the medium-high and high tornado hazard zones. Since the more urbanized eastern portions of the state are also the areas of higher tornado hazard, these results are not surprising.

Table 3.8b-4: State facilities in tornado hazard zones

Tornado Hazard Zone	Number of State Facilities	Total Building Value
Low	59	$61,036,978
Medium-Low	1,549	$3,085,340,258
Medium-High	6,184	$8,287,287,561
High	5,201	$11,195,704,078
Total	**12,993**	**$22,629,368,875**

The results of this analysis indicate 5,201 buildings are at high risk for tornados. A total of 150 different state agencies are situated within a high risk zone. The top five agencies by building value have been listed in table 3.8b-5. The agencies listed represent 14.3% of the buildings and 54.3% of total building value that is within a high risk zone.

Table 3.8b-5: The top five agencies in a high risk zone

Agency	Number of Buildings in High Hazard	Building Value in High Hazard
Virginia Commonwealth Uni-Academic Division	190	$1,573,954,598
George Mason University	152	$1,549,399,094
The College of William and Mary	210	$1,493,834,727
Old Dominion University	143	$832,500,001
Department of General Services	48	$628,599,085
Total	**743**	**$6,078,287,505**

Critical Facility Risk

Critical facilities were intersected with the Annual Tornado Hazard Frequency layer to determine the corresponding risk zone. The results of this analysis are in table 3.8b-6. A large number of education and emergency response services are identified as being in the Medium-High or High tornado hazard zones. Approximately 53% of critical facilities are located in high tornado hazard zones. Intensity-damage information due to tornadoes has not been quantified at this time; as a result annualized loss estimates have not been calculated for critical facilities.

Table 3.8b-6: Critical facilities in tornado hazard zones

Tornado Zones	Law Enforcement	Transportation	Public Health	Emergency Response	Education	Total
Low	0	0	0	0	0	**0**
Medium-Low	72	6	54	261	176	**569**
Medium-High	291	27	436	1,240	1,052	**3,046**
High	299	23	585	1,338	1,813	**4,058**
Total	**662**	**56**	**1,075**	**2,839**	**3,041**	**7,673**

Tornado Risk to Energy Pipelines

Severe wind associated with tornadoes can affect pipelines by damaging the infrastructure that supports pipeline operations such as power and telephone and satellite communications. Some pipelines require above ground facilities for their operations, like pump stations. Wind can damage these facilities, causing pipelines to be shutdown. In addition, severe wind events can make pipeline operation sites inaccessible, making it more difficult to fix the damaged equipment and restore operations. In some cases, pipeline operators may proactively shutdown pipeline operations prior to the onset of severe weather, to mitigate potential damages; this may cause supply interruptions.

Jurisdictional Risk

The jurisdictional tornado hazard rank is based on NCDC Storm Events database parameters, as well as the tornado hazard frequency analysis. The "geographic extent" score for a given jurisdiction is higher in areas with a higher tornado hazard frequency. These scores were assigned by calculating the area-weighted average tornado hazard frequency in each jurisdiction, and then applying the scoring system in Table 3.8b-3. Figure 3.8b-4 shows maximum geographic extent, as well as the other parameters, for tornado events on a countywide basis.

The overall tornado hazard rankings for jurisdictions in the Commonwealth were based on the geographic extent scores, population, and measures of historical impact from NCDC including property damage, crop damage, and deaths and injuries. The overall Tornado hazard rank for the Commonwealth, shown in Figure 3.8b-5, shows that the jurisdictions facing the greatest tornado risk are mostly in the eastern and northern parts of the state, although a few jurisdictions in southern and southwest Virginia also receive an elevated risk rating. Some jurisdictions were not classified as being "high" risk to tornadoes in 2010 plan, but recent tornado events in these jurisdictions have elevated them to this ranking (for example, Gloucester, Washington, and New Kent Counties).

The jurisdictions with a "high" tornado risk include:

- Loudoun County
- King George County
- Augusta County
- Fauquier County
- Gloucester County
- Washington County
- Chesterfield County
- Isle of Wight County
- Prince William County
- Dinwiddie County
- City of Fredericksburg
- Stafford County
- James City County
- Fairfax County
- Prince George County
- City of Alexandria
- Arlington County
- City of Petersburg
- Nottoway County
- City of Hampton
- City of Newport News
- City of Richmond
- Hanover County
- Henrico County
- City of Virginia Beach
- New Kent County
- City of Colonial Heights
- City of Manassas
- York County
- Henry County
- City of Hopewell
- City of Suffolk
- City of Fairfax
- City of Chesapeake
- City of Portsmouth
- City of Norfolk
- Albemarle County
- Spotsylvania County

Tornadoes occur almost every year in Virginia, and their incidence is significantly higher in the south-eastern and northern parts of the state. Although some jurisdictions may have few (or no) reported tornadoes in the historical record, tornadoes can still possibly occur in these jurisdictions.

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.

Twenty-three of the twenty-five local plans gave tornado a hazard rank and provided a general description of tornados, statistics and impacts. Some of the plans included tornado in the "wind" hazard for their region. A lot of ambiguity exists in how jurisdictions define specific hazards. This variability can drastically impact how the local plans are compared to each other; section 3.6 further addresses this issue.

Nine plans calculated annualized loss for tornado using the NCDC storm events database. The NCDC database was also used in the ranking for this revision. Table 3.11-7 compares the local and statewide loss values. Since both the local and statewide revision used NCDC one would assume that the values should be identical. The difference in the loss estimates can be attributed to several factors including the time period of the events. The statewide analysis uses events from 1951 through 2011, and the local plan updates were all completed at various times. NCDC used many different storm event categories in their database. The categories used in this analysis are fully described in section 3.3 and in Table 3.3-4; the categories used by the local plans were not provided.

Table 3.8b-7: Comparison of local plan and statewide annualized loss

PDC/Jurisdiction	Annualized Tornado Loss	
	Local Plan	2013 State Plan
Richmond and Crater	$2,924,370	$3,389,021
Northern Virginia	$2,612,298	$2,793,672
West Piedmont	$2,419,102	$2,447,041
Lower Peninsula	$605,884	$583,774
Rappahannock-Rapidan RC	$500,600	$511,282
Southside Hampton Roads	$614,377	$935,229
Commonwealth RC (Virginia's Heartland)	$126,783	$538,973
City of Franklin	$9,091	$0
Southampton County	$5,733	$26,731

Comparison with Local Ranking

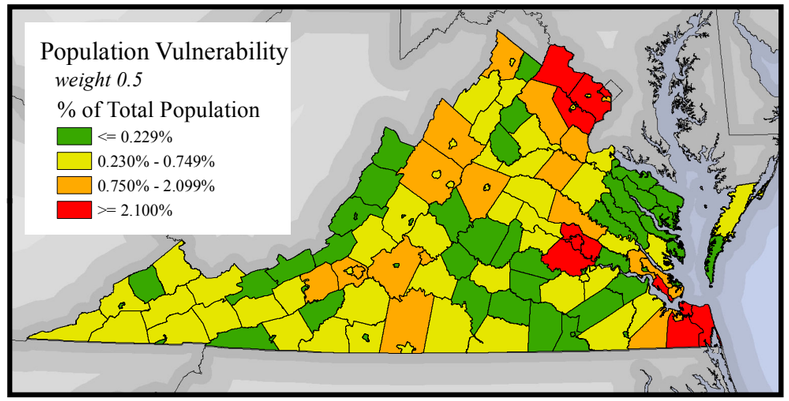
The Northern Virginia, Commonwealth Regional, George Washington, Northern Shenandoah Valley, and the City of Chesapeake plans ranked tornado as a high hazard, and the Lower Peninsula regional plan ranked tornado as a medium-high hazard.

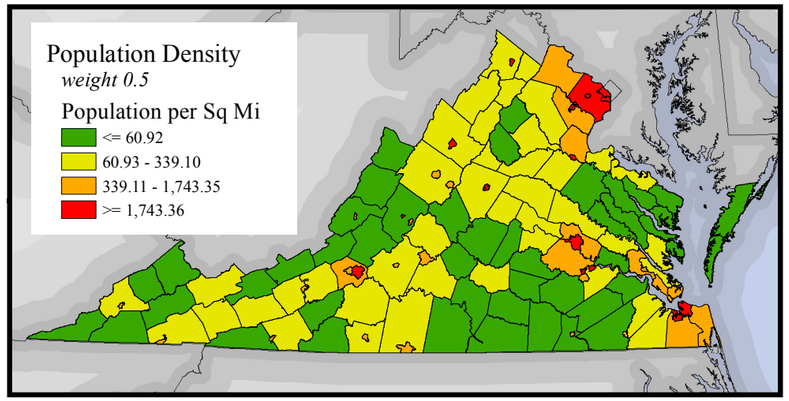
Overall, 5 PDC/local plans ranked tornado as high, one as medium-high, eight as medium, one as medium-low, and eight as a low hazard. The average of the local plans for tornado was medium. The 2013 statewide analysis has ranked tornado medium-high. Section 3.6 (Table 3.6-2) includes the complete ranking of all the local plans.

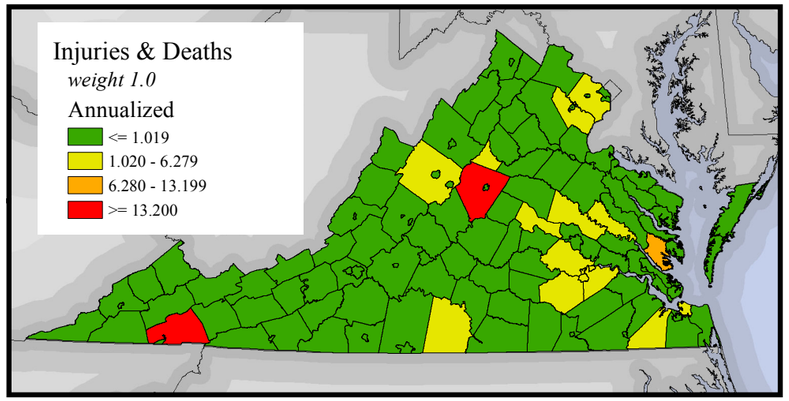
Changes in Development

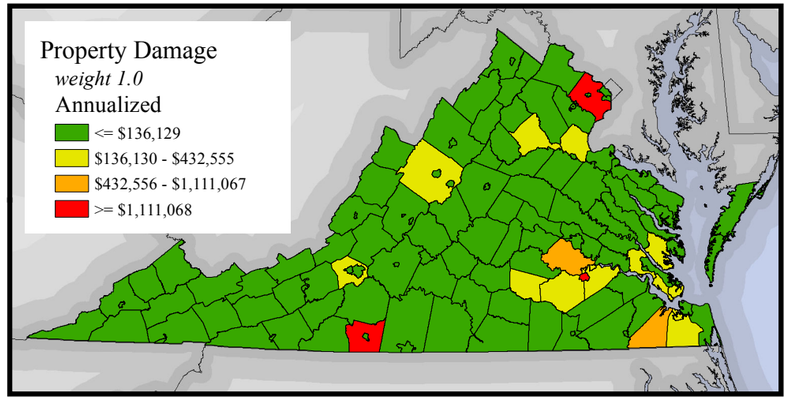
The majority of local plans did not specifically address changes in development for each hazard or the effects of changes in development on loss estimates. In most cases overall development patterns were discussed in general. Sixteen of the twenty-five local plans cite their comprehensive plans for current and future land use changes (section 3.2). No local plan addressed how or if tornado hazards are considered for changes in development.

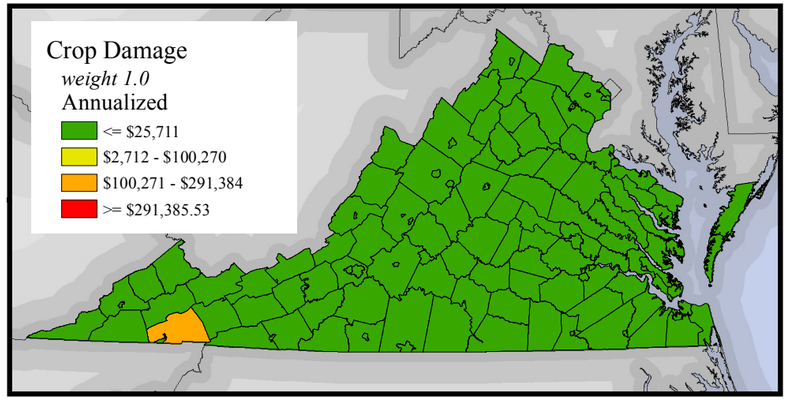
Figure 3.8b-4: Tornado Hazard Ranking Parameters and Risk Map

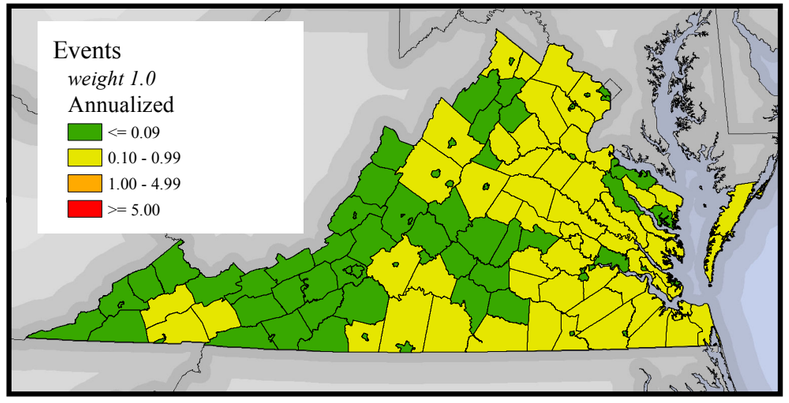


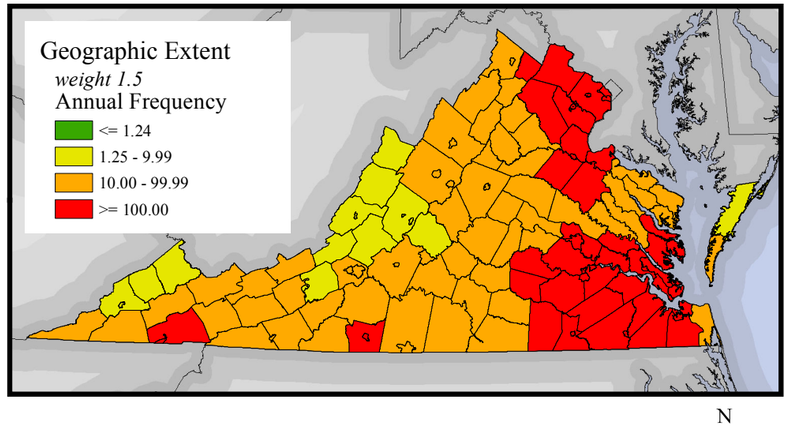


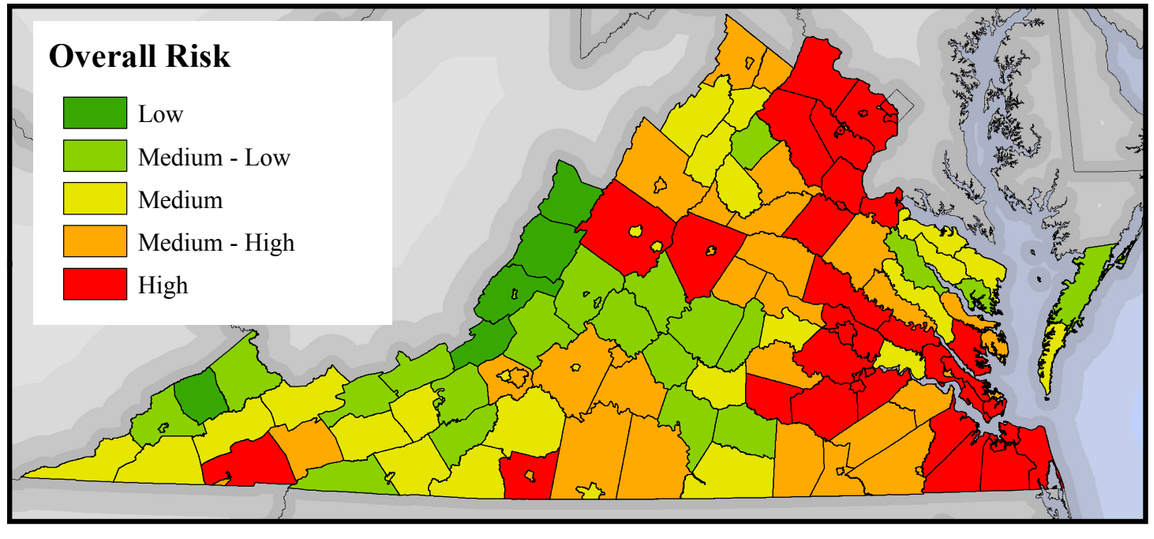












HAZARD RANKING:

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

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.

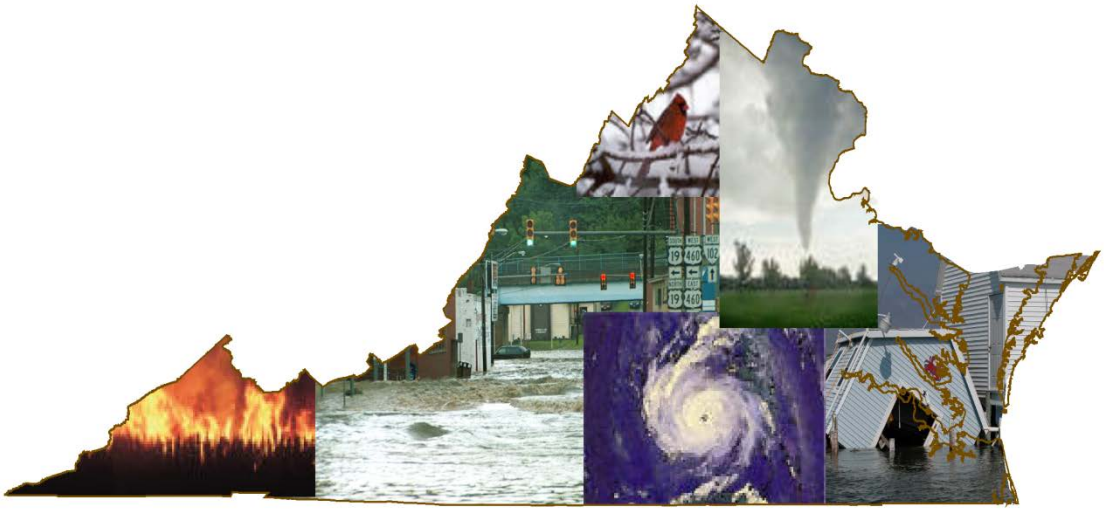
Table 3.8b-8: EMAP Analysis

Subject	Detrimental Impacts
Health and Safety of Public	Localized impacts are expected to be severe for the event area, and moderate for the outlying areas.
Health and Safety of Response Personnel	Localized impacts could be serious as local responders are working within the impacted area, if they live within the impacted area then they may be displaced for an extended period of time.
Continuity of Operations	Damage to facilities/personnel in the area of the event may require temporary relocation of some operations.
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 severe for the impacted areas, soil stability impacted, area likely to be vulnerable to landslides. With a high potential for debris, HAZMAT may be an issue.
Economic and Financial Condition	Local economic and financial conditions may be impacted for a long period of time depending on duration and geographical area of the event, as well as the size and capabilities of the local jurisdiction.
Public Confidence in the Jurisdiction's Governance	Ability to respond and recover may be questioned and challenged if planning, response, and recovery time is not sufficient

Table was modeled from the Missouri State Hazard Mitigation Plan

COMMONWEALTH OF VIRGINIA

Hazard Mitigation Plan



Chapter 3
Hazard Identification and Risk Assessment (HIRA)

Appendix 3.8c – Tornado Hazard Frequency Analysis

Appendix 3.8c: Tornado Hazard Frequency Analysis

John Hart, at the National Weather Service Storm Prediction Center in Norman Oklahoma, has developed a graphical program, SeverePlot[1], to display a database of tornado occurrence that was derived from the NCDC Storm Events Database. This database dates from 1950 to 2006, and also contains data on hail and high wind. Bryan Smith, as an intern with the National Weather Service in Indianapolis, has converted the SeverePlot program data into shapefiles which are ready to use in GIS software; these files are collectively referred to as SVRGIS.[2] Other researchers have developed tornado databases extending further back into history, or which contain additional attributes. However the SVRGIS dataset, based on SeverePlot data, was sufficient for the purpose of this analysis.

Within the SVRGIS dataset are two representations of tornadoes: tornado touchdown points and tornado track polylines. Both representations are based on a common database table which contains fields for tornado date, time, F-scale, length, width, area, touchdown coordinates, and liftoff coordinates. All tornado records in the database contain at least a touchdown location; those events with distinct touchdown and liftoff coordinates are represented with track polylines. Some tornado tracks in the database are quite long, crossing multiple counties. These long tracks may not refer to a single tornado, but rather, a group of similar tornadoes spawned from a single storm.

The geographical variation in tornado frequency was assessed on a grid system, with estimates of tornado frequency developed within each grid cell. These calculations are performed on an annual basis using a formula following after Schaefer (1986)[3]:

$$P = \frac{\sum_{i=1}^{n} T_i}{AY}$$

Where:
P = annual tornado hazard probability (or frequency) in analysis cell
T_i = damage area of ith tornado
A = area of analysis cell
Y = total number of years (period of record)

This formula is based not only on the number of tornadoes occurring in each analysis cell, but also on the area affected by the tornadoes in each cell. The result of this calculation, the annual tornado hazard frequency, is an estimate of the frequency with which any (and every) point in the analysis cell is impacted by a tornado.

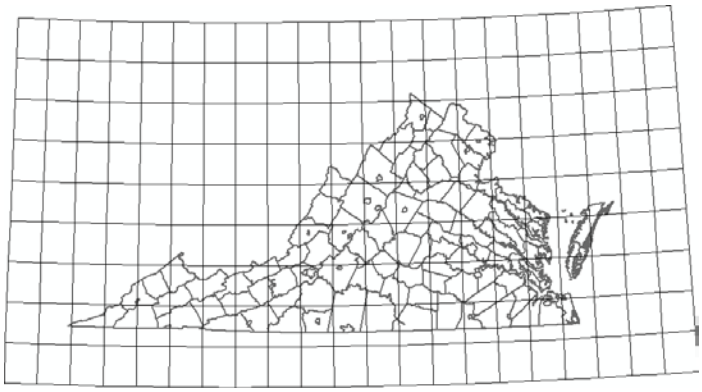


Figure 1: Analysis grid overlaid on Virginia

[1] The current version of this software is available online at: http://www.spc.noaa.gov/software/svrplot2/
[2] The current collection of SVRGIS data is available online at: http://www.crh.noaa.gov/ind/?n=svrgis
[3] Schaefer, J.T., Kelly, D.L., and Abbey, R.F. (1986). A Minimum Assumption Tornado-Hazard Probability Model. *Journal of Climate and Applied Meteorology*, Vol. 25, December 1986, pp 1934 – 1945.

The tornado hazard frequency in a given analysis cell will be higher if the historic tornadoes cover larger areas, reflecting the fact that a few very large tornadoes would impact more area than multiple smaller tornadoes.

Application of this formula requires an analysis grid, and a method for determining tornado damage area within each grid cell. An arbitrary grid based on geographic coordinates, akin to so-called "Marsden squares", was used for the analysis in this report, with grid cells measuring 0.5° on each side (refer to Figure 1). This results in planimetric areas of approximately 945 square miles per grid cell, although the actual area of such geographic "squares" varies with location.

Vector-based geometric intersection was the method selected for determining tornado damage area within each grid cell. In the SVRGIS data, the tornadoes represented only as touchdown points could potentially be analyzed with either raster or vector methods; however, to handle the tornadoes represented with track polylines, the vector-based geometric intersection method was easier to conceptualize. For those tornadoes with track polylines, each polyline was buffered to form a tornado track polygon that follows the path of the track. These tornado track polygons were intersected with the analysis cells to determine the portion of the tornado damage area that should be allocated to each analysis cell (especially important in the case where a tornado tracks across multiple analysis cells. Thus, the overall tornado damage area in each analysis cell was calculated as the sum of the damage areas from tornadoes reported as touchdown points, plus the sum of the damage areas from tornadoes reported as tracks (considering only the fraction of the total tornado damage area corresponding to the portions of the tracks within the analysis cell). Figure 2 illustrates the tornado damage areas from touchdown points and track polygons in an analysis cell.

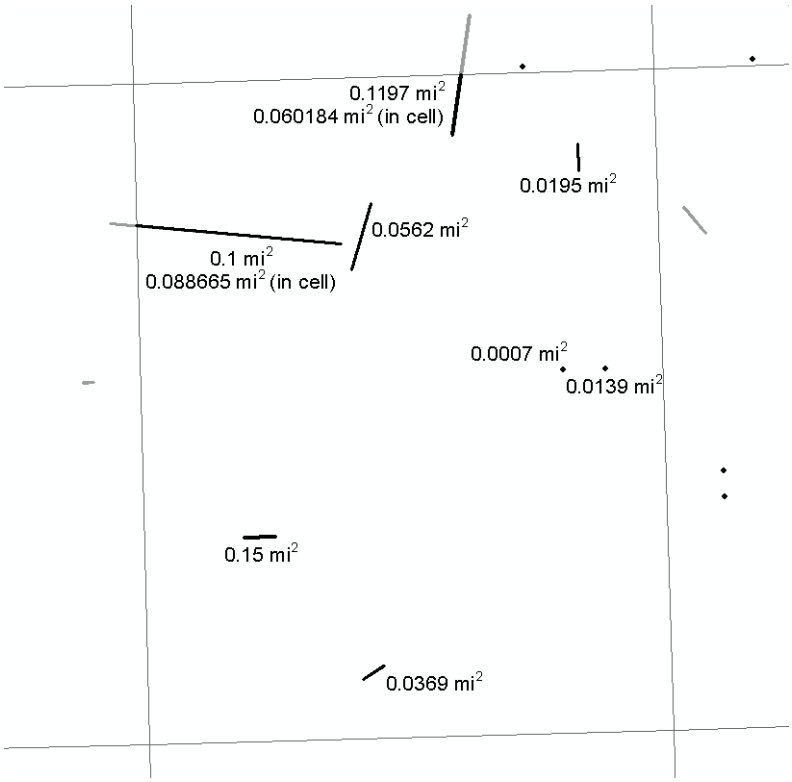


Figure 2: Tornado hazard areas within a sample analysis cell (track polygons appear as lines due to image scale)

To be clear, the tornado damage areas summed in each analysis cell are the areas (in square miles) reported in the original SVRGIS attribute tables. Despite the fact that the tornado track polygons have areas that

correspond to the original area in the SVRGIS attributes, the areas of these polygons varies somewhat due to the lack of precision in the touchdown and liftoff coordinates used in constructing the spatial representation. So, rather than using the area of the actual track polygon falling within the cell, the track polygon area falling in the cell was used to calculate the fraction of the total area of that tornado event which should be allocated to the analysis cell. This ensures that the total damage area reported in the original SVRGIS attributes is preserved.

The annual hazard frequency of each tornado intensity class (F-scale) was calculated separately; these results are added together to depict the overall tornado hazard frequency. In calculating the F0 and F1 intensity hazard frequencies, the 1985 – 2006 subset of the SVRGIS dataset was used, as this period was estimated to be more representative of the true frequency of these low-intensity tornadoes. In calculating the F2 and F3+ intensity hazard frequencies, the entire period of record (1950 – 2006) was used, as the reported frequency of occurrence has not changed noticeably over time.

An unfortunate result that is inherent in this hazard frequency approach is the treatment of analysis cells with no observed tornadoes: in these cells, the annual tornado hazard frequency is calculated to be exactly zero. While tornadoes could still theoretically occur, there is simply no information from which to estimate the hazard frequency in these cells. This is due primarily to the extreme improbability of a tornado at this location, as well as the lack of observers to witness historical tornadoes which may have occurred.

Virginia annual tornado hazard frequencies were calculated in each analysis grid cell, for tornado intensities F0, F1, F2, and F3+. These calculations were facilitated in part by a geoprocessing model that handled the intersection and area summarization calculations. The inputs to this model were a filtered subset of the tornado touchdown point and track polygon files (filtered by period of record, intensity level, and processed to ensure that each event is represented by either a touchdown point or a track –not both). The output of the model is a summary table that reports the tornado hazard area in each analysis grid cell. From these summary statistics, the corresponding annual hazard frequency values were calculated, and then joined to a dataset of the analysis cell centroids.

In calculating these annual hazard frequencies, a multiplier of one million was added to make the results easier to read. When interpreting these results, for example, a value of 1 actually means that the annual tornado hazard frequency at a point is 1 divided by 1 million, or 0.000001 – essentially, assuming that past trends prove true, that there would be a 1 in 1 million chance that a given point would experience a tornado in a given year. The annual tornado hazard frequency values can be displayed graphically by color coding the analysis cells according to their frequency values. Alternatively, the results may also be interpolated to a smoothed raster using various techniques, although such products can sometimes convey an artificially high sense of precision.