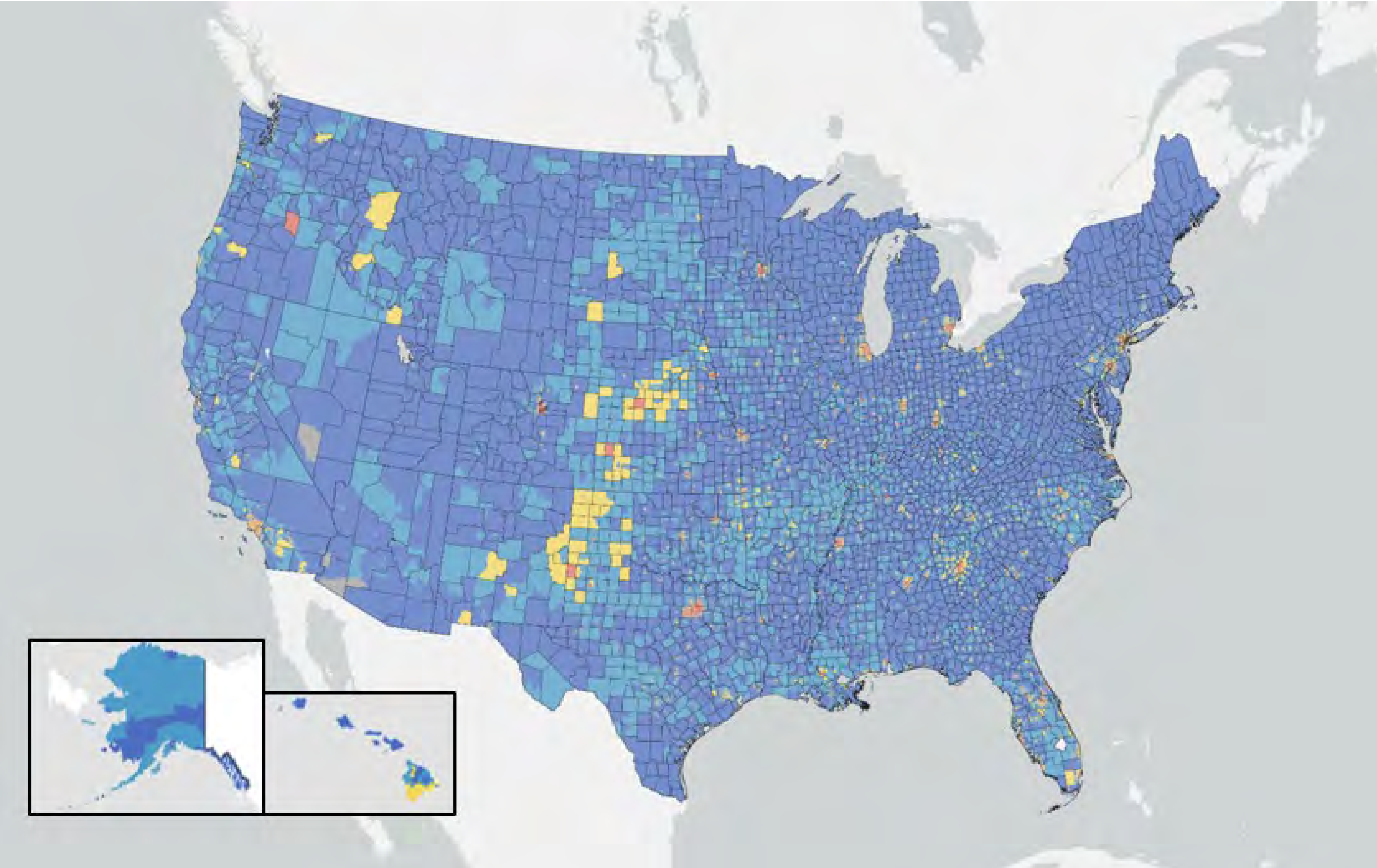

National Risk Index

Technical Documentation

December 2020

FEMA

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Acknowledgements

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1 Introduction

The National Risk Index (NRI) is a dataset and an application that help identify communities most at risk for natural hazards. The NRI leverages available source data for 18 natural hazards, social vulnerability, and community resilience to develop a baseline relative risk measurement for each United States county and Census tract. The NRI is intended to help users better understand the natural hazard risk of their communities or assigned areas. Intended users include planners and emergency managers at the local, regional, state, and federal levels, as well as other decision makers and interested members of the general public. Specifically, it can support decision making to:

- Update emergency operations plans
- Enhance hazard mitigation plans
- Prioritize and allocate resources
- Identify the need for more refined risk assessments
- Encourage community-level risk communication and engagement
- Educate homeowners and renters
- Support enhanced codes and standards
- Inform long-term community recovery

This report provides a detailed overview of the National Risk Index, including its background, data sources, and processing methodologies. It describes the high-level concepts used to develop the NRI and calculate its components. The methodologies for computing each hazard's Expected Annual Loss (EAL) are also explained in depth in the final sections of this report (*Sections 6 through 23*).

2 Background

All communities in the United States experience natural hazards, and there is a wide range of environmental, social, and economic factors that influence each community's risk to natural hazards. The likelihood that a community may experience a natural hazard can vary drastically, as can the associated consequences. Additionally, a community's risk is influenced by many social, economic, and ecological factors. FEMA, along with numerous federal, state, and local governments, academic institutions, nonprofit groups, and private industry (see *Figure 1*) collaborated to develop the National Risk Index as a baseline risk assessment application.

Beginning in 2016, FEMA's Natural Hazards Risk Assessment Program (NHRAP) started work on the NRI by adopting an established vision for a multi-hazard view of risk that combines the likelihood and consequence of natural hazards with social factors and resilience capabilities. The goal was to take a broad, holistic view and create a nationwide baseline of natural hazard risk. Through various partnerships and working groups, FEMA developed a methodology and procedure to create the NRI dataset, and then researched, designed, and built the NRI website and application.

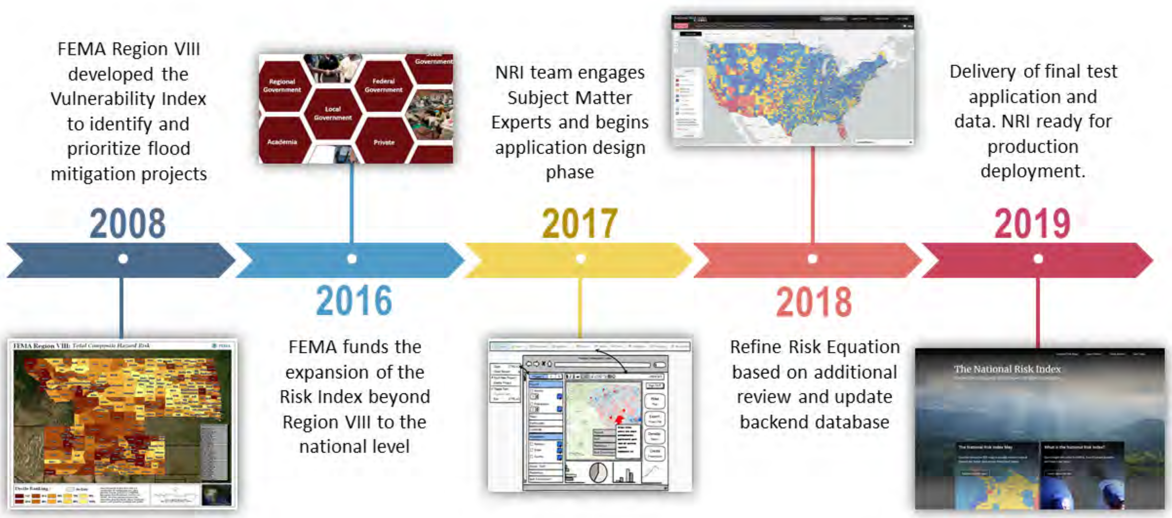

Figure 1: Timeline of the Development of the National Risk Index

The NRI Team conducted multiple workshops and sessions to discuss and determine the methodologies for translating raw source data into natural hazard risk factors for input into the NRI. The key objective of these exercises was to ensure that a vetted risk model or equation was leveraged throughout all methodological development and that certain factors were not being interpreted inconsistently across the 18 natural hazards.

2.1 Natural Hazard Selection

Natural hazard exposure across the country varies from location to location. The 18 natural hazards evaluated by the NRI were chosen after reviewing FEMA-approved State Hazard Mitigation Plans for all 50 states. Tribal hazard mitigation plans were not available at the time of the analysis, and island territories were excluded from the hazard selection process since data for most NRI hazards are not available. Note that Washington, DC, was initially excluded from the hazard selection analysis process; however, it was added to the project scope in 2017 after the hazard selection.

Natural hazards that were included in at least half of the FEMA-approved state plans, or those that were deemed to be of regional significance, were selected to the NRI (see *Figure 2*). A regionally significant hazard is defined as having the capacity to cause widespread, catastrophic damage, such as Hurricanes, Tsunami, and Volcanic Activity, but otherwise affected fewer than 25 states. It should be noted that one natural hazard, Subsidence, fit these criteria, but could not be evaluated by the NRI as there was no reliable, nationwide dataset cataloging this type of hazard event.

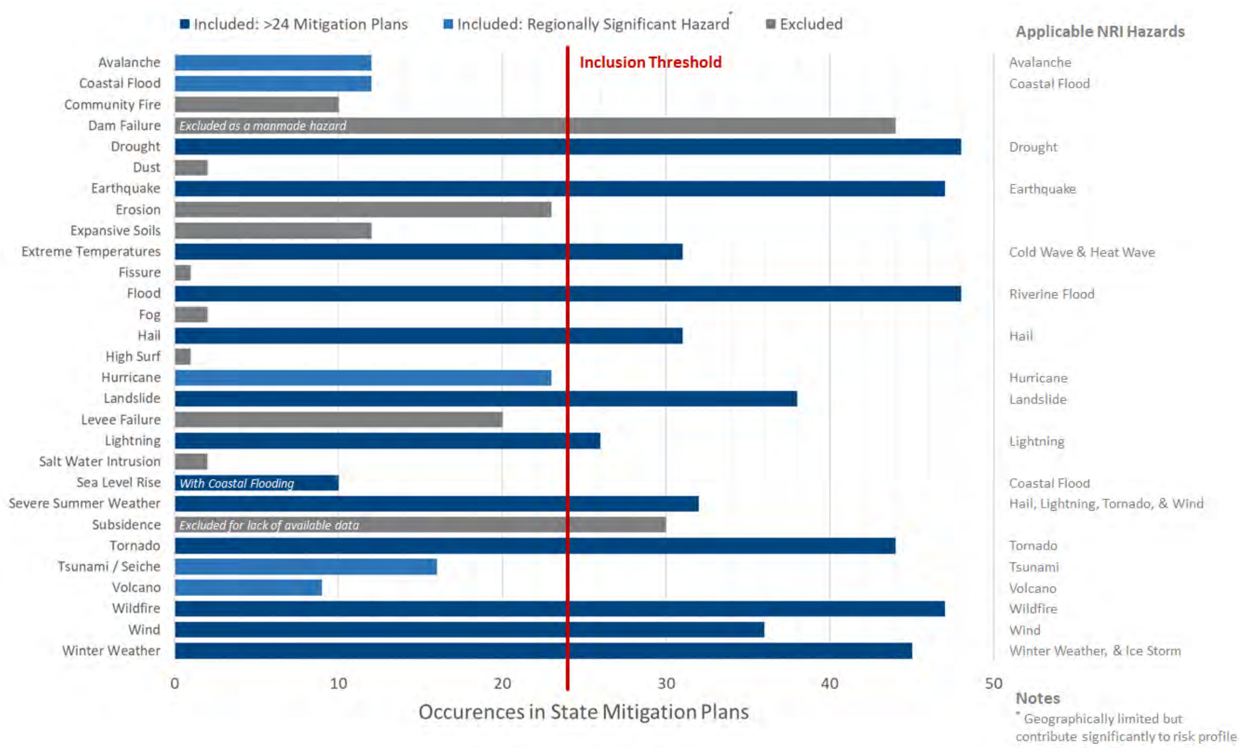

Figure 2: Determination of Hazard Inclusion Based on State Hazard Mitigation Plans

The State Hazard Mitigation Plan review revealed that both Dam Failure and Levee Failure hazards are profiled by many states, but the datasets needed to develop the EAL component of NRI are not nationally or publicly available. A levee analysis may be incorporated into the riverine or flood component if these manmade features are not included on floodplain maps or reflected in National Oceanic and Atmospheric Administration (NOAA) storm surge and coastal flood analysis. These hazards should not be discussed from traditional risk assessment. The State Hazard Mitigation Plan hazard analysis was completed in early 2016 and was limited to the FEMA-approved State Hazard Mitigation Plans. No territorial or tribal plans were reviewed due to their limited availability.

2.2 Working Groups

After a detailed literature review and hazard analysis, the NRI Team convened three working groups made of intended users, subject matter experts (SMEs), and interested stakeholders from all levels of government, private industry, nonprofits, and academia. Each working group was responsible for an aspect of the NRI's development and methodology. Experts in each group helped guide the NRI data and application development.

The Natural Hazards Working Group assessed and recommended datasets associated with the identified 18 natural hazards selected (as well as Subsidence prior to its recommended removal) and determined the best ways to incorporate associated data into the NRI.

The Social Vulnerability and Community Resilience Working Group reviewed and evaluated existing efforts to measure social vulnerability and community resilience to understand which components were most important (vulnerability or resilience, or both) and which indices should be used in the NRI. As a result, both Social Vulnerability and Community Resilience are components of the NRI.

The Data Analytics Working Group oversaw the spatial processing, normalization, and aggregation of data to arrive at a risk indexing methodology and calculation procedure that integrated the datasets identified by the other two working groups.

Together, the groups discussed and developed the National Risk Index, including the datasets and indices to incorporate, definitions of index components, data management strategies, metadata requirements, data processing and index creation methodologies, and the data visualization and interactive web mapping application requirements.

2.3 Literature Review

The NRI's project team reviewed literature in the fields of hazard mitigation, emergency management, hazard risk science, and other related fields. Centering around a search for natural hazard and exposure variables, the literature review identified multiple datasets, risk indices, research reports, methodologies, indicator lists, and existing risk assessment at national and global scales.

The team identified important risk indicator categories and specific indicators during the review (see *Table 1*).

Table 1: Literature Review Risk Indicators and Categories

Risk Indicator Categories	Personal Risk Indicators	
• Social • Economic • Environmental • Infrastructure	• Income • Age • Illnesses • Hospitals	• Road Systems • Economic Productivity • Housing • Community Revenue

After review, the team concluded the NRI would involve three components: natural hazard risk (likelihoods and consequences), social vulnerability, and community resilience.

2.4 Subject Matter Expert Review

Extensive development of the NRI began in 2017 and proceeded through the end of 2019. Over this period, the NRI team continually iterated on their data processing and risk calculation methodologies, and engaged with SMEs throughout. See *Appendix A – Contributors* for the full list of organizations whose members contributed to the SME reviews.

At major milestones, the team paused development to engage in broader, more comprehensive SME review periods. The first major milestone arrived in January 2019 where teams of SMEs were tasked to evaluate two competing draft methodologies: “Methodology 1,” which relied on unitless standardization of EAL, and “Methodology 2,” which standardized EAL to a dollar value measurement. Over the course of two weeks and many meetings, dozens of SMEs provided feedback to the NRI team, resulting in a clear consensus that although both methodologies were valid, Methodology 2 created a more robust measurement of risk and a more valuable dataset for the hazard planning and mitigation communities.

With clear direction on the methodology, the NRI team continued iterating through improvements to data sourcing and processing. From July through September 2019, they conducted a final comprehensive SME review period to focus on the new methodology’s results. More than 40 SMEs participated in over 20 review sessions and helped the team reach concurrence on the validity and value of the dataset. From these sessions, the NRI team was equipped to begin final iterations of the methodology and source data processing.

2.5 Data and Methodologies

Over the course of several years, with the help of hundreds of collaborators and contributors, and through unknown iterations of planning, design, and development, the NRI working groups concluded their work by reviewing and providing feedback on an iterative version of the National Risk Index dataset (December 2019).

Briefly stated, the NRI is a first-of-its-kind, nationwide, holistic assessment of baseline risk to natural hazards. Although it is based on extensive research and best practices in the risk assessment fields, the NRI’s methodology is unique and carefully constructed the specific needs of natural hazard risk assessment at both small and large geographic scales. A detailed overview of the risk calculation is available in *Section 3.1*.

The NRI's most important and central component, Expected Annual Loss (EAL), is a robust measurement that quantifies the anticipated economic damage resulting from natural hazards each year. Details of its equation and analytical techniques are available in *Section 4.3*. EAL consists of the best available datasets for 18 natural hazards of national and regional significance, with source data being processed to match the unique nature of each natural hazard. Full processing details for each hazard are available in *Sections 6 through 23*. Per the direction established at initiation, the dataset also includes measurements of social vulnerability and community resilience to quantify overall risk. These key components are detailed fully in *Section 4.1* and *Section 4.2*, respectively.

3 Risk Analysis Overview

Risk, in the most general terms, is often defined as the likelihood (or probability) of a natural hazard event happening multiplied by the expected consequence if a natural hazard event occurs. The generalized form of a risk equation is given in *Equation 1*.

Equation 1: Generalized Risk Equation

$$Risk = Likelihood \ x \ Consequence$$

3.1 Risk Calculation

In the National Risk Index, risk is defined as the potential for negative impacts as a result of a natural hazard. The risk equation behind the NRI includes three components: a natural hazards component, a consequence enhancing component, and a consequence reduction component. EAL is the natural hazards risk component, measuring the expected loss of building value, population, and/or agricultural value each year due to natural hazards. Social vulnerability is the consequence enhancing component and analyzes demographic characteristics to measure the susceptibility of a community's social groups to the adverse impacts of natural hazards. Community resilience is the consequence reduction component and uses demographic characteristics to measure a community's ability to prepare for, adapt to, withstand, and recover from the effects of natural hazards. These three risk components are combined into one risk value using *Equation 2*.

Equation 2: NRI Risk Equation

$$Risk = \ Expected \ Annual \ Loss \ \times Social \ Vulnerability \times \frac{1}{Community \ Resilience}$$

An overall composite Risk Index score and individual hazard Risk Index scores are calculated for each county and Census tract included in the NRI. A composite Risk Index score measures the relative risk of a location considering all 18 natural hazards included in the index. An individual hazard Risk Index score measures the relative natural hazard risk of a location for a single natural hazard. All scores are relative as each Census tract or county's score is evaluated in comparison with all other Census tracts or counties.

3.2 Scores and Ratings

In the NRI Risk Equation, each component is represented by a unitless index value that depicts a community's score relative to all other communities. From the three indices, the Risk Index score is calculated to measure a community's risk to all 18 natural hazards. The Risk Index is also a unitless index and represents a community's risk relative to all other communities. The Risk Index and EAL are provided as both composite score from the summation of all 18 natural hazards, as well as individual-hazard scores where each hazard is considered separately.

All calculations are performed separately at two levels-of-details—County and Census tract—so scores are relative only within their level-of-detail. It must be stressed that scores are relative, representing a community's relative position among all other communities for a given component and level-of-detail. Scores are not absolute measurements and should be expected to change over time either by their own changing measurements or changes in other communities.

All scores are constrained to a range of 0 (lowest possible value) to 100 (highest possible value). To achieve this range, the values of each component are rescaled using min-max normalization, which preserves their distribution while making them easier to understand. EAL values are heavily skewed by an extreme range of population and property value densities between urban and rural communities. To account for this, a cube root transformation is applied before min-max normalization. By applying cube root transformation, the NRI controls for this characteristic and provides scores with greater differentiation and usefulness. If the minimum value of the EAL is a nonzero number before normalization, an artificial minimum is set to 99% of that value so that entities expected to experience loss do not receive a 0 EAL score.

For every score there is also a qualitative rating that describes the nature of a community's score in comparison to all other communities, ranging from "Very Low" to "Very High." Because all ratings are relative, there are no specific numeric values that determine the rating. For example, a community's Risk Index score could be 8.9 with a rating of "Relatively Low," but its Social Vulnerability score may be 11.3 with a rating of "Very Low." The rating is intended to classify a community for a specific component in relation to all other communities.

To determine ratings, a methodology known as k-means clustering or natural breaks is applied to each score. This approach divides all communities into groups such that the communities within each group are as similar as possible (minimized variance) while the groups are as different as possible (maximized variance).

In the NRI application's maps and data visualizations, standard color schemes have been applied to the qualitative ratings. Risk Index ratings are represented using a diverging blue (Very Low) to red (Very High) color scheme. Ratings for EAL, Social Vulnerability, and Community Resilience are represented using sequential color schemes (e.g., single color at various intensities). According to the NRI, higher EAL, higher Social Vulnerability, and/or lower Community Resilience increase your overall risk. In general, darker shading in the map layers represents a higher contribution to overall risk. When source data are not available or a score cannot be calculated, then additional ratings are used and shown in white or shades of gray. The NRI's standard color schemes are shown in *Figure 3*.

Figure 3: National Risk Index Qualitative Rating Legend

Scores of 0 (zero) or missing values (“nulls”) in the EAL components receive ratings that reflect the logic behind the score. A county or tract for which the EAL is zero either has no building value, population, or crop value exposed to the hazard, or has a calculated hazard frequency of zero, except for hazards that apply a minimum annual frequency. These areas are displayed in the NRI application as having “No Expected Annual Loss” for the designated hazard.

In collaboration with SMEs most familiar with individual hazards and the source data used in the NRI, a priori definitions of hazard applicability have also been applied to help distinguish between where no hazard risk exists and where the hazard is deemed to be not possible. For example, Coastal Flooding EAL is not computed for inland areas. These areas are displayed in the NRI application as “Not Applicable” for EAL computation for the designated hazard.

Finally, if a component used to calculate the EAL of a Census tract or county for a hazard has a null value, the community is rated as “Insufficient Data.” For example, certain hazards, such as Wildfire, Lightning, and Landslide, only have source data used to determine frequency or exposure for the conterminous United States, meaning that both Alaska and Hawaii are rated as “Insufficient Data” to compute the EAL for those hazards. When a hazard is not applicable or there are insufficient data for a community, EAL for that hazard is simply not included in the community’s final summation and scoring. A summary of non-numerical ratings is provided *Table 2*.

Table 2: Definitions of Ratings without Numerical Scores

Rating	Risk Index	Expected Annual Loss	Social Vulnerability	Community Resilience
No Rating	EAL is zero, Social Vulnerability and/or Community Resilience data are not available.	n/a	n/a	n/a
No Expected Annual Loss	n/a	Hazard exposure or frequency is zero.	n/a	n/a
Not Applicable	Location is not considered at risk for hazard occurrence.	Location is not considered at risk for hazard occurrence.	n/a	n/a

Rating	Risk Index	Expected Annual Loss	Social Vulnerability	Community Resilience
Insufficient Data	Hazard source data are not available.	Hazard source data are not available.	n/a	n/a
Data Unavailable	n/a	n/a	Social Vulnerability data are not available.	Community Resilience data are not available.

3.3 Assumptions and Limitations

The National Risk Index dataset and application are meant for planning purposes only and are intended for use as a tool for broad, nationwide comparisons. Nationwide datasets used as inputs for the NRI are in many cases not as accurate as locally available data. Users with access to local data for each NRI risk factor should consider substituting those data to calculate a more accurate EAL value at the local level.

The NRI does not consider the intricate economic and physical interdependencies that exist across geographic regions. The user should be mindful that hazard impacts in surrounding counties or Census tracts can cause indirect losses in a location regardless of the location's risk profile.

The NRI's most recent source datasets only include a period of record up to 2017. It should be noted that the EAL values represent an extrapolation based on a snapshot in time. Extending source data collection beyond that time may result in varying Census tract or county EAL values due to changes in recorded hazard intensity and frequency, as well as fluctuations in local economic value and/or population density.

Most of the hazards evaluated by the NRI use a frequency model to determine EAL. This makes it difficult to accurately estimate EAL for high consequence, low frequency events. Certain rare hazards (such as Earthquake, Hurricane, Tsunami, and Volcanic Activity) benefit from using a probabilistic model that estimates the likelihood of a hazard event occurring over an extended period of time, which can then be annualized. Of these, only Earthquake has probabilistic source data that are sufficient for accurately estimating EAL.[1]

Best available nationwide data for some risk factors are rudimentary. More sophisticated risk analysis methodologies are available but require more temporally and spatially granular data for hazard exposure, frequency, and historic loss measurements.

The NRI methodology makes various efforts to control for possible discrepancies in source data but cannot correct for all accuracy problems present in that data. The NRI processing database is a complex system, and localized inaccuracies in source data have the potential to propagate.

[1] Federal Emergency Management Administration (FEMA). (2017). Hazus Estimated Annualized Earthquake Losses for the United States: FEMA Publication 366. Retrieved from https://www.fema.gov/sites/default/files/2020-07/fema_earthquakes_hazus-estimated-annualized-earthquake-losses-for-the-united-states_20170401.pdf.

Therefore, the NRI and its components should be considered a baseline measurement and a guideline for determining hazard risk but should not be used as an absolute measurement of risk.

4 Risk Components Overview

The risk score in the NRI is based on three components: Social Vulnerability, Community Resilience, and EAL, with EAL based on Exposure, Annualized Frequency, and Historic Loss components, for a total of five risk factors. Each risk factor contributes to either the likelihood or consequence aspect of risk and can be classified as one of two risk types: risk based on geographic location or risk based on the nature and historical occurrences of natural hazards. The five risk factors are summarized in *Table 3* and further described in this section.

Table 3: NRI Risk Components

NRI Risk Component	NRI Risk Factors	Risk Factor Description	Risk Equation Bin	Risk Type Assignment
Social Vulnerability	Social Vulnerability	Consequence Enhancer	Consequence	Geographic Risk
Community Resilience	Community Resilience	Consequence Reducer	Consequence	Geographic Risk
Expected Annual Loss	Exposure	Expected Consequence	Consequence	Natural Hazard Risk
Expected Annual Loss	Annualized Frequency	Probability of Occurrence	Likelihood	Natural Hazard Risk
Expected Annual Loss	Historic Loss	Expected Consequence	Consequence	Natural Hazard Risk

4.1 Social Vulnerability

Social vulnerability is broadly defined as the susceptibility of social groups to the adverse impacts of natural hazards, including disproportionate death, injury, loss, or disruption of livelihood. Social vulnerability considers the social, economic, demographic, and housing characteristics of a community that influence its ability to prepare for, respond to, cope with, recover from, and adapt to environmental hazards.

As a consequence-enhancing risk factor, the Social Vulnerability score represents the relative level of social vulnerability for a given county or Census tract. A higher social vulnerability score results in a higher risk score. Because social vulnerability is unique to a geographic location—specifically, a county or Census tract—it is a geographic risk factor.

The Social Vulnerability and Community Resilience Working Group reviewed multiple top-down and bottom-up indices and chose to recommend the University of South Carolina's Hazards and Vulnerability Research Institute (HVRI) Social Vulnerability Index (SoVI).

4.1.1 SOCIAL VULNERABILITY SOURCE DATA

Social Vulnerability source data provider*:* *University of South Carolina's Hazards and Vulnerability Research Institute (HVRI) Social Vulnerability Index (SoVI)*

SoVI is a location-specific assessment of social vulnerability that utilizes 29 socioeconomic variables (listed below) deemed to contribute to a community's reduced ability to prepare for, respond to, and recover from hazards.[2]

▪ Median gross rent for renter-occupied housing units ▪ Median age ▪ Median dollar value of owner-occupied housing units ▪ Per capita income ▪ Average number of people per household ▪ % population under 5 years or age 65 and over ▪ % civilian labor force unemployed ▪ % population over 25 with <12 years of education ▪ % children living in married couple families ▪ % female ▪ % female participation in the labor force ▪ % households receiving Social Security benefits ▪ % unoccupied housing units ▪ % families with female-headed households with no spouse present	▪ % population speaking English as second language (with limited English proficiency) ▪ % Asian population ▪ % African American (Black) population ▪ % Hispanic population ▪ % population living in mobile homes ▪ % Native American population ▪ % housing units with no car available ▪ % population living in nursing facilities ▪ % persons living in poverty ▪ % renter-occupied housing units ▪ % families earning more than $200,000 income per year ▪ % employment in service occupations ▪ % employment in extractive industries (e.g., farming) ▪ % population without health insurance (County SoVI only) ▪ Community hospitals per capita (County SoVI only)

The dataset was acquired from HVRI's SoVI website, and users looking for more information should consult HVRI.

4.1.2 PROCESSING SOCIAL VULNERABILITY SOURCE DATA FOR THE NRI

For the NRI, the SoVI dataset was incorporated using min-max transformation (0.01-100.00 scale). County and Census tract Social Vulnerability scores were classified into five qualitative categories, from "Very Low" to "Very High," using k-means clustering. Social Vulnerability scores are available for all counties, but they are absent for 292 Census tracts that have no population. Risk cannot be calculated for tracts without Social Vulnerability scores, so those Census tracts are rated "Insufficient Data."

[2] Cutter, S.L., Boruff, B.J. & Shirley, W.L. (2003). Social vulnerability to environmental hazards. Social Science Quarterly, 84(2): 242-261. Retrieved from https://doi.org/10.1111/1540-6237.8402002.

4.2 Community Resilience

Community Resilience is defined by FEMA as the ability of a community to prepare for anticipated natural hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions.[3]

There are multiple, well-established ways to define community resilience at the local level, and key drivers of resilience vary between locations. Because there are no nationally available, bottom-up community resilience indices available, the Social Vulnerability and Community Resilience Working Group chose to utilize a top-down approach. The NRI relies on using broad factors to define resilience at a national level and create a comparative metric to use as a risk factor. The Social Vulnerability and Community Resilience Working Group reviewed multiple top-down indices and chose to recommend the University of South Carolina's Hazards and Vulnerability Research Institute (HVRI) Baseline Resilience Indicators for Communities (HVRI BRIC) index.

The Community Resilience score is a consequence reduction risk factor of the NRI and represents the relative level of community resilience for a given location. A higher Community Resilience score results in a lower Risk score. Because Community Resilience is unique to a geographic location—specifically, a county—it is a geographic risk factor.

4.2.1 COMMUNITY RESILIENCE SOURCE DATA

Community Resilience source data provider: *University of South Carolina's Hazards and Vulnerability Research Institute (HVRI) Baseline Resilience Indicators for Communities (BRIC)*

Community resilience data for the NRI are supported by the HVRI BRIC. HVRI BRIC provides a sound methodology for quantifying community resilience by identifying the ability of a community to prepare and plan for, absorb, recover from, and more successfully adapt to the impacts of natural hazards. The HVRI BRIC dataset includes a set of 49 indicators that represent six types of resilience: social, economic, community capital, institutional capacity, housing/infrastructure, and environmental. It uses a local scale within a nationwide scope, and the national dataset serves as a baseline for measuring relative resilience. The data can be used to compare one place to another and determine specific drivers of resilience, and a higher HVRI BRIC score indicates a stronger and more resilient community.

4.2.2 PROCESSING COMMUNITY RESILIENCE SOURCE DATA FOR THE NRI

For the NRI, the HVRI BRIC dataset was in incorporated using min-max transformation (0.01-100.00 scale). Because HVRI BRIC has a potential range of 0.0 to 6.0, but the full range does not exist in the dataset, the normalized score for Community Resilience ranges from 41.2 to 64.7. HVRI BRIC is only available at the county level, so Community Resilience scores were inferred from counties to Census tracts by assigning each Census tract the value of its parent county. Community Resilience scores were classified into five qualitative categories, from "Very Low" to "Very High," using k-means clustering.

[3] National Institute of Standards and Technology (NIST). (2020). *Community Resilience*. Retrieved from: https://www.nist.gov/topics/community-resilience.

For more information on the creation of the HVRI BRIC, please refer to *HVRI's BRIC website* or the *geographies of community disaster resilience paper* published by Cutter, Ash, and Emrich (2014). [4,5]

4.3 Expected Annual Loss

The EAL for each Census tract or county is the average economic loss in dollars resulting from natural hazards each year. EAL is computed for each hazard type and only quantifies loss for relevant consequence types (i.e., buildings, people, or agriculture). For example, most natural hazards only significantly impact buildings and population, so the loss to agriculture is not included in the computation. However, the EAL for Drought only quantifies the damage to crops and livestock (agriculture) in its computation. A consequence type is only included in the EAL computation for a hazard if at least 10% of the total reported economic loss due to the hazard (see *Section 5.4*) is of that consequence type.

All loss is quantified as a dollar amount. While building and agriculture loss are quantified in dollars in the source data, population loss is quantified as the number of fatalities and injuries and must be converted to ensure all EAL values use a common unit of measurement. Population loss is monetized using the value of statistical life approach in which each fatality or ten injuries is treated as $7.4 million of economic loss, an inflation-adjusted Value of Statistical Life (VSL) used by FEMA.[6] To adjust for inflation, all historic losses are converted to 2016 dollars.

4.3.1 CALCULATING EXPECTED ANNUAL LOSS

EAL is calculated using a multiplicative equation that considers the consequence risk factors of natural hazard exposure and historic loss, and the likelihood risk factor of natural hazard frequency for 18 natural hazards. The EAL value for each consequence type is calculated by multiplying the total exposure value of an area by the estimated annual frequency of a natural hazard event and by the historic loss ratio (see *Equation 3*). See *Section 5* for further explanation of these EAL components and how they are computed. EAL values are computed at the Census block level (or for some hazards, the Census tract level) for each relevant consequence type and summed to produce a composite EAL for each hazard (see *Equation 4*). A cubic root transformation is applied to each hazard-specific EAL value to address skew. The resulting transformed values are then min-max normalized (0.00 – 100.00 scale) to produce an EAL score for each hazard. A total EAL is also summed from all hazard EALs for the area and a total EAL score is calculated using the same cubic root transformation and min-max normalization process.

[4] Cutter, S.L., Ash, K.D., & Emrich, C.T. (2014). The geographies of community disaster resilience. Global Environmental Change, 29, 65-77. https://doi.org/10.1016/j.gloenvcha.2014.08.005.
[5] See also Mitigation Framework Leadership Group (MitFLG), Federal Emergency Management Agency (FEMA). (2016). Draft Interagency Concept for Community Resilience Indicators and National-Level Measures. Washington, DC: Department of Homeland Security (DHS). Retrieved from https://www.fema.gov/media-library-data/1466085676217-a14e229a461adfa574a5d03041a6297c/FEMA-CRI-Draft-Concept-Paper-508_Jun_2016.pdf.
[6] Federal Emergency Management Agency (FEMA). (2016). Benefit-cost sustainment and enhancements: baseline standard economic value methodology report. Retrieved from https://www.caloes.ca.gov/RecoverySite/Documents/Benefit%20Cost%20Sustainment.pdf.

Hazard-specific Risk Index scores are calculated using individual hazard EAL scores. Overall Risk Index scores are calculated using the composite EAL score.

Equation 3: Hazard-Specific Expected Annual Loss by Consequence Type

$$Expected\ Annual\ Loss_{Hazard_{Consequence\ Type}} = Exposure_{Hazard_{Consequence\ Type}} \times Frequency_{Hazard} \times Historic\ Loss\ Ratio_{Hazard_{Consequence\ Type}}$$

Equation 4: Composite Hazard-Specific Expected Annual Loss

$$Expected\ Annual\ Loss_{Hazard_{Total}} = Expected\ Annual\ Loss_{Hazard_{Building\ Value}} + Expected\ Annual\ Loss_{Hazard_{Population\ Value}} + Expected\ Annual\ Loss_{Hazard_{Agriculture\ Value}}$$

While each hazard uses the same components to calculate EAL, these computations require different approaches due to the varying nature of the hazards and the differences in source data format. A set of common analytical techniques (see *Section 4.3.2*) are leveraged to achieve the best possible normalization between all hazards for accurate NRI calculation. The process for computing the EAL and its components for each individual hazard will be described in the hazard-specific sections of this paper (*Sections 6 through 23*).

See *Table 4* for a simplified example of a county-level EAL calculation for the hazard Hail. All three consequence types are included in the calculation of Hail EAL. By multiplying the county's consequence exposure, hazard frequency, and consequence-specific historic loss ratio, an EAL value for that consequence type is determined. The values for each consequence are summed to produce the composite EAL for the county. This composite EAL is used to derive the hazard's EAL score for that county. This computation includes a min-max normalization using the hazard-specific composite EAL values of all counties in the nation. The composite EAL for Hail is summed with the composite EAL values for the 17 other hazards to calculate the total EAL, which is scored in the same way.

Table 4: Example of a County-Level EAL Calculation for Hail

EAL Component	Building Value	Population	Agriculture Value
Exposure	$23.14 M	182,265 people or $1.35 T	$120,000
Frequency	9.7 events/year	9.7 events/year	9.7 events/year
Historic Loss Ratio	1.6e-8	3.2e-8	1.4e-7
Expected Annual Loss	$3,478	0.054 people or $399,954	$156

4.3.2 ANALYTICAL TECHNIQUES

Arriving at a dollar value representing the EAL due to each of the 18 hazards for every county and Census tract in the United States requires multiple analytical techniques utilized across all hazards to ensure the most accurate representation of loss.

NRI Processing Database

To support the processing of the NRI, a dedicated SQL Server database environment was established. Using a relational database to store and analyze each dataset used to compute the NRI provides a variety of benefits. The database allows for computational efficiencies when calculating the components of the EAL for more than 11 million Census blocks in the United States. Grouping and aggregation functions can be used to easily roll these values into the Census tract- and county-level values displayed in the NRI application. Implementation of NRI methodologies in stored procedures allows for application and adaptation of complex business logic and spatial analysis. The NRI processing database also makes quality control easier by allowing complex calculations to be processed in steps with the output for each step accessible in its own table. Records for each Census block can be checked to identify outliers and any possible problems with the methodology or algorithms. Additionally, repeatable processes can be modified and run in smaller portions, cutting down on processing time as methodology is adapted. For example, a change in source data for a hazard only requires the replacement of hazard-specific source data tables and for the reprocessing of a single hazard. The NRI processing database also supports version control and allows backups of each version to be stored securely.

Most spatial functions, such as buffering and intersection, are performed within the NRI processing database. However, some processes, such as land use tabulation, necessitate the use of ArcGIS tools and functions. The outputs of these external processes are transferred and stored within the NRI processing database where they are used to compute the components of the EAL.

Geographic/Administrative Layers

EAL components may be calculated at three different administrative layers: Census block, Census tract, and county. The most granular level is the Census block and, where possible, values are calculated at this level and then aggregated. The source of the boundaries for these layers is the U.S. Census Bureau's 2017 TIGER/Line shapefiles.[7] The shapefiles include United States territories and some large bodies of water, which are either manually removed or clipped based on a county boundary shapefile provided by Esri.[8] All spatial layers use the North America Albers Equal Area Conic projection. *Figure 4* provides examples of Census block, Census tract, and county boundaries.

[7] U.S. Census Bureau. (2017). *Cartographic Boundary Shapefiles* [cartographic dataset]. Retrieved from https://www.Census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.2017.html.

[8] Esri, TomTom North America, Inc., & U.S. Census Bureau. (2012). *USA County Boundaries* [cartographic dataset]. Retrieved from https://www.arcgis.com/home/item.html?id=f16090f6d3da48ec8f144a0771c8fec4.

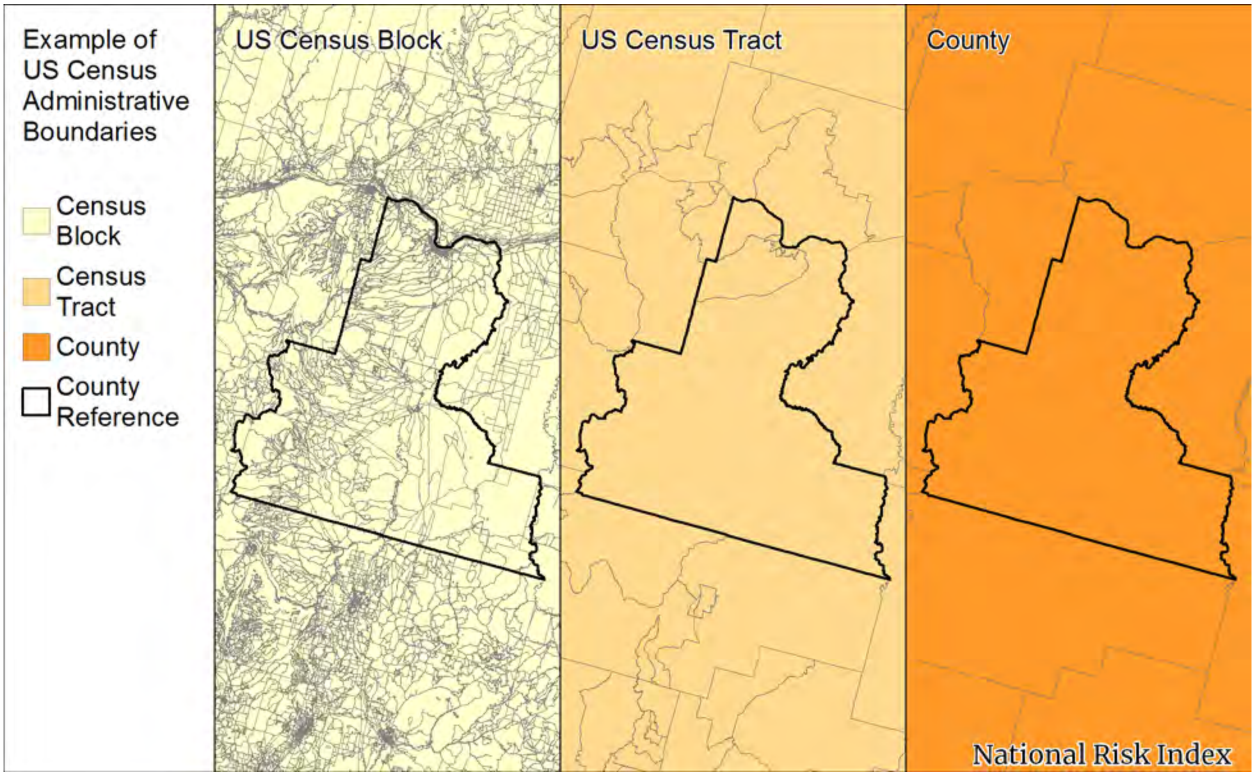

Figure 4: Example of County, Census Tract, Census Block Shapes

Determining County-Level Possibility of Hazard Occurrence

Not all hazards are able to occur in all areas. For example, Coastal Flooding cannot occur in Kansas, and Avalanches cannot occur on flat terrain. The NRI logically differentiates areas where a given hazard is unlikely or has never occurred from areas where that hazard is impossible using a control table in the database that designates where each hazard can occur. This table is based on counties that intersect past hazard event polygons generated through spatial processing, have some possibility of occurrence as identified by probabilistic or susceptibility source data, or have recorded loss due to hazard occurrence.

Base Calculation and Aggregation

One of the NRI's strengths is that it determines the EAL for an area at the lowest geographical level deemed appropriate, predominantly the Census block level. EAL is determined by assessing the combination of a specific location's frequency of occurrence and associated consequence if it were to occur (for example, how often Riverine Flooding occurs in the area and what buildings, population, and crops are potentially affected). For many hazard types, frequency and exposure can be highly localized. Modeling the event frequency in coordination with its exposure provides the best assessment of its expected impact.

The Census block is currently the lowest administrative level at which population and building value data are nationally, consistently, and publicly available. By performing the EAL calculation at the

Census block level, the NRI is more accurately assessing EAL by looking at specific frequency and exposure combinations at the lowest possible resolution. The NRI provides the most relevant aggregations to its users, namely EAL values at the Census tract and county levels. For most hazards, Census tract- and county-level exposure and frequency are calculated by “rolling up” or aggregating values from the Census block level.

Representation of Hazards as Spatial Polygons

EAL components for each hazard are derived from one or more sources of spatial hazard information. This can include identified hazard-susceptible areas, spatiotemporal records of past hazard occurrences, and countywide records of economic loss due to a hazard event. The format of spatial source data vary by hazard. Frequency and exposure calculations typically require spatiotemporal records of past hazards or probabilistic modelling. To achieve a uniform level of accuracy, any spatial hazard source data were converted to vector polygon format and intersected with the Census blocks or tracts.

Necessary conversions are performed either with tools available in Esri’s ArcGIS software or with SQL Server’s spatial operations. Common methods of hazard conversion used for NRI calculation are the buffering of points and lines to form polygons, and raster-to-polygon conversion.

Point and line representations of hazard events or hazard-susceptible areas are buffered by different distances depending on the hazard. Point buffers allow for better representation of event coverage or area of possible impact. Path representations, such as those for Tornado and Hurricane, are included in the source data as a series of points with a common identifier (e.g., StormID). These are connected by a line or multi-segmented line. The line is then buffered by a distance depending on the intensity of the Tornado (Enhanced-Fujita scale) or Hurricane (Saffir-Simpson scale) event. See the spatial processing discussion in the hazard-specific sections (*Sections 6 through 23*) for more detail on buffering techniques.

Conversion from raster to polygon vector format is performed by using ArcGIS’s Create Fishnet tool to form a grid of rectangular cells that match the extent and dimensions of the original raster and then using the Extract Values to Table tool to insert the cell values of the raster into the corresponding fishnet polygon’s attribute table. In vector format, attributes from the source raster data can be used to filter or select the data needed for hazard specific methodology calculations.

Intersection

Determining areas of spatial intersection between hazard events or susceptible areas and the various levels of reference layers is an essential function used in calculating EAL. The results of these intersections are stored in the NRI processing database and used for multiple purposes. For many hazards, the quantification of a hazard’s exposure is done at the Census block level. This requires the computation of intersecting areas of exposure. *Figure 5* provides an example of a hazard event shape intersecting a Census block.

Frequency computations also typically involve counting the number of hazard event polygons that intersect the Census block. Widespread hazards, like Hurricanes, often require a larger administrative layer to more accurately represent the frequency of hazard events. For these types of hazards, the intersection is performed with a 49-by-49 km fishnet grid and the count of the fishnet grid cell is inherited by the Census blocks it encompasses, using an area-weighted value when a Census block intersects more than one cell.

Figure 5: Example of Intersection Between Hazard Event and Census Block

The 49-by-49 km grid cell size was used because of analysis conducted early in the project that roughly estimated the average Census tract size to be 4,900 m^2 (or 70-by-70 m) and the average county size to be 2,500 km^2 (or 50-by-50 km), which was reduced slightly to 49-by-49 km to ensure the county size was a multiple of the tract size. Though the use of a grid at the average Census tract resolution was discarded, the use of the 49-by-49 km fishnet grid was maintained for the calculation of frequency for widespread hazards.

Tabulation

Tabulation refers to the process of calculating the composition of a vector shape by overlaying it on a raster layer inside a GIS. The GIS computes the area of raster cells completely contained within the vector shape by raster value.

The land use tabulation process is performed by using the Tabulate Area tool in Esri's ArcGIS software. All spatial layers use the North America Albers Equal Area Conic projection. A layer containing county boundaries is tabulated against the 2017 CropScape raster file,[9] which describes the land use of the conterminous United States in 30-by-30-m cells using 132 distinct raster values. The output layer contains a record for each county (by county FIPS code) with fields for each class (crop types, developed areas, etc.) displaying the area (in square meters) of each type of land use within the county. There are five classes of developed area (Developed, Developed Open Space, and Developed Low, Medium, and High Intensity) that can be summed to get the total developed area of the county. The area values of all crop classes can be summed to give a total agricultural area. This same tabulation is performed at the Census tract and Census block level to support the computation of developed area densities at these levels. The EAL calculations for most hazards utilize the developed area density values at the Census block level (see the *Intersection* Section).

The CropScape layer only contains information for the conterminous United States. For Alaska and Hawaii, a similar tabulation process is carried out substituting the 2016 National Land Cover Database (NLCD) raster files[10] for both states. NLCD uses the same classification types for developed land as CropScape. It has two classifications for agricultural land: Pasture/Hay and Cultivated Crops.

Primary tabulation involves summing the total area of interest (e.g., developed land use) and dividing by the total area of raster cells contained. The shape area (e.g., Census block, Census tract, or county) is multiplied by this developed area percent to calculate the developed area (in square kilometers). To speed up calculations, the intersected shapes are classified as whether they completely contain the Census block, tract, or county (for which developed area and crop/pasture area had already been calculated). For such shapes, the values were transferred over without tabulation. Tabulated areas are approximations based on the cell size of the source raster and can exceed the area of the shape being tabulated. In these cases, the total area of the shape is set as the ceiling of the tabulation area results.

Very small intersections of hazard event shapes with Census blocks can be too small to tabulate against 900-m^2 raster cells. If not all shapes are tabulated using the primary method, secondary methods are pursued. Secondary methods are hazard-specific. For example, secondary tabulation of Drought-Census tract shapes involves extracting the raster value at the centroid of the shape. The entire area of the shape is classified as the raster value extracted at the centroid. On the other hand, Riverine Flooding shapes, as many administrative boundaries are drawn using rivers, are winding and narrow (see the shape on the right in *Figure 6*). A centroid-based approach is not the most accurate. For this reason, raster cell centroids representing developed areas were exported. SQL Spatial routines then calculated whether a developed land-use was within 42 meters (the hypotenuse distance of a 30-by-30 m raster cell). If so, the entire shape was deemed developed. If not, the shape was considered to have zero developed area.

[9] US Department of Agriculture (USDA), National Agricultural Statistics Service (NASS). (2017). *Published crop-specific data layer* [online dataset]. Retrieved from https://nassgeodata.gmu.edu/CropScape/.
[10] Multi-Resolution Land Characteristics Consortium. (2016). *National Land Cover Database (NLCD)* [online dataset]. Retrieved from https://www.mrlc.gov/data.

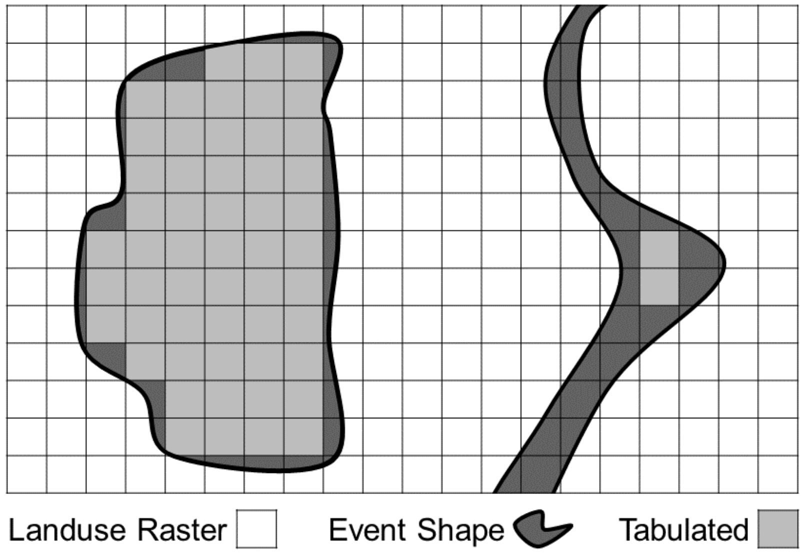

Figure 6: Land Use Raster Tabulation

5 Natural Hazards Expected Annual Loss Components

The NRI represents natural hazard in terms of EAL, which incorporates data for natural hazard exposure, annualized frequency, and historic loss. A single "mental model" was leveraged throughout all methodological processes in calculating these EAL components so that certain risk factors were not being interpreted inconsistently across the 18 natural hazards.

5.1 Natural Hazards

Natural hazards are defined as environmental phenomena that have the potential to impact societies and the human environment. These should not be confused with other types of hazards, such as manmade hazards. For example, a flood resulting from changes in river flows is a natural hazard, whereas flooding due to a dam failure is a considered manmade hazard by the NRI.

Natural hazard events can induce secondary natural hazard events. For example, Landslides can be caused by an Earthquake. Natural hazards are distinct from natural disasters. A natural hazard is the threat of an event that will likely have a negative impact. A natural disaster is the negative impact following an actual occurrence of the natural hazard in the event that it significantly harms a community. The NRI only considers primary natural hazard events and not their results or after-effects.

The NRI considers 18 natural hazards. These hazards are listed below and described in more detail in the final sections of this report (*Sections 6 through 23*).

Avalanche
Coastal Flooding
Cold Wave
Drought
Earthquake
Hail
Heat Wave
Hurricane
Ice Storm
Landslide
Lightning
Riverine Flooding
Strong Wind
Tornado
Tsunami
Volcanic Activity
Wildfire
Winter Weather

5.2 Natural Hazard Annualized Frequency

The annualized natural hazard frequency is defined as the expected frequency or probability of an event happening per year. Frequency is derived either from the number of recorded events each year over a given period or the modeled probability of an event occurring each year. The NRI considers that natural hazards can occur in places where they may have not yet been recorded to-date and that hazards may have occurred in locations without being recorded. Therefore, the NRI has built-in minimum representative frequency values for certain geographical areas and hazards, such as Hurricane, Ice Storm, Landslide, Tornado, and Tsunami.

5.2.1 SELECTING SOURCE DATA

Annualized frequency data are derived from multiple sources and depend on the natural hazard. Data sources were identified through public knowledge, guidance by SMEs, and research. Examples of selected data sources include the National Weather Service (NWS), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the U.S. Army Corps of Engineers (USACE), the Smithsonian databases, and the U.S. Department of Agriculture (USDA). See the hazard-specific sections (*Sections 6 through 23*) for more information on spatial data sources.

5.2.2 ANNUALIZED FREQUENCY METHODOLOGY

The natural hazard annualized frequency is the expected frequency for a given hazard event and measures the actual or expected number of events or event days each year. Not all events are considered relevant for frequency calculation. SMEs established that some hazards meet certain criteria to be included as a hazard event capable of causing damage e.g., Hail size of diameter greater than 0.75 in. (See the hazard-specific sections for more information on these criteria). Annualized frequency can be defined as the number of historical occurrences of a natural hazard within a known period of record per geographic area, as seen below in *Equation 5*:

Equation 5: Annualized Frequency Equation

$$Annualized\ Frequency = \frac{Number\ of\ Recorded\ Events}{Period\ of\ Record}$$

In some cases, as with Wildfire and Earthquake, the best available source data consist of probabilistic statistics contained in raster files that are used to compute an annualized frequency. In these cases, the frequency value represents the probability of a hazard event occurring in a given year.

For hazards that track actual hazard occurrences, the historical event count quantifies either the number of distinct hazard events that have occurred (e.g., Hurricanes to hit the area) or the count of days on which a hazard has occurred (e.g., on how many days a Hail event was reported). The determination of whether hazard occurrence was defined by event-days or discrete events was based on SME review of the source data. This determination depended on how hazard occurrence was recorded as well as how economic loss was reported. *Table 5* gives the frequency basis (event or event-day) for each hazard.

Table 5: Geographic Level of Event Count Determination and Hazard Occurrence Basis

Natural Hazard	Geographic Level of Historic Event Count Determination	Hazard Occurrence Basis
Avalanche	County	Distinct events
Coastal Flooding	No event count	No event count
Cold Wave	Census Block	Event days
Drought	Census Tract	Event days
Earthquake	No event count	No event count
Hail	49-km Fishnet	Event days
Heat Wave	Census Block	Event days
Hurricane	49-km Fishnet	Distinct events
Ice Storm	49-km Fishnet	Event days
Landslide	Census Tract	Distinct events
Lightning	4-km Fishnet (Source raster cell)	Distinct events
Riverine Flooding	County	Distinct events
Strong Wind	49-km Fishnet	Event days
Tornado	49-km Fishnet	Distinct events
Tsunami	Census Tract	Distinct events
Volcanic Activity	Census Block	Distinct events
Wildfire	No event count	No event count
Winter Weather	Census Block	Event days

While the NRI application reports information at the Census tract and county level, often the data used to determine this information are captured at either a lower or higher level. Predominantly, EAL components are assessed at the Census block level, so the number of hazard events (or event-days) that have historically occurred is determined for each Census block.

Depending on the nature of the hazard and its source data, the event count used to calculate frequency can be initially captured at the Census block, Census tract, county, or 49-by-49 km fishnet grid cell level. See each hazard's frequency section (e.g., *Section 6.5*, *Section 7.5*, etc.) for specific hazard event count methodology. *Table 5* provides the geographic level at which event count information is determined for use in frequency calculations for each hazard.

For large geographic areas and areas with a statistically significant number of events recorded, the logic supporting *Equation 5* is sound and is used as one approach for calculating annualized frequency in the NRI for some natural hazards. However, for hazards with few events historically recorded, due to urban bias and varying demographics across the country, this equation is not always accurate or representative. Additionally, as geographic boundaries are partitioned into much smaller regions (counties, Census tracts, and Census blocks), further challenges are uncovered resulting from the fact that geographic areas that have not been historically impacted by a hazard and/or recorded hazard events are being calculated as having no risk from that hazard. (Remember, the EAL and NRI risk equation is multiplicative, and, therefore, any individual factor of zero results in a total NRI score of 0.)

Consider an example (*Figure 7*) where four Tornadoes hit a single Census tract (say, "Tract A") near its geographic border. Using Equation 5, the annualized frequency for "Tract A" would be calculated using a 4 in the numerator. However, given the Tornado event locations (specifically, their proximity to the neighboring tracts), these four events could easily have occurred within, say, "Tract B." Therefore, "Tract B" should not be represented as having no (zero) risk, and, yet, it would be zero if annualized frequency was deemed to be zero based on the fact that no Tornado has historically occurred in "Tract B." Natural hazard events cannot be expected to respect arbitrarily drawn political boundaries. Thus, in evaluating risk, hazard occurrence definition should account for events in nearby Census blocks or tracts that easily could have impacted a given area.

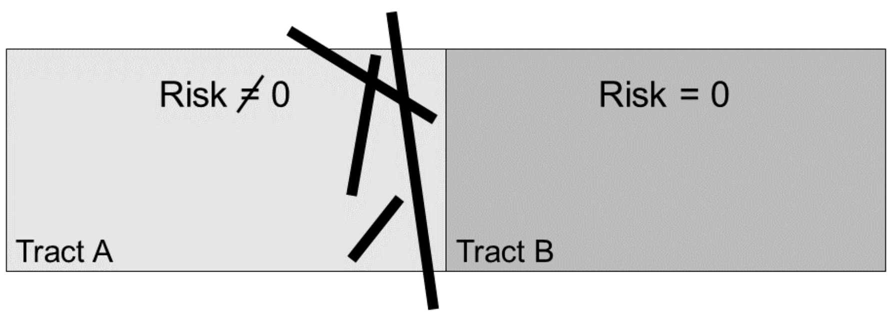

Figure 7: Example of the Issues with a Simplistic Annualized Frequency Methodology

Three main solutions were incorporated to spread the area of hazard influence used to calculate frequency and/or exposure. Hazard-specific frequency methodologies may use some or all of these approaches:

1. **Hazard Event Counting Using a 49-by-49 km Fishnet Grid**: This approach involves creating a fishnet grid covering the United States and counting the number of events (or event-days) of hazard occurrence within each cell. Areas within the cell inherit the event count (or receive an area-weighted event count when intersecting multiple cells; see *Section 5.2.3*) and frequency is then calculated according to *Equation 5*. Hazards using this approach include Hail, Hurricane, Ice Storm, Strong Wind, and Tornado.
2. **Minimum Annual Frequency**: A minimum annual frequency (MAF) is assigned to areas that have not experienced a hazard occurrence recorded by the source data but are determined to be at some risk due to their location (see the *Determining County-Level Possibility of Hazard Occurrence Section*). Appropriate MAF values were identified by natural hazard SMEs. The estimated values were typically low given the fact that historic events had never been recorded over the period of record, which sometimes dated back multiple centuries. Minimum values were typically defined in the format of "once in the period of record," or

similar. Hazards using this approach include Avalanche, Hurricane, Ice Storm, Landslide, Riverine Flooding, Tornado, and Tsunami.

3. **Hazard Event Shape Buffering**: Hazards with widespread and/or unpredictable event locations are buffered using SME-determined distances to create more representative areas with potential exposure to natural hazards. Buffering also allows events with relatively small surface areas to be smoothed together into general representative shapes to eliminate gaps that may exist between historically recorded hazard events (see *Figure 8*). Hazards using this approach include Hail, Hurricane, Strong Wind, Tornado, Tsunami, and Volcanic Activity.

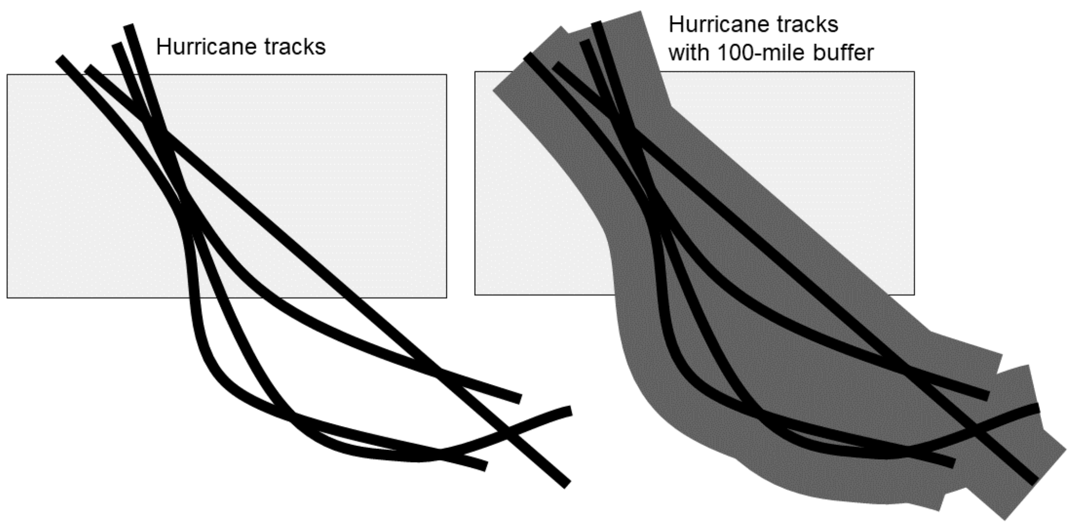

Figure 8: Example of Buffering Hazard Events to Determine Areas Applicable to Minimum Frequency Values

Some hazards do not require any of these solutions due to the nature of the source data or the widespread prevalence of the hazard. For example, the spatial data for Cold Wave, Heat Wave, and Winter Weather events cover areas the size and shape of NWS Forecast Zones and counties. These events can occur across the entire United States, so it is not necessary to spread the hazards' area of influence any further.

5.2.3 DATA AGGREGATION

In most instances, annualized frequency is calculated first at the Census block level. In cases where the event count is evaluated at the fishnet level (see *Table 5*), the Census block inherits the event count from the fishnet cell that encompasses it, or, if a Census block intersects multiple fishnet cells, an area-weighted count is calculated as computed in *Equation 6.* Applying this equation to the example in *Figure 9* results in a Census block event count of about 22. This fishnet-aggregated count is used to calculate the Census block frequency.

Equation 6: Census Block Area-Weighted Fishnet Event Count Calculation

$$Census\ Block\ Event\ Count = \frac{\sum(Fishnet\ Event\ Count \times Area\ of\ Fishnet\ Intersection\ )}{Area\ of\ Census\ Block}$$

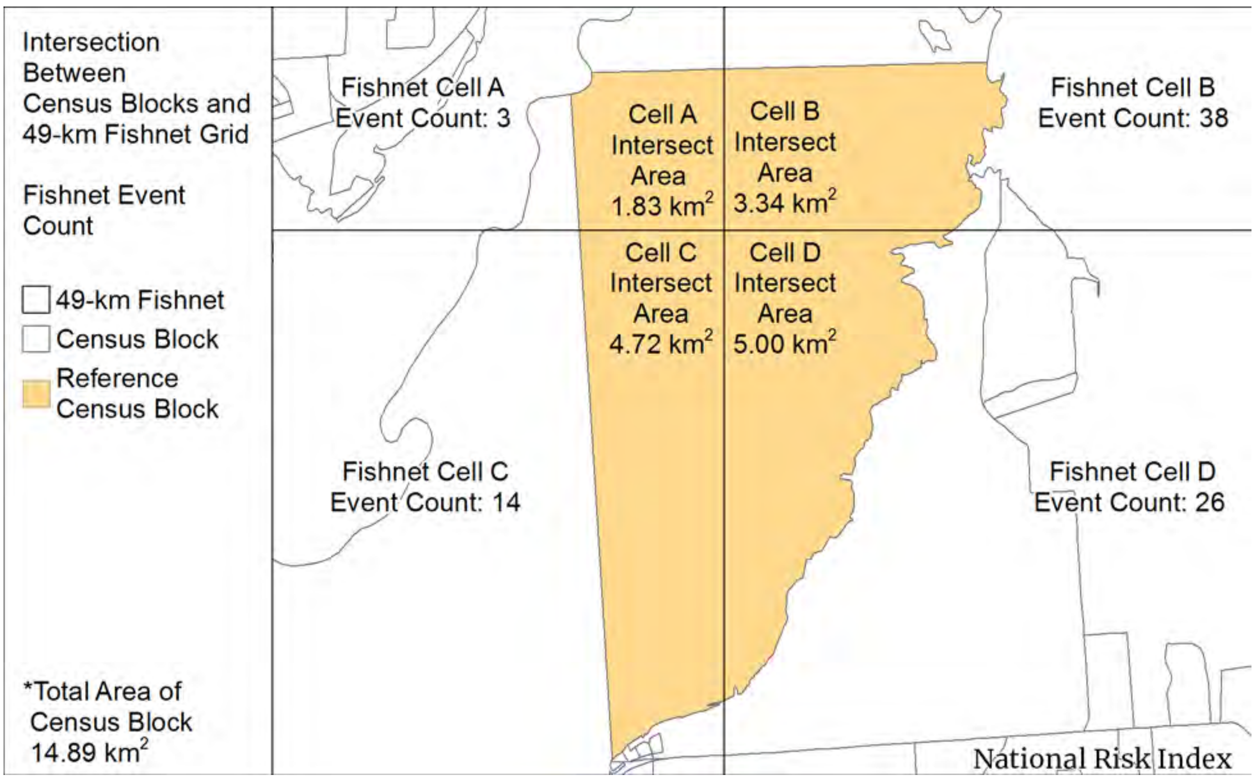

Figure 9: Aggregation from Fishnet Cell to Census Block Example

The NRI rolls up data from the Census block to the Census tract and county level, usually by leveraging area-weighted aggregation as computed in *Equation 7*. These Census tract- and county-level frequency values may not exactly match that of dividing the number of historical hazard events at the Census tract and county level by the period of record, as they are based on an area-weighted aggregation.

Equation 7: Census Tract and County Frequency Aggregations

$$Census\ Tract\ Frequency = \frac{\sum(Census\ Block\ Frequency \times Area\ of\ Census\ Block)}{Area\ of\ Census\ Tract}$$

$$County\ Frequency = \frac{\sum(Census\ Block\ Frequency \times Area\ of\ Census\ Block)}{Area\ of\ County}$$

For a few natural hazards (typically those that are widespread, such as Tsunami or Drought), annualized frequency is calculated at the Census tract level, after which the Census block simply inherits the value of its parent tract (see *Table 5*). Avalanche and Riverine Flooding natural hazards are the only hazards for which annualized frequency is calculated at the county level directly, and the Census tracts and blocks then inherit the value of their parent county.

5.3 Natural Hazard Exposure

Natural hazard exposure is defined as the representative value of buildings, population, or agriculture potentially exposed to a natural hazard event. Data sources with the best available national-level data for each hazard were selected to perform a spatial analysis and compute areas of exposure.

5.3.1 SELECTING SOURCE DATA

The initial spatial processing of the source data for each hazard is used to identify areas of natural hazard exposure. Data sources were selected for their accuracy, long period of record, and spatial component, based on the best available, national-level data per natural hazard. Sources were identified through public knowledge, SME recommendations, and research. Providers of natural hazard exposure data include:

- *National Oceanic and Atmospheric Administration (NOAA)*
- *USC Hazards & Vulnerability Research Institute (HVRI)*
- *Spatial Hazard Events & Losses Database for the United States (SHELDUS)*
- *United States Army Corps of Engineers (USACE)*
- *United States Geological Survey (USGS)*
- *United States Department of Agriculture (USDA)*
- *National Weather Service (NWS)*
- *Federal Emergency Management Agency (FEMA)*

5.3.2 CONSEQUENCE TYPES

A natural hazard consequence is defined in the NRI as economic loss or bodily harm to individuals that is directly caused by a natural hazard event. Consequences of natural hazard events are categorized into three different types: buildings, population, and agriculture.

Buildings

Building exposure is defined as the dollar value of the buildings determined by the source data to be exposed to a hazard according to a hazard-specific methodology. The maximum possible building exposure of an area (Census block, Census tract, or county) is its building value as recorded in Hazus 4.2, Service Pack 01 (SP1),[11] which provides 2018 valuations of the 2010 Census.[12]

Population

Population exposure is defined as the estimated number of people determined by the source data to be exposed to a hazard according to a hazard-specific methodology. The maximum possible population exposure of an area (Census block, Census tract, or county) is its population as recorded in Hazus 4.2 SP1. The VSL was used to express population exposure in terms of dollars.

Agriculture

Agriculture exposure is defined as the estimated dollar value of the crops and livestock determined by the source data to be exposed to a hazard according to a hazard-specific methodology. This is derived from the USDA 2017 Census of Agriculture[13] county-level value of crop and pastureland.

5.3.3 EXPOSURE METHODOLOGY

Natural hazard exposure is typically calculated at the Census block level and then aggregated to the tract and county level by summing the block exposure values within the parent tract or parent county. See each hazard's exposure section for more information.

Some hazard exposure areas are represented as polygons in the source data, while others are represented as points, lines, or raster cells. Hazard exposure is based on either historic event locations or areas of identifiable risk (e.g., Tsunami inundation zones). Eventually, every relevant record in the source data is processed into a polygon via a hazard-specific methodology. This polygon represents an area of exposure to the hazard.

To calculate the natural hazard's representative size for a given area, the NRI leverages a few techniques, such as using subject matter expertise to define a single representative hazard size, calculating historical average event occurrence sizes, or defining the size of probabilistic/susceptible zones for hazards within the area of interest using existing source data (*Figure 10*).

[11] Federal Emergency Management Agency (FEMA). (2018). *Hazus 4.2, Service Pack 01 Release*. Retrieved from https://msc.fema.gov/portal/resources/hazus.
[12] U.S. Census Bureau. (2010). *2010 Census*. Retrieved from http://www.Census.gov/2010Census/data/.
[13] U.S. Department of Agriculture. (2017). *2017 Census of Agriculture*. Retrieved from https://www.nass.usda.gov/Publications/AgCensus/2017/index.php.

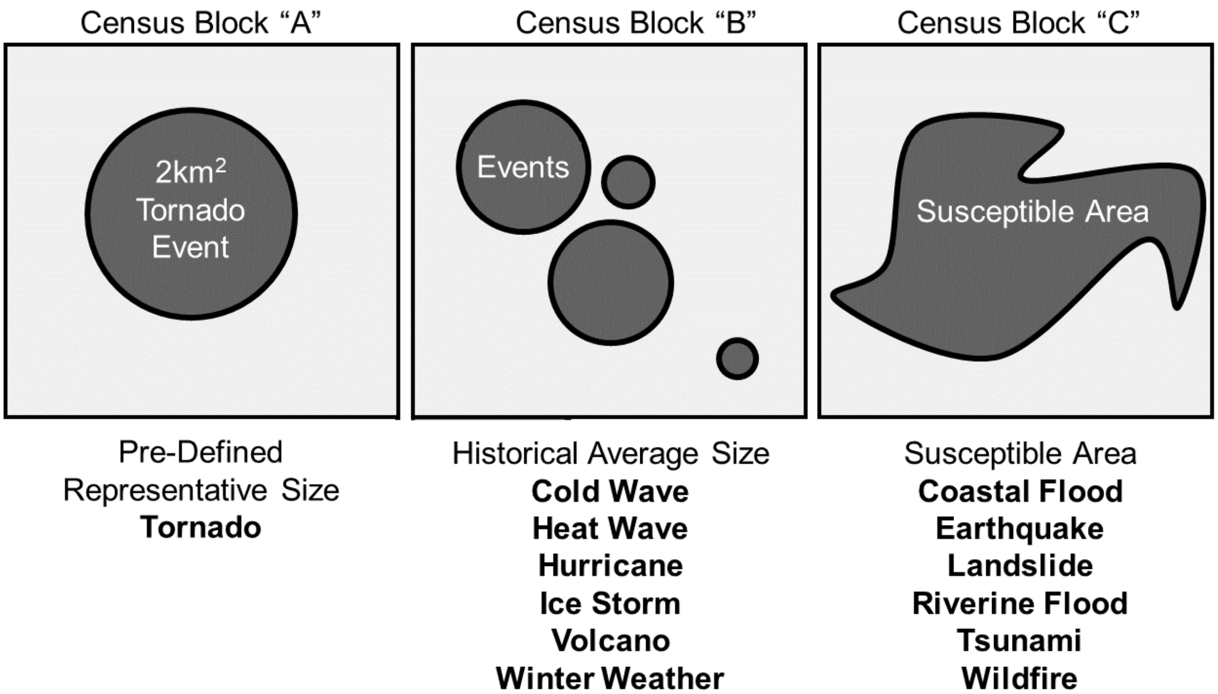

Figure 10: Examples of Representative Hazard Size

To estimate exposure, the hazard event or susceptible area polygons are intersected with the appropriate administrative layer polygons and the resulting intersect shape defines the area of hazard exposure. Once the area of exposure is defined, one of three generalized approaches are executed within the NRI processing database to estimate the exposure value within the administrative area. The approach used for a natural hazard was determined by the hazard's recorded historic events, hazard susceptibility maps, and subject matter expertise.

Appendix B – Hazard Data Characteristics Comparison describes the type of exposure method used for each of the 18 hazards. The general approaches to modeling exposure include:

1. **Developed Area/Agricultural Area Density Concentrated Exposure.** The NRI determined area of hazard exposure intersected with the administrative area is multiplied by the density of either the population or building value within the developed land of the area to calculate the worst-case concentration of hazard consequence. To estimate agriculture exposure, this method uses the density of crop and livestock value within the agricultural land of the area.

2. **Widespread Hazard Event Exposure.** The entire Census block is considered to be exposed. This approach is leveraged for hazards where the extent likely spans the entire area of interest and the boundaries are indefinable.

3. **Pre-Defined Representative Exposure.** Subject matter experts define a default, representative exposure value for areas of interest deemed at risk of natural hazard events.

Approach 1. Developed Area/Agricultural Area Density Concentrated Exposure

Exposure is calculated for most of the natural hazards using the developed area density approach. This approach uses the area of the hazard event exposure shape (intersection of hazard shape with the administrative area) multiplied by the developed area density of the administrative area to generate the worst-case representative property damage or population that could result from a future natural hazard event within the area.

The Hazus 4.2 SP1 data provide building value and population estimates at each administrative reference layer (Census block, Census tract, and county). For certain hazards, a density estimate was needed for the hazard's exposure calculation. Rather than only calculating an average density value for each administrative layer (i.e., by dividing the population of a Census block by the area of the Census block), effort was made to refine the density estimate by first estimating where people and buildings might exist within an area. Using the USDA CropScape 2017 raster, which categorizes land types and use (see *Figure 11*), a spatial tabulation process was used to derive an estimate of the developed area within each administrative reference layer. This same tabulation process was used to estimate the crop and pasture area as well (see the *Tabulation Section*).

With an estimate of the developed area and crop and pasture area for each record of the administrative reference layers, densities were then calculated. Using the Hazus data's Building Stock Value and Population estimates for each administrative layer, the ratio of developed area within an administrative reference over its whole area was used to calculate the building value and population densities. These densities represent an assumption that population and the presence of buildings are concentrated in developed areas rather than being equally distributed across an administrative area.

Note that, in cases where the Hazus data report population and or building value and the tabulation process did not identify any developed land area, the record was assigned an average density value calculated as the building value (or population) divided by the total area of the record. For cases where the tabulation process identified developed area but the Hazus data did not report any population or building values, the densities where set to 0. This ensures that the tabulation process, which can be spatially imprecise due to the resolution of the source rasters, does not count adjacent developed area as developed area within the administrative area when Hazus data do not consider it populated or developed.

To compute the building and population value densities, the building and population values of the administrative layer (Census block, Census tract, or county) are divided by the total developed area (determined for the tabulation process) of the administrative layer, as in *Equation 8*.

Equation 8: Census Block Building and Population Value Density

$$BldgValueDen_{CB} = \frac{BldgValue_{CB}}{DevArea_{CB}}$$

$$PopDen_{CB} = \frac{Pop_{CB}}{DevArea_{CB}}$$

where:

$BldgValueDen_{CB}$	is the building value density calculated at the Census block level (in dollars per square kilometer).
$BldgValue_{CB}$	is the total building value of the Census block as recorded in Hazus 4.2 (in dollars).
$DevArea_{CB}$	is the total developed area of the Census block tabulated from CropScape or NLCD raster files (in square kilometers).
$PopDen_{CB}$	is the population density calculated at the Census block level (in people per square kilometer).
Pop_{CB}	is the total population of the Census block as recorded in Hazus 4.2.

For agriculture, the USDA 2017 Census of Agriculture provides an estimated dollar value of crop and livestock within each county. The county value is divided by the total agricultural area of the county to find its crop value density (see *Equation 9*). The county-level agricultural value density is inherited by any Census tracts or Census blocks that contain crop or pastureland.

Equation 9: County Crop Value Density

$$AgValueDen_{Co} = \frac{AgValue_{Co}}{AgArea_{Co}}$$

where:

$AgValueDen_{Co}$	is the agricultural value density calculated at the county level (in dollars per square kilometer).
$AgValue_{Co}$	is the total crop and livestock value of the county as reported in the 2017 Census of Agriculture (in dollars).
$AgArea_{Co}$	is the total agricultural area of the county (in square kilometers).

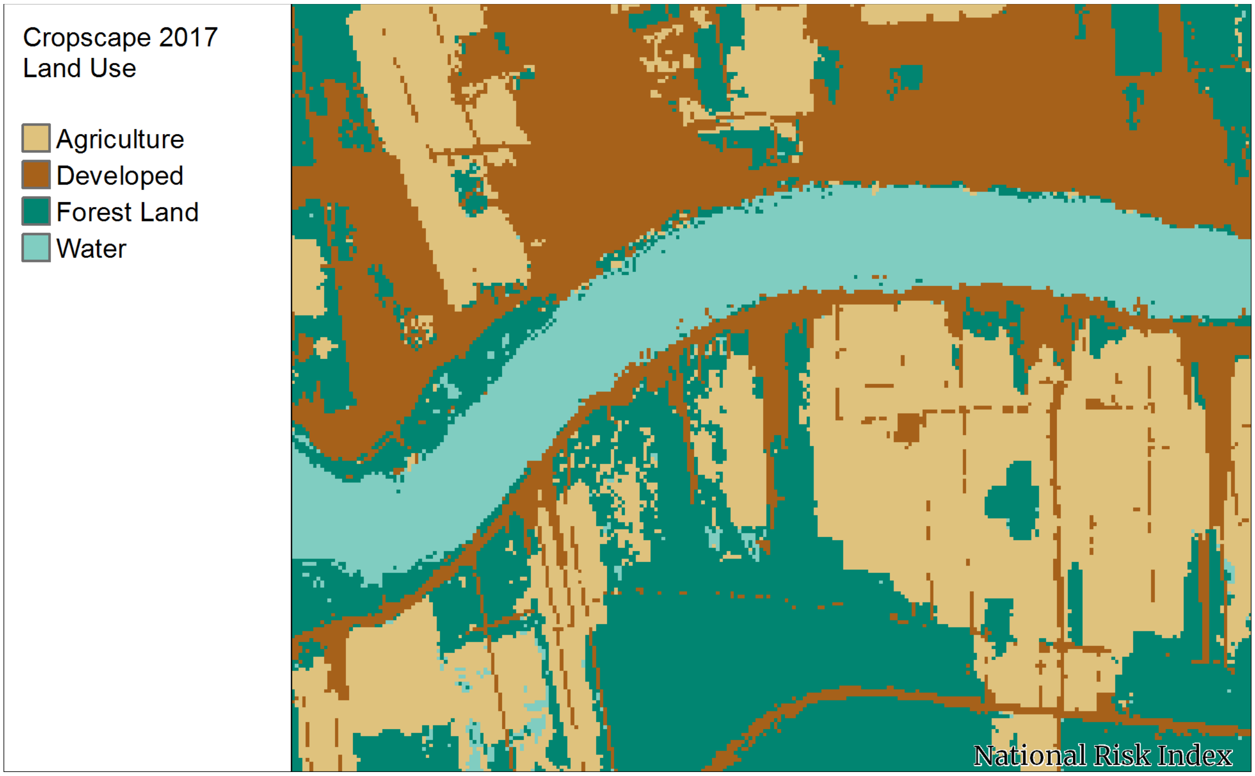

Figure 11: CropScape Developed Land Layer

Approach 2. Widespread Hazard Event Exposure

For certain natural hazards where extent is widespread with indefinable boundaries, the entire area of interest is considered exposed. For these natural hazards, exposure values are defined to be the entire area of interest's building value, crop and livestock value, or population as recorded by Hazus 4.2 SP1 or the 2017 Census of Agriculture.

Approach 3. Hazard-Specific Representative Exposure

Avalanche and Tornado each have a unique method of calculating exposure. For Avalanche, a single exposure value, defined by SMEs, is pre-determined and assigned to all areas deemed at risk of Avalanche events. A review of the source data found that 98% of historical Tornado events impact an area of 50 km^2 or less, with the average damage area being 2.07 km^2, so a 2 km^2 area was used to estimate an average area impacted by a Tornado. This representative footprint area is multiplied by the average building or population density of the Census tract to find exposure.

5.3.4 DATA AGGREGATION

Natural hazard exposure is calculated at the Census block level and then is aggregated to the tract and county level by summing the block exposure values within the parent tract or parent county (with the exception of Avalanche, Drought, Earthquake, and Tornado, which are initially calculated at the tract level). Detailed methodologies per hazard are explained in the hazard-specific sections of this report (*Sections 6 through 23*).

5.4 Natural Hazard Historic Loss Ratio

The Historic Loss Ratio (HLR) is an area-specific estimate of the percentage of the exposed consequence type (building value, population, or agriculture value) expected to be lost due to a single hazard occurrence. In concept, it is the average of the loss ratios associated with past hazard events and is used to estimate the potential impact of a future hazard events. To begin the determination of this value, a Loss Ratio per Basis (event or event-day) (LRB) is calculated for each historical loss-causing hazard occurrence (for each relevant consequence type) as the value of the loss divided by the exposed consequence value.

A Bayesian credibility analysis is then performed with the individual LRBs at multiple geographic levels (county, surrounding area, regional, and/or national) to better balance historic loss accuracy with geographic precision and characteristics. The resulting HLR (by consequence type) is a Bayesian-adjusted ratio that is the summed weighted average of various geospatial groupings of the consequence LRBs at the relevant geographic levels for the hazard. This Bayesian-adjusted resulting HLR value, computed for each County-Hazard-Consequence type combination, serves as a prediction of the ratio of loss to exposed consequence value that can be expected from a single hazard occurrence. Computation of the HLR also considers hazard events that resulted in no loss prior to performing the Bayesian credibility spatial modelling analysis. This ensures that HLR can be multiplied by frequency within the risk equation without over-inflating the EAL value.

5.4.1 SELECTING SOURCE DATA: SHELDUS

Historic Losses source data provider: *Arizona State University*, *Spatial Hazard Events and Losses Database of the United States (SHELDUS)*[14]

Arizona State University's Spatial Hazard Events and Losses Database of the United States (SHELDUS) loss data were used for most natural hazards. SHELDUS provides county-level data that correspond to nearly all of the natural hazards represented by the NRI. It offers a further degree of description by identifying events by peril as well as hazard. SHELDUS aggregates property damage, crop losses, injuries, and fatalities due to a peril by month, year, and county since 1960. Most of the data at the event level were collected by NOAA and published in the monthly Storm Data and Unusual Weather Phenomena report, though information for some hazards is extracted from additional resources.

SHELDUS represents the best available data on economic, population, and agricultural losses due to natural hazards. However, there are many cases where the geographic precision of the recorded loss is imperfect. In these cases, the exact location of injuries and fatalities may be unknown due to regional reporting from the source data interpreted by SHELDUS, often based on a forecast zone that

[14] Center for Emergency Management and Homeland Security, Arizona State University. (2017). Spatial Hazard Events and Losses Database for the United States, Version 16.0. [online database]. Retrieved from https://cemhs.asu.edu/sheldus.

covers multiple counties. For example, in *Table 6*, an Ice Storm injury is recorded as 0.5 for two neighboring counties and both have the same level of property damage. This signifies that the precise location of the damage associated with this event could not be determined between the two counties, so the damage is split evenly between them. The NRI utilizes SHELDUS data as compiled and does nothing to alter the source information.

Table 6: Sample SHELDUS Data, Aggregated by Peril, County, and Year-Month

County FIPS	Year	Month	Peril	Number of Records	Duration Days	Crop Damage (2016 $)	Property Damage (2016 $)	Injuries	Fatalities
01001	1996	4	Hail	1	1	3,115.02	18,690.11	0	0
32003	1996	6	WindVortex	2	1	0	7,787.55	0	1
05007	2009	1	Ice	1	3	0	17,643,421.41	0.5	0
05143	2009	1	Ice	1	3	0	17,643,421.41	0.5	0

Data were downloaded at the peril level, aggregated to a county-month level, and mapped via a control table in the NRI processing database to the appropriate NRI-defined natural hazards. Peril data were downloaded because natural hazard types as defined in SHELDUS do not directly map into the natural hazard definitions utilized in the NRI. For example, SHELDUS classifies all flooding perils under the hazard Flood, while the NRI explores two flooding hazards (Coastal and Riverine) and classifies the different flooding perils accordingly (see *Table 7*).

Table 7: NRI Hazard to SHELDUS Peril Mapping

NRI Hazard	SHELDUS Perils
Avalanche	Avalanche, AvalancheDebris, AvalancheSnow, SnowSlide
Coastal Flooding	Coastal, CoastalStorm, FloodCoastal, FloodTidal
Drought	Drought
Earthquake	Earthquake, Fire-following Earthquake, LandslideFollowingEQ, Liquefaction
Hail	Hail
Heat Wave	Heat, HeatWave
Hurricane	CycloneExtratropical, CycloneSubtropical, CycloneUnspecified, HurricaneTropicalStorm, NorEaster, StormSurge, TropicalDepression, TropicalStorm
Ice	Ice Storm
Landslide	Landslide, LandslideSlump, MudFlow, Mudslide, RockSlide
Lightning	FireStElmos, Lightning
Riverine Flooding	FloodFlash, FloodIceJam, Flooding, FloodLakeshore, FloodLowland, FloodRiverine, FloodSmallStream, FloodSnowmelt
Strong Wind	Derecho, Wind, WindStraightLine
Tornado	FireTornado, Tornado, Waterspout, WindTornadic, WindVortex,
Tsunami	Tsunami, TsunamiSeiche
Volcanic Activity	Ashfall, Lahar, LavaFlow, PyroclasticFlow, Vog, Volcano
Wildfire	FireBrush, FireBush, FireForest, FireGrass, Wildfire
Winter Weather	Blizzard, StormWinter, WinterWeather

SHELDUS records were downloaded for all perils and all counties in the United States with loss damage inflation-adjusted to 2016 dollars. Loss types included property damage, injuries, fatalities, and crop damage. The loss records utilized for the HLR computation of most hazards range from January 1995 through December 2016 as loss data captured during and after 1995 were deemed to be the most accurately and uniformly collected, due to the standardization of collection practices in 1995. However, data from January 1960 to December 2016 were used to compute HLR for two hazards: Earthquake and Volcanic Activity (see *Sections 10.6* and *21.7*). Older data were also used to identify which counties had ever experienced hazard-specific loss, ensuring that these were set in the NRI processing database as counties where there was some possibility of the hazard occurring (see *Determining County-Level Possibility of Hazard Occurrence Section*).

SHELDUS data include counties that no longer exist, and these counties are marked with an asterisk (*) in the County Name field. The NRI does not currently convert the loss in those counties to the counties that have replaced them. Very few of the counties were dissolved after 1994, so the impact of the missing loss data is minimal.

5.4.2 SELECTING SOURCE DATA: NWS STORM EVENTS DATABASE

National Weather Service, Storm Events Database[15]

Unlike the other natural hazards included in the NRI, the loss information for Cold Wave is derived from the NWS's Storm Events Database. Loss data for property damage and crop damage are recorded in the same manner as the SHELDUS data, much of which originates from the Storm Events Database. Unlike SHELDUS, the Storm Events Database includes natural hazard events with no reported loss.

Dollar amounts in the Storm Events Database are not inflation-adjusted, so these were converted to 2016 dollars using the Bureau of Labor Statistics Consumer Price Index[16] to correspond with the SHELDUS inflation-adjusted dollar amounts, using *Equation 10*.

Equation 10: Conversion to 2016 Dollars

$$V_{Mo_{2016}} = V_{Orig} \times \frac{CPI_{Mo_{2016}}}{CPI_{Mo_{Year}}}$$

where:

$V_{Mo_{2016}}$	is the dollar value in 2016 dollars.
V_{Orig}	is the original dollar value (assumed dollar value at the time of the loss event).
$CPI_{Mo_{2016}}$	is the Consumer Price Index for the month of the loss event in 2016.
$CPI_{Mo_{Year}}$	is the Consumer Price Index for the month/year of the loss event.

Some loss records in the Storm Events Database are designated with a forecast zone rather than a county, so each must be joined to a county via a county-zone correlation table with data that are also provided by the NWS (see *Section 8.2*). Cold Wave events also have start and end dates recorded so the number of event-days can be computed. Cold Wave events extracted from the Storm Events Database use the same date range as most of the data utilized from SHELDUS, 1/1/1995 to 12/31/2016. The resulting extracted records mimic the structure of the SHELDUS data in that all records are aggregated by county, peril, year, and month.

5.4.3 CONSEQUENCE TYPES

The consequence types in the loss data sources are treated as direct corollaries to consequence types measured for NRI Hazard exposure.

[15] National Weather Service. (2017). *Storm Events Database, Version 3.0.* [online database]. Retrieved from https://www.ncdc.noaa.gov/stormevents/.
[16] Bureau of Labor Statistics. (2019). *Consumer Price Index for all urban consumers* [online dataset]. Retrieved from https://www.bls.gov/data/.

Property

Property loss is defined as the SHELDUS—or NWS—reported damage to property caused by the hazard event in 2016 dollars. In the calculation of HLR, property loss is treated as the equivalent of building value recorded in Hazus 4.2 SP1. However, SHELDUS property damage can include other types of property, like vehicles or infrastructure, that would not be reported in the Census data used by Hazus to estimate building value. This is a caveat to consider when working with this data. SHELDUS and Hazus data remain the best available estimates of loss and value that could be utilized for the NRI.

Population

Population loss is defined as the SHELDUS—or NWS—reported number of fatalities and injuries caused by the hazard event. To combine fatalities and injuries for the computation of population loss value, an injury is counted as one-tenth (1/10) of a fatality.

The NWS Storm Events Database classifies injuries and fatalities as direct or indirect. For the purposes of the NRI, both direct and indirect injuries and fatalities are counted in the population loss value.

Agriculture

Agriculture loss is defined as the SHELDUS—or NWS—reported damage to crops and livestock caused by the hazard event in dollars. SHELDUS also tracks crop indemnity payments for USDA-insured crop loss; however, the total crop/livestock damage value was considered to be more inclusive and the crop indemnity data are not used.

5.4.4 HISTORIC LOSS RATIO METHODOLOGY

Conceptually, the Historic Loss Ratio (HLR) is the representative percentage of a location's hazard exposure area that experiences loss due to a hazard, or the average rate of loss associated with the occurrence of a hazard.

This could be computed as the average of the individual occurrence loss rates (referred to here as Loss Ratios per Basis). However, HLR cannot be calculated in these simple terms and be considered accurate. Many counties that have not experienced a loss-causing event during the time period captured from SHELDUS may be in close proximity to counties that share similar characteristics and have experienced loss to the hazard. For example, it may be inaccurate to say that a county's likely loss ratio to Hurricane is zero just because it has not experienced a loss-causing Hurricane event during the 22-year window, especially if it borders counties that have experienced loss to Hurricanes. A better approximation of the HLR is achieved by applying a Bayesian spatial weighting matrix to smooth the loss ratio data spatially and ensure that historic loss is represented in a rational way without allowing anomalous hazard events to distort the data. To implement Bayesian credibility weighting, loss ratio averages and variances need to be computed for spatial groupings of national, surrounding, county, and, for some hazards, regional levels. The nature of the source data requires some pre-processing within the database to ensure that all historical hazard events are included in the loss ratio calculations, including per-basis record expansion of the native SHELDUS records and the insertion of records representing hazard occurrences that did not result in economic loss. See *Section 5.4.5* for more information on limitations and assumptions associated with this methodology.

Loss Record Expansion to per Basis Records

Native SHELDUS and NWS records represent loss aggregated on a county, year, month, and peril basis. Each row includes the number of reported loss-causing peril events for the month in the county and the total duration days of the events. For example, the January 2009 Ice Storm event in *Table 8* lasted three days. The basis of Ice Storm occurrences is the event-day as this definition better captures the variability in duration for Ice Storm events. Without the resolution of knowing which event-day the damage occurred on, the loss is divided among the days so that each event-day record has an equal portion of the total loss (see *Table 9*). In this example, the three event-day records replace the native SHELDUS record. Similarly, a single native SHELDUS peril month record for an event-based hazard like Hurricane could describe two separate events. This native record would be replaced with two records, each representing a single event with half the loss of the native aggregated record. Because SHELDUS does not specify the amount of loss associated with each of the events, each SHELDUS record is expanded based on the occurrence basis (Number of Records for event basis and Duration Days for event-day basis) if the basis count is greater than one (see *Table 5*). This record count expansion process is performed because loss ratios will ultimately be computed for each event (or event-day) record. Having a record for each hazard occurrence per basis unit better supports the process of determining loss ratio averages and variance.

Table 8: Native SHELDUS Loss Records

County FIPS	Year	Month	Peril	Event Records	Duration (Days)	Crop Damage (2016 $)	Property Damage (2016 $)	Injuries	Fatalities
5007	2009	1	Ice	1	3	0	17,643,421.41	0.5	0
1097	1998	9	Hurricane Tropical Storm	2	5	681,464.65	23,749,724.65	0	1

Table 9: Expanded SHELDUS Loss Records

County FIPS	Year	Month	Peril	Native Loss Record Expanded per Basis	Crop Damage (2016 $)	Property Damage (2016 $)	Injuries	Fatalities
5007	2009	1	Ice	EventDay	0	5,881,140.47	0.1666	0
5007	2009	1	Ice	EventDay	0	5,881,140.47	0.1666	0
5007	2009	1	Ice	EventDay	0	5,881,140.47	0.1666	0

County FIPS	Year	Month	Peril	Native Loss Record Expanded per Basis	Crop Damage (2016 $)	Property Damage (2016 $)	Injuries	Fatalities
1097	1998	9	Hurricane, Tropical Storm	Event	340,732.33	11,874,862.33	0	0.5
1097	1998	9	Hurricane, Tropical Storm	Event	340,732.33	11,874,862.33	0	0.5

Loss Ratio Per Basis Calculation

After this expansion of records to convert the loss data to loss per single event or event-day is performed, the Loss Ratio per Basis (LRB) is calculated for each event or event-day occurrence for each consequence type (building, population, or agriculture) according to *Equation 11*.

Equation 11: Loss Ratio per Basis Calculation

$$LRB_{Haz_{Co_{CnsqType}}} = \frac{Loss_{Haz_{Co_{CnsqType}}}}{HLRExposure_{Haz_{Co_{CnsqType}}}}$$

where:

$LRB_{Haz_{Co_{CnsqType}}}$ is the Loss Ratio per Basis (event or event-day) representing the ratio of loss to exposure experienced by a specific county due do the occurrence of a specific hazard event, performed for each relevant consequence type (building, population, and agriculture).

$Loss_{Haz_{Co_{CnsqType}}}$ is the loss (by consequence type) experienced from the hazard event (or event day) documented to have occurred in the county (in dollars).

$HLRExposure_{Haz_{Co_{CnsqType}}}$ is the total value (by consequence type) estimated to have been exposed to the event or event-day hazard occurrence (in dollars).

The definition of the HLR exposure variable in the LRB formula does not always match the definition of the exposure component utilized in the EAL formula. For hazards that can occur almost anywhere or affect large geographic areas, the HLR exposure is the entire county's building, population, or agriculture value. Hazards that only occur in certain susceptible areas, such as floodplains and tsunami inundation zones, use the HLR exposure value associated with those areas. Tornado HLR exposure is defined by the area footprint of specific historical Tornado paths. Avalanche is a unique case that requires the use of default exposure values. The HLR exposure types utilized for each hazard can be seen in the table below. Specific methods of determining HLR exposure in the LRB calculation can be found in the HLR section for each hazard. *Table 10* lists the exposure types used in each hazard's LRB calculation.

Table 10: HLR Exposure Types Used in Loss Ratio per Basis Calculation

Natural Hazard	HLR Exposure Type
Avalanche	Default Value
Coastal Flooding	Value Defined by Hazard Intersect
Cold Wave	Total County Value
Drought	Total County Value
Earthquake	Total County Value
Hail	Total County Value
Heat Wave	Total County Value
Hurricane	Total County Value
Ice Storm	Total County Value
Landslide	Value Defined by Hazard Intersect
Lightning	Total County Value
Riverine Flooding	Value Defined by Hazard Intersect
Strong Wind	Total County Value
Tornado	Historical Footprint Matched to Specific SHELDUS Loss
Tsunami	Value Defined by Hazard Intersect
Volcanic Activity	Value Defined by Hazard Intersect
Wildfire	Value Defined by Hazard Intersect
Winter Weather	Total County Value

Non-Loss Causing Hazard Occurrence

Hazards may occur without resulting in recorded loss to buildings, population, or agriculture. For example, Lightning may strike with a high frequency, but have few loss-causing events. SHELDUS does not record events in which no loss was reported. In an effort to capture events that do not cause loss, a count of historic year-month events is produced from hazard source data and compared to a count of loss-producing events from SHELDUS. When the hazard historic event source records more events than SHELDUS, a number of zero-loss records are inserted into the set of LRBs to make up the difference between historic events and loss-causing events from SHELDUS so that the event counts for both metrics are equal.

Computing loss ratio averages and variances without including the zero-loss records produces very different results than when they are included. For example, a county with 100 historical Lightning strikes may only have two loss-causing events, one causing $40,000 in damage to buildings and the other causing $60,000. If the building exposure value is $10M, the loss ratios for each loss-causing event would be 0.004 and 0.006, respectively. If only the LRBs for two loss-causing events were considered, the average would be 0.005. Including the 98 Lightning strikes that did not result in loss lowers the average to 0.0001, a more accurate approximation of the average Lightning strike's impact on the county as not every Lightning strike is a loss-causing event.

The output of the LRB calculation (see *Equation 11*) and all corrective record insertion is stored in the LRB table within the NRI processing database, and are then used to compute Bayesian metrics and calculate the weighting factors that are applied to find the Bayesian-adjusted HLR for each consequence type for the county. *Table 11* illustrates the content of the LRB database table after the corrective record insertions. Notice the loss ratios for three Ice Storm event-days in one county in January 2009. These have been expanded from a single SHELDUS record based on duration days and consequence types. Also, one zero-loss record for each relevant consequence type has been inserted to recognize an Ice Storm event-day that occurred within the county (based on the historical event source data) but resulted in no economic loss. These records can then be used to calculate loss ratio averages and variance.

Table 11: Sample Data from the Loss Ratio per Basis Table

Hazard	Peril	Basis	Year	Month	Conseq. Type	Conseq. Exposure	Conseq. Loss per Basis	Conseq. Ratio per Basis Unit	Record Type
Ice Storm	Ice	Event Day	2009	1	People	221339	0.01666667	7.53E-08	Peril Basis Expansion
Ice Storm	Ice	Event Day	2009	1	People	221339	0.01666667	7.53E-08	Peril Basis Expansion
Ice Storm	Ice	Event Day	2009	1	People	221339	0.01666667	7.53E-08	Peril Basis Expansion
Ice Storm	Ice	Event Day	2009	1	Property	2.3138E+10	5881140.47	0.00025	Peril Basis Expansion
Ice Storm	Ice	Event Day	2009	1	Property	2.3138E+10	5881140.47	0.00025	Peril Basis Expansion
Ice Storm	Ice	Event Day	2001	11	People	221339	0	0	SHELDUS Native Record
Ice Storm	Ice	Event Day	2001	11	Property	2.3138E+10	310468.525	0.0000134	SHELDUS Native Record
Ice Storm	Inserted Zero-Loss Record	Event Day			People	221339	0	0	Inserted Zero-Loss Record
Ice Storm	Inserted Zero-Loss Record	Event Day			Property	2.3138E+10	0	0	Inserted Zero-Loss Record

Bayesian Credibility

To apply Bayesian credibility weighting factors and balance Historic Loss accuracy with geographic precision in areas where small sample sizes result in volatile Historic Loss estimates, LRB averages and variance may be calculated at several levels: county, surrounding 196-by-196-km fishnet grid cell,[17] regional, and national. These geographic levels define which spatial grouping (or set) of LRBs are used to calculate the average and variance values. The county-level grouping includes all LRBs for the county, the surrounding grouping includes LRBs for all counties that intersect the same 196-by-196-km fishnet cell, and national includes all LRBs. The formulas in *Equation 12* illustrate the computation of the loss ratio average and variance.

Equation 12: Geographic Level Consequence Ratio Average and Variance Computations

$$avgLRB_{Haz_{Level_{CnsqType}}} = \frac{\sum LRB_{Haz_{Level_{CnsqType}}}}{CountEvents_{Haz_{Level_{CnsqType}}}}$$

$$varLRB_{Haz_{Level_{CnsqType}}} = \frac{\sum (LRB_{Haz_{Level_{CnsqType}}} - avgLRB_{Haz_{Level_{CnsqType}}})^2}{CountEvents_{Haz_{Level_{CnsqType}}}}$$

where:

$avgLRB_{Haz_{Level_{CnsqType}}}$	is the average value of all Loss Ratio per Basis (event or event-day) records of the consequence type for the geographic level due to the hazard.
$LRB_{Haz_{Level_{CnsqType}}}$	is the Loss Ratio per Basis (event or event-day) of the consequence type within the geographic area due to the hazard occurrence basis.
$CountEvents_{Haz_{Level_{CnsqType}}}$	is the total number of records of hazard events or event-days occurring in the geographic area (includes any non-loss causing events/event-days identified).
$varLRB_{Haz_{Level_{CnsqType}}}$	is the consequence Loss Ratio per Basis variance of the geographic level due to the hazard.

Credibility increases as a function of sample size and decreased LRB variance. In other words, the higher the credibility at a given geographic level, the higher the contribution to the location's calculated Historic Loss value. *Figure 12* illustrates possible loss ratio variance in neighboring

[17] The 196-by-196 km fishnet grid cell is roughly the area of four average counties. See the *Intersection Section* for more information on the use of the 49-by-49 km fishnet resolution to represent average county area.

counties. Weighting factors in the Bayesian credibility calculation are what determines the contribution of each geographic level to the final HLR value.

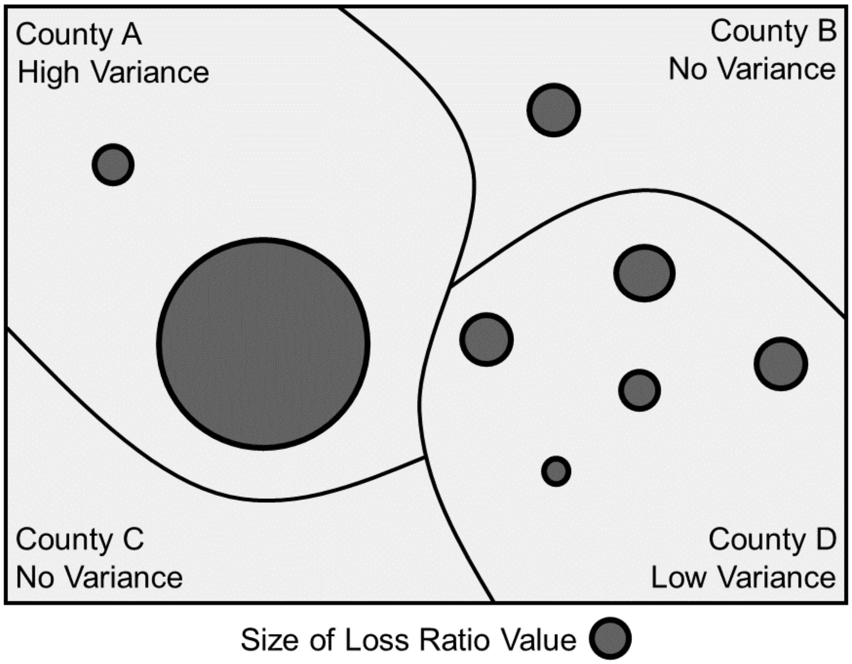

Figure 12: Example of Variance in County Loss Ratio Values

Weighting factors are derived from the variance values (calculated using *Equation 12*) at each geographic level according to *Equation 13*. For the surrounding fishnet level, if the county intersects more than one fishnet grid cell, the cell with the lowest LRB variance value is used as this provides the data with the best fit.

Equation 13: HLR Bayesian Weighting Factor Calculation

$$Wt_{Denom} = \frac{1}{varLRB_{Haz_{Ntl}}{}_{CnsqType}} + \frac{1}{varLRB_{Haz_{Reg}}{}_{CnsqType}} + \frac{1}{varLRB_{Haz_{Sur}}{}_{CnsqType}} + \frac{1}{varLRB_{Haz_{Co}}{}_{CnsqType}}$$

$$Wt_{Haz_{Ntl}}{}_{CnsqType} = \frac{1/varLRB_{Haz_{Ntl}}{}_{CnsqType}}{Wt_{Denom}}$$

$$Wt_{Haz_{Reg}}{}_{CnsqType} = \frac{1/varLRB_{Haz_{Reg}}{}_{CnsqType}}{Wt_{Denom}}$$

$$Wt_{Haz_{Sur}}{}_{CnsqType} = \frac{1/varLRB_{Haz_{Sur}}{}_{CnsqType}}{Wt_{Denom}}$$

$$Wt_{Haz_{Co}}{}_{CnsqType} = \frac{1/varLRB_{Haz_{Co}}{}_{CnsqType}}{Wt_{Denom}}$$

where:

Wt_{Denom}	is the sum of the inverted variances calculated at each geographic level, used as a denominator for the level weighting factors.
$Wt_{Haz_X}{}_{CnsqType}$	is the weighting factor to be applied to the average consequence LRB for the hazard at *X* level (national, regional, surrounding, county).
$varLRB_{Haz_X}{}_{CnsqType}$	is the consequence LRB variance for the hazard at *X* level (national, regional, surrounding, county).

For several hazards, regional Bayesian HLR weighting supplies a more accurate estimation of historic loss for areas that have not experienced economic loss due to hazard events during the hazard's period of record. This is especially true for areas where hazard frequency and severity are dependent on their geographic location and climate. For example, Ice Storm, Winter Weather, and Cold Wave will have a very different degree of impact on the Northeast than on the Southwest. For this reason, the Bayesian spatial weighting incorporates regional weighting rather than national for these hazards.

Most hazard-specific HLR region definitions are derived from the FEMA administrative region definitions. The only difference being that FEMA Regions I, II, and III are merged to form a region that is closer in size to that of the other regions (see *Figure 13*). The definition of regions for Hurricane utilizes the FEMA administrative region definitions, but further divides them into coastal regions (for the East and Gulf coasts) and inland regions along a county-level boundary that approximates the hurricane prone regions identified in the American Society of Civil Engineers (ASCE) 7-05, Minimum Design Loads for Buildings and Other Structures (see *Figure 14*).[18]

There was a need to define geographical groupings larger than states, but smaller than the nationwide grouping, so a regional definition was required. Because FEMA has a pre-existing definition of regions that is logical and groups states by similar geographical and climatological characteristics, a decision was made to modify the existing region definition rather than create new region definitions.

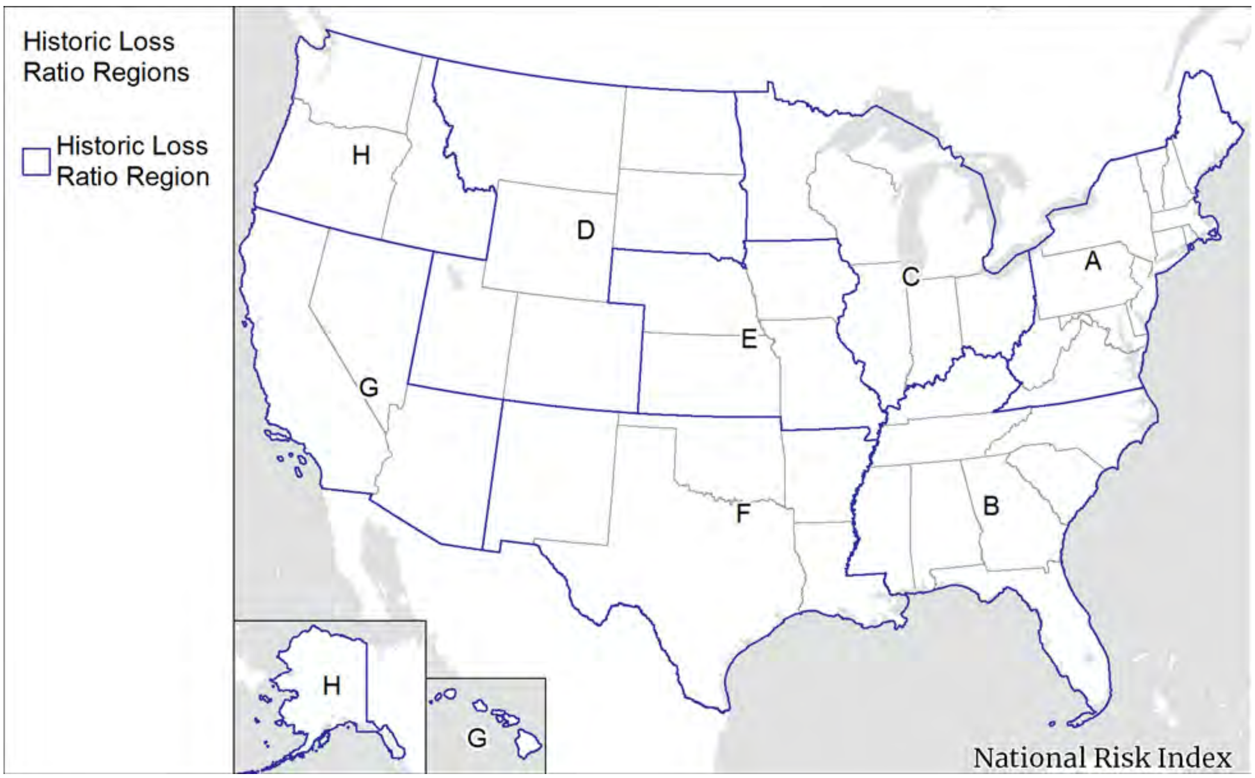

Figure 13: Historic Loss Ratio Region Definitions

[18] American Society of Civil Engineers. (2005). Minimum design loads for buildings and other structures (ASCE/SEI 7-05). Reston, VA: American Society of Civil Engineers.

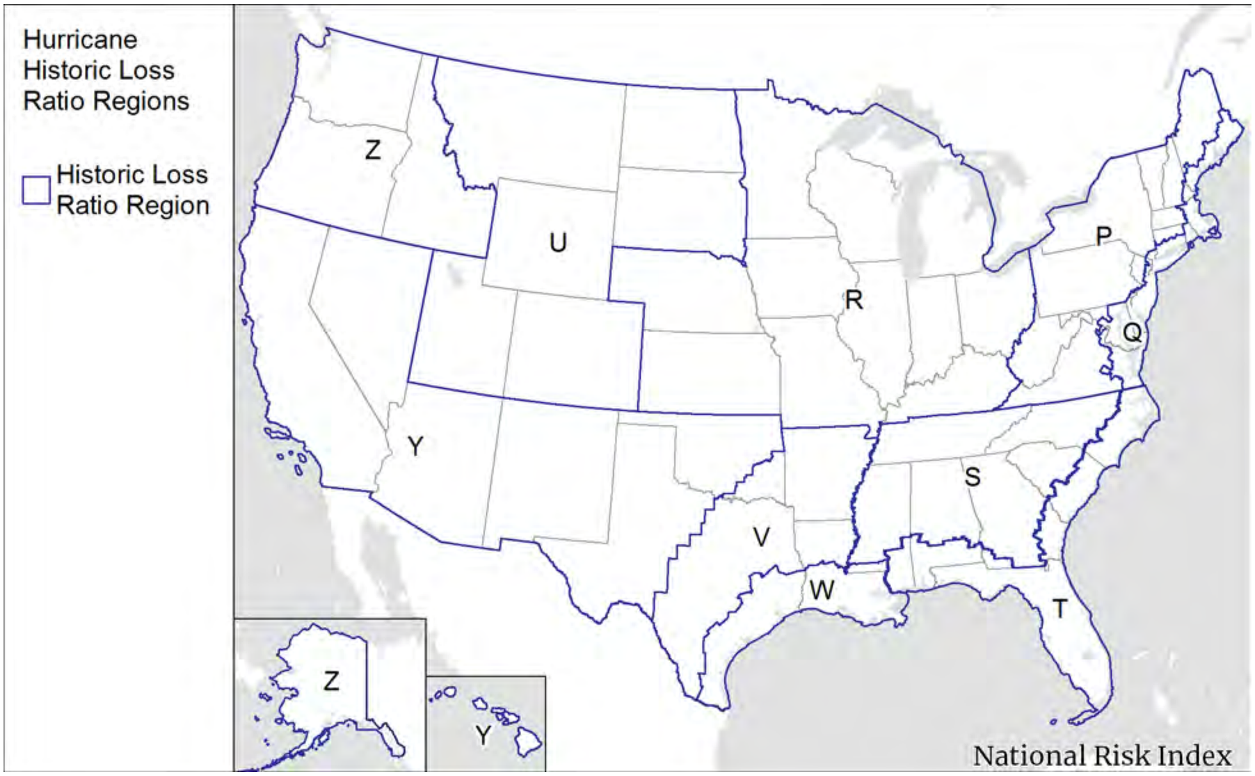

Figure 14: Hurricane Historic Loss Ratio Region Definitions

The HLR for each relevant consequence type is calculated as the sum of its weighted average county, surrounding fishnet, regional, and national average LRB (see *Equation 14*). Levels not used for a specific hazard are removed from the computation.

Equation 14: County Bayesian-Adjusted HLR Calculation

$$HLR_{Haz\,Co_{CnsqType}} = \left(avgLRB_{Haz\,Ntl_{CnsqType}} \times Wt_{Haz\,Ntl_{CnsqType}}\right) + \left(avgLRB_{Haz\,Reg_{CnsqType}} \times Wt_{Haz\,Reg_{CnsqType}}\right) + \left(avgLRB_{Haz\,Sur_{CnsqType}} \times Wt_{Haz\,Sur_{CnsqType}}\right) + \left(avgLRB_{Haz\,Co_{CnsqType}} \times Wt_{Haz\,Co_{CnsqType}}\right)$$

where:

$HLR_{Haz\,Co_{CnsqType}}$ is the Historic Loss Ratio for the hazard at the county level by consequence type.

$avgLRB_{Haz_{X_{CnsqType}}}$ is the average LRB by consequence type for the hazard at *X* level (national, regional, surrounding, county).

$Wt_{Haz_{X_{CnsqType}}}$ is the weighting factor applied to the LRB by consequence type for the hazard at *X* level (national, regional, surrounding, county).

This Bayesian-adjusted resulting HLR value, computed for each County-Hazard-Consequence type combination, serves as a prediction of the ratio of loss to exposed consequence value that can be expected from a single hazard occurrence. When multiplied by the frequency of hazard occurrence in an area and the consequence value exposed to the hazard, the historic loss ratio allows for the estimation of an area's EAL of that consequence type due to the hazard.

HLR Inheritance

The Bayesian-adjusted county HLR is inherited by the Census blocks and Census tracts within the county when used in the NRI EAL calculations, as in *Equation 15*.

Equation 15: Census Tract and Census Block HLR Inheritance

$$HLR_{Haz_{Co_{CnsqType}}} = HLR_{Haz_{CT_{CnsqType}}} = HLR_{Haz_{CB_{CnsqType}}}$$

where:

$HLR_{Haz_{Co_{CnsqType}}}$ is the Bayesian-adjusted Historic Loss Ratio, a hazard-county-consequence type specific value.

$HLR_{Haz_{CT_{CnsqType}}}$ is the inherited Historic Loss Ratio for the hazard at the Census tract level.

$HLR_{Haz_{CB_{CnsqType}}}$ is the inherited Historic Loss Ratio for the hazard at the Census block level.

5.4.5 LIMITATIONS AND ASSUMPTIONS IN HISTORIC LOSS RATIO METHODOLOGY

Several factors are not entirely accounted for in the calculation of HLR. Certain processes, such as Bayesian credibility adjustments, attempt to correct some of these limitations. This section addresses some of the assumptions that are intrinsic within the current methodology and how these can limit the accuracy of the calculation.

Evaluating historic economic loss from SHELDUS over a relatively brief period of time and comparing it to a static HLR exposure value does not account for changes in development patterns over these years. For example, a hazard event in 1995 may have a low HLR when its loss is compared to its 2010 Hazus-derived exposure value; however, because of increased development and population influx over the years, its HLR would be much higher if the same loss were compared to the actual 1995 exposure value. There is an inherent assumption in the methodology that all buildings, population, and agriculture exposed to the hazard are static in economic value and quantity over the data period. Additionally, the SHELDUS loss values are inflation-adjusted to 2016 dollars, and Hazus-derived exposure values are in 2018 dollars based on 2010 valuations. There is an assumption that these dollar values are comparable.

Since the HLR calculation is based on historical events, it does not project reductions due to enhanced mitigation efforts and improved building standards that have changed over time (i.e., a seawall being built after a destructive flooding event may reduce the damage caused by subsequent flooding events).

Characterizing agriculture losses from events is highly complex and can vary based on a number of factors, including supply and demand, substitution effects, crop rotation, and seasonality. The simplified HLR calculations use crop and livestock distribution and values based on agriculture data from CropScape and the Census of Agriculture.

There are many cases where the geographic precision of the recorded loss is imperfectly captured in SHELDUS. The regional reporting data used to compile SHELDUS may mention multiple counties for a loss-causing event. In these cases, the loss is spread equally over the counties where the hazard occurred, though the loss may have only occurred in one county. Also, loss may only occur in a portion of the county, yet the HLR will apply to the entire county due to loss not being recorded with any granularity below the county level.

5.5 Validating Expected Annual Loss Estimates to Historical Losses

The diversity of the hazards and source data included in the calculation of the NRI presents a significant challenge to provide accurate and meaningful results for the variety of potential lenses through which the results may be viewed, such as:

- Hazard EAL rankings within a county
- County EAL rankings within a hazard
- County EAL rankings across all hazards
- Hazard EAL rankings all counties

As an attempt to validate the EAL, historic loss from SHELDUS for the period from 1995 to 2016 was aggregated for the entire nation for each hazard and divided by the period of record (22 years) to give a rough nationwide hazard annualized loss estimate.[19] This value was compared to the aggregated EAL estimate calculated for the NRI for its corresponding hazard. All but two (Earthquake and Volcanic Activity) of the natural hazard EALs are within the same order of magnitude as the experienced historic losses, and half of the hazards are within a factor of 2.

[19] For Cold Wave, the historic loss data were aggregated from the NWS Storm Events Database for 1996 to 2016 and divided by the 21-year period of record.

When evaluating the historical record, losses for some hazards are driven by relatively few events. For example, from 1960 to 2016, 50% of all hurricane consequences were caused by only 8 storms. Similarly, from 1995 to 2016, 50% of all riverine flooding consequences were caused by only 48 events. The same pattern applies to Earthquakes and Volcanic Activity. These events are statistical outliers where high-value urban areas have been impacted by severe hazard events. For Wildfire and Earthquake, annualized frequency uses probabilistic statistics to compute an annualized frequency. Use of probabilistic data to calculate EALs for these hazards account for the probability that the outlier event may occur. Reliance on historical data alone for the other hazards will generally underestimate the EALs for hazards where losses are driven by the rare catastrophic events. For this reason, Hurricane EALs are significantly lower (~75%) than their historical losses. This is because, for every severe hurricane that directly strikes a major city, there may be dozens of glancing blows from minor hurricanes or tropical storms that cause minimal damage. The HLR approach calculates an average value; thus, HLRs are weighted toward the more common, lower loss events rather than the rare catastrophic events.

Despite these outliers, a relatively high level of agreement between the NRI-calculated EAL and the historical loss records serves as an indication that the NRI estimated annual hazard loss is fairly aligned with actual recorded historic loss.

6 Avalanche

An Avalanche is a mass of snow in swift motion traveling down a mountainside.

6.1 Spatial Source Data

Susceptible Area Source: [National Avalanche Center,](https://avalanche.org)[20] *Avalanche Forecast Zone Map*

The National Avalanche Center (NAC) has defined Avalanche Forecast reporting zones that represent the areas for which various regional Avalanche centers provide forecasts. These forecast zones cover a small subset of areas with Avalanche potential, but these areas are where people and property are most likely to be impacted by Avalanche damage. For the NRI effort, these Avalanche Forecast reporting zones are used to identify geographic areas with Avalanche risk. (See *Figure 15*.) The NAC also provides a database, compiled by the Colorado Avalanche Information Center, of U.S. Avalanche Accident Reports with accidents resulting in death. However, few of these reports before 2011 contain geographic coordinates and most do not supply geospatial precision beyond the state in which the accident occurred.

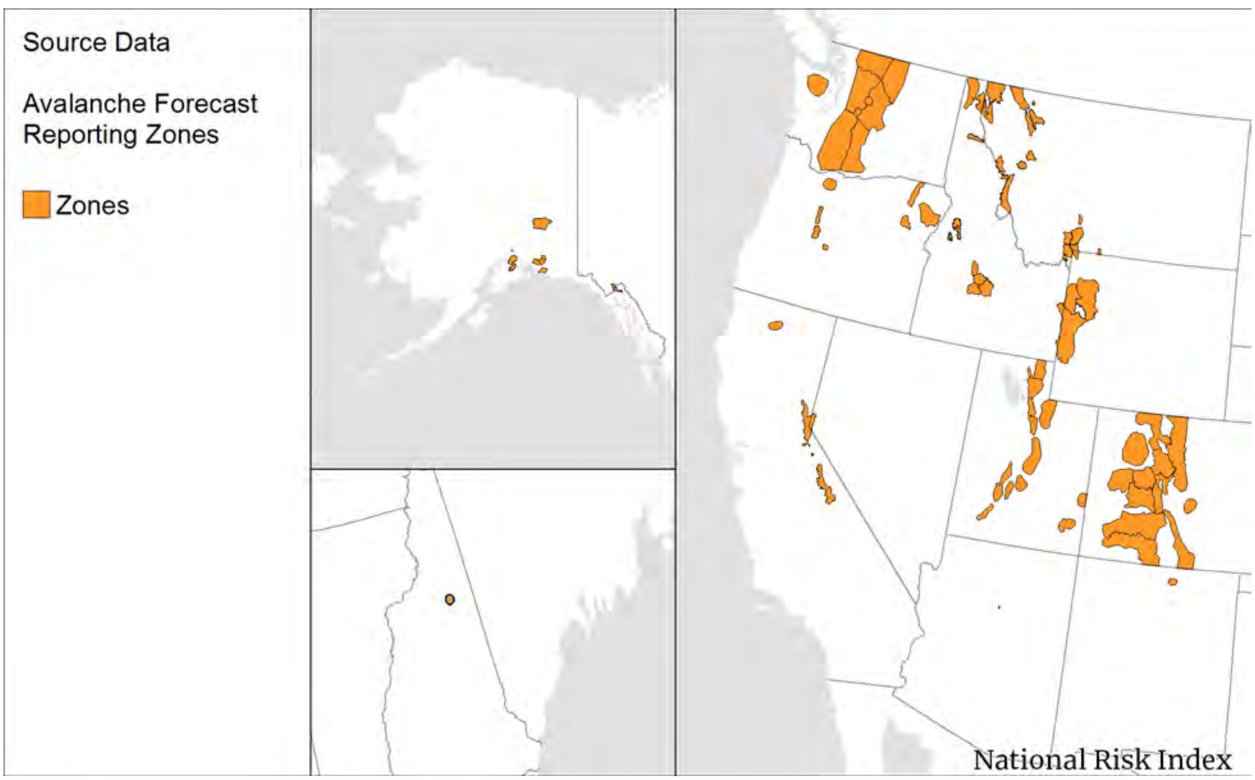

Figure 15: Avalanche Forecast Reporting Zones

[20] National Avalanche Center. (2018). *Avalanche forecast zone map* [online dataset]. Retrieved from https://avalanche.org.

Historical Event Source: *Arizona State University*[21], *Spatial Hazard Events and Losses Database of the United States*

Because the best alternative source of individual Avalanche events only supplied quality spatial information on population impact after 2011, SHELDUS Avalanche event data were selected as the source for Avalanche frequency computation at the county level. For more information on SHELDUS, see *Section 5.4.1*.

6.1.1 PERIOD OF RECORD

To utilize the most accurate SHELDUS records, data from 1/1/1960 to 12/31/2016 are used to calculate frequency, so the period of record for which Avalanche data are utilized is 57.04 years.

6.2 Determination of Possibility of Hazard Occurrence

To distinguish between areas where no Avalanche events have occurred and those where such events are not deemed possible, a control table was generated to designate which counties have some probability of being impacted by an Avalanche event. Any county that intersected an Avalanche forecast zone or had experienced economic loss due to credible Avalanche events (as recorded in SHELDUS) is included as one in which Avalanche events are possible (see *Figure 16*).

[21] Center for Emergency Management and Homeland Security, Arizona State University. (2017). Spatial Hazard Events and Losses Database for the United States, Version 16.0 [online database]. Retrieved from https://cemhs.asu.edu/sheldus

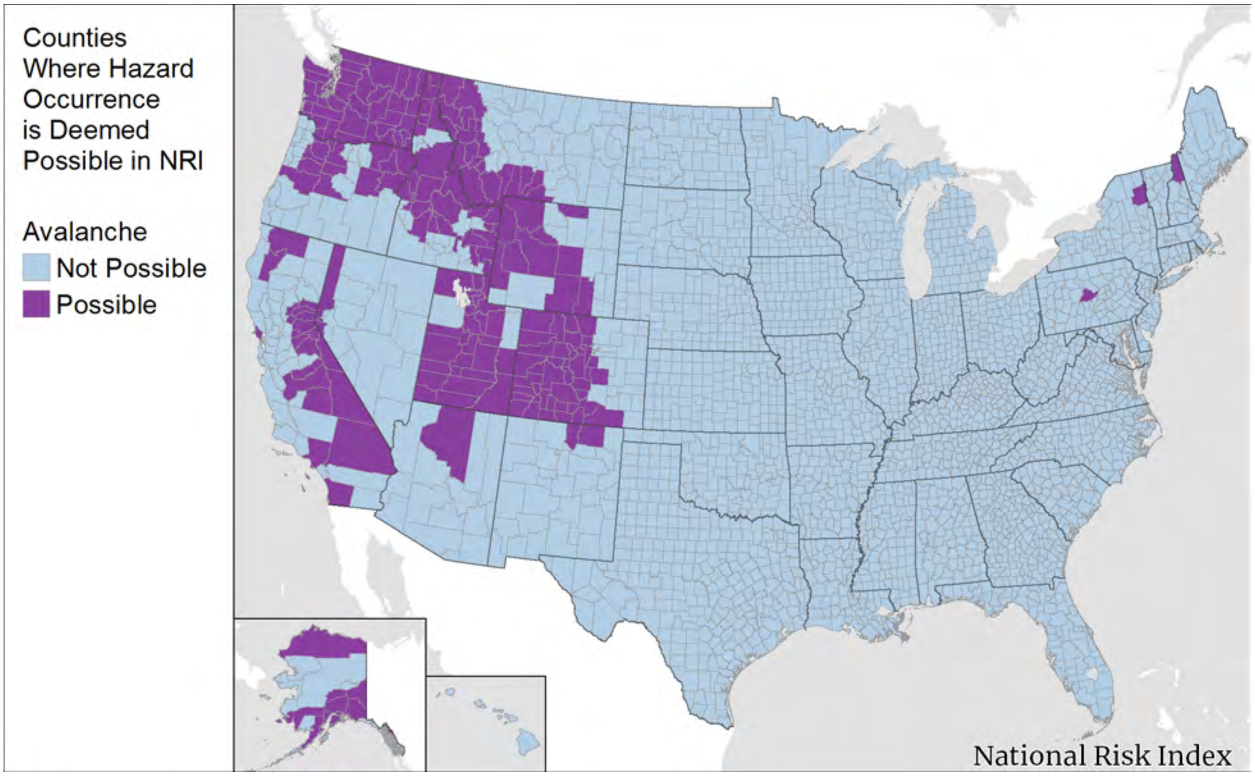

Figure 16: Map of Counties Deemed Possible for Avalanche Occurrence

6.3 Exposure

Avalanche exposure is set to a default value for building and population in Census tracts within counties where Avalanches were deemed possible. Analysis of the loss data presented in SHELDUS led to a consensus on a default building exposure value of $1M and a default population exposure of 5 people. Avalanches occur in sparsely populated mountainous areas, so exposure values tend to be low.

6.3.1 COUNTY-LEVEL EXPOSURE ESTIMATION

At the county level, the exposure value is the maximum consequence type exposure value of all the Census tracts within the county, which is essentially the same default Census tract exposure.

6.4 Historic Event Count

The count of historic Avalanche events is computed as the number of SHELDUS-recorded Avalanche events that have occurred within the county from January 1960 to December 2016. Because the exact location of the event within the county cannot be determined from the SHELDUS record, Historic Event Counts are not supplied at the Census tract level.

6.5 Frequency

The frequency value represents the number of Avalanche loss-causing events each year over the period of record (57.04 years). This annualized frequency is calculated at the county level. The Census tract inherits the county-level value, and the Census tract value is used in the EAL calculations.

Frequency calculations use the SHELDUS Avalanche events for the county and divide by the period of record using *Equation 16*.

Equation 16: County Avalanche Frequency

$$Freq_{AVLN_{Co}} = \frac{EventCount_{AVLN_{Co}}}{PeriodRecord_{AVLN}}$$

where:

$Freq_{AVLN_{Co}}$	is the annualized frequency of Avalanche events determined for a specific county (events per year).
$EventCount_{AVLN_{Co}}$	is the total number of SHELDUS Avalanche events that have impacted the county.
$PeriodRecord_{AVLN}$	is the period of record for Avalanche (57.04 years).

6.5.1 MINIMUM ANNUAL FREQUENCY

If a county intersects an Avalanche forecast zone but has not experienced a loss-causing Avalanche event, it is assigned a minimum annual frequency of 0.01 or once in 100 years. This was determined by SMEs to be an acceptable assumption.

6.5.2 FREQUENCY INHERITANCE

The Census tract inherits its frequency value from the county that contains it as in *Equation 17*.

Equation 17: Census Tract Avalanche Frequency Inheritance

$$Freq_{AVLN_{CT}} = Freq_{AVLN_{Co}}$$

where:

$Freq_{AVLN_{CT}}$	is the annualized frequency of Avalanche events determined for a specific Census tract (events per year).

$Freq_{AVLN_{Co}}$ is the annualized frequency of Avalanche events determined for a specific county (events per year).

Figure 17 displays annualized Avalanche frequency at the county level.

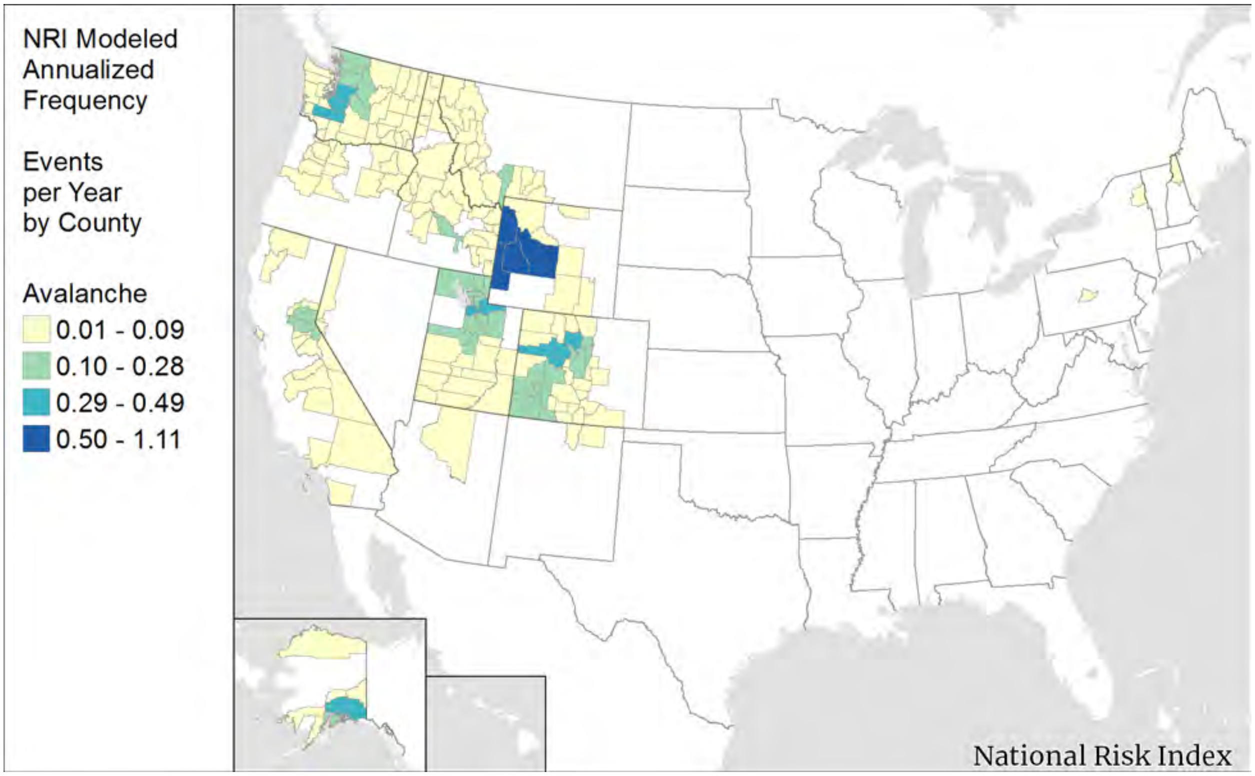

Figure 17: Annualized Avalanche Frequency by County

6.6 Historic Loss Ratio

The Avalanche HLR is the representative percentage of a location's hazard exposure area that experiences loss due to an Avalanche event, or the average rate of loss associated with the occurrence of an Avalanche event.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Three peril types are mapped to the hazard Avalanche (see *Table 12*). These are expanded on an event basis based on the event count field in SHELDUS[22] (see *Section 5.4.1*).

[22] For Avalanche loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

Table 12: Avalanche Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Avalanche	2/15/1902	1,023
AvalancheSnow	1/23/1900	26
SnowSlide	1/0/1900	0

The HLR exposure value used in the LRB calculation is the default consequence value of the county (building value exposure of $1M and population exposure of 5 people; see *Section 6.3*). The LRB for each SHELDUS-documented event and each consequence type (building and population) is calculated using *Equation 18*.

Equation 18: Loss Ratio per Basis Calculation for a Single Avalanche Event

$$LRB_{AVLN\,Co_{CnsqType}} = \frac{Loss_{AVLN\,Co_{CnsqType}}}{HLRExposure_{AVLN\,Co_{CnsqType}}}$$

where:

$LRB_{AVLN\,Co_{CnsqType}}$ is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Avalanche event. Calculation is performed for each consequence type (building and population).

$Loss_{AVLN\,Co_{CnsqType}}$ is the loss (by consequence type) experienced from the Avalanche event documented to have occurred in the county (in dollars).

$HLRExposure_{AVLN\,Co_{CnsqType}}$ is the maximum default value (by consequence type) of all the Census tracts within the county estimated to have been exposed to the Avalanche event (in dollars).

SHELDUS is the only utilized source of historic event data for Avalanche, so no zero-loss events are inserted into the Loss Ratio table. After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at the county and national level.

Figure 18 and *Figure 20* display the largest weighting factor contributor in the Bayesian credibility calculations for the Avalanche HLR of every county. This contributor is not necessarily the only weighting contributing to the county’s HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Avalanche events within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by national events. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from national-level loss data. *Figure 19* and *Figure 21* represent the final county-level HLR values for Avalanche.

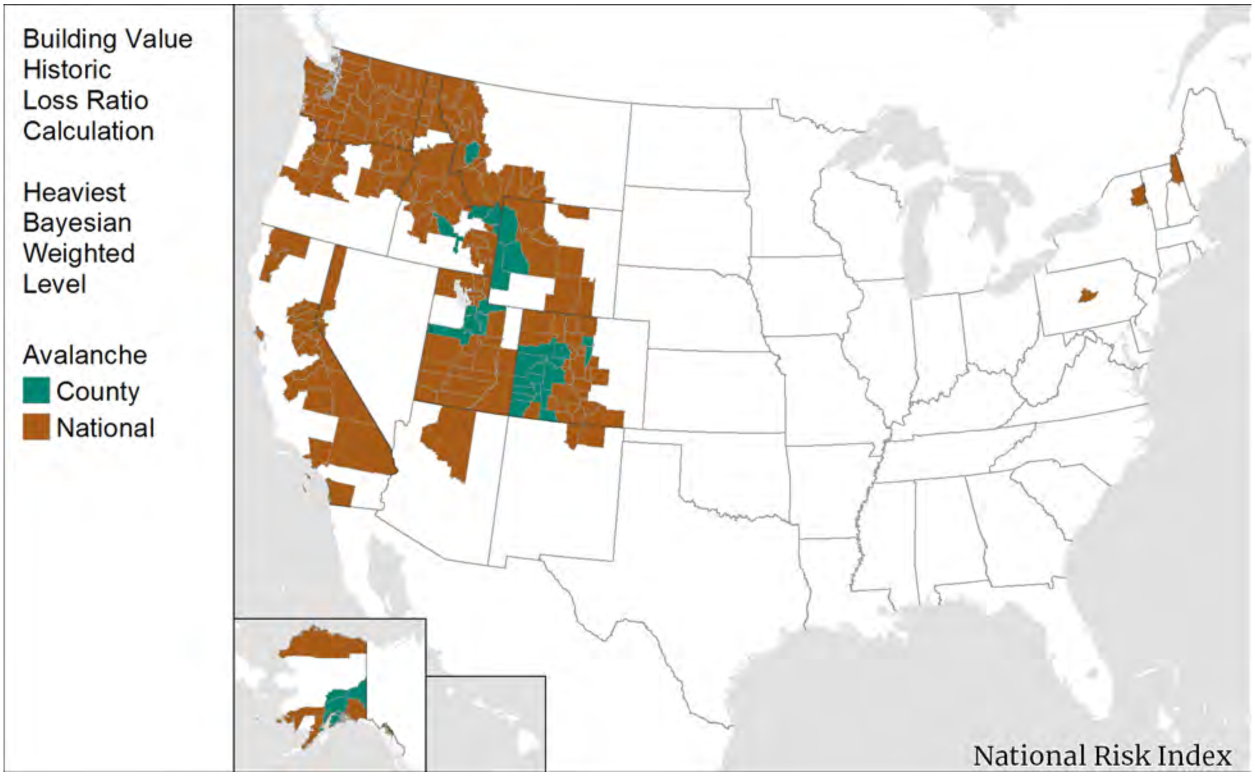

Figure 18: Avalanche Heaviest Bayesian Weighted Level – Building Value

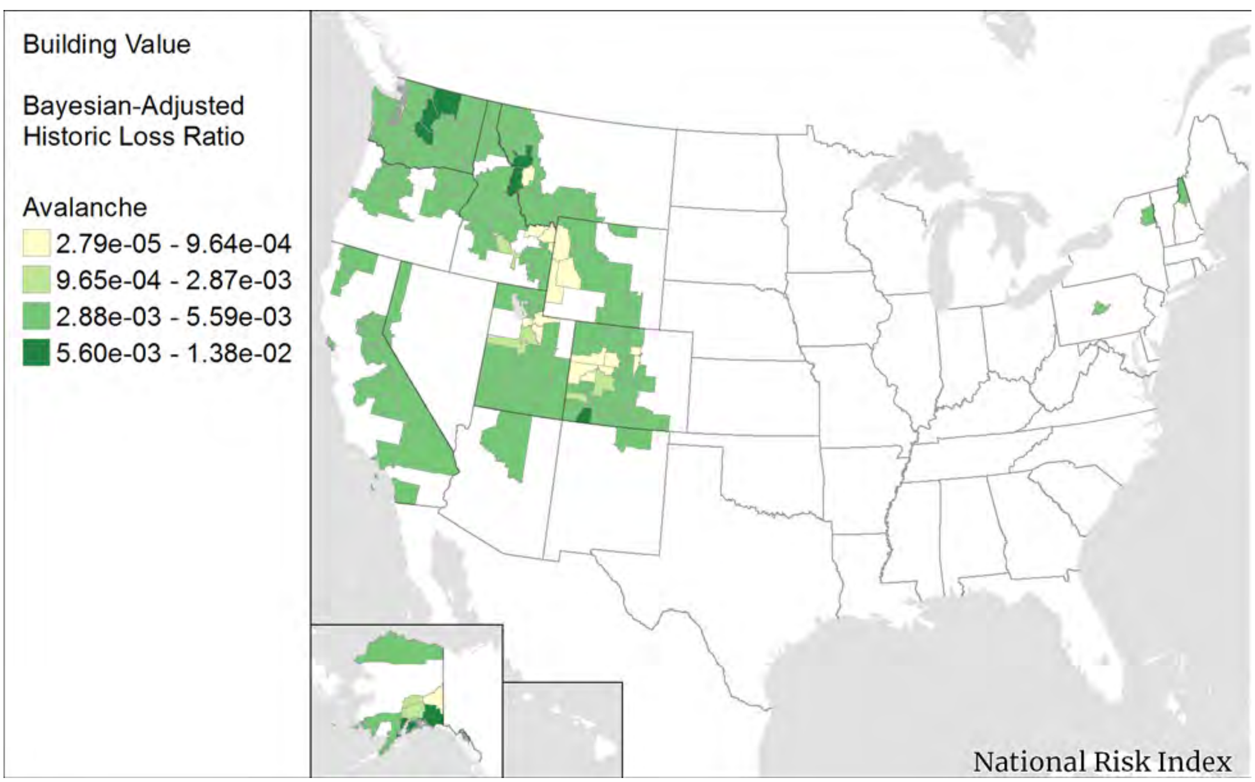

Figure 19: Avalanche HLR – Building Value

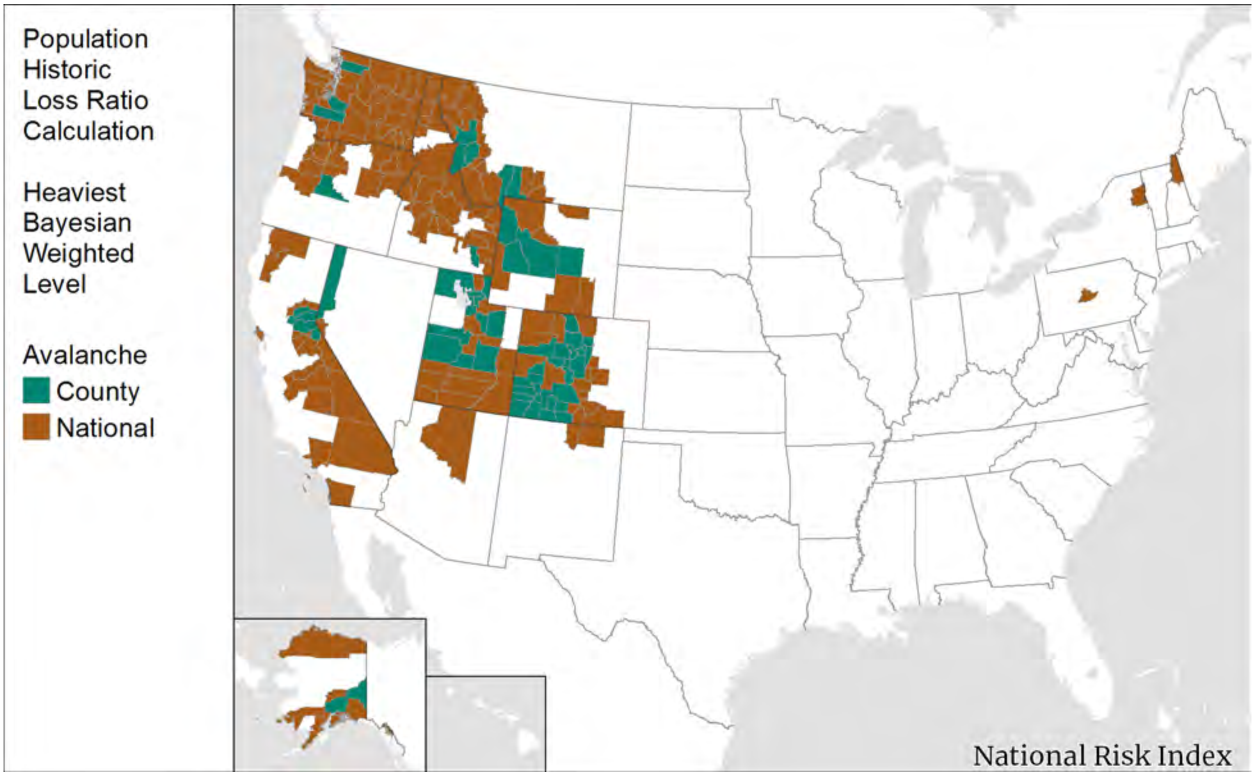

Figure 20: Avalanche Heaviest Bayesian Weighted Level – Population

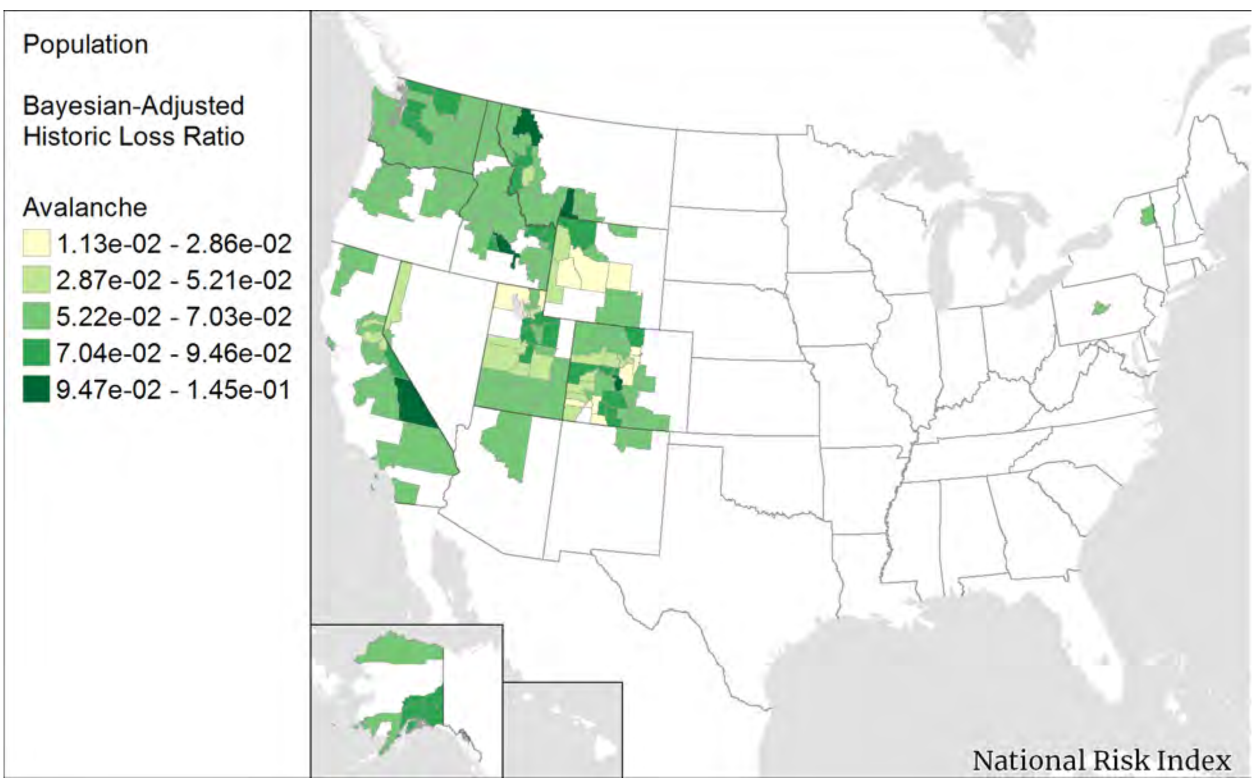

Figure 21: Avalanche HLR – Population

The resulting HLR is then inherited by the Census tracts within the county.

6.7 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census tract level using *Equation 19*.

Equation 19: Census Tract Expected Annual Loss to Avalanche

$$EAL_{AVLN_{CT_{Bldg}}} = Exposure_{AVLN_{CT_{Bldg}}} \times Freq_{AVLN_{CT}} \times HLR_{AVLN_{CT_{Bldg}}}$$
$$EAL_{AVLN_{CT_{Pop}}} = Exposure_{AVLN_{CT_{Pop}}} \times Freq_{AVLN_{CT}} \times HLR_{AVLN_{CT_{Pop}}}$$

where:

$EAL_{AVLN_{CT_{Bldg}}}$	is the Expected Annual Loss to building value due to Avalanche events for a specific Census tract (in dollars).
$Exposure_{AVLN_{CT_{Bldg}}}$	is the building value exposed to Avalanche events in the Census tract (in dollars).
$Freq_{AVLN_{CT}}$	is the annualized Avalanche frequency for the Census tract (events per year).
$HLR_{AVLN_{CT_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Avalanche for the Census tract.
$EAL_{AVLN_{CT_{Pop}}}$	is the Expected Annual Loss to population value due to Avalanche events for a specific Census tract (in dollars).
$Exposure_{AVLN_{CT_{Pop}}}$	is the population value exposed to Avalanche events in the Census tract (in dollars).
$HLR_{AVLN_{CT_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Avalanche for the Census tract.

The total EAL value at the county level is the sum of the aggregated values of the building and population loss at the Census tract level as in *Equation 20*.

Equation 20: County Expected Annual Loss to Avalanche

$$EAL_{AVLN_{Co}} = \sum_{CT}^{Co} EAL_{AVLN_{CT_{Bldg}}} + \sum_{CT}^{Co} EAL_{AVLN_{CT_{Pop}}}$$

where:

$EAL_{AVLN_{Co}}$	is the total Expected Annual Loss due to Avalanche events for a specific county (in dollars).
$\sum_{CT}^{Co} EAL_{AVLN_{CT_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Avalanche events for all Census tracts in the county (in dollars).
$\sum_{CT}^{Co} EAL_{AVLN_{CT_{Pop}}}$	is the summed Expected Annual Loss to population value due to Avalanche events for all Census tracts in the county (in dollars).

Figure 22 shows the total EAL (building value and population combined) to Avalanche events.

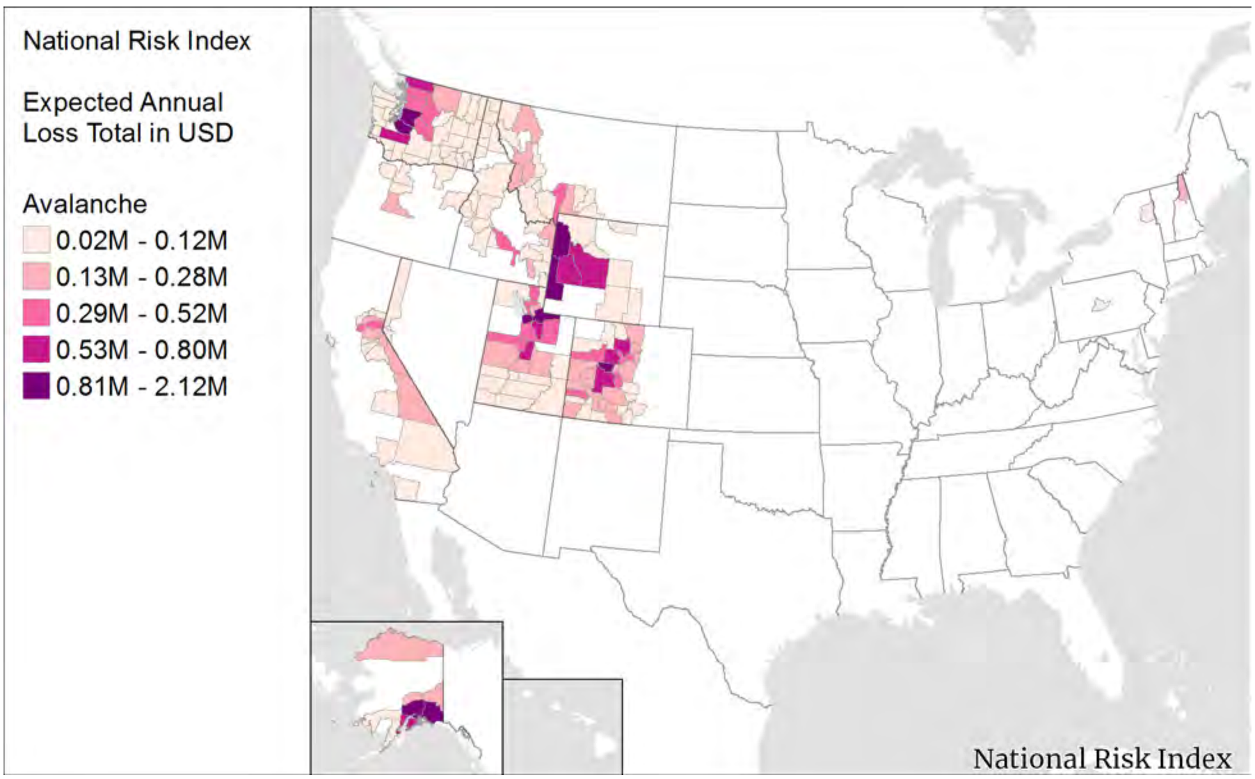

Figure 22: Total Expected Annual Loss by County to Avalanche

With the Avalanche total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Avalanche Risk Index score.

7 Coastal Flooding

Coastal Flooding is when water inundates or covers normally dry coastal land as a result of high or rising tides or storm surges.

7.1 Spatial Source Data

Susceptible Area Source: *National Flood Insurance Program, National Flood Hazard Layer*[23]

The National Flood Hazard Layer (NFHL) contains several layers depicting flood information, including levee locations, Flood Insurance Rate Map (FIRM) boundaries, and Special Flood Hazard Areas (SFHA) or floodplain polygons. The SFHA polygons for 1% annual chance and 0.2% annual chance were downloaded in shapefile format for use in the calculation of Coastal Flooding exposure and frequency.

Susceptible Area Source: *NOAA Office for Coastal Management, Flood Frequency and Sea Level Rise*[24]

The Sea Level Rise (SLR) data made available by NOAA's Office for Coastal Management contain multiple spatial layers for each state, including layers describing SLR and Flood Frequency. SLR polygon layers depict various SLR scenarios ranging from 0-6 feet above Mean Higher High Water (MHHW). The Flood Frequency raster file describes areas that flood due to high tides when Coastal Flood warning thresholds are exceeded with cell values of 1. All other cells contain no information. The polygon layer for the 6-foot SLR scenario and the Flood Frequency raster file for each state were downloaded for use in the calculation of Coastal Flooding exposure and frequency.

Susceptible Area Source: *NOAA National Hurricane Center, Sea, Lake, and Overland Surges from Hurricane*[25]

Sea, Lake, and Overland Surges from Hurricane (SLOSH) Maximum of the Maximum (MOM) raster files are modeled based on hurricane categories 1-5, along the Gulf and Atlantic coastline from Texas to Maine. These areas represent near-worst case scenarios and were derived from the storm surge inundation maps created by the National Hurricane Center (NHC). Cell values represent the storm surge level above ground in one-foot increments. The set of all hurricane category raster files was downloaded for use in the calculation of Coastal Flooding exposure and frequency.

[23] National Flood Insurance Program, Federal Emergency Management Agency. (2018). National Flood Hazard Layer [online dataset]. Retrieved from https://www.fema.gov/national-flood-hazard-layer-nfhl.

[24] Office for Coastal Management, National Oceanic and Atmospheric Administration. (2018). Sea Level Rise [online dataset]. Retrieved from https://coast.noaa.gov/slrdata/.

[25] National Hurricane Center, National Oceanic and Atmospheric Administration. (2018). National Storm Surge Hazard Maps, Version 2 [online dataset]. Retrieved from https://www.nhc.noaa.gov/nationalsurge/#data.

Susceptible Area Source: *NOAA National Hurricane Center, HURDAT2 Best Track Data Archive*[26]

The NHC, a component of NOAA's National Centers for Environmental Prediction, maintains several databases including the HURDAT2 Best Track Data Archive. The dataset is the most comprehensive source of information on both Atlantic and Pacific tropical and subtropical cyclones.[27]

It contains a series of storm observation records at six-hour intervals with location, maximum wind speed, central pressure, and (beginning in 2004) cyclone size. The observation records are organized by storm with a unique identifier and include temporal data (date and time). The dataset is the result of a post-storm analysis and contains the official assessment of a storm's path and characteristics. It also can include storm observations that were not available in real-time during the storm.

7.1.1 PERIOD OF RECORD

Coastal Flooding frequency calculation is based on the model of the 1% annual chance floodplain rather than historical flood events, so the period of record is 100 years.

7.2 Spatial Processing

Coastal spatial processing included numerous complex steps in order to complete EAL and risk calculations. The process uniquely modeled Coastal Flooding exposure by the sub-type of flooding (e.g., sea level rise, tidal flooding, and hurricane surge) and calculated corresponding annual frequencies for each flooding sub-type. The sub-types of flooding included in NRI Coastal Flooding are:

- Sea level rise and tidal flooding (SLRHT)
- SFHA 100-year flood area
- SFHA 500-year flood area
- Hurricane surge for category 1-5 (SLOSH)

All spatial datasets are first extracted and, if necessary, converted to polygon vector format. NFHL layers are extracted for 1% annual chance coastal floodplains and 0.2% annual chance floodplains according to their flood-zone sub-type. "V" Zones in the data signify coastal 1% annual chance floodplains. "X" Zones in the data signify 0.2% annual chance floodplains, not necessarily coastal. All state Coastal Flood Frequency rasters are converted to polygons and dissolved into a single layer. All state coastal 6-foot SLR layers are dissolved into a single layer.

The resulting polygon layers are then reconfigured to create eight new layers. Coastal SLR and Flood Frequency are combined to form a single SLRHT layer. A SFHA 1% annual chance delta layer is

[26] National Hurricane Center, National Oceanic and Atmospheric Administration. (2018). HURDAT2 Best Track Data Archive [online dataset]. Retrieved from https://www.nhc.noaa.gov/data/.

[27] Landsea, C. W. & Franklin, J.L. (2013). Atlantic hurricane database uncertainty and presentation of a new database format. *Monthly Weather Review*, *141*, 3576-3592.

created by removing the areas in the SLRHT layer from the NFHL source data of the 1% annual chance coastal floodplain. A SFHA 0.2% annual chance delta layer is generated by selecting any county polygons that intersect with the SFHA 1% annual chance delta layer, intersecting those county polygons with the NFHL source data of the 0.2% annual chance floodplain, and removing all SFHA 1% annual chance delta and SLRHT areas. (See *Figure 23* for a visualization of these layers.) Each SLOSH raster file (for hurricane categories 1-5) is converted into a polygon vector format (see *Figure 24*).

All flood layers described above are then combined into a single merged Coastal Flood Zone footprint. This layer will be used to compute surrogates for Coastal Flooding exposure and frequency at the Census tract and county level.

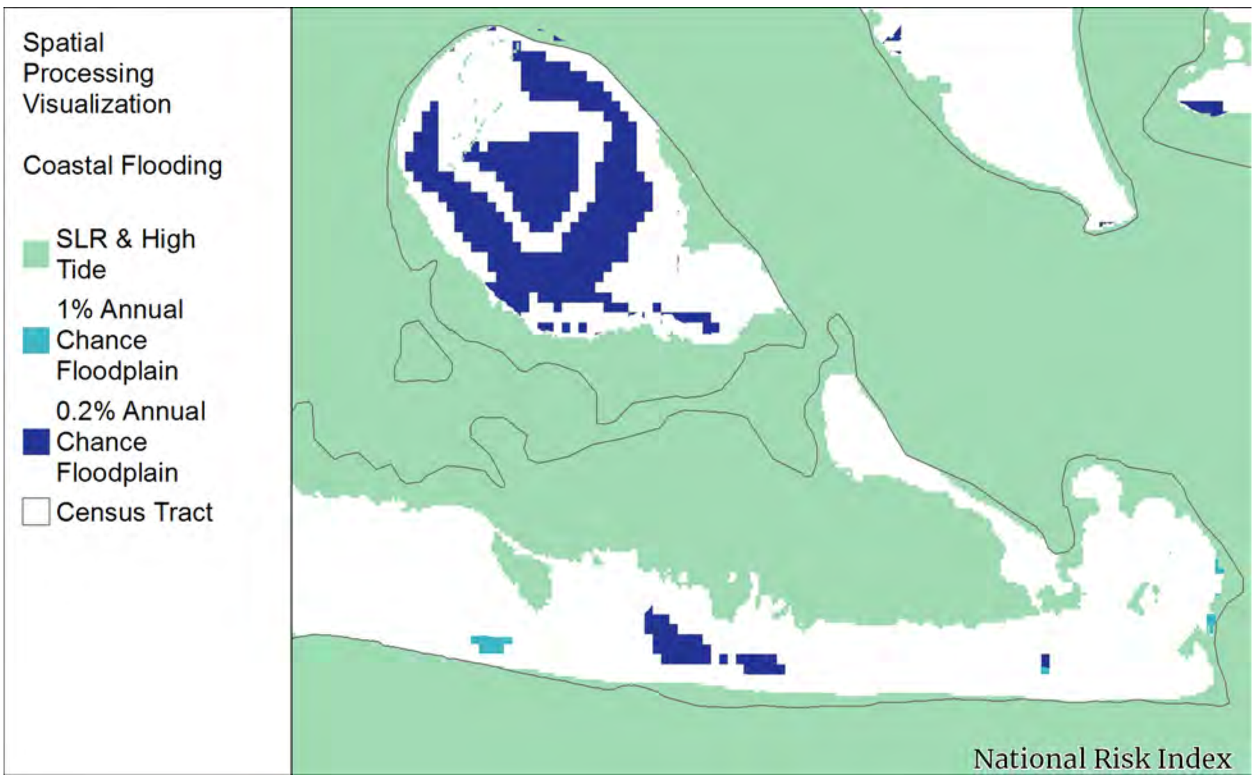

Figure 23: Coastal Flooding Sub-Types (1% Annual Chance and 0.2% Annual Chance Floodplain Delta, Unioned Sea Level Rise and High Tide)

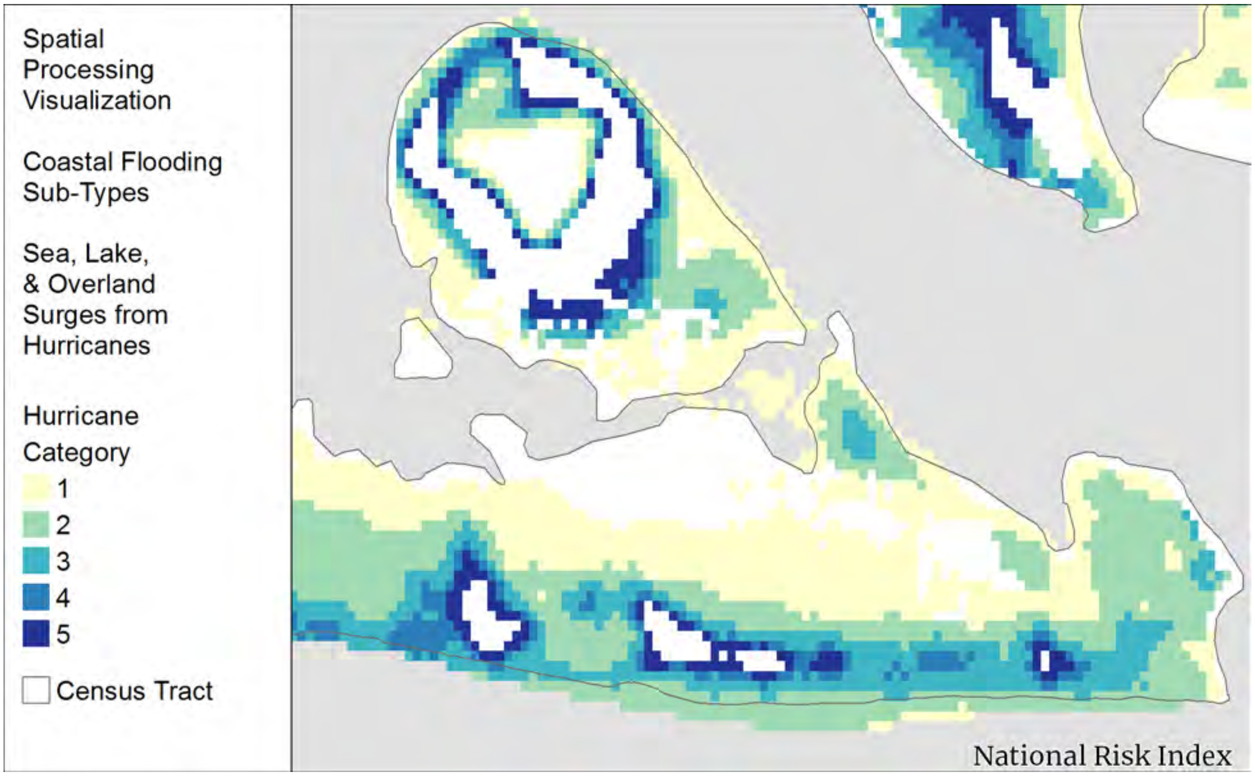

Figure 24: Coastal Flooding Sub-Types (SLOSH Layers, Categories 1-5)

7.3 Determination of Possibility of Hazard Occurrence

To distinguish between areas where no Coastal Flooding events have occurred and those where such events are not deemed possible, a control table was generated to designate which counties have some probability of being impacted by a Coastal Flooding event. Any county that intersected the combined Coastal Flood Zone footprint, bordered coastal waterways (including the coastline of the Great Lakes), or had experienced economic loss due to Coastal Flooding events (as recorded in SHELDUS) is included as one in which Coastal Flooding events are possible (see *Figure 25*).

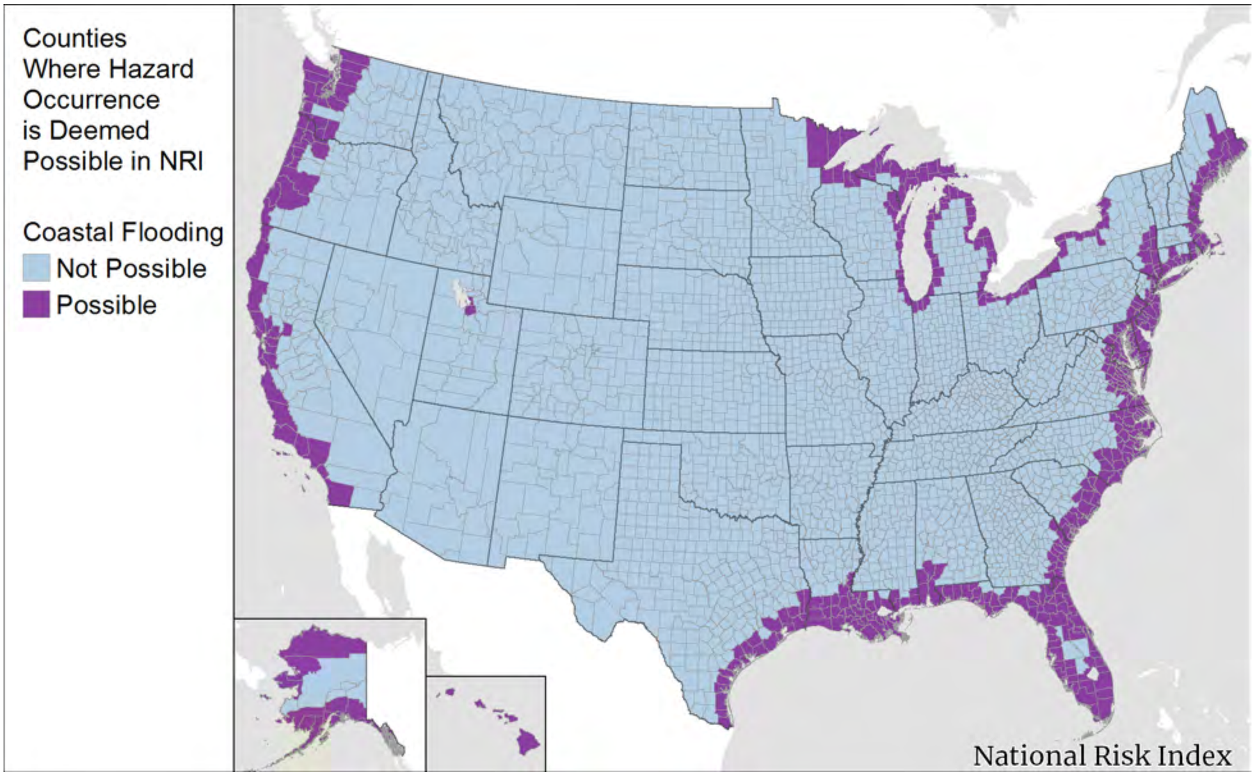

Figure 25: Map of Counties Deemed Possible for Coastal Flooding Occurrence

7.4 Exposure

To identify areas of exposure, each of the Coastal Flooding polygon layers (unioned Sea Level Rise and High Tide, 1% annual chance floodplain delta, 0.2% annual chance floodplain delta, and each of the five SLOSH category layers) are independently intersected with the Census block polygons within the NRI processing database. These intersected Census block areas are then tabulated to determine the percent of the area that is developed within them (see *Section 4.3.2*). The resulting tables contain the layer polygon's unique identifier, Census block number, the intersected area, the developed area of intersection, and whether the total intersected area is developed (see *Table 13*). All area values are in square kilometers.

Table 13: Sample Data from the Coastal Flood 1% Annual Chance-Census Block Intersection Table

CoastalFlood Zone100yrID	CensusBlock	IntersectedAreaKm^2	AreaDevelopedKm^2	IsDeveloped
391	150030099021008	0.007010063	0.001979101	No
445	150030098012011	0.111088226	0	No
2112	480079501002007	1.59E-06	1.59E-06	Yes

To determine exposure value for buildings and population, the developed area of the Coastal Flooding polygon intersecting each Census block is multiplied by the developed area building value density and the developed area population density of the Census block to model the conservative-case concentration of exposure within the Census block. These Census block building and population value densities have been calculated by dividing the total values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers; see *Equation 21*). The VSL was used to express population exposure in terms of dollars.

Equation 21: Census Block Coastal Flooding Building and Population Exposure

$$Exposure_{SubType_{CB_{Bldg}}} = IntsctDevArea_{SubType_{CB}} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{SubType_{CB_{Pop}}} = IntsctDevArea_{SubType_{CB}} \times DevAreaDen_{CB_{Pop}} \times VSL$$

where:

$Exposure_{SubType_{CB_{Bldg}}}$	is the estimated building value found in the Coastal Flooding sub-type in a specific Census block (in dollars).
$IntsctDevArea_{SubType_{CB}}$	is the intersected developed area of the Coastal Flooding sub-type with the Census block (in square kilometers).
$DevAreaDen_{CB_{Bldg}}$	is the developed area building value density of the Census block (in dollars per square kilometer).
$Exposure_{SubType_{CB_{Pop}}}$	is the population exposed to the Coastal Flooding sub-type in a specific Census block (in people).
$DevAreaDen_{CB_{Pop}}$	is the developed area population density of the Census block (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).

These calculations are performed for each layer so that exposure values for each sub-type of flood zone and consequence type are calculated.

7.4.1 EXPOSURE AGGREGATION

Each sub-type of Coastal Flooding is essentially its own kind of hazard and has its own estimated exposure and frequency of occurrence. Exposure and frequency for all Coastal Flooding sub-types are combined at the Census block level prior to being multiplied by the county-level HLR for EAL computation. For display in the NRI application, a single exposure value is needed. Individual Census block exposure values for each flooding sub-type cannot simply be summed to get total exposure as this would dramatically overestimate actual exposure by counting areas multiple times. Instead, the merged Coastal Flood Zone footprint is intersected with the Census tracts and the intersecting developed area is multiplied by the Census tract developed area density value to find the Census tract exposure. The county-level exposure surrogate is the aggregation of its Census tracts' exposure values (see *Equation 22*) but is not used in the calculation of the EAL for Coastal Flooding.

Equation 22: Census Tract and County Coastal Flooding Exposure

$$Exposure_{CFLD\,CT\,CnsqType} = IntsctDevArea_{AllZones\,CT} \times DevAreaDen_{CT\,CnsqType}$$

$$Exposure_{CFLD\,Co\,CnsqType} = \sum_{CT}^{Co} Exposure_{CFLD\,CT\,CnsqType}$$

where:

$Exposure_{CFLD\,CT\,CnsqType}$	is the consequence type exposure to Coastal Flooding in a specific Census tract (in dollars).
$IntsctDevArea_{AllZones\,CT}$	is the intersected developed area of the merged all Coastal Flood Zone footprint with the Census tract (in square kilometers).
$DevAreaDen_{CT\,CnsqType}$	is the developed area consequence value density of the Census tract (in dollars per square kilometer).
$Exposure_{CFLD\,Co\,CnsqType}$	is the consequence type exposure to Coastal Flooding in a specific county (in dollars).
$\sum_{CT}^{Co}$	is the sum for all Census tracts in the county.

7.5 Frequency

The frequency value represents the modeled frequency of a Coastal Flooding event occurring per year. Coastal Flooding frequency is calculated at the Census block level by Coastal Flooding sub-type. The 1% annual chance and 0.2% annual chance floodplain delta layers and the unioned Sea Level Rise and High Tide layer are each separately intersected with the Census block polygons.

Each sub-type of Coastal Flooding has a different annual frequency, as listed below:

- SFHA 1% annual chance: 0.01
- SFHA 0.2% annual chance: 0.002
- Union of sea level rise and tidal flooding: 3.0
- SLOSH polygon: varies by hurricane category (see below)

To calculate SLOSH frequencies, the SLOSH layers for each Hurricane category must be used in conjunction with historical Hurricane paths of those categories. The HURDAT2 hurricane points are buffered by the average radius of storm force winds (in miles) based upon each point's hurricane category as seen in *Table 14*. (More information on the spatial processing of Hurricane source data can be found in *Section 13.2*.)

Table 14: Hurricane Categorization with Average Radius of Storm Force Winds

ID	Storm Category	Minimum Wind Speed (mph)	Maximum Wind Speed (mph)	Minimum Wind Speed (kts)	Maximum Wind Speed (kts)	Average Radius of Hurricane/Tropical Storm Force Winds (miles)
0	Tropical Storm	39	73.9	33	63.9	15
1	Category 1	74	95.9	64	82.9	26.45
2	Category 2	96	110.9	83	95.9	39.1
3	Category 3	111	129.9	96	112.9	43.7
4	Category 4	130	156.9	113	136.9	50.03
5	Category 5	157	9999	137	9999	54.04
6	Other	0	38.9	0	32.9	0

For the SLOSH frequency calculation, the buffered Hurricane points are intersected with a 49-by-49-km fishnet grid. For each fishnet grid cell and hurricane reference ID, the maximum hurricane category that that storm achieved (in the fishnet grid cell) was computed and used to represent that specific hurricane within the fishnet cell. The number of hurricanes by category (max strength achieved within the cell) were summed for each fishnet grid cell. For those coastal counties that intersect SLOSH polygons, the number of hurricanes for each category (determined from its intersected 49-km fishnet grid cells with the maximum fishnet count used if the area intersects multiple cells) was stored and divided by the period of record of the dataset (167.11 and 69.04 years for the Atlantic and Pacific Ocean basins, respectively) to compute annualized frequency for the hurricane category in each county as in *Equation 23*.

Equation 23: SLOSH Frequency Calculation

$$Freq_{SLOSH\,Co_{HRCNCat}} = \frac{Max(EventCount_{HRCNCat\,Fish_{Co}})}{P_{HRCN}}$$

where:

$Freq_{SLOSH\,Co_{HRCNCat}}$ is the annualized SLOSH frequency for the Hurricane category in a specific county (events per year).

$Max(EventCount_{HRCNCat\,Fish_{Co}})$ is the maximum number of unique storm events of the Hurricane category that intersect the fishnet cell(s) intersecting the county.

P_{HRCN} is the period of record for Hurricane, either 167.11 for Atlantic storms or 69.04 for Pacific storms (in years).

In cases where no historical hurricane of a specific category strength had been observed in a fishnet grid cell touching the county, a minimum hurricane category count value of 1 was assigned, thus the “default” frequency for that hurricane category would be 1 over the period of record. This default setting was utilized mostly in cases of hurricane categories 4 and 5. The Census block inherits the SLOSH frequency value of the county that contains it.

7.5.1 FREQUENCY AGGREGATION

In the NRI application, an area-weighted average frequency value is provided at both the Census tract and county level. This is computed as an aggregation of the intersected areas of each Coastal Flood zone sub-layer with each Census block in the Census tract or county (see *Equation 24*). Multiplying this area-weighted average frequency value by the summary exposure values will not match the EAL values presented, as the EAL calculation utilizes the unique Census block-level combination of coastal sub-type exposure and associated frequencies.

Equation 24: Census Tract Area-Weighted Coastal Flooding Frequency

$$
\begin{aligned}
Freq_{CFLD_{CT}} = \frac{1}{Area_{CT}}\Bigg[&\left(\sum_{CB}^{CT}(IntsctArea_{100Yr_{CB}}) \times Freq_{100Yr}\right) \\
&+ \left(\sum_{CB}^{CT}(IntsctArea_{500Yr_{CB}}) \times Freq_{500Yr}\right) \\
&+ \left(\sum_{CB}^{CT}(IntsctArea_{SLRHT_{CB}}) \times Freq_{SLRHT}\right) \\
&+ \left(\sum_{CB}^{CT}(IntsctArea_{SLOSH1_{CB}}) \times Freq_{SLOSH1_{CB}}\right) \\
&+ \left(\sum_{CB}^{CT}(IntsctArea_{SLOSH2_{CB}}) \times Freq_{SLOSH2_{CB}}\right) \\
&+ \left(\sum_{CB}^{CT}(IntsctArea_{SLOSH3_{CB}}) \times Freq_{SLOSH3_{CB}}\right) \\
&+ \left(\sum_{CB}^{CT}(IntsctArea_{SLOSH4_{CB}}) \times Freq_{SLOSH4_{CB}}\right) \\
&+ \left(\sum_{CB}^{CT}(IntsctArea_{SLOSH5_{CB}}) \times Freq_{SLOSH5_{CB}}\right)\Bigg]
\end{aligned}
$$

where:

$Freq_{CFLD_{CT}}$ is the annualized area-weighted frequency of Coastal Flooding events in a specific Census tract (events per year).

$Area_{CT}$ is the total area of the Census tract (in square kilometers).

$\sum_{CB}^{CT}(IntsctArea_{100Yr_{CB}})$ is the sum of the intersected area of the 1% annual chance coastal floodplain with the Census block for all Census blocks within the tract (in square kilometers).

$Freq_{100Yr}$ is the annualized frequency of 1% annual chance Coastal Flooding (1 event per 100 years or 0.01 events per year).

$\sum_{CB}^{CT}(IntsctArea_{500Yr_{CB}})$ is the sum of the intersected area of the 0.2% annual chance coastal floodplain with the Census block for all Census blocks within the tract (in square kilometers).

$Freq_{500Yr}$ is the annualized frequency of 0.2% annual chance Coastal Flooding (1 event per 500 years or 0.002 events per year).

$\sum_{CB}^{CT}(IntsctArea_{SLRHT_{CB}})$ is the sum of the intersected area of the Sea Level Rise and High Tide area with the Census block for all Census blocks within the tract (in square kilometers).

$Freq_{SLRHT}$ is the annualized frequency of Sea Level Rise and High Tide Coastal Flooding (3 events per year).

$\sum_{CB}^{CT}(IntsctArea_{SLOSH1-5_{CB}})$ is the sum of the intersected area of the SLOSH Hurricane category with the Census block for all Census blocks within the tract (in square kilometers).

$Freq_{SLOSH1-5_{CB}}$ is the annualized frequency of the SLOSH Hurricane category at the Census block level (events per year).

The county-level frequency surrogate uses the same formula as the Census tract surrogate, substituting the total county area and aggregating all Census blocks within the county. *Figure 26* displays annualized Coastal Flooding frequency at the county level.

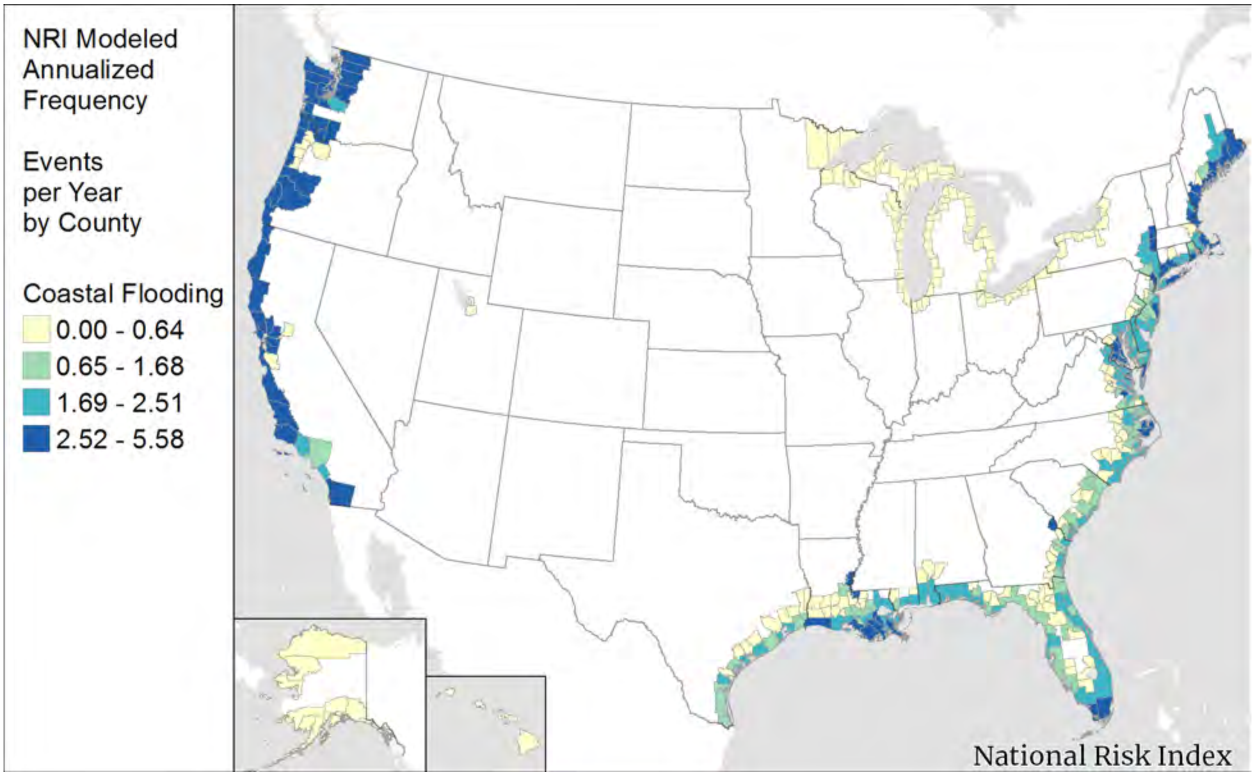

Figure 26: Annualized Coastal Flooding Frequency by County

7.6 Historic Loss Ratio

The Coastal Flooding HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Coastal Flooding event, or the average rate of loss associated with the occurrence of a Coastal Flooding event.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Four peril types are mapped to the hazard Coastal Flooding (see *Table 15*). These are expanded on an event basis based on the event count field in SHELDUS[28] (see *Section 5.4.1*).

Table 15: Coastal Flooding Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Coastal	213	276
CoastalStorm	22	22
FloodCoastal	566	754
FloodTidal	1	1

[28] For Coastal Flooding loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

The HLR exposure value used in the LRB calculation is the value of the county's area that is susceptible to Coastal Flooding. This value is determined by summing the developed area exposure values of the Census tracts that intersect the merged Coastal Flooding layer footprint (see *Section 7.4.1*). The LRB for each SHELDUS-documented event and each consequence type (building and population) is calculated using *Equation 25*.

Equation 25: Loss Ratio per Basis Calculation for a Single Coastal Flooding Event

$$LRB_{CFLD\,Co_{CnsqType}} = \frac{Loss_{CFLD\,Co_{CnsqType}}}{HLRExposure_{CFLD\,Co_{CnsqType}}}$$

where:

$LRB_{CFLD\,Co_{CnsqType}}$ is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Coastal Flooding event. Calculation is performed for each consequence type (building and population).

$Loss_{CFLD\,Co_{CnsqType}}$ is the loss (by consequence type) experienced from the Coastal Flooding event documented to have occurred in the county (in dollars).

$HLRExposure_{CFLD\,Co_{CnsqType}}$ is the value (by consequence type) of the susceptible area estimated to have been exposed to the Coastal Flooding event (in dollars).

A Historic Event Count is not computed for Coastal Flooding, so no zero-loss events are inserted into the Loss Ratio table. After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and regional. The regional definition for Coastal Flooding is the FEMA-defined regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 27 and *Figure 29* display the largest weighting factor contributor in the Bayesian credibility calculations for the Coastal Flooding HLR of every county. This contributor is not necessarily the only weighting contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Coastal Flooding events within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or regional events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from regional-level loss data. If an entire region has not experienced a loss-causing Coastal Flooding event during the period of record, the coastal counties in that region receive the national average HLR for Coastal Flooding. *Figure 28* and *Figure 30* represent the final county-level HLR values for Coastal Flooding.

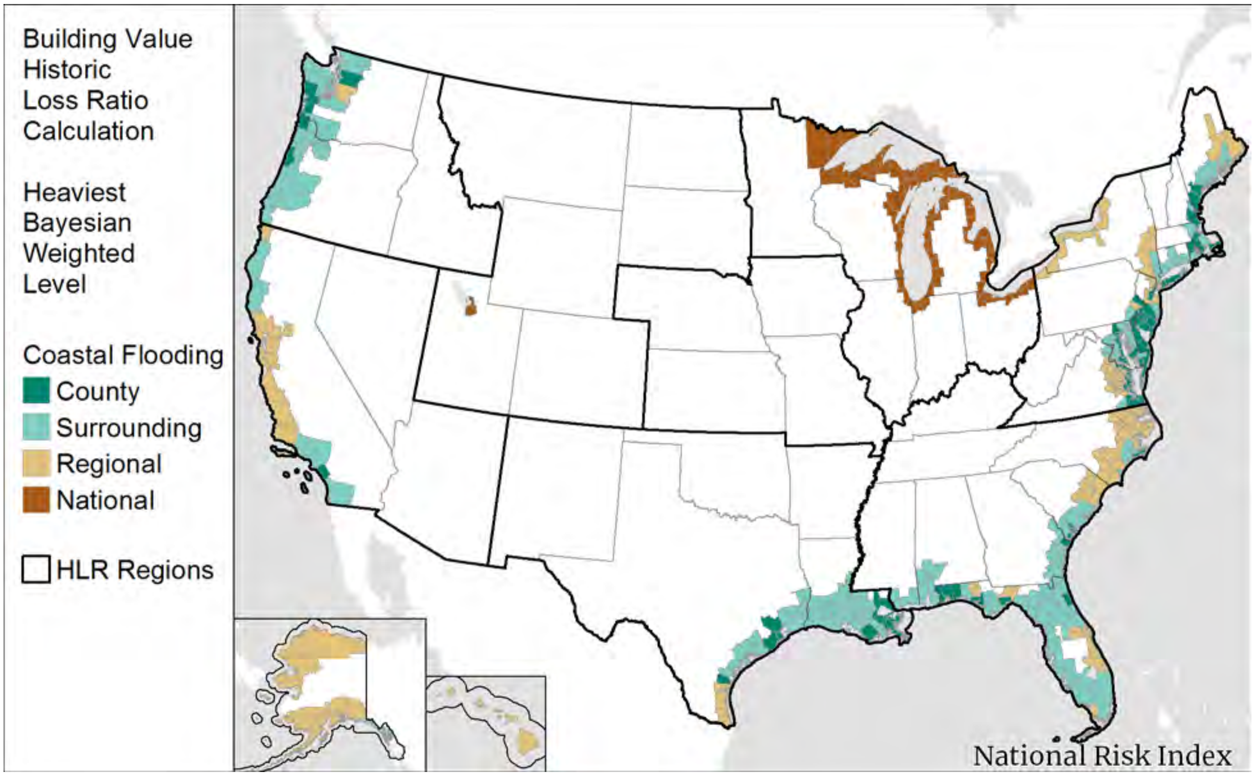

Figure 27: Coastal Flooding Heaviest Bayesian Weighted Level – Building Value

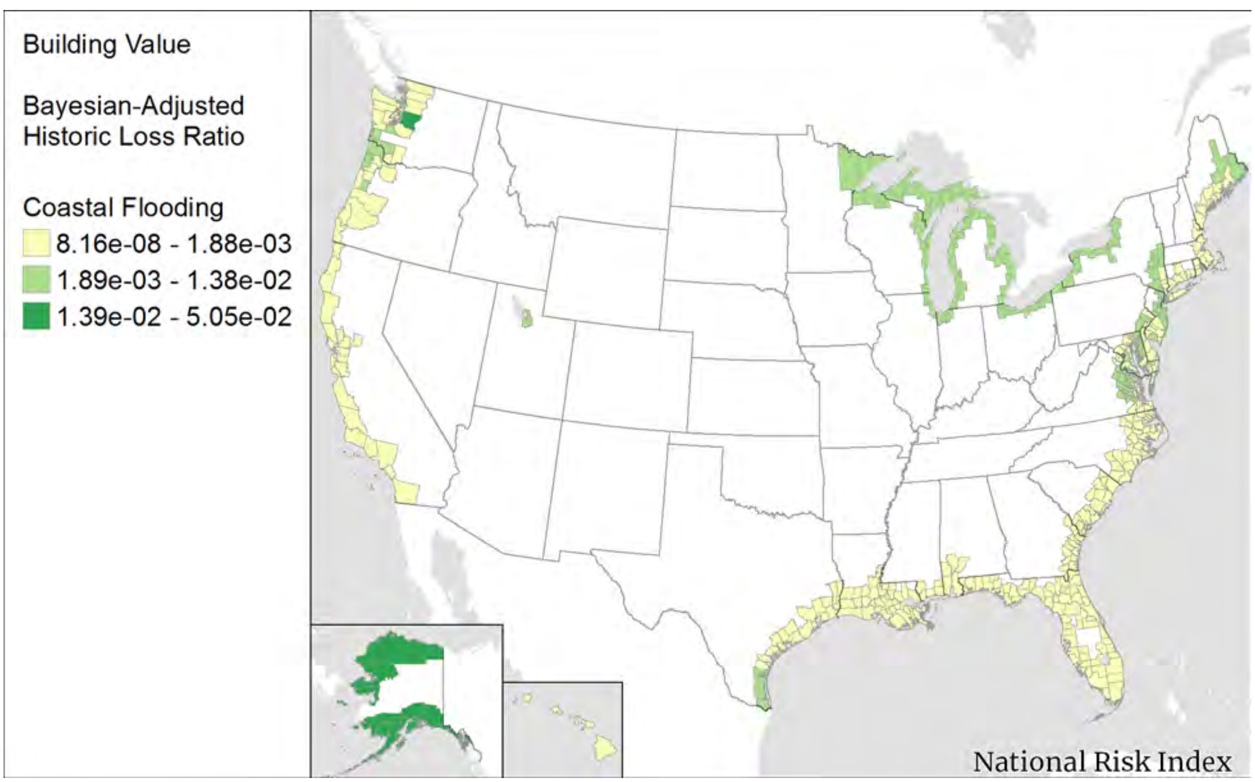

Figure 28: Coastal Flooding HLR – Building Value

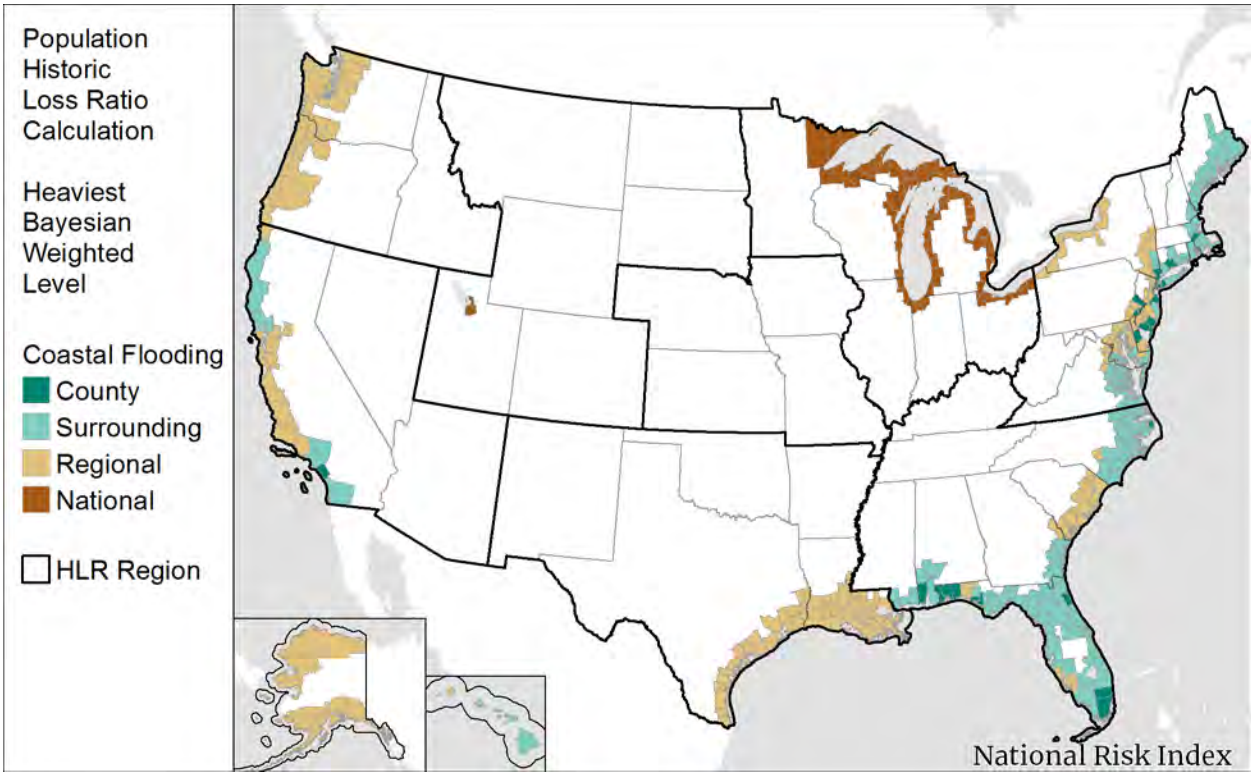

Figure 29: Coastal Flooding Heaviest Bayesian Weighted Level – Population

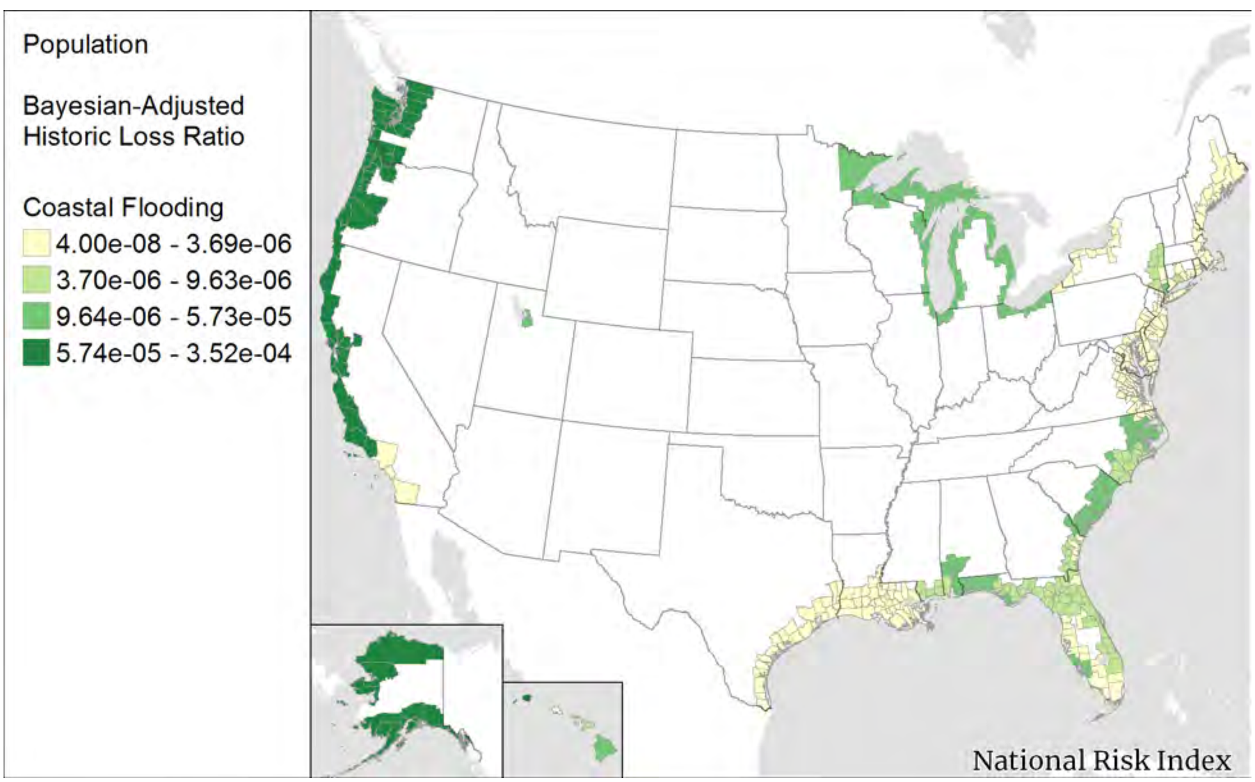

Figure 30: Coastal Flooding HLR – Population

The resulting HLR is then inherited by the Census blocks and Census tracts within the county.

7.7 Expected Annual Loss

In the EAL calculation, each unique sub-type exposure footprint and its frequency are multiplied together at a Census block level and summed to get a Frequency-Exposure value for the Census block as in *Equation 26*.

Equation 26: Census Block Coastal Flooding Frequency-Exposure Calculation

$$
\begin{aligned}
FreqExp_{CFLD\,CB_{CnsqType}} &= \left(Exposure_{100Yr\,CB_{CnsqType}} \times Freq_{100Yr}\right) \\
&+ \left(Exposure_{500Yr\,CB_{CnsqType}} \times Freq_{500Yr}\right) \\
&+ \left(Exposure_{SLRHT\,CB_{CnsqType}} \times Freq_{SLRHT}\right) \\
&+ \left(Exposure_{SLOSH1\,CB_{CnsqType}} \times Freq_{SLOSH1\,CB}\right) \\
&+ \left(Exposure_{SLOSH2\,CB_{CnsqType}} \times Freq_{SLOSH2\,CB}\right) \\
&+ \left(Exposure_{SLOSH3\,CB_{CnsqType}} \times Freq_{SLOSH3\,CB}\right) \\
&+ \left(Exposure_{SLOSH4\,CB_{CnsqType}} \times Freq_{SLOSH4\,CB}\right) \\
&+ \left(Exposure_{SLOSH5\,CB_{CnsqType}} \times Freq_{SLOSH5\,CB}\right)
\end{aligned}
$$

where:

$FreqExp_{CFLD\,CB_{CnsqType}}$	is the product of Coastal Flooding frequency and exposure for the consequence type for a specific Census block.
$Exposure_{100Yr\,CB_{CnsqType}}$	is the consequence value exposed to the 1% annual chance coastal floodplain in the Census block (in dollars).
$Freq_{100Yr}$	is the annualized frequency of 1% annual chance Coastal Flooding (1 event per 100 years, or 0.01 events per year).
$Exposure_{500Yr\,CB_{CnsqType}}$	is the consequence value exposed to the 0.2% annual chance coastal floodplain in the Census block (in dollars).
$Freq_{500Yr}$	is the annualized frequency of 0.2% annual chance Coastal Flooding (1 event per 500 years, or 0.002 events per year).
$Exposure_{SLRHT\,CB_{CnsqType}}$	is the consequence value exposed to Sea Level Rise and High Tides in the Census block (in dollars).

$Freq_{SLRHT}$ is the annualized frequency of Sea Level Rise and High Tide Coastal Flooding (3 events per year).

$Exposure_{SLOSH1-5_{CB}{}_{CnsqType}}$ is the consequence value exposed to the SLOSH Hurricane category in the Census block (in dollars).

$Freq_{SLOSH1-5_{CB}}$ is the annualized frequency of the SLOSH Hurricane category in the Census block (events per year).

Using these Frequency-Exposure values, the EAL can be computed at the Census block level using *Equation 27*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 27: Census Block Expected Annual Loss to Coastal Flooding

$$EAL_{CFLD_{CB}{}_{Bldg}} = FreqExp_{CFLD_{CB}{}_{Bldg}} \times HLR_{CFLD_{CB}{}_{Bldg}}$$

$$EAL_{CFLD_{CB}{}_{Pop}} = FreqExp_{CFLD_{CB}{}_{Pop}} \times HLR_{CFLD_{CB}{}_{Pop}}$$

where:

$EAL_{CFLD_{CB}{}_{Bldg}}$ is the Expected Annual Loss to building value due to Coastal Flooding events for a specific Census block (in dollars).

$FreqExp_{CFLD_{CB}{}_{Bldg}}$ is the product of Coastal Flooding frequency and exposure for building value for the Census block.

$HLR_{CFLD_{CB}{}_{Bldg}}$ is the Bayesian-adjusted building Historic Loss Ratio for Coastal Flooding for the Census block.

$EAL_{CFLD_{CB}{}_{Pop}}$ is the Expected Annual Loss to population value due to Coastal Flooding events for a specific Census block (in dollars).

$FreqExp_{CFLD_{CB}{}_{Pop}}$ is the product of Coastal Flooding frequency and exposure for population value for the Census block.

$HLR_{CFLD_{CB}{}_{Pop}}$ is the Bayesian-adjusted population Historic Loss Ratio for Coastal Flooding for the Census block.

The total EAL values at the Census tract and county level are sums of the aggregated values of the building and population loss at the Census block level as in *Equation 28*.

Equation 28: Census Tract and County Expected Annual Loss to Coastal Flooding

$$EAL_{CFLD_{CT}} = \sum_{CB}^{CT} EAL_{CFLD_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{CFLD_{CB_{Pop}}}$$

$$EAL_{CFLD_{Co}} = \sum_{CB}^{Co} EAL_{CFLD_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{CFLD_{CB_{Pop}}}$$

where:

$EAL_{CFLD_{CT}}$	is the total Expected Annual Loss due to Coastal Flooding events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{CFLD_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Coastal Flooding events for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{CFLD_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Coastal Flooding events for all Census blocks in the Census tract (in dollars).
$EAL_{CFLD_{Co}}$	is the total Expected Annual Loss due to Coastal Flooding events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{CFLD_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Coastal Flooding events for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{CFLD_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Coastal Flooding events for all Census blocks in the county (in dollars).

Figure 31 shows the total EAL (building value and population combined) to Coastal Flooding events.

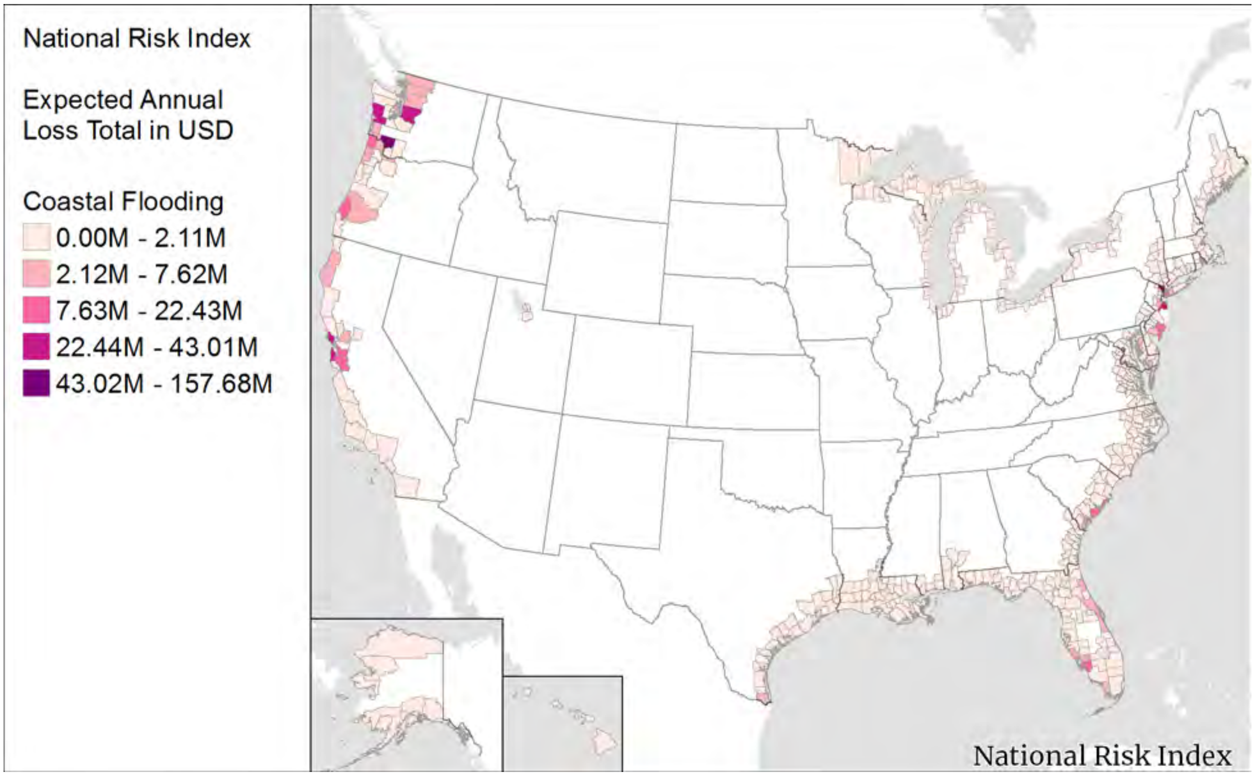

Figure 31: Total Expected Annual Loss by County to Coastal Flooding

With the Coastal Flooding total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Coastal Flooding Risk Index score.

8 Cold Wave

A Cold Wave is a rapid fall in temperature within 24 hours and extreme low temperatures for an extended period. The temperatures classified as a Cold Wave are dependent on the location and defined by the local NWS weather forecast office.

8.1 Spatial Source Data

Historical Event Generating Source: *National Weather Service, Weather Alerts*[29]

Historical Event Compiling Source: *Iowa State University, Iowa Environmental Mesonet*[30]

The NWS is continuously issuing weather alerts based on current weather conditions. Each alert is coded by type and significance, and conceptually can serve as documentation of the potential for weather event activities in a specific area. Archived NWS alerts are aggregated, continuously updated, and made available for download in shapefile format by Iowa State University's Iowa Environmental Mesonet. Data include geometry for each alert's issued area and attributes related to each alert's severity and phenomena type. Weather alerts are also timestamped with the time of issuance and the time of expiration. A table describing this dataset's attributes can be found in *Appendix C*.

Because the spatial representations of the alert areas will be intersected with Census blocks for the determination of exposure and frequency, it is important to use the best possible resolution of the Cold Wave alert.

The geometry shape for each alert record represents the geographic area for which the NWS alert applied. However, the Mesonet shapes are simplified versions of the more detailed NWS Public Forecast Zone shape originally associated with the alert record. Because the Mesonet tabular data still retain the reference ID for the NWS Public Forecast Zone, it can be used to relate to the zone associated with each alert record.

The NWS Public Forecast Zones can be downloaded in shapefile format[31] and represent the codified areas for which weather alerts are issued by NWS. The Public Forecast Zones shape definitions are predominantly derived from county boundaries. While the Public Forecast Zone boundaries are more refined than those substituted into the Mesonet data, they are not at the same resolution as the current county boundaries derived from Census blocks.

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[29] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *Active Alerts* [online dataset]. Retrieved from https://www.weather.gov/.

[30] Department of Agronomy, Iowa State University. (2018). *Iowa Environmental Mesonet* [online database]. Retrieved from https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml.

[31] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *NWS Public Forecast Zones* [online dataset]. Retrieved from https://www.weather.gov/gis/PublicZones.

Utilizing the Public Forecast Zone shapefile in conjunction with the Public Forecast Zone – County Correlation file,[32] a determination was made as to which Public Forecast Zones have single-county coverage and which are either sub-county zones or made of portions of multiple counties. For perspective, the following approximate distribution of forecast zone composition were found:

- 70% of the zones are single-county coverage.
- 20% are cases where a single county is subdivided into multiple zones.
- 10% are zones that breach parts of multiple contiguous counties.

For those Forecast Zones covering a single county, the U.S. Census 2017 county boundaries are substituted. For all other zone shapes, the native NWS Public Forecast Zone shape found in the Mesonet data or correlation file is used. See *Figure 32* for an example of the differences in the spatial resolution of weather alert boundaries.

Another aspect of the NWS Public Forecast Zones is that they can and have changed over time. In the Mesonet data (2005 through 2017), there are 4,364 distinct Forecast Zones referenced that do not exist in the current NWS Public Forecast Zone shapefile. This occurs when an NWS Public Forecast Zone has been modified in shape, renamed, and/or "retired" from use.

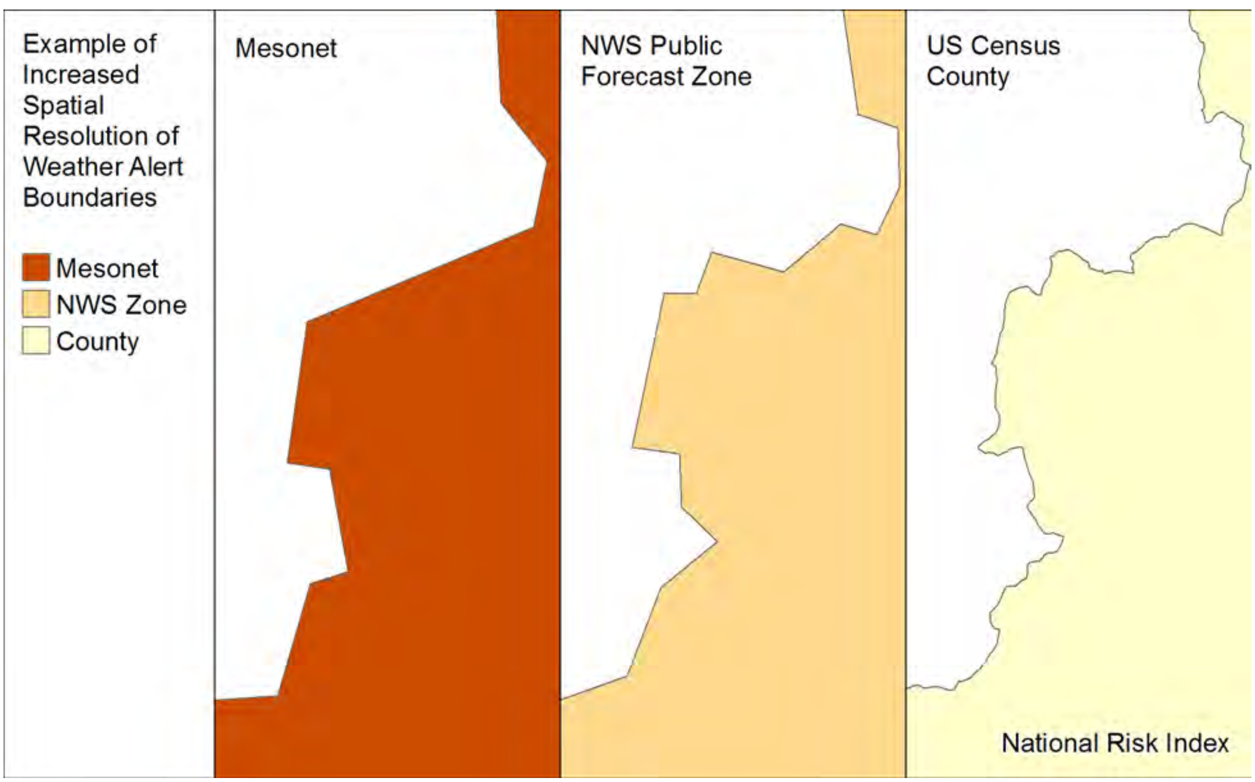

Figure 32: Three Boundary Definitions – Mesonet, Forecast Zone, U.S. Census County

[32] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *Zone-County Correlation File* [online dataset]. Retrieved from https://www.weather.gov/gis/ZoneCounty.

Further research found that the NWS maintains a downloadable Change History log of the various changes in Forecast Zone areas since 1997. This text file does not contain the pre- nor post-shape of the altered forecast zone. Archived versions of these changes are likely available via contact with NWS, but the effort to match the NWS issued alert record to the version-controlled shape representation of the forecast zone at the time of alert issue seems to be beyond the scope of the NRI processing effort, though a Mesonet representative was contacted to see if Forecast Zone shapes associated with each year of alert data had been archived. Unfortunately, no such archival information was available. For cases where the more refined NWS Forecast Zone shape is unavailable, the simplified Mesonet boundary version shape is used.

8.1.1 PERIOD OF RECORD

In the 1990s and early 2000s, the NWS's system of recording watch, warnings, and advisories (WWA) made automated processing too difficult. So, in 2005, the Valid Time Extent Code (VTEC) system was implemented, which allowed for the easy automated parsing of alert data. Therefore, NWS weather events data were downloaded for 2005 through 2017. The date range utilized for the NRI is 11/12/2005 to 12/31/2017, so the period of record for which Cold Wave data are utilized is 12.14 years.

8.2 Spatial Processing

With the intended spatial processing goal of intersecting NWS event shapes to determine the Census block area impacted by each event, there are three main preparatory efforts required prior to the intersection of Cold Wave event polygons with Census block polygons for the purposes of calculating Cold Wave exposure and frequency.

Cold Wave weather event alerts are extracted from the dataset based on the VTEC significance code (SIG field) and the phenomena code (PHENOM or TYPE field) values. Only Warning alerts (SIG = 'W') of the Phenomena type "Extreme Cold" (EC) or "Wind Chill" (WC) are considered NRI Cold Wave events (see *Table 16*).

To remove unintended error in spatial results due to the use of the simplified event area shapes contained in the Mesonet data, event areas with a higher resolution version are substituted. This substitution uses the NWS Public Forecast Zone shape associated with the alert record or, in cases where the forecast zone is for a single county, a better resolution version of the county boundary area.

Table 16: Original Mesonet Cold Wave Records

WFO	ISSUED	EXPIRED	PHENOM	SIG	NWS_UGC	AREA_KM2
DLH	201712250600	201712261800	WC	W	MNZ018	4648.70996
BIS	201701032106	201701041807	WC	W	NDZ020	1888.72131
MSO	201402061433	201402061725	EC	W	MTZ043	5891.24316

Cold Wave occurrences are measured in event-days as this more accurately represents the variability of Cold Wave event duration. To capture this, each native alert record with a duration greater than a single day is replaced with multiple records, one for each day of the original record's duration.

If a Cold Wave event's duration on any given day is less than 6 hours, then the event is assigned to the day having the greatest duration of the event. This handles cases where the event occurs in the late evening and actually endures for a greater length of time on the next calendar day than on the day the alert was issued.

For cases where the event duration is longer, the following logic is used: If a weather event's duration is greater than 6 hours, assign the event to all days on which 6 or more hours occur. For example, if a 14-hour weather event was issued for 2 AM until 6 PM on January 1, then the event would be assigned to January 1. If the alert was issued from 11 PM on January 1 to 1 PM on January 2, then the event would be assigned to only January 2. If the alert was issued from 7 PM on January 1 to 9 AM on January 2, then the event would be assigned to both January 1 and January 2.

Additionally, there are some data quality issues with the Mesonet data. For example, some warnings have an expiration date that is prior to the issue date. In these cases, a single record is used and assigned the issue date. To illustrate this concept, the Cold Wave events in *Table 17* are expanded to create the Cold Wave event-day records in *Table 18*.

Table 17: Sample Cold Wave Data after Zone Shape Re-Sourcing

ColdwaveID	WFO	Issued	Expired	PHENOM	SIG	NWS_UGC	AreaKm2	NewShapeSource
1189968	DLH	1/5/2014 0:00	1/7/2014 17:07	WC	W	WIZ002	3917.1735	Census County
56139	BIS	1/3/2017 21:06	1/4/2017 18:07	WC	W	NDZ020	1886.0719	Census County

Table 18: Sample Data from the Cold Wave Date Expansion Table

ExpansionID	ColdwaveID	Issued	Expired	DateType	ColdwaveHours
10771	1189968	1/5/2014 0:00	1/6/2014 0:00	Expanded Dates - Issued	24
10772	1189968	1/6/2014 0:00	1/7/2014 0:00	Expanded Dates - New Dates	24
10773	1189968	1/7/2014 0:00	1/7/2014 17:07	Expanded Dates - Expired	17.11666
6749	56139	1/4/2017 0:00	1/4/2017 18:07	Expanded Dates - Expired	18.11666

To avoid overestimating the area of influence a “single” distinct weather event has due to multiple NWS alerts being issued for that same weather event, a process to combine all Cold Wave event areas occurring on the same day (Year, Month, Day specific) into one representative event shape is performed. This process results in a single event impact area shape for each day on which a Cold Wave event occurred. These Cold Wave event-day polygons can then be intersected with the Census block polygons to determine Cold Wave exposure and frequency.

8.3 Determination of Possibility of Hazard Occurrence

Cold Waves can occur almost anywhere in the United States as the definition of a Cold Wave is locally defined by the area’s weather forecast office. For example, a forecast office in Texas may define a Cold Wave differently than a forecast office in New York. Therefore, all counties were deemed possible for Cold Wave occurrence.

8.4 Exposure

To identify areas of exposure, the Cold Wave event-day polygons (also referred to as Cold Wave Date Expansions to acknowledge the spatiotemporal processing described in *Section 7.2*) are intersected with the Census block polygons within the NRI processing database. The resulting table contains the Cold Wave event-day’s unique identifier, Census block number, and the intersected area in square kilometers (see *Table 19*).

Table 19: Sample Data from the Cold Wave Expansion Census Block Intersection Table

ColdwaveDateExpansionID	CensusBlock	IntersectedAreaKm2
2025	120830011043089	0.0331315054931641
2025	120830011043090	0.00229587890625
2025	120830011043091	0.00324445764160156

To determine exposure value, the average coverage of a Cold Wave event-day is found by summing the intersected areas for all Cold Wave event-days that intersected the Census block and dividing this sum by the number of intersecting event-days. This is multiplied by the developed area building value density, the developed area population density, and the agricultural value density of the Census block to model the conservative-case concentration of exposure within the Census block. These developed area Census block building, population, and agricultural value densities have been calculated by dividing the Census block total values (as recorded in Hazus 4.2 SP1) by the developed or agricultural land area (in square kilometers; see *Equation 29*). The VSL was used to express population exposure in terms of dollars.

Equation 29: Census Block Cold Wave Exposure

$$Exposure_{CWAV_{CB_{Bldg}}} = \frac{\sum IntsctArea_{CWAV_{CB}}}{EventCount_{CWAV_{CB}}} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{CWAV_{CB_{Pop}}} = \left(\frac{\sum IntsctArea_{CWAV_{CB}}}{EventCount_{CWAV_{CB}}} \times DevAreaDen_{CB_{Pop}}\right) \times VSL$$

$$Exposure_{CWAV_{CB_{Ag}}} = \frac{\sum IntsctArea_{CWAV_{CB}}}{EventCount_{CWAV_{CB}}} \times AgValueDen_{CB}$$

where:

$Exposure_{CWAV_{CB_{Bldg}}}$	is the building value exposed to Cold Wave event-days in a specific Census block (in dollars).
$\sum IntsctArea_{CWAV_{CB}}$	is the sum of the intersected areas of past Cold Wave event-days with the Census block (in square kilometers).
$EventCount_{CWAV_{CB}}$	is the total number of Cold Wave event-days that intersect the Census block.
$DevAreaDen_{CB_{Bldg}}$	is the developed area building value density of the Census block (in dollars per square kilometer).
$Exposure_{CWAV_{CB_{Pop}}}$	is the population value exposed to Cold Wave event-days in a specific Census block (in dollars).
$DevAreaDen_{CB_{Pop}}$	is the developed area population density of the Census block (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).
$Exposure_{CWAV_{CB_{Ag}}}$	is the agricultural value exposed to Cold Wave event-days in a specific Census block (in dollars).
$AgValueDen_{CB}$	is the agriculture value density of the Census block (in dollars per square kilometer).

It should be noted that, for a Cold Wave event-day polygon's intersection with a Census block to be included, the area of the intersection must cover at least 5% of the Census block. This is a spatial modeling technique to correct for the small intersect "slivers" generated by differing versions of county boundary geometry being used.

Because the exposure model uses a conservative-case concentration of exposure and a developed area density value, it is possible to mathematically generate an exposure value that is greater than the total value of the Census block. The Hazus-recorded population and building value and the Census of Agriculture-reported crop and livestock value for the Census block are considered ceilings on exposure. For example, if the calculated exposed population exceeds the Hazus-recorded population, then the Hazus-recorded population is used as the population exposure value for the Census block.

8.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 30*).

Equation 30: Census Track and County Cold Wave Exposure Aggregation

$$Exposure_{CWAV\,CT_{Bldg}} = \sum_{CB}^{CT} Exposure_{CWAV\,CB_{Bldg}}$$

$$Exposure_{CWAV\,Co_{Bldg}} = \sum_{CB}^{Co} Exposure_{CWAV\,CB_{Bldg}}$$

$$Exposure_{CWAV\,CT_{Pop}} = \sum_{CB}^{CT} Exposure_{CWAV\,CB_{Pop}}$$

$$Exposure_{CWAV\,Co_{Pop}} = \sum_{CB}^{Co} Exposure_{CWAV\,CB_{Pop}}$$

$$Exposure_{CWAV\,CT_{Ag}} = \sum_{CB}^{CT} Exposure_{CWAV\,CB_{Ag}}$$

$$Exposure_{CWAV\,Co_{Ag}} = \sum_{CB}^{Co} Exposure_{CWAV\,CB_{Ag}}$$

where:

$Exposure_{CWAV\,CT_{Bldg}}$	is the building value exposed to Cold Wave event-days in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{CWAV\,CB_{Bldg}}$	is the summed value of all buildings exposed to Cold Wave for each Census block within the Census tract (in dollars).
$Exposure_{CWAV\,Co_{Bldg}}$	is the building value exposed to Cold Wave event-days in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{CWAV\,CB_{Bldg}}$ is the summed value of all buildings exposed to Cold Wave for each Census block within the county (in dollars).

$Exposure_{CWAV\,CT_{Pop}}$ is the population value exposed to Cold Wave event-days in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{CWAV\,CB_{Pop}}$ is the summed value of all population exposed to Cold Wave for each Census block within the Census tract (in dollars).

$Exposure_{CWAV\,Co_{Pop}}$ is the population value exposed to Cold Wave event-days in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{CWAV\,CB_{Pop}}$ is the summed value of all population exposed to Cold Wave for each Census block within the county (in dollars).

$Exposure_{CWAV\,CT_{Ag}}$ is the agricultural value exposed to Cold Wave event-days in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{CWAV\,CB_{Ag}}$ is the summed value of all agricultural value exposed to Cold Wave for each Census block within the Census tract (in dollars).

$Exposure_{CWAV\,Co_{Ag}}$ is the agricultural value exposed to Cold Wave event-days in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{CWAV\,CB_{Ag}}$ is the summed value of all agricultural value exposed to Cold Wave for each Census block within the county (in dollars).

8.5 Historic Event-Day Count

The count of historic Cold Wave event-days is computed as the number of distinct Cold Wave event-day polygons that intersect a Census block and have an area of intersection that is at least 5% of the block's total area. This count uses the same Cold Wave expansion Census block intersection table used to find exposure at the Census block level and will be used to compute frequency at the Census block level.

Historic Event-Day Counts are also supplied at the Census tract and county levels as the number of distinct Cold Wave event-day polygons that intersect the Census tract and county, respectively.

8.6 Frequency

The number of recorded Cold Wave event-days each year over the period of record (12.14 years) is used to estimate the frequency of Cold Waves in an area. Because a Cold Wave event can occur over several days or a single day, an event-day basis was used to estimate frequency as this method better captures the variability in duration between events. The annualized frequency is calculated at the Census block level, and this Census block-level value is used in the EAL calculations.

Frequency calculations use the same intersection between Cold Wave event-days (or Cold Wave Date Expansion) polygons and Census block polygons that were used to calculate exposure. The count of distinct Cold Wave event-day polygons intersecting each Census block is recorded and used to calculate the annualized frequency of Cold Wave event-days as in *Equation 31*.

Equation 31: Census Block Cold Wave Frequency

$$Freq_{CWAV_{CB}} = \frac{EventCount_{CWAV_{CB}}}{PeriodRecord_{CWAV}}$$

where:

$Freq_{CWAV_{CB}}$	is the annualized frequency of Cold Wave event-days determined for a specific Census block (event-days per year).
$EventCount_{CWAV_{CB}}$	is the number of Cold Wave event-days that intersect the Census block.
$PeriodRecord_{CWAV}$	is the period of record for Cold Wave (12.14 years).

8.6.1 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level. To achieve this, the frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 32*. Given this, it is possible that the frequency value reported by the NRI application does not exactly match that achieved by dividing the number of Cold Wave events at the Census tract and county level by the period of record.

Equation 32: Census Tract and County Area-Weighted Cold Wave Frequency Aggregation

$$Freq_{CWAV_{CT}} = \frac{\sum_{CB}^{CT}\left(Freq_{CWAV_{CB}} \times Area_{CB}\right)}{Area_{CT}}$$

$$Freq_{CWAV_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{CWAV_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{CWAV\,CT}$	is the annualized area-weighted Cold Wave frequency for a specific Census tract (event-days per year).
$Freq_{CWAV\,CB}$	is the annualized Cold Wave frequency associated with a specific Census block (event-days per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{CWAV\,Co}$	is the annualized area-weighted Cold Wave frequency for a specific county (event-days per year).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 33 displays annualized Cold Wave frequency at the county level.

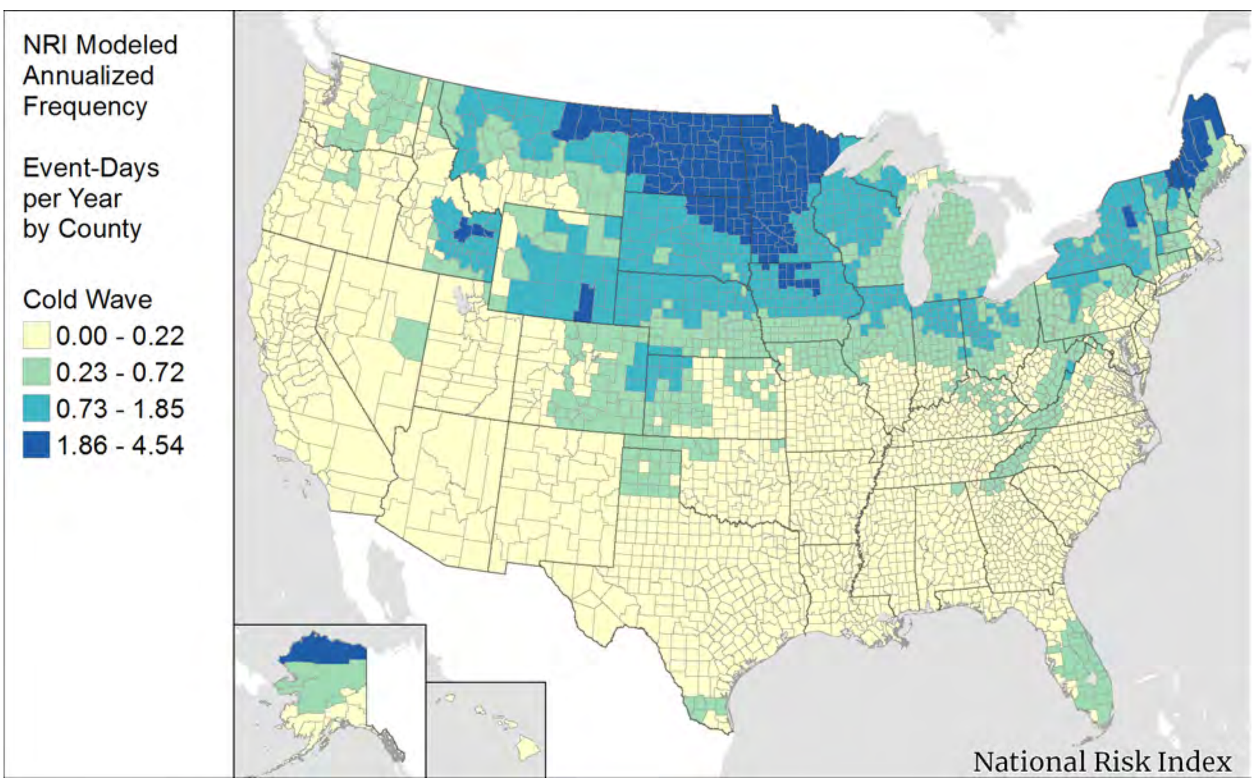

Figure 33: Annualized Cold Wave Frequency by County

8.7 Historic Loss Ratio

The Cold Wave HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Cold Wave event-day, or the average rate of loss associated with the occurrence of a Cold Wave event-day. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the hazard Cold Wave.

Historic Loss data are aggregated from the NWS Storm Events Database[33] at the county level, so this is the lowest level at which HLR can be calculated. NWS events from 1995 to 2016 are included in the HLR calculation. Three types of storm events in the Storm Events Database are categorized as Cold Wave by the NRI (see *Table 20*). These native loss records are expanded on an event basis based on the number of event duration days from the Storm Events Database (see *Section 5.4.2*).

Table 20: Event Types and Recorded Events from 1995-2016

Event Type	Total NWS Records with Loss	Total NWS Events
Cold/Wind Chill	1,051	12,879
Extreme Cold/Wind Chill	306	10,111
Frost/Freeze	957	10,282

The HLR exposure value used in the LRB calculation is a county-level value that represents the dollar value of the total building value, the entire population of a county as recorded in the Hazus 4.2 SP1 data, or the total Census of Agriculture-reported crop and livestock value. The LRB for each NWS Storm Event-documented event-day and each consequence type (building, population, and agriculture) is calculated using *Equation 33*.

Equation 33: Loss Ratio per Basis Calculation for a Single Cold Wave Event-Day

$$LRB_{CWAV\,Co_{CnsqType}} = \frac{Loss_{CWAV\,Co_{CnsqType}}}{HLRExposure_{Co_{CnsqType}}}$$

where:

$LRB_{CWAV\,Co_{CnsqType}}$ is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Cold Wave event-day. Calculation is performed for each consequence type (building, population, and agriculture).

$Loss_{CWAV\,Co_{CnsqType}}$ is the loss (by consequence type) experienced from the Cold Wave event-day documented to have occurred in the county (in dollars).

[33] National Weather Service, National Oceanic and Atmospheric Administration. (2017). Storm Events Database, Version 3.0 [online database]. Retrieved from https://www.ncdc.noaa.gov/stormevents/.

$HLRExposure_{Co_{CnsqType}}$ is the total value (by consequence type) of the county estimated to have been exposed to the Cold Wave event-day (in dollars).

Cold Waves can occur with a high frequency in areas, but often result in no recorded loss to buildings or population. Unlike SHELDUS, the NWS Storm Events Database includes all hazard events, regardless of whether they resulted in economic loss. To replicate the same process of padding the loss data with zero-loss records, only NWS events with recorded loss were included as the initial loss dataset. This count was then compared to the historic event count experienced within the Cold Wave source data period of record (2005 to 2017; see *Section 8.1.1*). For Cold Wave, the historic year-month event count is extracted using the intersection between the Cold Wave event-day polygons and the Census block polygons used to calculate exposure and frequency (see *Table 19*). The date when the Cold Wave alert was issued for each Cold Wave event-day polygon is used to sync the event to its year-month. A list of distinct Cold Wave alert issue dates is compiled for the event-day polygon-Census block intersections within the county, and the historic year-month event count is the number of distinct Cold Wave alert issue dates in this list.

If the number of loss-causing Cold Wave event records from the NWS Storm Events Database is less than the summed historic year-month event counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, regional, and national. The regional definition for Cold Wave is derived from the FEMA regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 34, *Figure 36,* and *Figure 38* display the largest weighting factor contributor in the Bayesian credibility calculations for the Cold Wave HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Cold Wave event-days within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local, regional, or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing event-days or have widely varying loss ratios get the most influence from regional- or national-level loss data. *Figure 35*, *Figure 37*, and *Figure 39* represent the final county-level HLR values for Cold Wave.

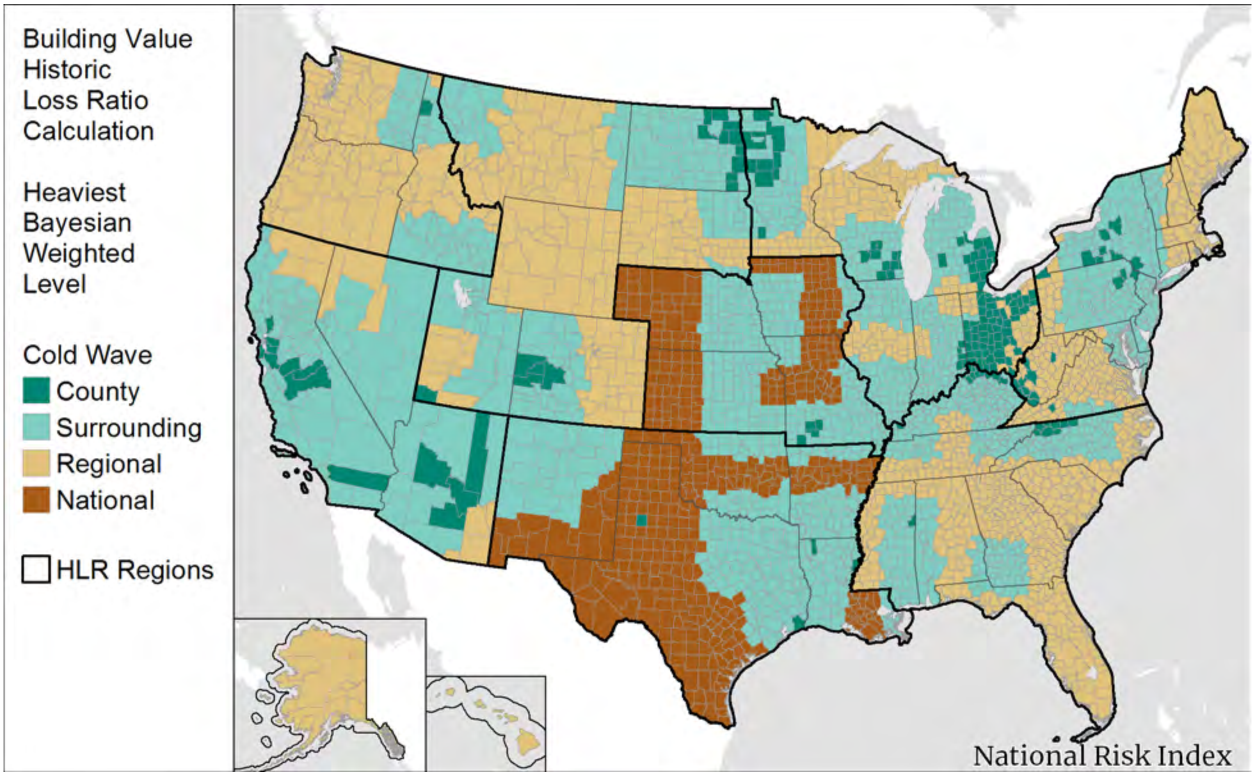

Figure 34: Cold Wave Heaviest Bayesian Weighted Level – Building Value

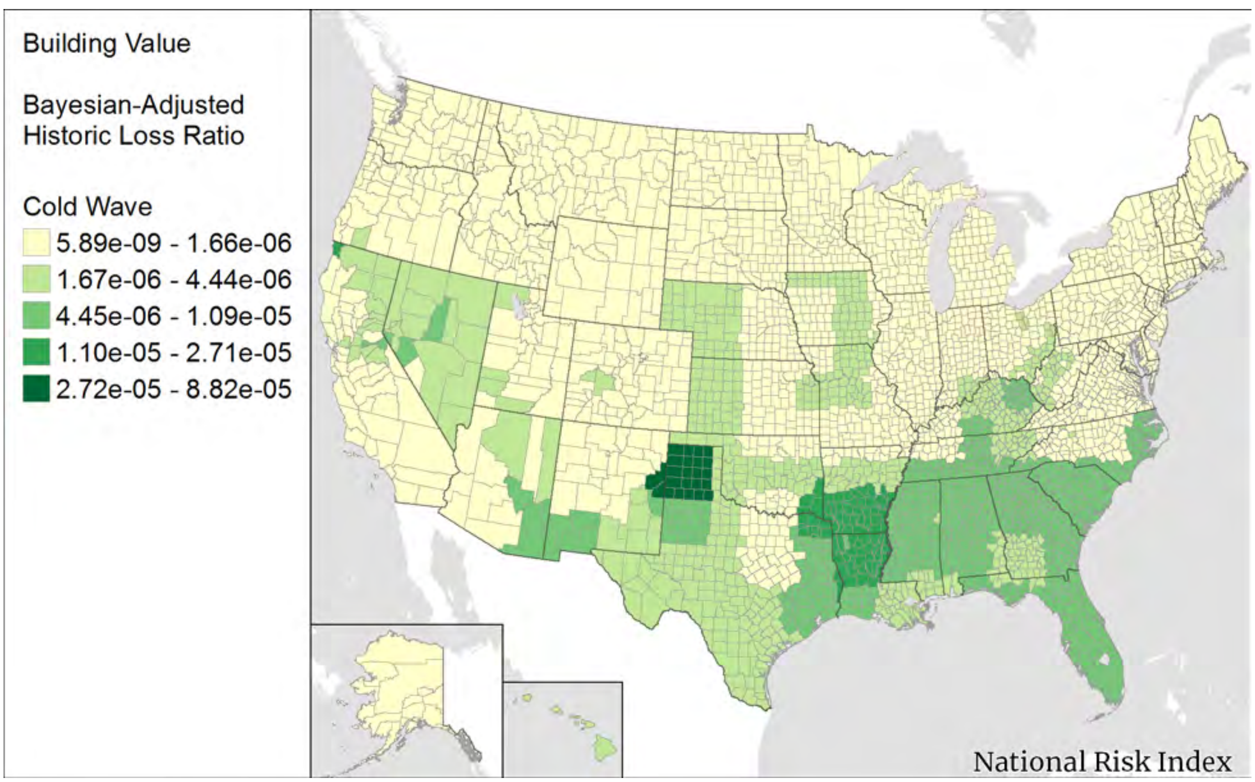

Figure 35: Cold Wave HLR – Building Value

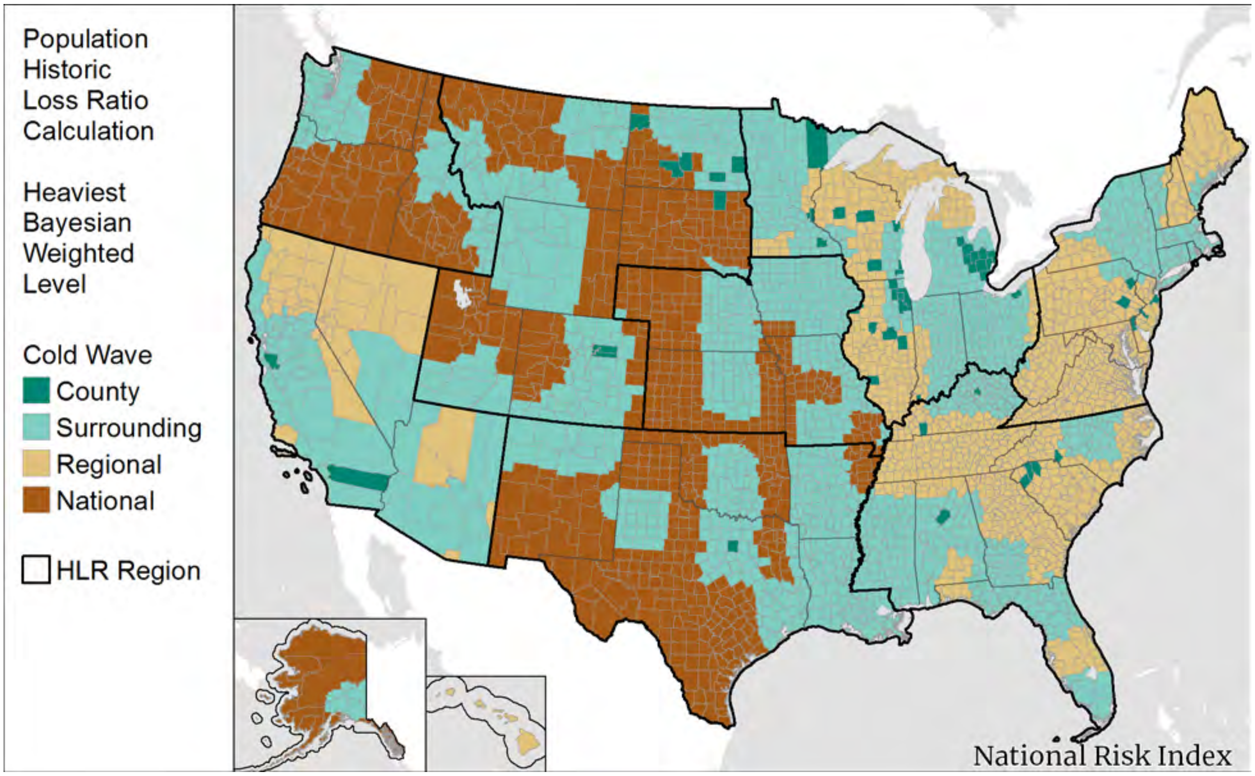

Figure 36: Cold Wave Heaviest Bayesian Weighted Level – Population

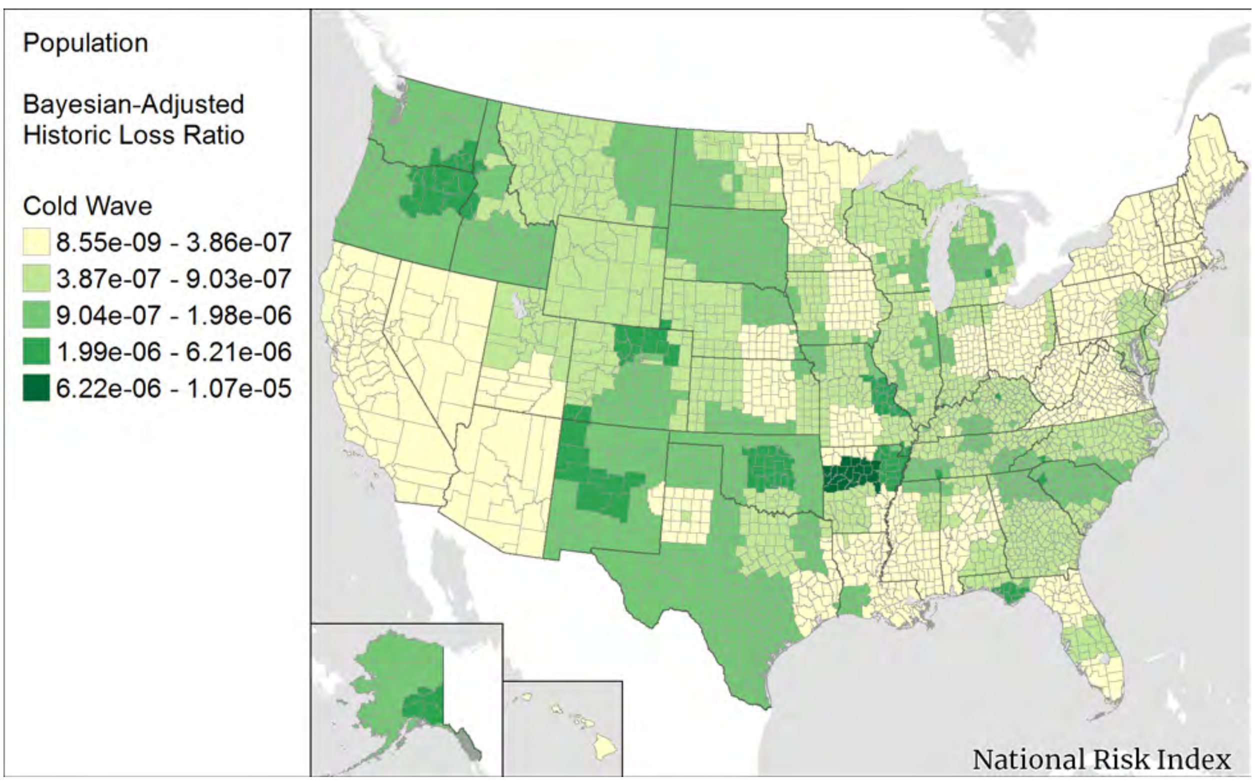

Figure 37: Cold Wave HLR – Population

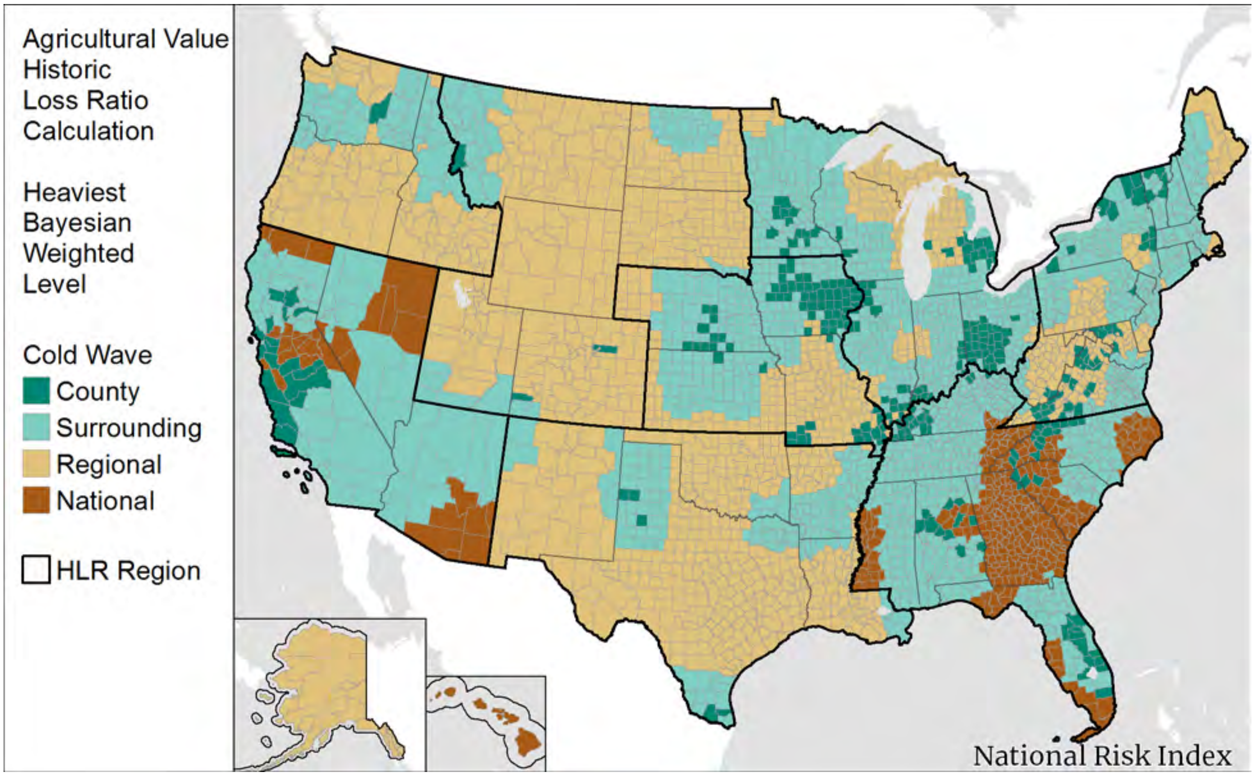

Figure 38: Cold Wave Heaviest Bayesian Weighted Level – Agriculture Value

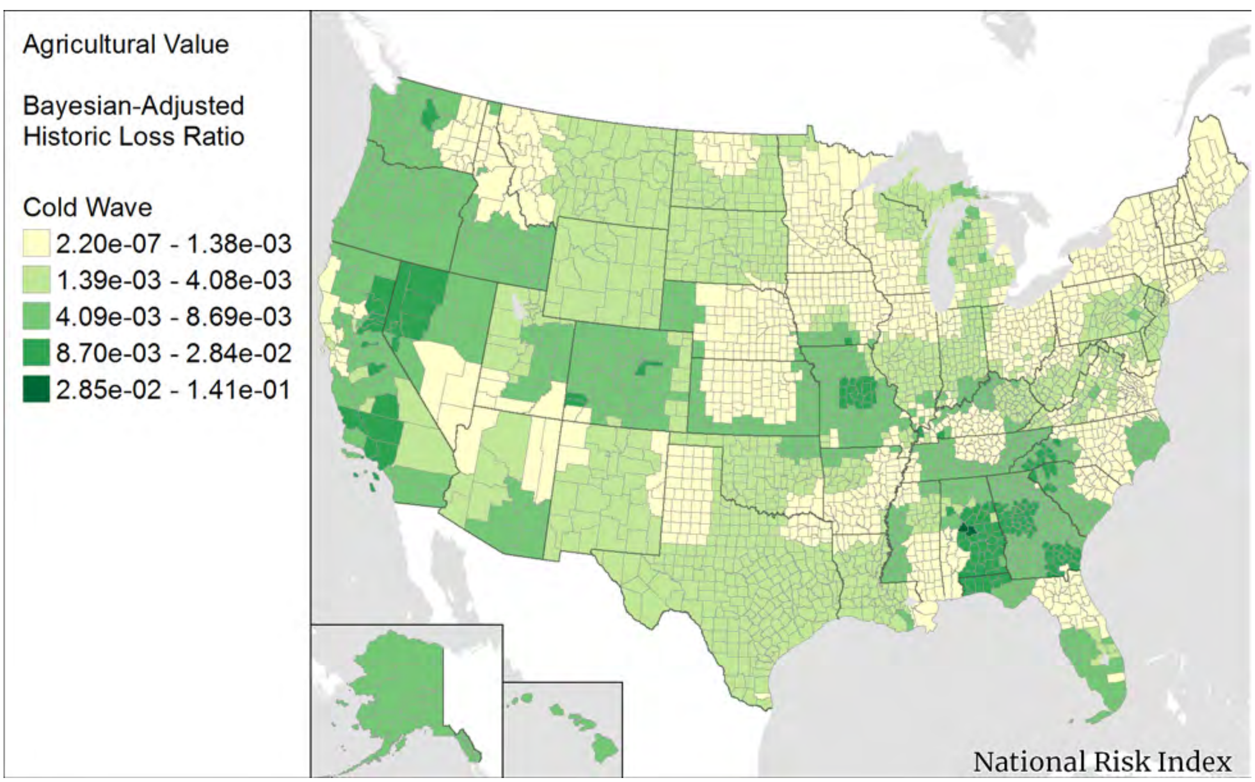

Figure 39: Cold Wave HLR – Agriculture Value

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

8.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 34*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 34: Census Block Expected Annual Loss to Cold Wave

$$EAL_{CWAV_{CB_{Bldg}}} = Exposure_{CWAV_{CB_{Bldg}}} \times Freq_{CWAV_{CB}} \times HLR_{CWAV_{CB_{Bldg}}}$$

$$EAL_{CWAV_{CB_{Pop}}} = Exposure_{CWAV_{CB_{Pop}}} \times Freq_{CWAV_{CB}} \times HLR_{CWAV_{CB_{Pop}}}$$

$$EAL_{CWAV_{CB_{Ag}}} = Exposure_{CWAV_{CB_{Ag}}} \times Freq_{CWAV_{CB}} \times HLR_{CWAV_{CB_{Ag}}}$$

where:

$EAL_{CWAV_{CB_{Bldg}}}$	is the Expected Annual Loss to building value due to Cold Wave events for a specific Census block (in dollars).
$Exposure_{CWAV_{CB_{Bldg}}}$	is the building value exposed to Cold Wave events in the Census block (in dollars).
$Freq_{CWAV_{CB}}$	is the annualized Cold Wave frequency for the Census block (event-days per year).
$HLR_{CWAV_{CB_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Cold Wave for the Census block.
$EAL_{CWAV_{CB_{Pop}}}$	is the Expected Annual Loss to population value due to Cold Wave events for a specific Census block (in dollars).
$Exposure_{CWAV_{CB_{Pop}}}$	is the population value exposed to Cold Wave events in the Census block (in dollars).
$HLR_{CWAV_{CB_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Cold Wave for the Census block.

$EAL_{CWAV_{CB_{Ag}}}$ is the Expected Annual Loss to agriculture value due to Cold Wave events for a specific Census block (in dollars).

$Exposure_{CWAV_{CB_{Ag}}}$ is the agriculture value exposed to Cold Wave events in the Census block (in dollars).

$HLR_{CWAV_{CB_{Ag}}}$ is the Bayesian-adjusted agriculture Historic Loss Ratio for Cold Wave for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building and population loss at the Census block level (see *Equation 35*).

Equation 35: Census Tract and County Expected Annual Loss to Cold Wave

$$EAL_{CWAV_{CT}} = \sum_{CB}^{CT} EAL_{CWAV_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{CWAV_{CB_{Pop}}} + \sum_{CB}^{CT} EAL_{CWAV_{CB_{Ag}}}$$

$$EAL_{CWAV_{Co}} = \sum_{CB}^{Co} EAL_{CWAV_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{CWAV_{CB_{Pop}}} + \sum_{CB}^{Co} EAL_{CWAV_{CB_{Ag}}}$$

where:

$EAL_{CWAV_{CT}}$ is the total Expected Annual Loss due to Cold Wave events for a specific Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{CWAV_{CB_{Bldg}}}$ is the summed Expected Annual Loss to building value due to Cold Wave events for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{CWAV_{CB_{Pop}}}$ is the summed Expected Annual Loss to population value due to Cold Wave events for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{CWAV_{CB_{Ag}}}$ is the summed Expected Annual Loss to agriculture value due to Cold Wave events for all Census blocks in the Census tract (in dollars).

$EAL_{CWAV_{Co}}$ is the total Expected Annual Loss due to Cold Wave events for a specific county (in dollars).

$\sum_{CB}^{Co} EAL_{CWAV_{CB_{Bldg}}}$ is the summed Expected Annual Loss to building value due to Cold Wave events for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{CWAV_{CB_{Pop}}}$ is the summed Expected Annual Loss to population value due to Cold Wave events for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{CWAV_{CB_{Ag}}}$ is the summed Expected Annual Loss to agriculture value due to Cold Wave events for all Census blocks in the county (in dollars).

Figure 40 shows the total EAL (building value and population combined) to Cold Wave events.

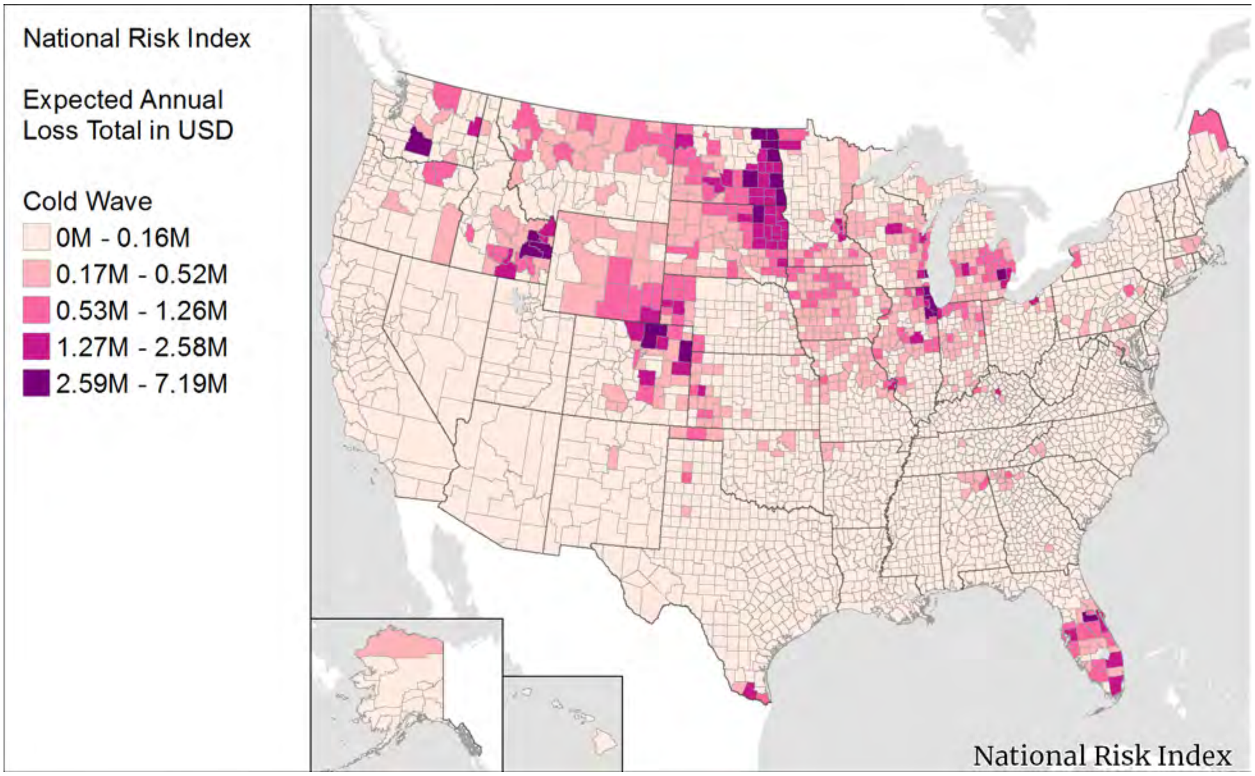

Figure 40: Total Expected Annual Loss by County to Cold Wave

With the Cold Wave total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Cold Wave Risk Index score.

9 Drought

A Drought is a deficiency of precipitation over an extended period of time resulting in a water shortage.

9.1 Spatial Source Data

Historical Event Source: *University of Nebraska-Lincoln National Drought Mitigation Center (NDMC), U.S. Drought Monitor*[34]

The NDMC provides shapefiles representing areas experiencing Drought on a weekly basis since 2000 (see *Figure 41*). Each Drought polygon is categorized by intensity from Abnormally Dry to Exceptional Drought. The Drought Monitor uses multiple indices and indicators to classify Drought severity, and they rely on local condition reports from expert observers (see *Table 21*).

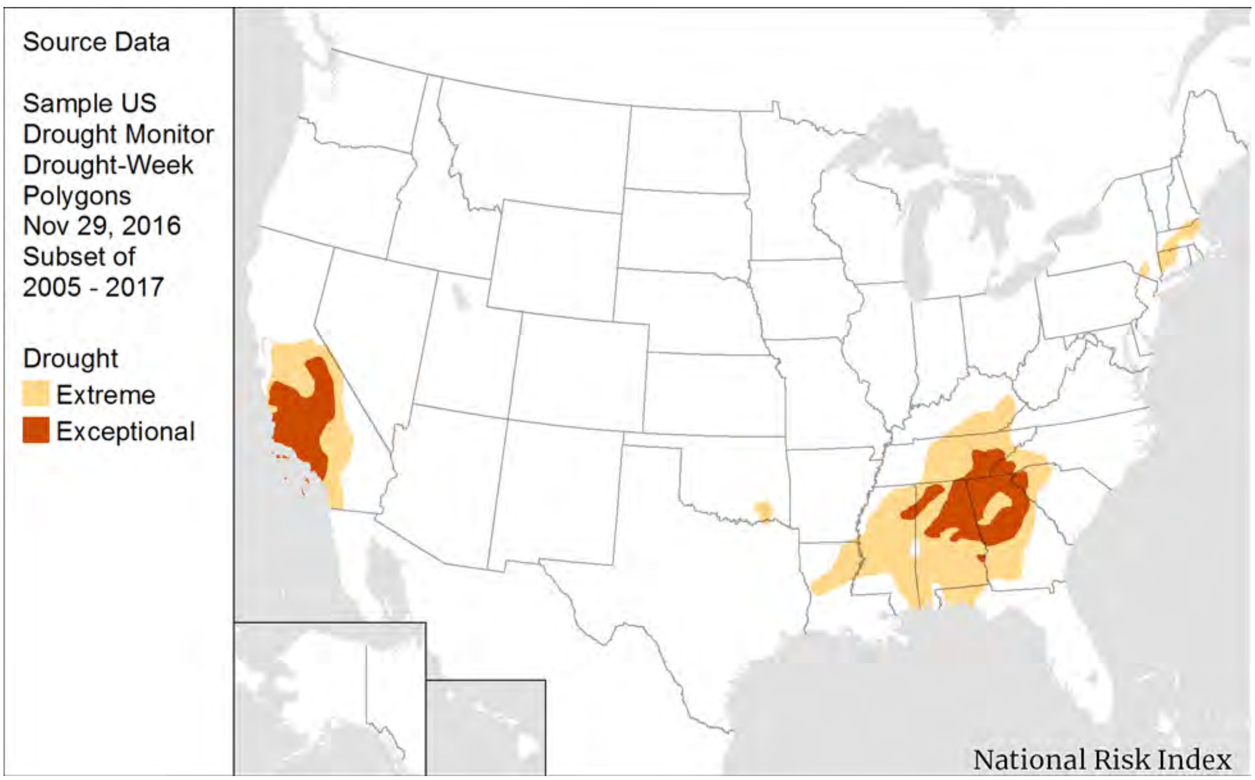

Figure 41: Sample Drought Shape

[34] National Drought Mitigation Center, University of Nebraska-Lincoln & National Oceanic and Atmospheric Administration. (2018). US Drought Monitor [online database]. Retrieved from https://droughtmonitor.unl.edu/Data/GISData.aspx.

Table 21: Drought Category Descriptions

Category Type	Value	Description
Dryness	D0	Abnormally Dry – used for areas showing dryness but not yet in drought, or for areas recovering from drought.
Drought Intensity	D1	Moderate Drought
Drought Intensity	D2	Severe Drought
Drought Intensity	D3	Extreme Drought
Drought Intensity	D4	Exceptional Drought

9.1.1 PERIOD OF RECORD

The U.S. Drought Monitor data include Droughts from 1/1/2000 to 12/31/2017, so the period of record for which Drought data are utilized is 18 years.

9.2 Spatial Processing

The drought shapefiles associated with each week from January 2000 through December 2017 are extracted and loaded into the NRI processing database. The data initially consist of 10,010 drought-week records. Only the most severe Drought events are analyzed in NRI, so only Drought Intensity categories DM3 (Extreme Drought) and DM4 (Exceptional Drought) were utilized. Drought-week polygons are then intersected with the Census tract polygons to calculate exposure and frequency.

9.3 Determination of Possibility of Hazard Occurrence

Drought can occur almost anywhere under the right conditions, so all counties were deemed possible for Drought occurrence.

9.4 Exposure

To identify areas of exposure, the Drought-week polygons are intersected with the Census tract polygons within the NRI processing database. The resulting table contains the Drought-week polygon's unique identifier, Census tract number, the intersected area, and the area of intersection containing crop or pastureland (see *Table 22*). All areas are in square kilometers.

Table 22: Sample Data from the Drought Census Tract Intersection Table

DroughtID	CensusTract	IntersectedAreaKm2	AreaCropPastureKm2
4146	47065011001	10.5401941730042	0
4146	47073050602	16.8104900265808	0
4146	47089070900	169.275131709686	169.275131709686

To determine exposure value, the average coverage of a Drought event-week is found by summing the intersected areas for all Drought event-weeks that intersected the Census tract and dividing this sum by the number of intersecting event-weeks. This is multiplied by the total agricultural value density of the Census tract. The Census tract agricultural value density has been calculated by dividing the total agricultural value of the Census tract by its agricultural land area (in square kilometers; see *Equation 36*).

Equation 36: Census Tract Drought Exposure

$$Exposure_{DRGT\,CT\,Ag} = \frac{\sum IntsctArea_{DRGT\,CT\,Ag}}{EventDayCount_{DRGT\,CT}} \times AgValueDen_{CT}$$

where:

$Exposure_{DRGT\,CT\,Ag}$	is the agricultural value exposed to Drought for a specific Census tract (in dollars).
$\sum IntsctArea_{DRGT\,CT\,Ag}$	is the sum of the intersected areas of past Drought event-days with the Census tract (in square kilometers).
$EventDayCount_{DRGT\,CT}$	is the total number of Drought event-days that intersect the Census tract.
$AgValueDen_{CT}$	is the agriculture value density of the Census tract (in dollars per square kilometer).

The CropScape-derived crop value for the Census tract is considered a ceiling on exposure. If the calculated exposed crop value exceeds the CropScape-derived value, then the CropScape value is used as the crop exposure value for the Census tract.

9.4.1 EXPOSURE AGGREGATION

To calculate exposure at the county level, the exposure values for each Census tract within the county are summed as in *Equation 37*.

Equation 37: County Drought Exposure Aggregation

$$Exposure_{DRGT\,Co\,Ag} = \sum_{CT}^{Co} Exposure_{DRGT\,CT\,Ag}$$

where:

$Exposure_{DRGT\,Co\,Ag}$	is the agricultural value exposed to Drought for a specific county (in dollars).

$\sum_{CT}^{Co} Exposure_{DRGT_{CT_{Ag}}}$ is the summed value of all agricultural areas exposed to Drought for each Census tract within the county (in dollars).

9.5 Historic Event-Day Count

The count of historic Drought event-days is computed as the number of distinct Drought event-week polygons that intersect a Census tract multiplied by seven. This count uses the same Drought Census tract intersection table used to find exposure at the Census tract level and will be used to compute frequency at the Census tract level.

A Historic Event-Day Count is also supplied at the county level as the number of distinct Drought event-week polygons that intersect the county multiplied by seven.

9.6 Frequency

The frequency value represents the number of recorded Drought event-days each year over the period of record (18 years). The annualized frequency is calculated at the Census tract level, and the Census tract-level value is used in the EAL calculations.

Frequency calculations use the same intersection between Drought event-week polygons and Census tract polygons that were used to calculate exposure. The historic event day-count described above is used to calculate the annualized frequency of Drought event-days as in *Equation 38*.

Equation 38: Census Tract Drought Frequency

$$Freq_{DRGT_{CT}} = \frac{EventDayCount_{DRGT_{CT}}}{PeriodRecord_{DRGT}}$$

where:

$Freq_{DRGT_{CT}}$ is the annualized frequency of Drought determined for a specific Census tract (event-days per year).

$EventDayCount_{DRGT_{CT}}$ is the number of Drought event-days (event-weeks multiplied by seven) that intersect the Census tract.

$PeriodRecord_{DRGT}$ is the period of record for Drought (18 years).

9.6.1 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at the county level, so these values may not exactly match that of dividing the number of recorded Drought event-days at the county level by the period of record. The frequency values at the Census tract level are rolled up to the county level using area-weighted aggregations as in *Equation 39*.

Equation 39: County Area-Weighted Drought Frequency

$$Freq_{DRGT\,Co} = \frac{\sum_{CT}^{Co}(Freq_{DRGT\,CT} \times Area_{CT})}{Area_{Co}}$$

where:

$Freq_{DRGT\,Co}$	is the annualized Drought frequency calculated for a specific county (event-days per year).
$Freq_{DRGT\,CT}$	is the annualized Drought frequency associated with a specific Census tract (event-days per year).
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$\sum_{CT}^{Co}$	is the sum for all Census tracts in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 42 displays annualized Drought frequency at the county level.

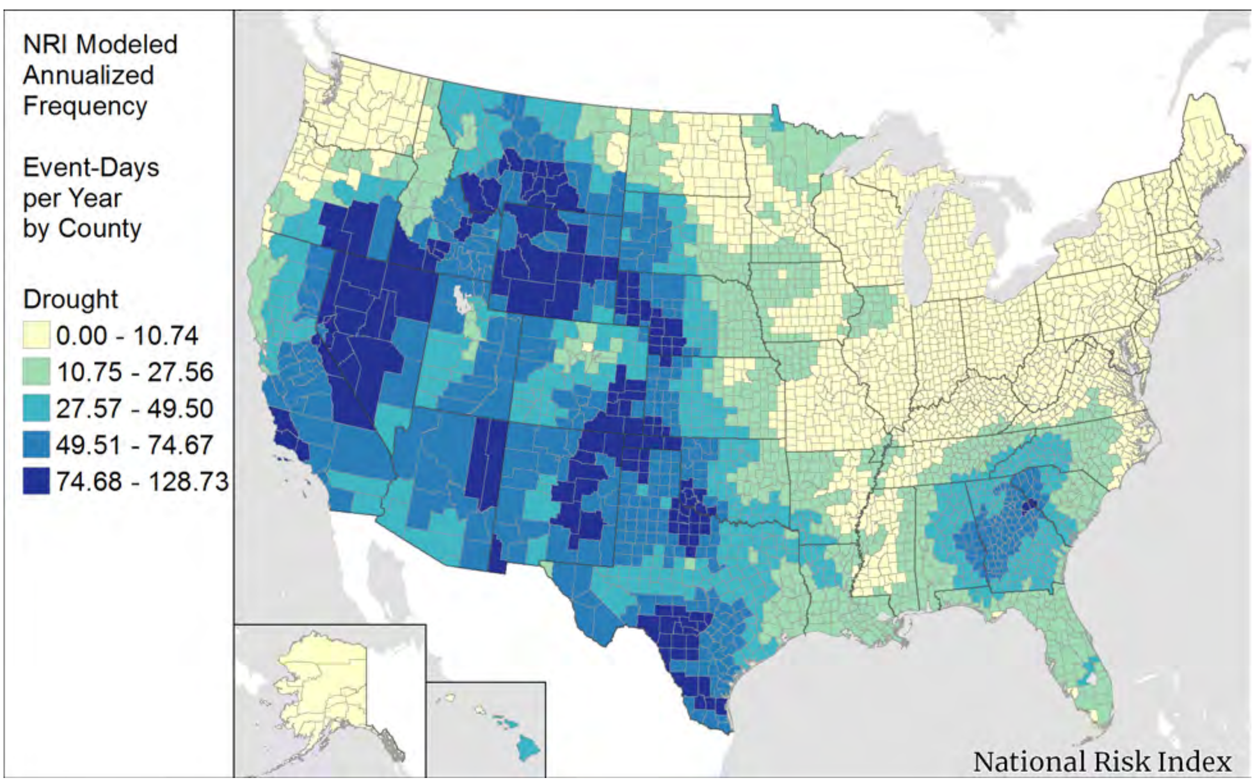

Figure 42: Annualized Drought Frequency by County

9.7 Historic Loss Ratio

The Drought HLR is the representative percentage of a location's Drought exposure area that experiences loss due to a Drought event-day, or the average rate of loss associated with the occurrence of a Drought event-day. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Drought hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. One peril type is mapped to the hazard Drought (see *Table 23*). Loss records are expanded on an event-day basis based on the number of event duration days from SHELDUS[35] (see *Section 5.4.1*).

Table 23: Drought Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Drought	6,634	190,431

The HLR exposure value used in the LRB calculation is a county-level value that represents the dollar value of the total crop and livestock value of the county as estimated in the USDA 2017 Census of Agriculture data. The LRB for each SHELDUS-documented event-day is calculated using *Equation 40*.

Equation 40: Loss Ratio per Basis Calculation for a Single Drought Event-Day

$$LRB_{DRGT\,Co_{Ag}} = \frac{Loss_{DRGT\,Co_{Ag}}}{HLRExposure_{Co_{Ag}}}$$

where:

$LRB_{DRGT\,Co_{Ag}}$	is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Drought event-day, performed for agricultural loss.
$Loss_{DRGT\,Co_{Ag}}$	is the agricultural loss experienced from the Drought event-day documented to have occurred in the county (in dollars).
$HLRExposure_{Co_{Ag}}$	is the total agricultural value of the county estimated to have been exposed to the Drought event-day (in dollars).

Drought event-days can occur with a high frequency in areas, but often result in no recorded loss to agriculture. SHELDUS does not record events in which no loss occurred, so a number of zero-loss

[35] For Drought loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

event-days are inserted into the data to align the event-day count in the HLR calculation to the historic event-day count experienced within the SHELDUS period of record (1995 to 2016). For Drought, the historic year-month event count is extracted using the intersection between the Drought event-week polygons and the Census tract used to calculate frequency. The observation date of each Drought event-week polygon is used to sync the event to its year-month. A list of distinct Drought observation dates is compiled for the event-week polygon-Census tract intersections that intersect the county, and the historic year-month event count is the number of distinct Drought observation dates in this list. The event-day count per month has a ceiling of 31 event-days, so any month that experiences 5 drought-weeks (converted to 35 days) is given a count of 31.

If the number of loss-causing Drought event-day records from SHELDUS is less than the summed historic year-month event day counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and regional. The regional definition for Drought is derived from the FEMA regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 43 displays the largest weighting factor contributor in the Bayesian credibility calculations for the Drought HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Drought event-days within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or regional events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing event-days or have widely varying loss ratios get the most influence from regional-level loss data. *Figure 44* represents the final county-level HLR values for Drought.

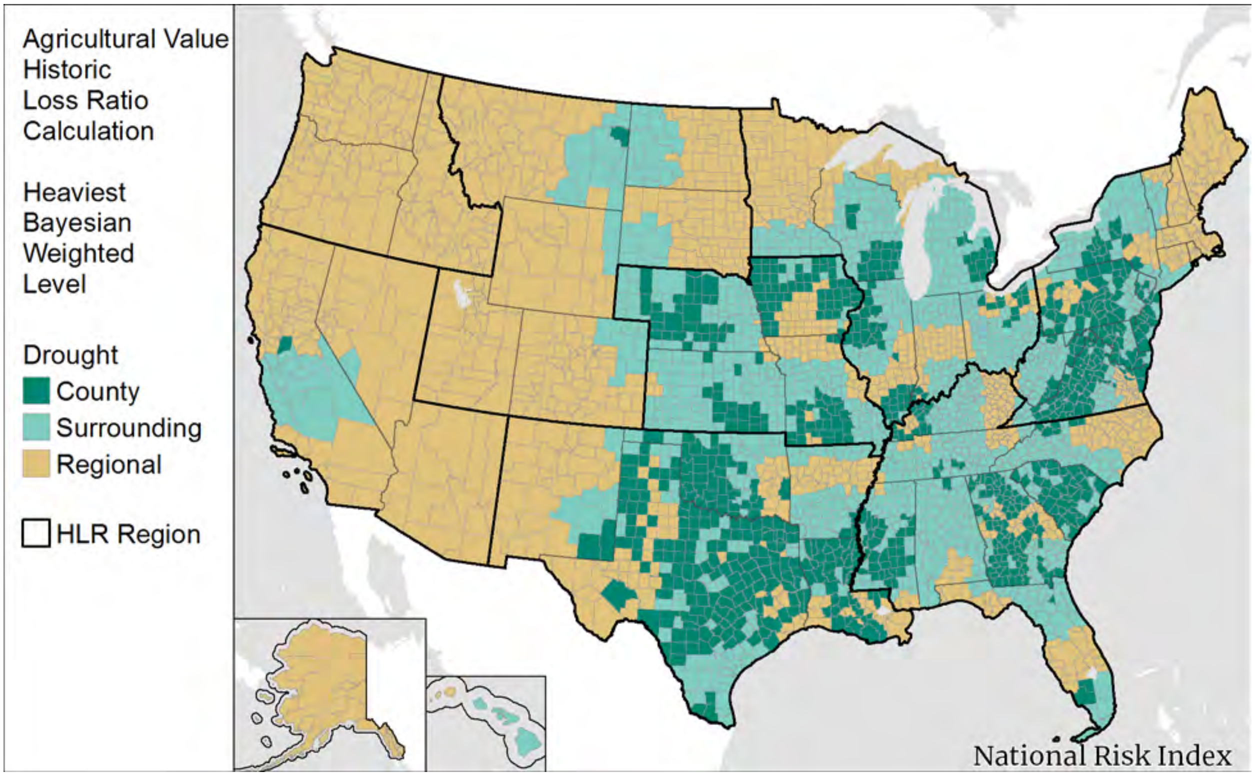

Figure 43: Drought Heaviest Bayesian Weighted Level – Agriculture Value

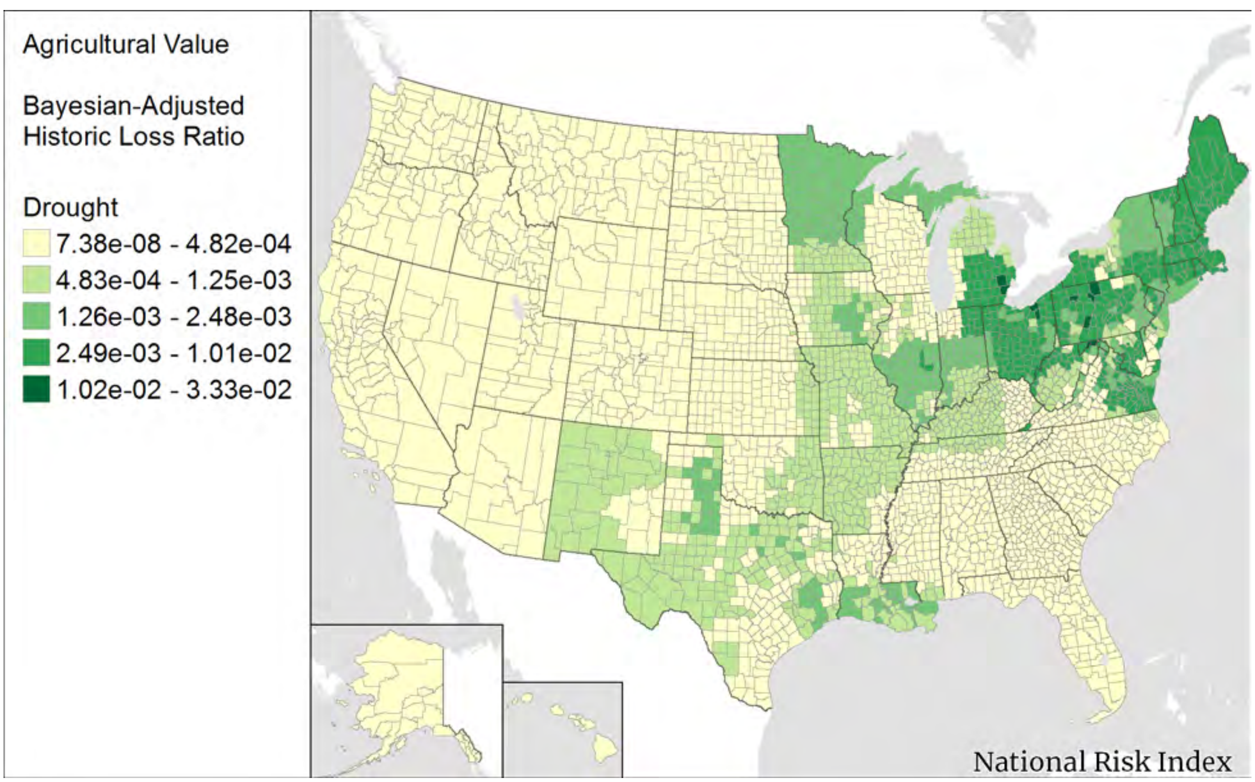

Figure 44: Drought HLR – Agriculture Value

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

9.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census tract level as in *Equation 41*. Performing the base calculations once at the Census tract level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 41: Census Tract Expected Annual Loss to Drought

$$EAL_{DRGT_{CT_{Ag}}} = Exposure_{DRGT_{CT_{Ag}}} \times Freq_{DRGT_{CT}} \times HLR_{DRGT_{CT_{Ag}}}$$

where:

$EAL_{DRGT_{CT_{Ag}}}$	is the Expected Annual Loss to agriculture value due to Drought events for a specific Census tract (in dollars).
$Exposure_{DRGT_{CT_{Ag}}}$	is the agriculture value exposed to Drought events in the Census tract (in dollars).
$Freq_{DRGT_{CT}}$	is the annualized Drought frequency for the Census tract (event-days per year).
$HLR_{DRGT_{CT_{Ag}}}$	is the Bayesian-adjusted agriculture Historic Loss Ratio for Drought for the Census tract.

The total EAL values at the county level are the aggregated values of the crop loss at the Census tract level as in *Equation 42*.

Equation 42: County Expected Annual Loss to Drought

$$EAL_{DRGT_{Co_{Ag}}} = \sum_{CT}^{Co} EAL_{DRGT_{CT_{Ag}}}$$

where:

$EAL_{DRGT_{Co_{Ag}}}$	is the total Expected Annual Loss due to Drought for a specific county (in dollars).
$\sum_{CT}^{Co} EAL_{DRGT_{CT_{Ag}}}$	is the summed Expected Annual Loss to agriculture value due to Drought events for all Census tracts in the county (in dollars).

Figure 45 shows the total EAL (agriculture only) to Drought events.

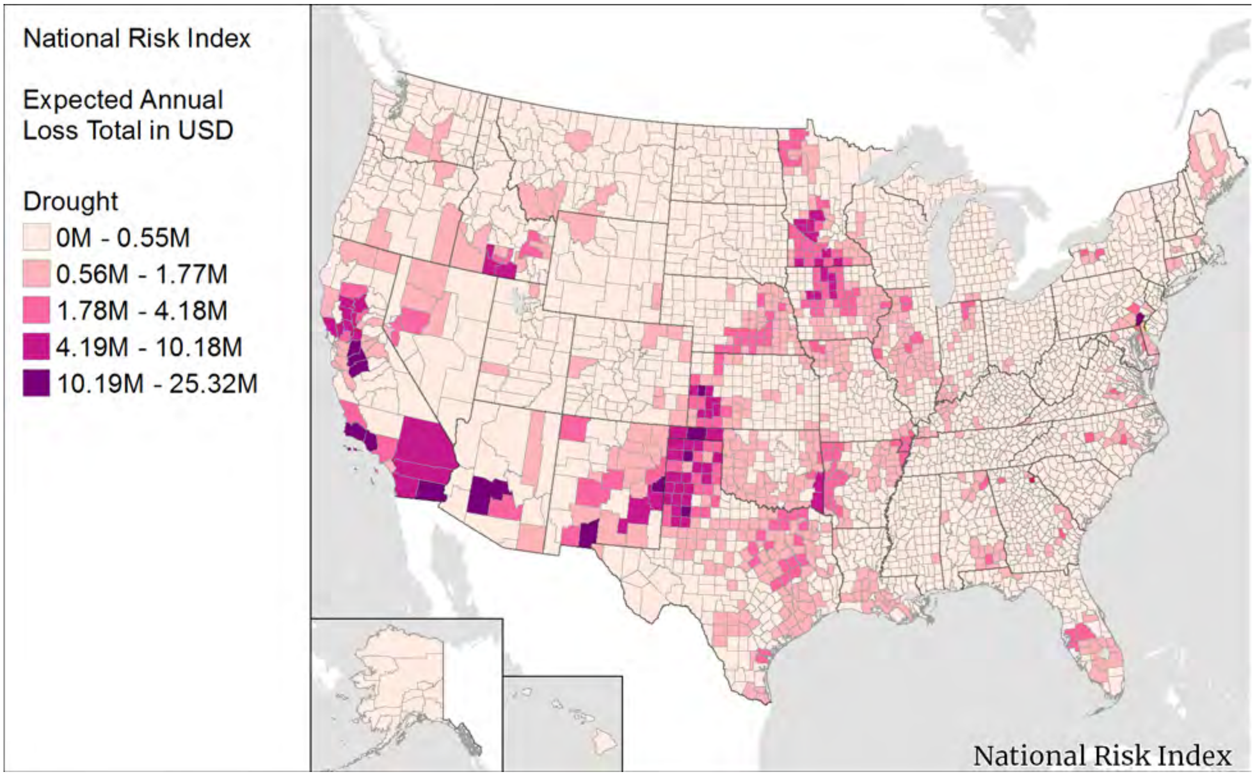

Figure 45: Total Expected Annual Loss by County to Drought

With the Drought total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Drought Risk Index score.

10 Earthquake

An Earthquake is a shaking of the earth's surface by energy waves emitted by slowly moving tectonic plates overcoming friction with one another underneath the earth's surface.

10.1 Spatial Source Data

Susceptible Area Source: USGS, Kenneth Rukstales

The USGS supplied a geodatabase of raster datasets covering the entire United States in which the cells give the 100-year probability of Minor-Damage Earthquake Shaking (see *Figure 46*). Cell values range from 0 to 100. These raster files are derived from the hazard model used to create USGS National Seismic Hazard Maps.[36]

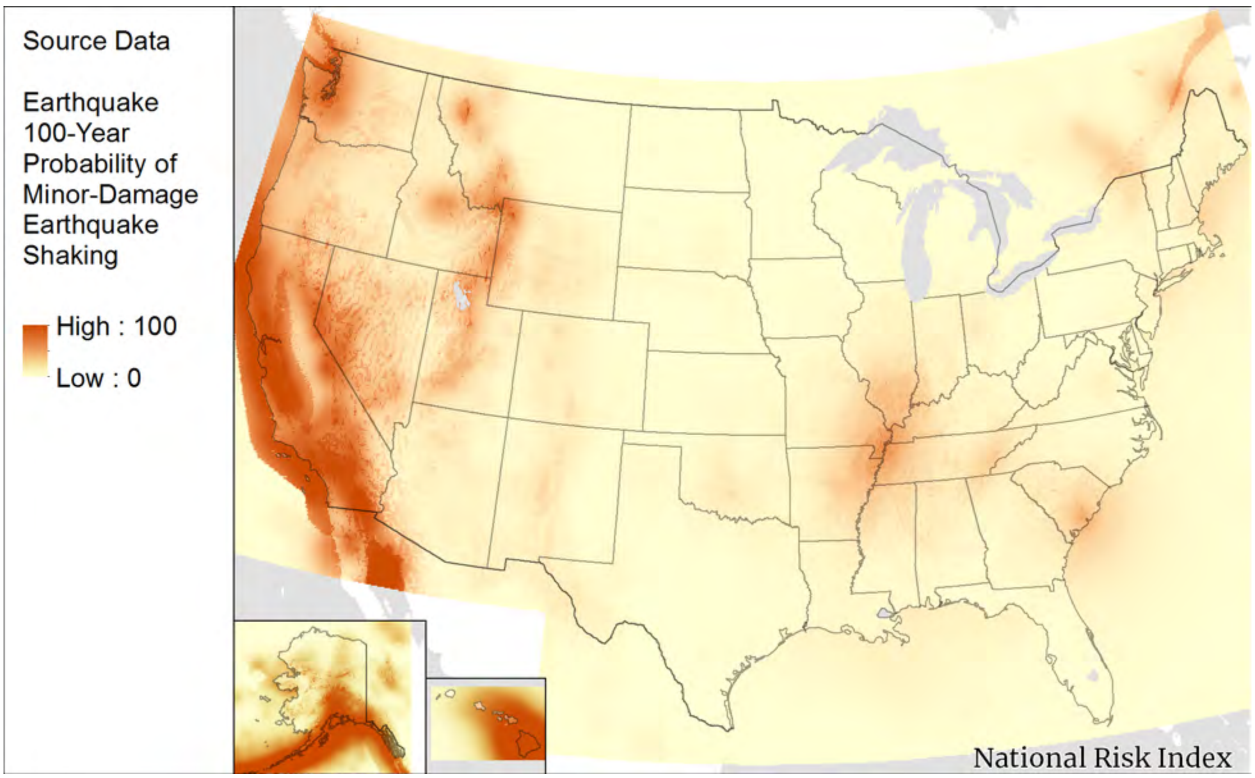

Figure 46: Map of Earthquake Probability Raster

Loss Quantification Source: *Federal Emergency Management Agency, Hazus P-366 Study*[37]

[36] United States Geological Survey. (2018). Introduction to the National Seismic Hazard Maps. Retrieved from https://earthquake.usgs.gov/hazards/learn/.

[37] Federal Emergency Management Agency. (2017). *Hazus estimated annualized earthquake losses for the United States.* Washington, DC: Federal Emergency Management Agency, Department of Homeland Security. Retrieved from https://www.fema.gov/sites/default/files/2020-07/fema_earthquakes_hazus-estimated-annualized-earthquake-losses-for-the-united-states_20170401.pdf.

FEMA's Hazus tool "uses a uniform engineering-based approach to measure damages, casualties and economic losses from earthquakes nationwide." The P-366 study uses Hazus to determine Earthquake risk throughout the United States at both the Census tract and county levels (see *Table 24* for sample data). Rather than recreate the work of Hazus, the Census tract- and county-level data produced by this study were loaded into the NRI processing database as a reference table and a simple lookup of building and population exposure is performed. P-366 also calculates an Annualized Earthquake Loss value that is used as the NRI EAL value for buildings at the Census tract and county levels. A separate measure of annualized population loss is provided by P-366 as the estimation of Level 4 severity injuries (instantaneous deaths or mortal injuries) expected annually due to Earthquakes. These loss values can be combined to find the EAL.

Table 24: Sample Census Tract-Level Data from Hazus P-366

Census Tract	County Name	State	TotalExp_Bldg_1k	Pop_2010	AEL_1mil	Level4Injury_2pm
2013000100	Aleutians East	AK	479651	3141	0.366149	0.007988
6019004212	Fresno	CA	977086	10762	0.275099	0.001295
15003000902	Honolulu	HI	482524	4088	0.151932	0.004374

10.2 Spatial Processing

While the final EAL values are extracted from the Hazus P-366 study, ancillary data are provided by the NRI for exposure, frequency, and HLR at the Census tract and county level. Exposure can be extracted from the P-366 data and HLR is derived from SHELDUS. However, frequency could not be extracted as a simplified value. The raster datasets supplied by USGS allow for the computation of an annualized probability value to serve as frequency, though this value will not be used in the EAL calculation.

To determine the intersections of the Earthquake probability raster cells with Census blocks, the USGS raster-formatted data are converted to a vector format (i.e., polygons). Converting the raster dataset to vector format greatly improves the processing speed and repeatability of resource-intensive intersection functions performed within the NRI processing database. A polygon fishnet for which the cell dimensions and coverage match the raster datasets was created to make the conversion. Because these polygons matched the cells of the raster datasets, the coordinates of each polygon's centroid could be used to query each raster and return its associated value for the corresponding raster cell. The result is that Earthquake probability is now tabularly related to a single-cell Earthquake-probability fishnet polygon (see *Figure 47*) that can then be intersected with the Census blocks to determine Earthquake frequency at the Census block level. Because the original values represent a 100-year probability, the values were then divided by 100 to create an annualized probability value.

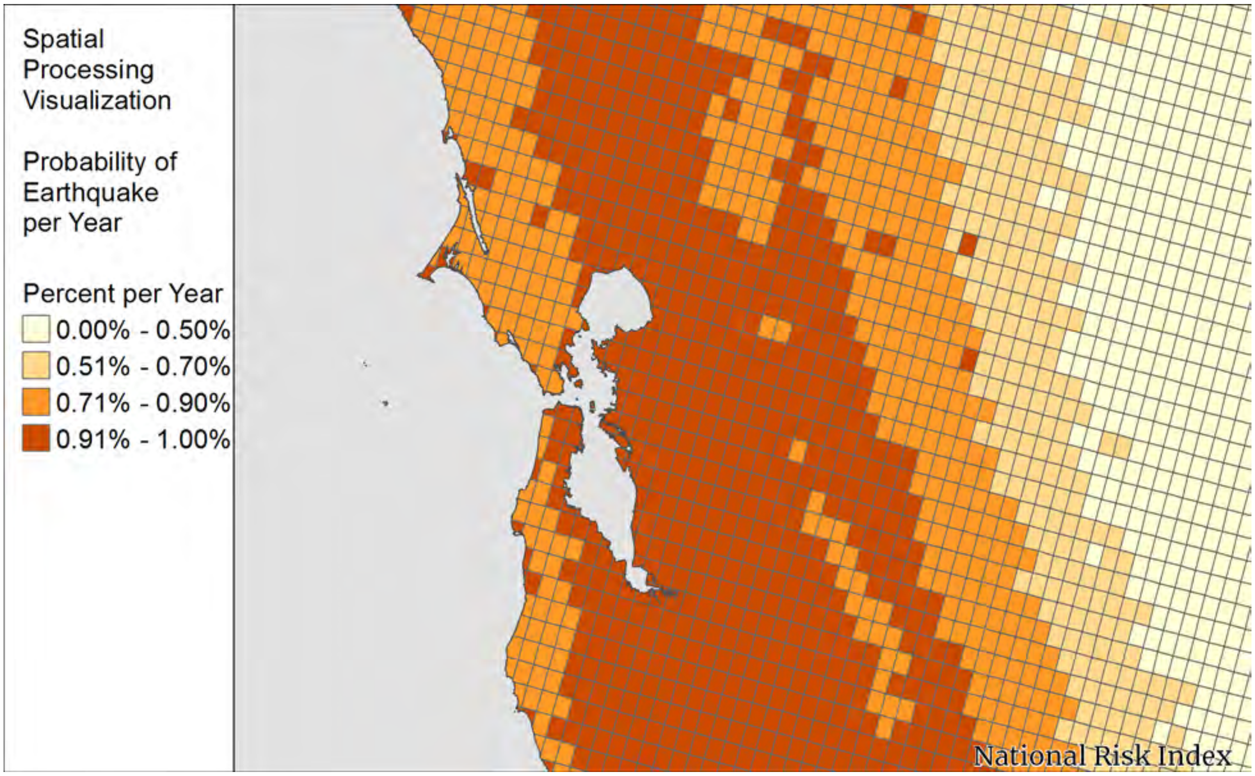

Figure 47: Map of Earthquake Fishnet

10.3 Determination of Possibility of Hazard Occurrence

In the P-366 data, every county has some degree of Earthquake risk; therefore, all counties were deemed possible for Earthquake occurrence.

10.4 Exposure

Like the other exposure values produced by the NRI, Hazus bases its exposure values on the Hazus 4.2 SP1 building values and population data. Exposure values are extracted from the P-366 study data at the Census tract and county levels.

A small subset of exposure values from P-366 exceed the Hazus-recorded building values or populations for the Census tract or county. These values were left as is rather than being lowered to the Hazus values.

10.5 Frequency

The frequency value represents the area-weighted probability of an Earthquake occurrence (at least minor-damage shaking) impacting a location in a given year. The annualized frequency is calculated at the Census block level.

Earthquake-probability fishnet polygons are intersected with the Census block polygons within the NRI processing database. The resulting table contains the fishnet polygon's unique identifier, Census block number, and the intersected area in square kilometers (see *Table 25*).

Table 25: Sample Data from the Earthquake Fishnet Census Block Intersection Table

EarthquakeFishnetID	CensusBlock	IntersectedAreaKm2
422655	1.92E+14	0.003866
422655	1.92E+14	0.010595
422655	1.92E+14	0.019825

This intersection between Earthquake-probability fishnet polygons and Census block polygons is used to calculate frequency at the Census block level as in *Equation 43*.

Equation 43: Census Block Area-Weighted Fishnet Earthquake Frequency

$$Freq_{ERQK_{CB}} = \frac{\sum_{Fish}^{CB}\left(IntsctArea_{ERQK_{Fish_{CB}}} \times Prob_{ERQK_{Fish_{CB}}}\right)}{Area_{CB}}$$

where:

$Freq_{ERQK_{CB}}$ is the annualized area-weighted frequency of Earthquake determined for a specific Census block (probability per year).

$IntsctArea_{ERQK_{Fish_{CB}}}$ is the intersected area of the Earthquake probability fishnet grid cell where the Earthquake probability was greater than 0 with the Census block (in square kilometers).

$Prob_{ERQK_{Fish_{CB}}}$ is the probability of Earthquake occurrence for the intersecting fishnet grid cell.

$\sum_{Fish}^{CB}$ is the sum for all fishnet grid cells that intersect the Census block.

$Area_{CB}$ is the total area of the Census block (in square kilometers).

10.5.1 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level as aggregates of the Census block values. These values are surrogates as the final EAL values are extracted from the P-366 study, and it was not possible to derive an equivalent frequency component from the P-366 data. The frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 44*.

Equation 44: Census Tract and County Area-Weighted Earthquake Frequency Aggregation

$$Freq_{ERQK_{CT}} = \frac{\sum_{CB}^{CT}\left(Freq_{ERQK_{CB}} \times Area_{CB}\right)}{Area_{CT}}$$

$$Freq_{ERQK_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{ERQK_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{ERQK_{CT}}$	is the annualized area-weighted Earthquake frequency calculated for a specific Census tract (probability per year).
$Freq_{ERQK_{CB}}$	is the annualized Earthquake frequency associated with a specific Census block (probability per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{ERQK_{Co}}$	is the annualized area-weighted Earthquake frequency calculated for a specific county (probability per year).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 48 displays annualized Earthquake frequency at the county level.

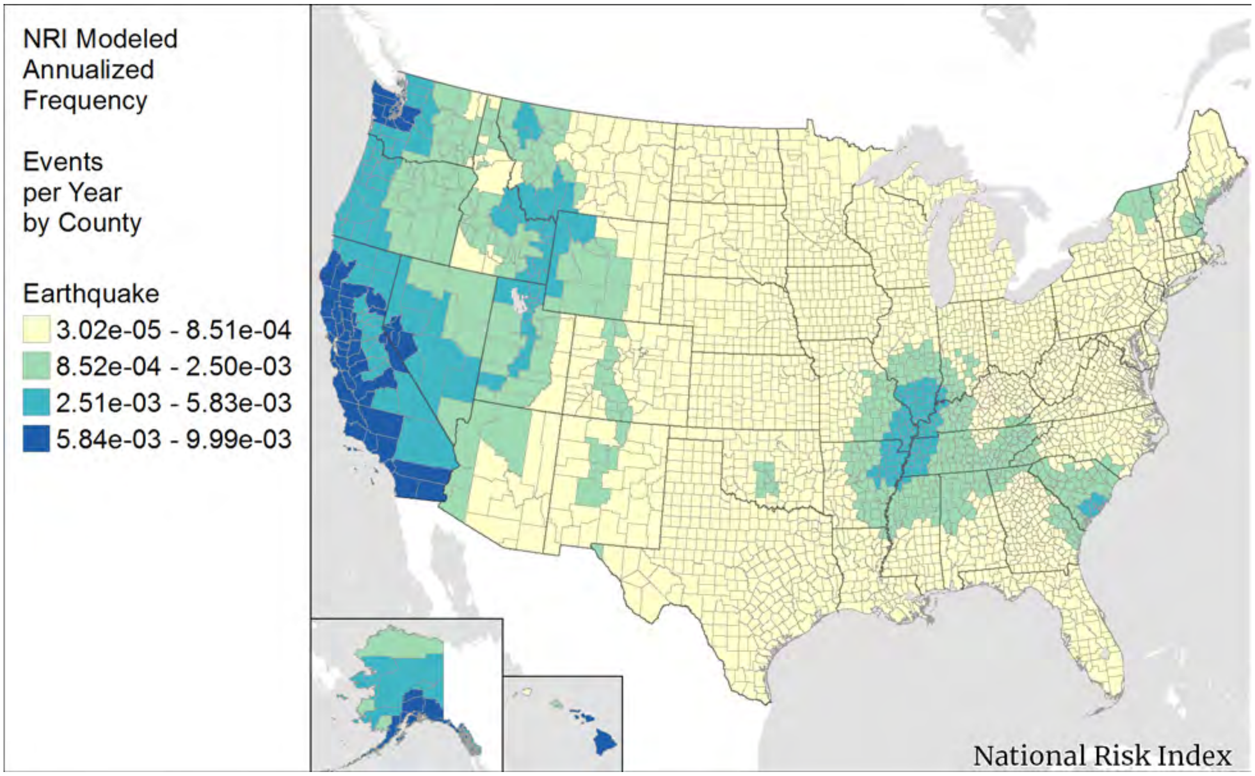

Figure 48: Annualized Earthquake Frequency by County

10.6 Historic Loss Ratio

The Earthquake HLR is the representative percentage of a location's hazard exposure area that experiences loss due to an Earthquake event, or the average rate of loss associated with the occurrence of an Earthquake event. HLR values displayed in the NRI are surrogate values as the final EAL values at the Census tract and county level are extracted from the P-366 study. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Earthquake hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1960 to 2016 are included in the HLR calculation. Two peril types are mapped to the hazard Earthquake (see *Table 26*). These are expanded on an event basis based on the number of records from SHELDUS[38] (see *Section 5.4.1*).

[38] For Earthquake loss information, SHELDUS compiles data from the Global Significant Earthquake Database produced by NOAA's National Centers for Environmental Information and Stover, Carl W. and Jerry L. Coffman, 1993. Seismicity of the United States, 1568-1989 (revised). US Geological Survey Professional Paper 1527, Washington, D.C.: US Government Printing Office, p. 418.

Table 26: Earthquake Peril Types and Recorded Events from 1960-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Earthquake	206	208
LandslideFollowingEQ	1	2

The HLR exposure value used in the LRB calculation represents the dollar value of the total building value or the entire population of a county as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event and each consequence type (building and population) is calculated using *Equation 45*.

Equation 45: Loss Ratio per Basis Calculation for a Single Earthquake Event

$$LRB_{ERQK\,Co_{CnsqType}} = \frac{Loss_{ERQK\,Co_{CnsqType}}}{HLRExposure_{Co_{CnsqType}}}$$

where:

$LRB_{ERQK\,Co_{CnsqType}}$ is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Earthquake event. Calculation is performed for each consequence type (building and population).

$Loss_{ERQK\,Co_{CnsqType}}$ is the loss (by consequence type) experienced from the Earthquake event documented to have occurred in the county (in dollars).

$HLRExposure_{Co_{CnsqType}}$ is the total value (by consequence type) of the county estimated to have been exposed to the Earthquake event (in dollars).

A Historic Event Count is not computed for Earthquake, so no zero-loss events are inserted into the Loss Ratio table. After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and national.

Figure 49 and *Figure 51* display the largest weighting factor contributor in the Bayesian credibility calculations for the Earthquake HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Earthquake events within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from national-level loss data. *Figure 50* and *Figure 52* represent the final county-level HLR values for Earthquake.

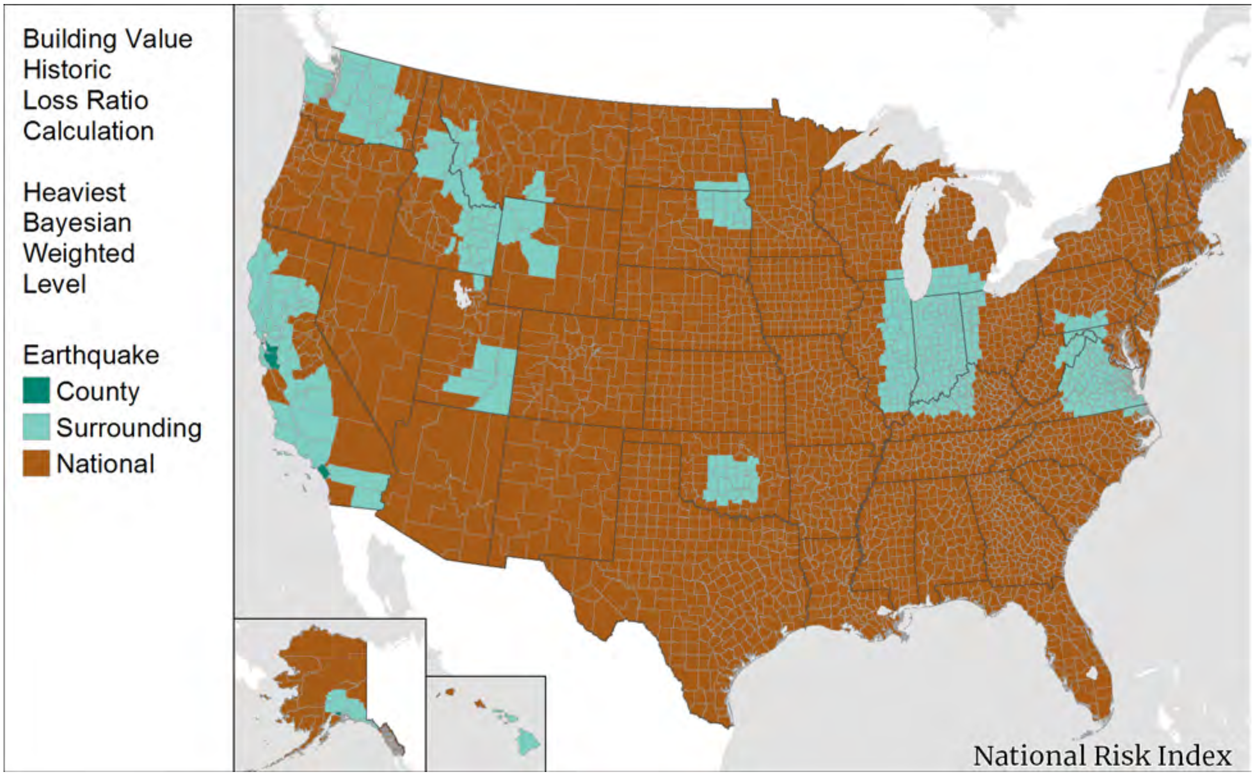

Figure 49: Earthquake Heaviest Bayesian Weighted Level – Building Value

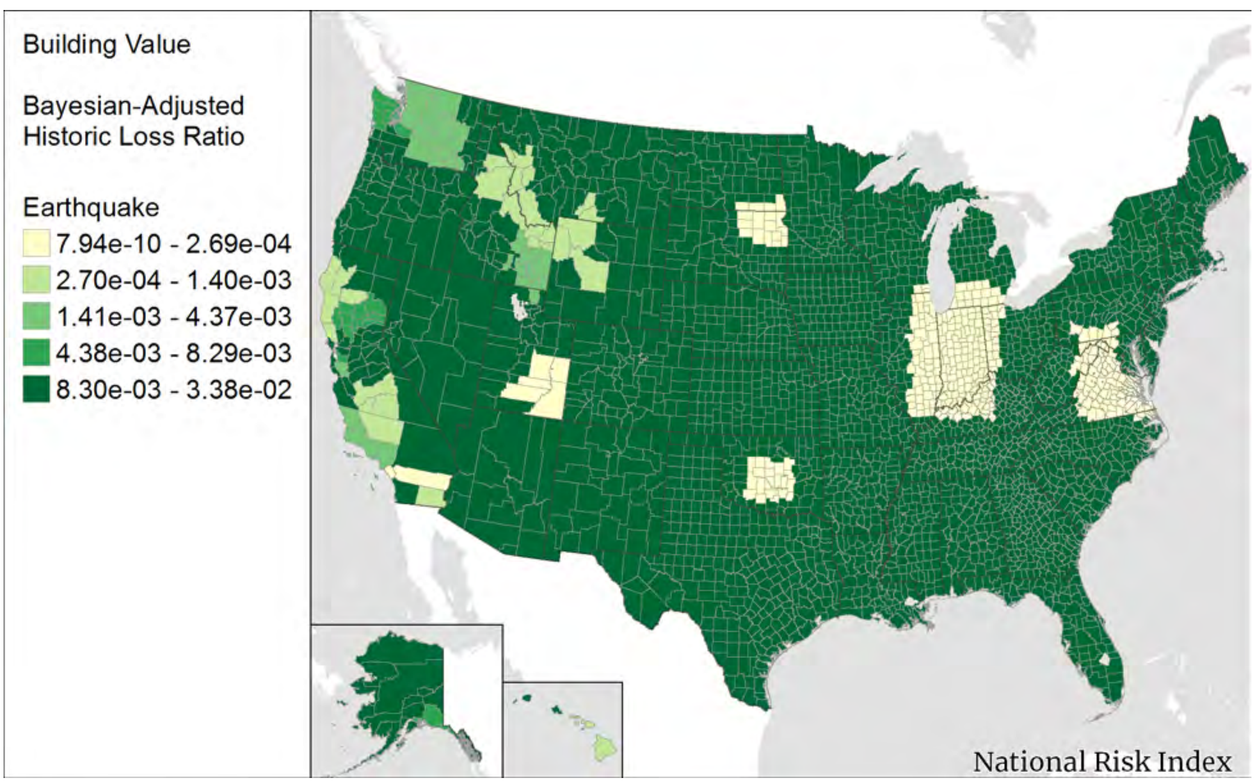

Figure 50: Earthquake HLR – Building Value

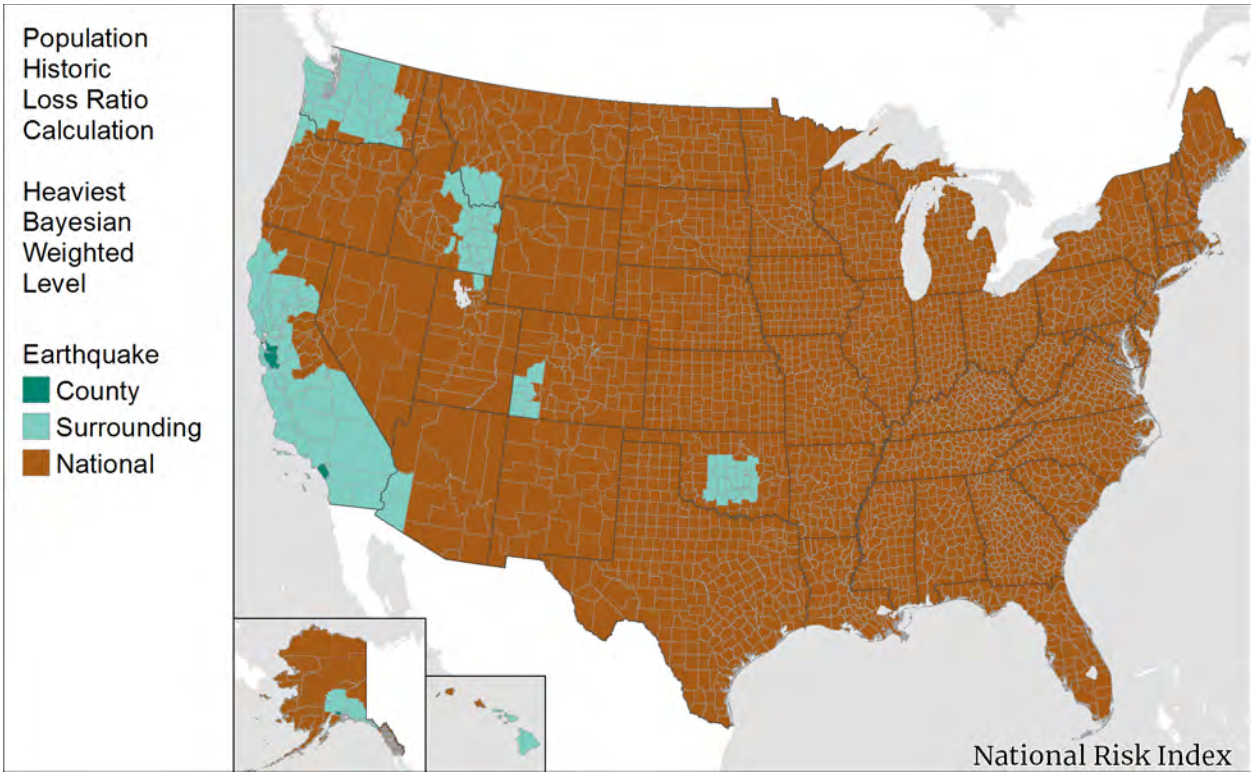

Figure 51: Earthquake Heaviest Bayesian Weighted Level – Population

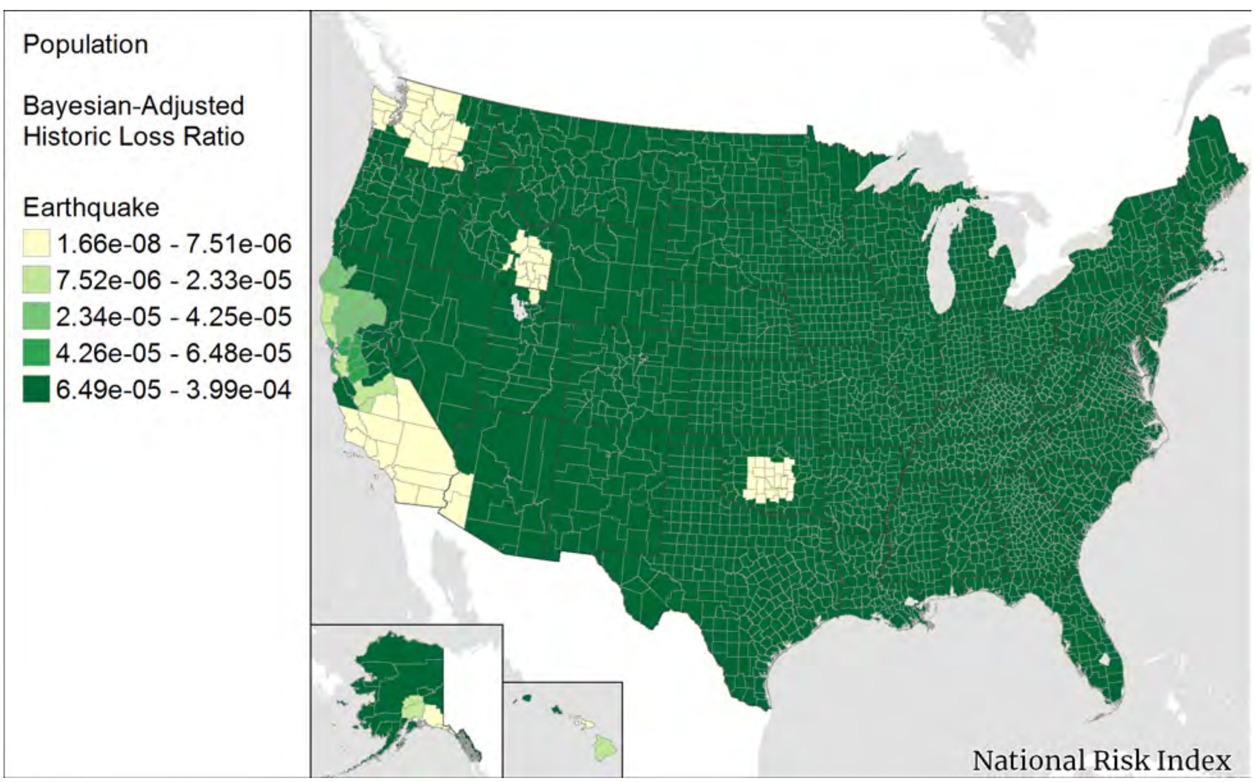

Figure 52: Earthquake HLR – Population

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census tracts within the county.

10.7 Expected Annual Loss

EAL values are extracted from the P-366 study data at the Census tract and county levels. Exposure, frequency, and HLR are provided at the Census tract and county level as surrogate values but are not used to compute the EAL values.

The P-366 data compute the Annualized Earthquake Loss (AEL), the estimated long-term value of earthquake losses to the general building stock in any single year in a specified geographic area, as well as an annualized population loss value. The AEL is computed by multiplying losses from eight potential ground motions by their respective annual frequencies of occurrence and summing the values. The population loss estimation is based on the correlation between building damage and the number and severity of casualties. The summed P-366 loss values are used as the total EAL at the Census tract and county level as in *Equation 46*.

Equation 46: Census Tract and County Expected Annual Loss to Earthquake

$$EAL_{ERQK_{CT}} = AEL_{CT} + (PopLoss_{CT} \times VSL)$$

$$EAL_{ERQK_{Co}} = AEL_{Co} + (PopLoss_{Co} \times VSL)$$

where:

$EAL_{ERQK_{CT}}$	is the total Expected Annual Loss due to Earthquake events for a specific Census tract (in dollars).
AEL_{CT}	is the annual Earthquake loss to buildings for a specific Census tract by the P-366 study (in dollars).
$PopLoss_{CT}$	is the population loss estimation for a specific Census tract by the P-366 study (in people).
VSL	is the Value of Statistical Life ($7.4M per person).
$EAL_{ERQK_{Co}}$	is the total Expected Annual Loss due to Earthquake events for a specific county (in dollars).
AEL_{Co}	is the annual Earthquake loss to buildings for a specific county by the P-366 study (in dollars).
$PopLoss_{Co}$	is the population loss estimation for a specific county by the P-366 study (in people).

Figure 53 shows the total EAL (building value and population combined) to Earthquake events.

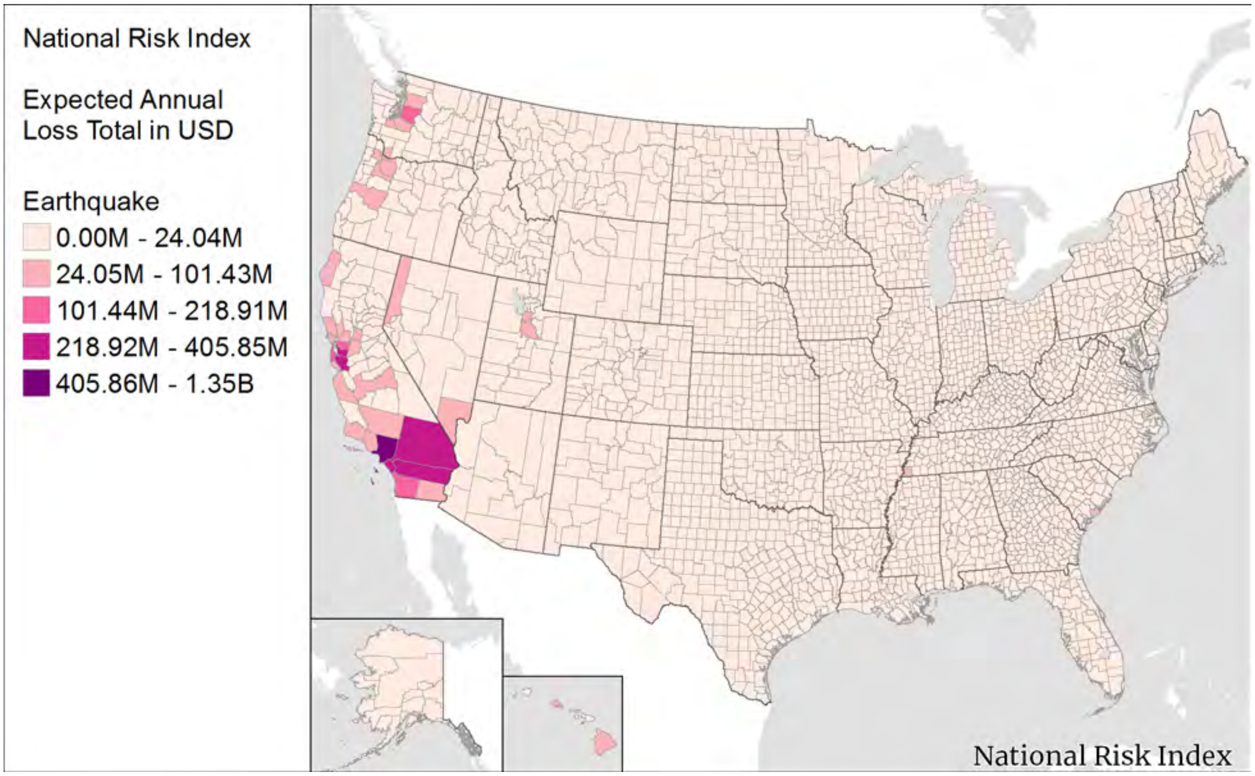

Figure 53: Total Expected Annual Loss by County to Earthquake

With the Earthquake total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Earthquake Risk Index score.

11 Hail

Hail is a form of precipitation that occurs during thunderstorms when raindrops, in extremely cold areas of the atmosphere, freeze into balls of ice before falling towards the earth's surface.

11.1 Spatial Source Data

Historical Event Source: *National Weather Service, Storm Prediction Center, Severe Weather Database Files*[39]

The Storm Prediction Center compiles all records of Hail events from the NWS's monthly Storm Data publication and makes them available in CSV format on the Warning Coordination Meteorologist's (WCM) website. These files record spatiotemporal information (start and end coordinates, date, time) as well as economic loss and hail size in inches (see *Table 27* and *Figure 54*).

Table 27: Sample Hail Data from the Storm Prediction Center (SPC)

Om (Hail ID)	Date	St (state)	Mag (Hail Size in inches)	Inj (Injuries)	Fat (Fatalities)	Loss (Property Loss in $)	Closs (Crop Loss in $)	Slon (Start Longitude)	Slat (Start Latitude)
4095	5/23/2010 11:20:00 PM	AK	0.75	0	0	0	0	-150.22	65
317151	7/19/2011 2:50:00 PM	OR	1.00	1	0	0	0	45.3	-118.14
2016-06082	6/22/2016 2:19:00 AM	ND	1.75	0	0	25000	50000	-104.04	47.94

[39] National Weather Service, Storm Prediction Center. (2017). Severe Weather Database files, Hail, 1955-2017 [online dataset]. Retrieved from http://www.spc.noaa.gov/wcm/.

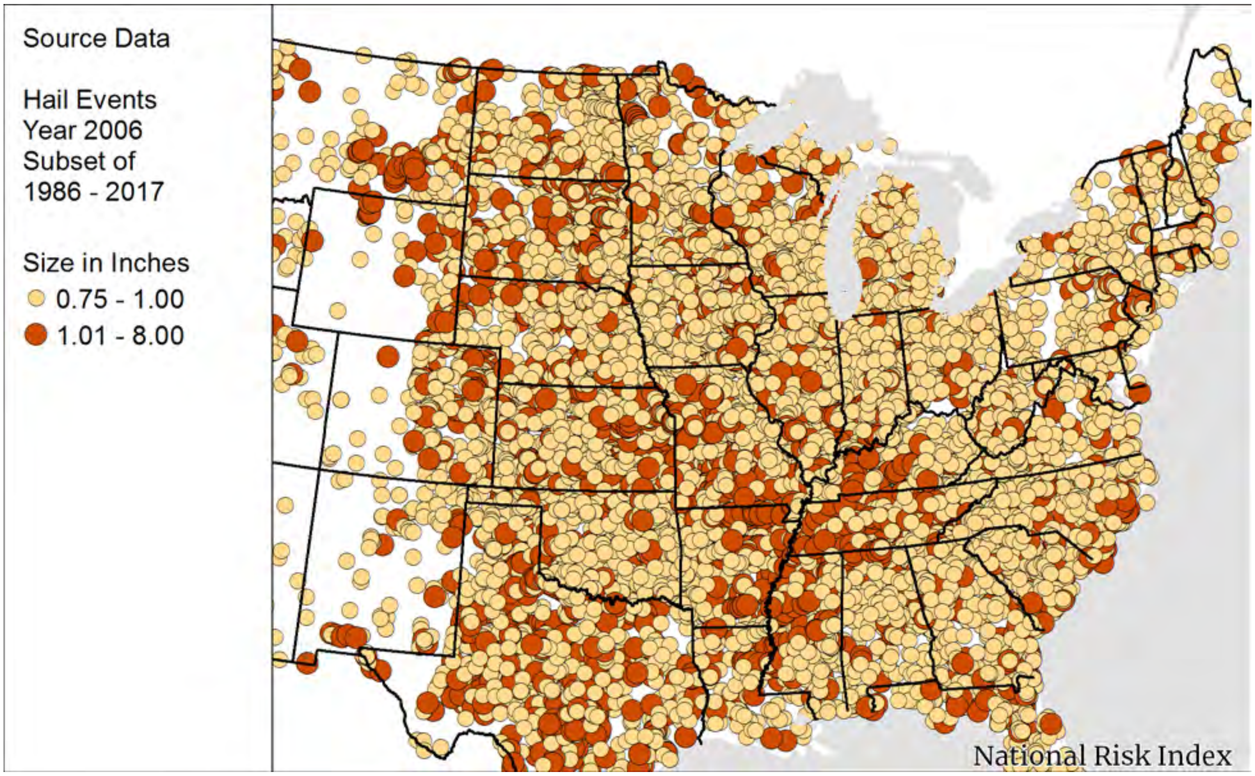

Figure 54: Map of Hail Source Data Points

11.1.1 PERIOD OF RECORD

To use only the most accurate data, Hail data between 1/1/1986 and 12/31/2017 are analyzed, so the period of record for which Hail data are utilized is 32 years.

11.2 Spatial Processing

The source data include fields for two sets of coordinates: a start and an end. This is mainly because the data share their format with the data for tornadoes. Most Hail events only have start coordinates (or the end coordinates match the start coordinates), so the points are projected from these coordinates. Any events outside of the period of record are filtered out. Additionally, smaller Hail size events were filtered out. Due to changes in NWS standards for reportable Hail, events before 2010 are required to meet a Hail size threshold of 0.75-in, and those after 2010 must meet a 1.0-in size threshold. Anything below the threshold is not used in the analysis of Hail EAL. An 80-km buffer was created from the remaining points and, because multiple records were often recorded for a single date, the buffer polygons were dissolved on date to produce a layer of Hail event-day polygons. The Hail event-day polygons can then be used to estimate frequency at the Census block level.

The buffer is not an attempt to represent the area of impact by a Hail event, but rather an effort to estimate the area where Hail may have been present. Hail reporting can be influenced by urban bias, meaning that a Hail event in a populated area is more likely to be reported than if the same event had occurred in a rural area. Additionally, the position of the Hail event reported in the source data is not guaranteed to be the actual location of the occurrence but may be the location of a nearby weather station or reporting center. The use of the 80-km buffering allows the reported location to be spread across a broader area (see *Figure 55*).

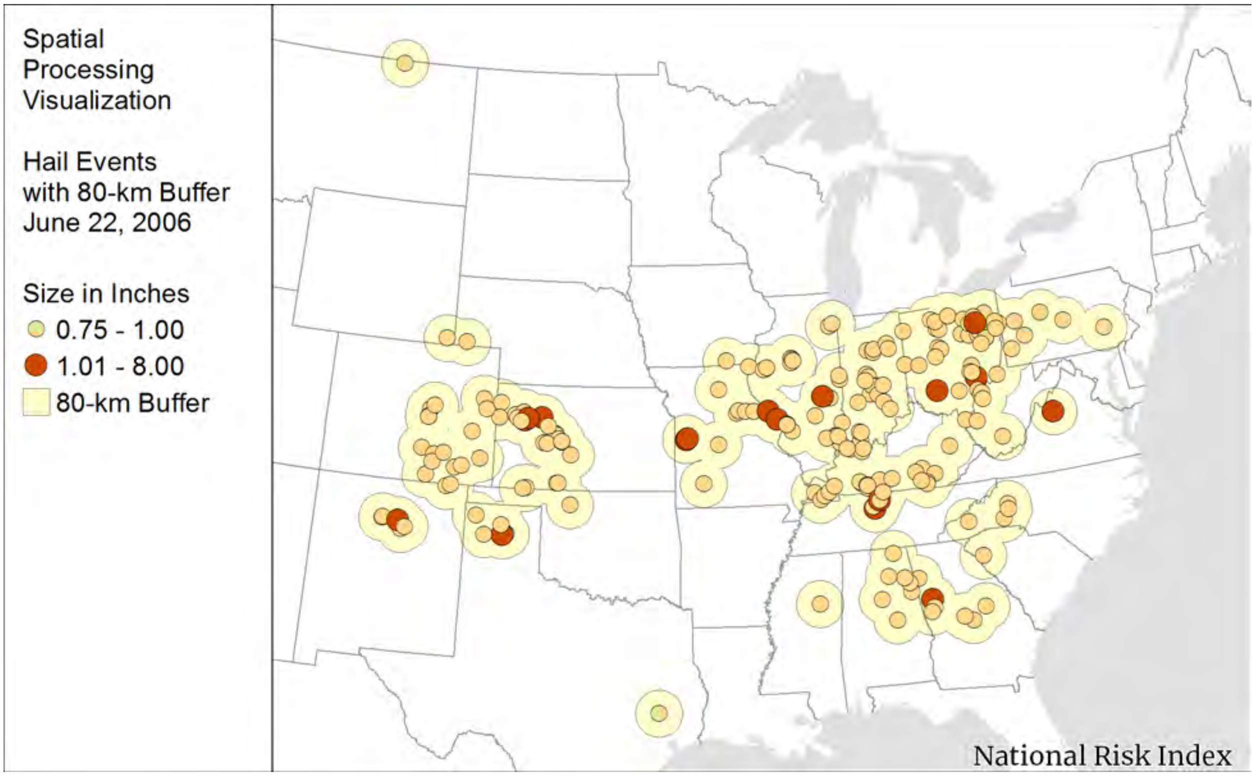

Figure 55: Map of Buffered Hail Points

11.3 Determination of Possibility of Hazard Occurrence

Hail can occur almost anywhere under the right conditions, so all counties were deemed possible for Hail occurrence.

11.4 Exposure

Because Hail can occur anywhere, the entire building, population, and agricultural value of a Census block, Census tract, and county are considered exposed to Hail.

11.5 Historic Event-Day Count

The count of historic Hail event-days is computed as the number of distinct Hail event-day polygons that intersect a 49-by-49-km fishnet grid cell that encompasses the Census block, or, if the Census block intersects multiple fishnet grid cells, an area-weighted count of the cells that intersect the Census block (see *Appendix D – Fishnet Event Count*). This count is used to compute Hail event-day frequency.

Historic Event-Day Counts are also supplied at the Census tract and county levels as the area-weighted number of Hail event-days that intersect the Census tract and county, respectively.

11.6 Frequency

The number of recorded Hail event-days each year over the period of record (32 years) is used to estimate the frequency of Hail event-days in an area. This annualized frequency is calculated at the Census block level, and the Census block-level value is used in the EAL calculations.

Frequency calculations use the Hail event-day polygons created from the source data (as described in *Section 11.2*), as well as their corresponding computed duration days from the pre-processing of the data. The footprint polygons are intersected with a 49-by-49-km fishnet grid. The sum of Hail event-days for the polygons intersecting each grid cell is recorded, and the Census block inherits this aggregated event-day count from the grid cell that encompasses it. If the Census block intersects multiple fishnet grid cells, an area-weighted average count is calculated (see *Appendix D – Fishnet Event Count*). The Hail event-day count is then divided by the period of record as in *Equation 47*.

Equation 47: Census Block Hail Frequency

$$Freq_{HAIL_{CB}} = \frac{EventDayCount_{HAIL_{CB}}}{PeriodRecord_{HAIL}}$$

where:

$Freq_{HAIL_{CB}}$	is the annualized frequency of Hail event-days determined for a specific Census block (event-days per year).
$EventDayCount_{HAIL_{CB}}$	is the number of Hail event-days calculated for the Census block.
$PeriodRecord_{HAIL}$	is the period of record for Hail (32 years).

11.6.1 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level. These values may not exactly match that of dividing the number of recorded Hail event-days at the Census tract and county level by the period of record, as the event count for frequency is a fishnet area-weighted event count including Hail events that may have impacted the surrounding area but not the county or Census tract itself. The frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 48*.

Equation 48: Census Tract and County Area-Weighted Hail Frequency Aggregation

$$Freq_{HAIL_{CT}} = \frac{\sum_{CB}^{CT}(Freq_{HAIL_{CB}} \times Area_{CB})}{Area_{CT}}$$

$$Freq_{HAIL_{Co}} = \frac{\sum_{CB}^{Co}(Freq_{HAIL_{CB}} \times Area_{CB})}{Area_{Co}}$$

where:

$Freq_{HAIL_{CT}}$	is the annualized area-weighted Hail frequency calculated for a specific Census tract (event-days per year).
$Freq_{HAIL_{CB}}$	is the annualized Hail frequency calculated for a specific Census block (event-days per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{HAIL_{Co}}$	is the annualized area-weighted Hail frequency calculated for a specific county (event-days per year).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 56 displays annualized Hail frequency at the county level.

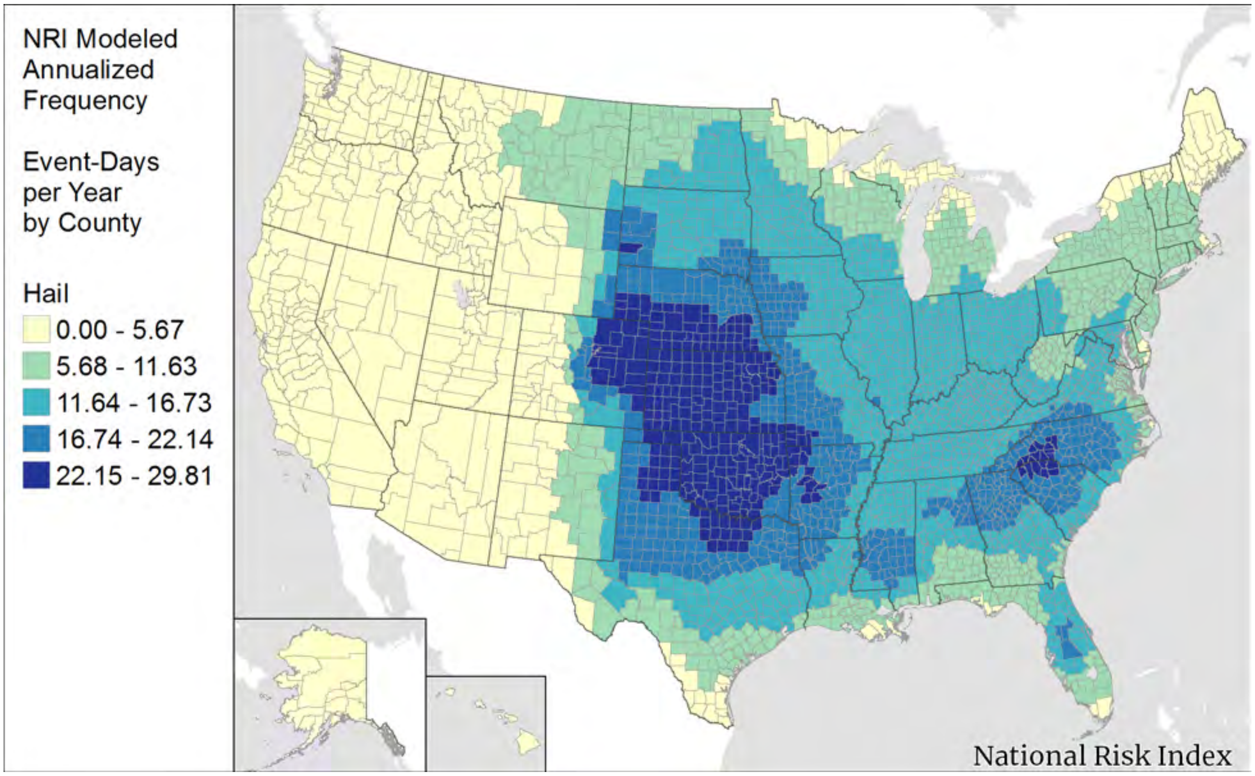

Figure 56: Annualized Hail Frequency by County

11.7 Historic Loss Ratio

The Hail HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Hail event-day, or the average rate of loss associated with the occurrence of a Hail event-day. For a detailed description of the HLR calculation process, see *Section 5.4.* The HLR parameters described below are specific to the Hail hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. One peril type is mapped to the hazard Hail (see *Table 28*). These are expanded on an event-day basis based on the number of event duration days from SHELDUS[40] (see *Section 5.4.1*).

Table 28: Hail Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Hail	16,149	16,227

The HLR exposure value used in the LRB calculation is a county-level value that represents the dollar value of the total building value or the entire population of a county as recorded in Hazus 4.2 SP1, or

[40] For Hail loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

the total crop and livestock value of the county as estimated in the USDA 2017 Census of Agriculture data. The LRB for each SHELDUS-documented event-day and each consequence type (building, population, and agriculture) is calculated using *Equation 49*.

Equation 49: Loss Ratio per Basis Calculation for a Single Hail Event-Day

$$LRB_{HAIL_{Co_{CnsqType}}} = \frac{Loss_{HAIL_{Co_{CnsqType}}}}{HLRExposure_{Co_{CnsqType}}}$$

where:

$LRB_{HAIL_{Co_{CnsqType}}}$	is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Hail event-day. Calculation is performed for each consequence type (building, population, and agriculture).
$Loss_{HAIL_{Co_{CnsqType}}}$	is the loss (by consequence type) experienced from the Hail event-day documented to have occurred in the county (in dollars).
$HLRExposure_{Co_{CnsqType}}$	is the total value (by consequence type) of the county estimated to have been exposed to the Hail event-day (in dollars).

Hail event-days can occur with a high frequency in areas, but often result in no recorded loss to buildings, population, or agriculture. SHELDUS does not record events in which no loss occurred, so a number of zero-loss event-days are inserted into the data to align the event count in the HLR calculation to the historic event count experienced within the SHELDUS period of record (1995 to 2016). For Hail, a historic year-month event count is extracted using an intersection between the Hail event-day polygons and the Census blocks. The observation date of each Hail event-day polygon is used to sync the event to its year-month. A list of distinct Hail observation dates is compiled for the event-day polygon-Census block intersections that intersect the county, and the historic year-month event count is the number of distinct Hail observation dates in this list.

If the number of Hail event-day records from SHELDUS is less than the summed historic year-month event-day counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, regional, and national. The regional definition for Hail is derived from the FEMA regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 57, *Figure 59*, and *Figure 61* display the largest weighting factor contributor in the Bayesian credibility calculations for the Hail HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Hail event-days within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local, regional, or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing event-days or have widely varying loss ratios get the most influence from regional or national-level loss data. *Figure 58*, *Figure 60*, and *Figure 62* represent the final county-level HLR values for Hail.

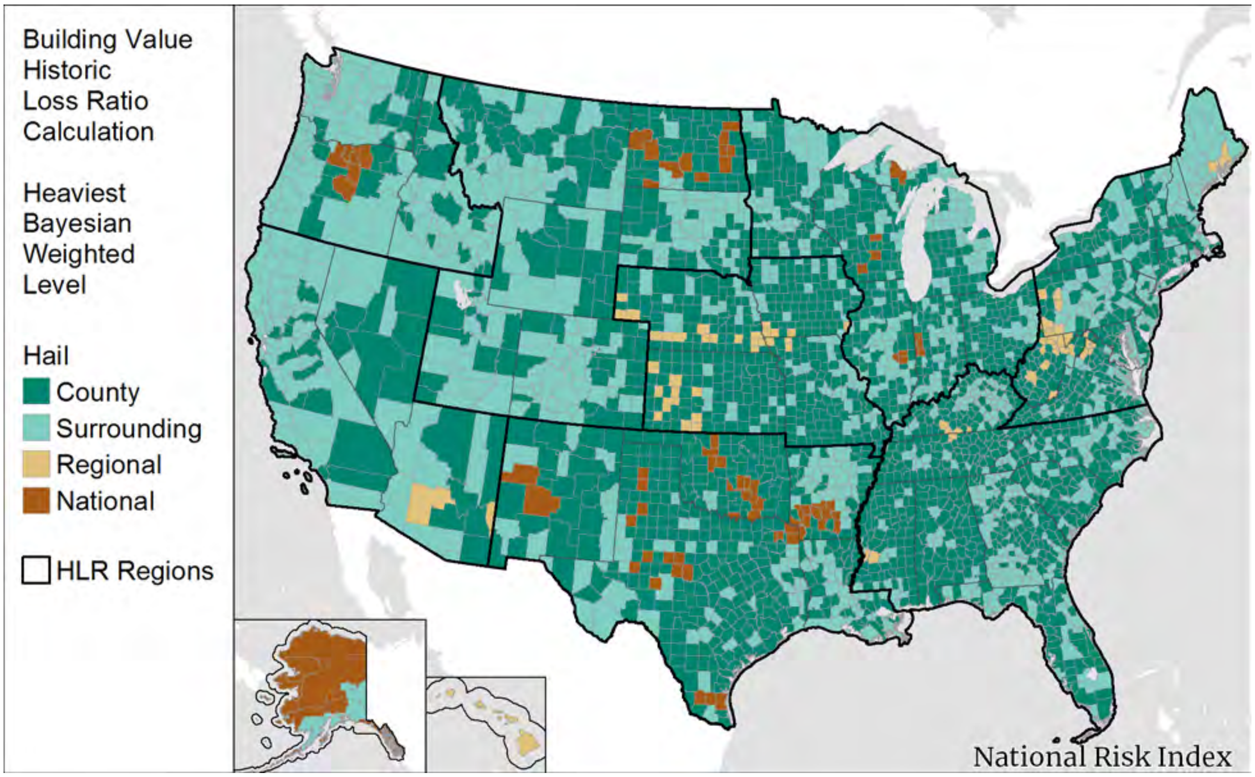

Figure 57: Hail Heaviest Bayesian Weighted Level – Building Value

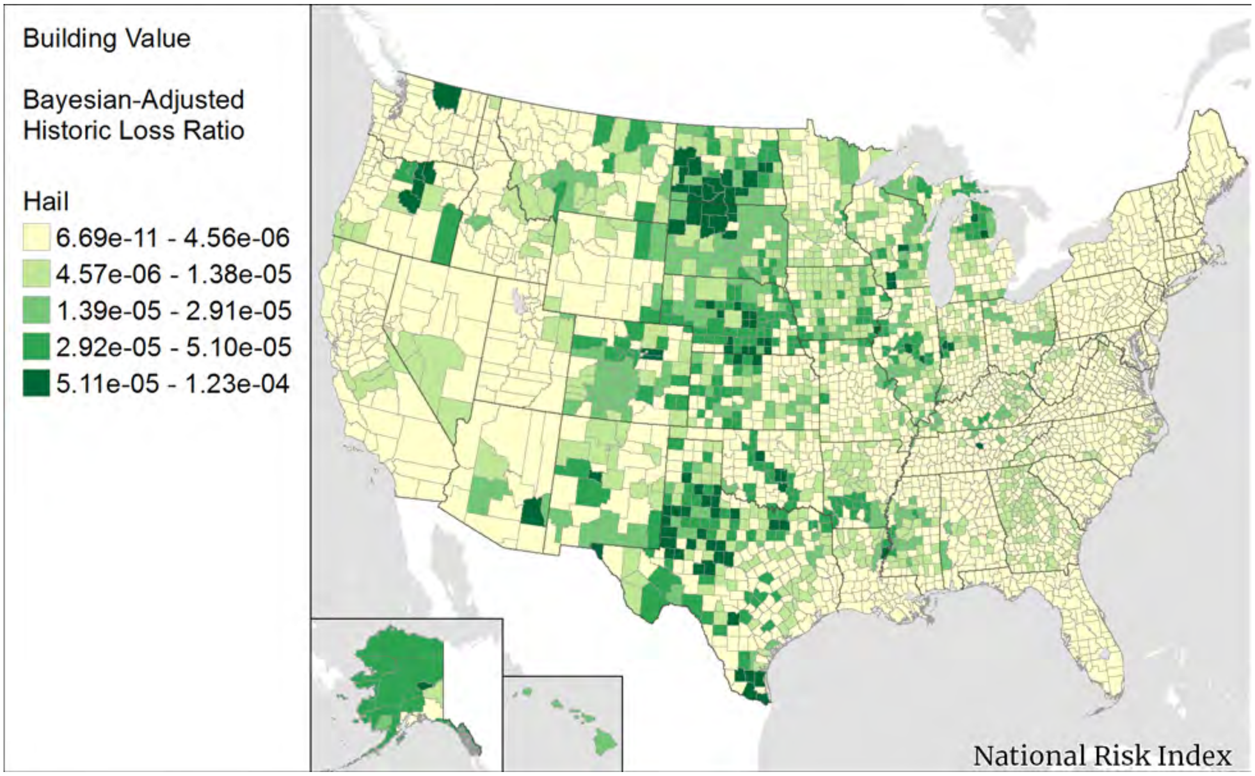

Figure 58: Hail HLR – Building Value

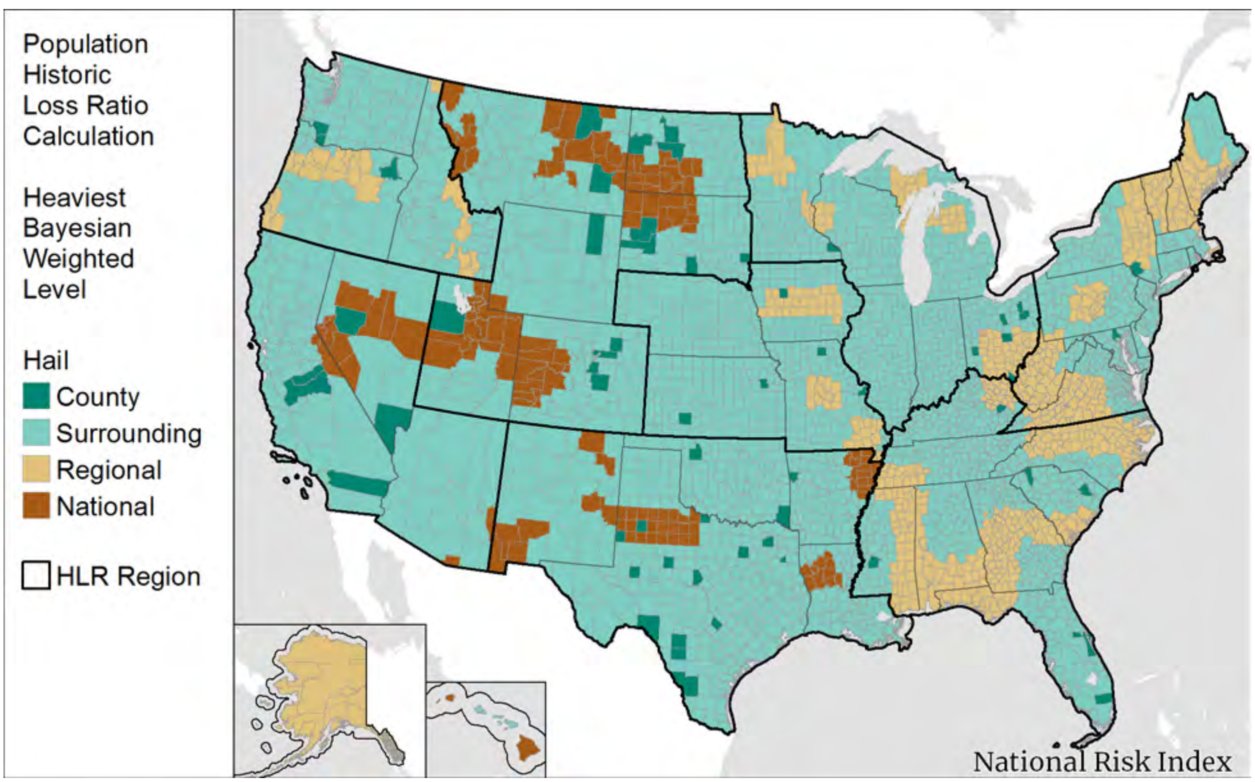

Figure 59: Hail Heaviest Bayesian Weighted Level -- Population

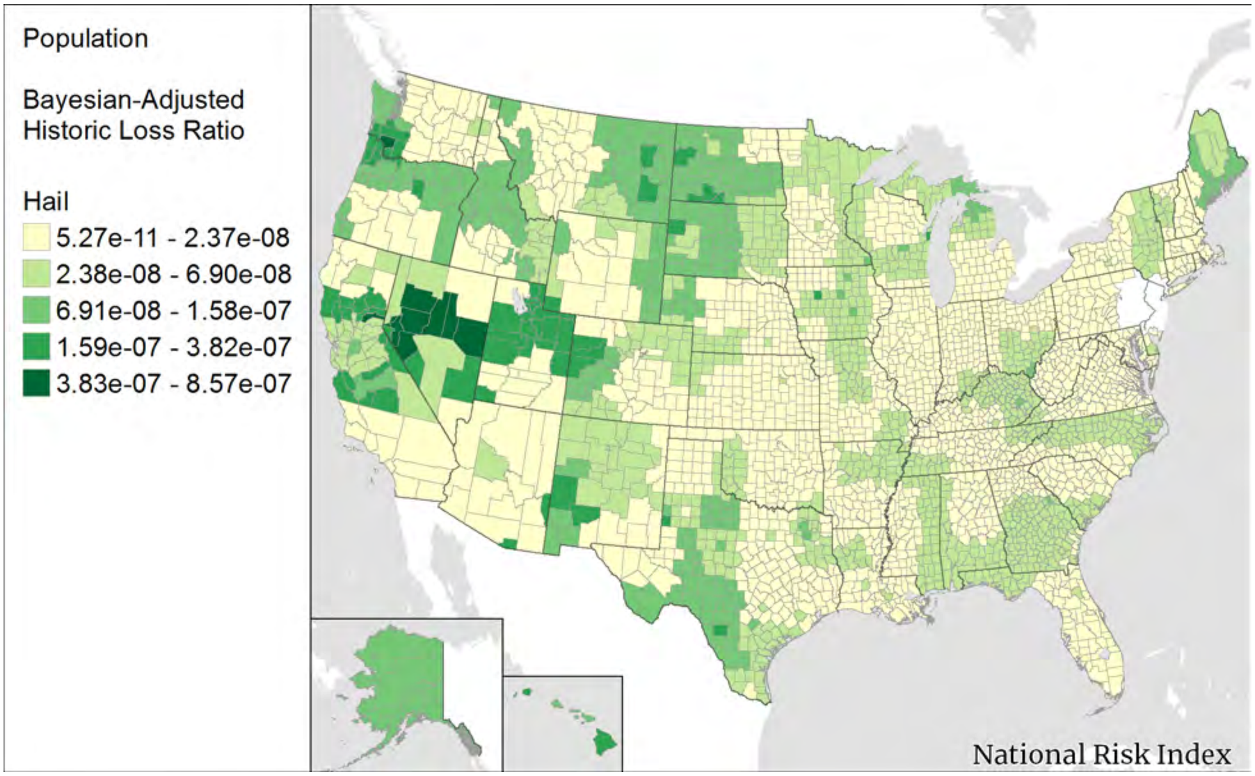

Figure 60: Hail HLR -- Population

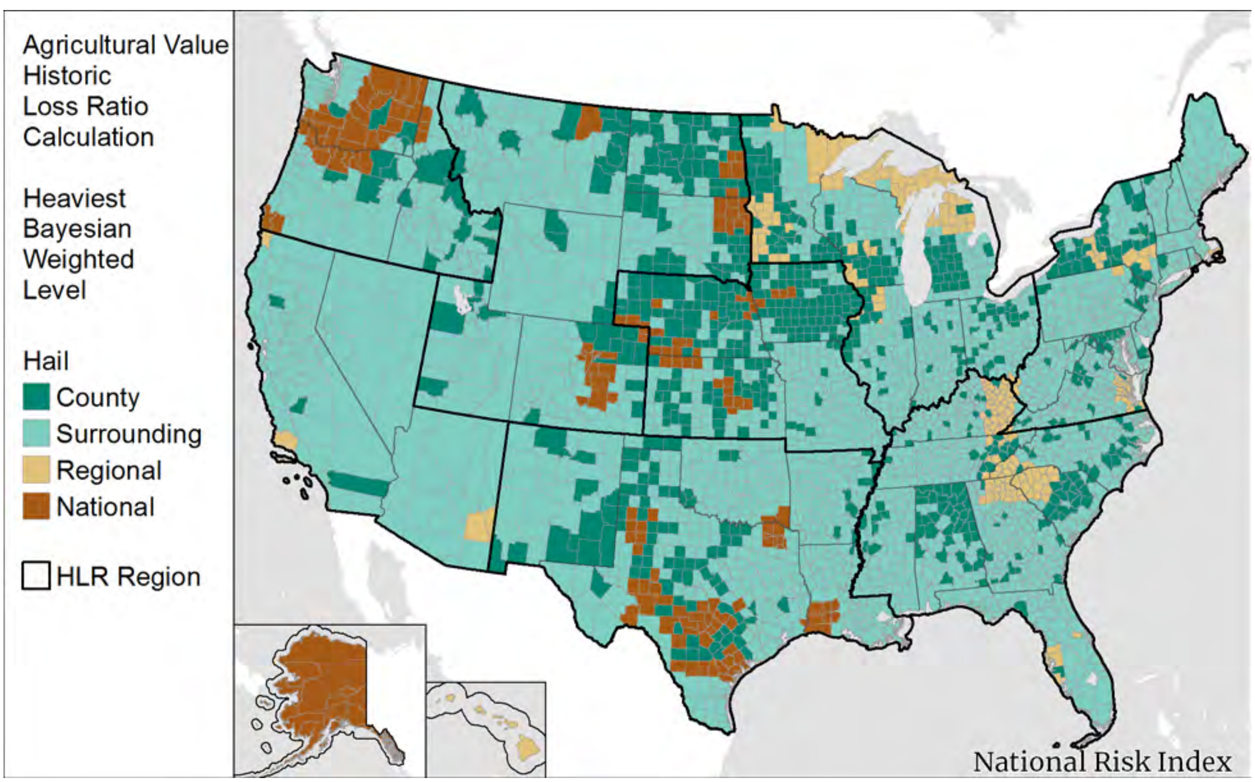

Figure 61: Hail Heaviest Bayesian Weighed Level – Agriculture Value

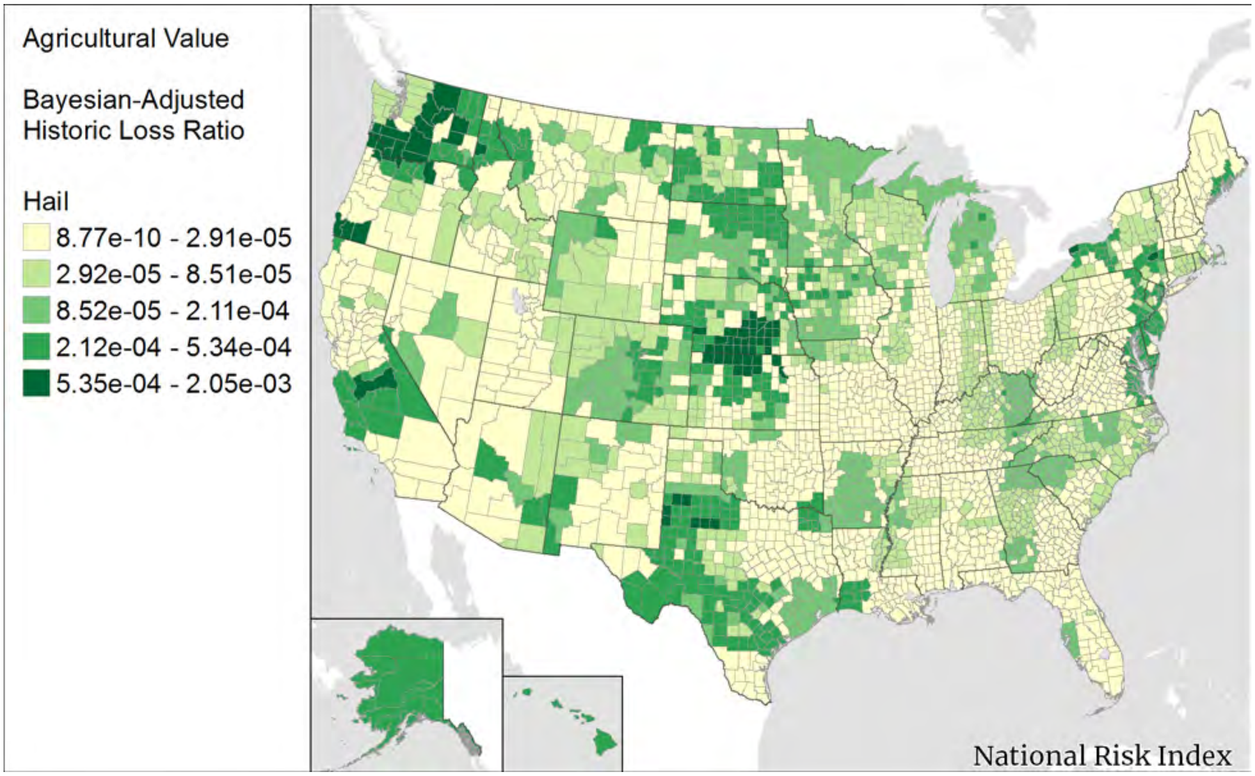

Figure 62: Hail HLR – Agriculture Value

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

11.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level (see *Equation 50*). Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 50: Census Block Expected Annual Loss to Hail

$$EAL_{HAIL_{CB_{Bldg}}} = Exposure_{HAIL_{CB_{Bldg}}} \times Freq_{HAIL_{CB}} \times HLR_{HAIL_{CB_{Bldg}}}$$

$$EAL_{HAIL_{CB_{Pop}}} = Exposure_{HAIL_{CB_{Pop}}} \times Freq_{HAIL_{CB}} \times HLR_{HAIL_{CB_{Pop}}}$$

$$EAL_{HAIL_{CB_{Ag}}} = Exposure_{HAIL_{CB_{Ag}}} \times Freq_{HAIL_{CB}} \times HLR_{HAIL_{CB_{Ag}}}$$

where:

$EAL_{HAIL_{CB_{Bldg}}}$ is the Expected Annual Loss to building value due to Hail events for a specific Census block (in dollars).

$Exposure_{HAIL_{CB_{Bldg}}}$ is the building value exposed to Hail events in the Census block (in dollars).

$Freq_{HAIL_{CB}}$ is the annualized Hail frequency calculated for the Census block (event-days per year).

$HLR_{HAIL_{CB_{Bldg}}}$ is the Bayesian-adjusted building Historic Loss Ratio for Hail for the Census block.

$EAL_{HAIL_{CB_{Pop}}}$ is the Expected Annual Loss to population value due to Hail events for a specific Census block (in dollars).

$Exposure_{HAIL_{CB_{Pop}}}$ is the population value exposed to Hail events in the Census block (in dollars).

$HLR_{HAIL_{CB_{Pop}}}$ is the Bayesian-adjusted population Historic Loss Ratio for Hail for the Census block.

$EAL_{HAIL_{CB_{Ag}}}$ is the Expected Annual Loss to agriculture value due to Hail events for a specific Census block (in dollars).

$Exposure_{HAIL_{CB_{Ag}}}$ is the agriculture value exposed to Hail events in the Census block (in dollars).

$HLR_{HAIL_{CB_{Ag}}}$ is the Bayesian-adjusted agricultural Historic Loss Ratio for Hail for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building, population, and agriculture loss at the Census block level as in *Equation 51*.

Equation 51: Census Tract and County Expected Annual Loss to Hail

$$EAL_{HAIL_{CT}} = \sum_{CB}^{CT} EAL_{HAIL_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{HAIL_{CB_{Pop}}} + \sum_{CB}^{CT} EAL_{HAIL_{CB_{Ag}}}$$

$$EAL_{HAIL_{Co}} = \sum_{CB}^{Co} EAL_{HAIL_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{HAIL_{CB_{Pop}}} + \sum_{CB}^{Co} EAL_{HAIL_{CB_{Ag}}}$$

where:

$EAL_{HAIL_{CT}}$ is the total Expected Annual Loss due to Hail events for a specific Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{HAIL_{CB_{Bldg}}}$ is the summed Expected Annual Loss to building value due to Hail events for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{HAIL_{CB_{Pop}}}$ is the summed Expected Annual Loss to population value due to Hail events for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{HAIL_{CB_{Ag}}}$	is the summed Expected Annual Loss to agriculture value due to Hail events for all Census blocks in the Census tract (in dollars).
$EAL_{HAIL_{Co}}$	is the total Expected Annual Loss due to Hail events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{HAIL_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Hail events for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{HAIL_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Hail events for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{HAIL_{CB_{Ag}}}$	is the summed Expected Annual Loss to agriculture value due to Hail events for all Census blocks in the county (in dollars).

Figure 63 shows the total EAL (building value, population, and agriculture value combined) to Hail events.

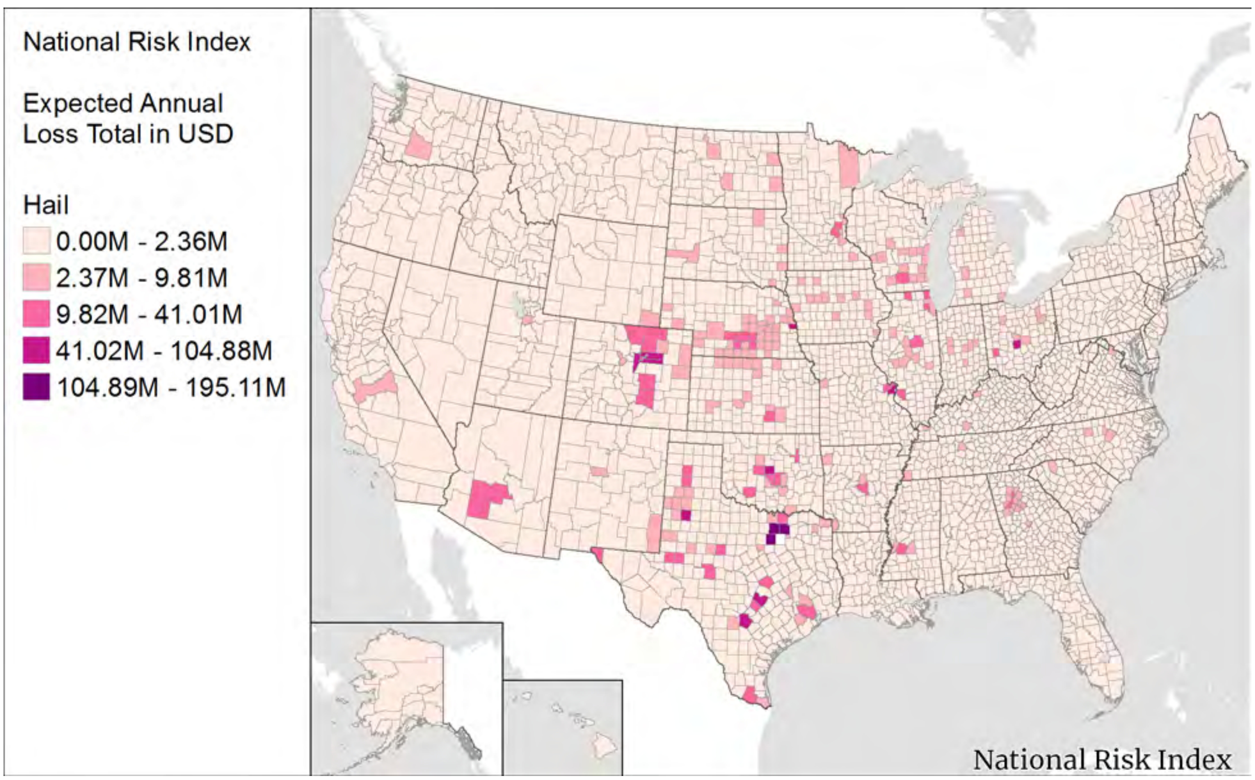

Figure 63: Total Expected Annual Loss by County to Hail

With the Hail total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Hail Risk Index score.

12 Heat Wave

A Heat Wave is a period of abnormally and uncomfortably hot and unusually humid weather typically lasting two or more days with temperatures outside the historical averages for a given area. The temperatures classified as a Heat Wave are dependent on the location and defined by the local NWS weather forecast office.

12.1 Spatial Source Data

Historical Event Generating Source: *National Weather Service, Weather Alerts*[41]

Historical Event Compiling Source: *Iowa State University, Iowa Environmental Mesonet*[42]

The NWS is continuously issuing weather alerts based on current weather conditions. Each alert is coded by type and significance and conceptually can serve as documentation of the potential for weather event activities in a specific area. Archived NWS alerts are aggregated, continuously updated, and made available for download in shapefile format by Iowa State University's Iowa Environmental Mesonet. Data include geometry for each alert's issued area and attributes related to each alert's severity and phenomena type. Weather alerts are also timestamped with the time of issuance and the time of expiration. A table describing this dataset's attributes can be found in *Appendix C – Mesonet-NWS Weather Event Attribute Description*.

Because the spatial representations of the alert areas will be intersected with Census blocks for the determination of exposure and frequency, it is important to use the best possible resolution of the Heat Wave alert.

The geometry shape for each alert record represents the geographic area for which the NWS alert applied. However, the Mesonet shapes are simplified versions of the more detailed NWS Public Forecast Zone shape originally associated with the alert record. Because the Mesonet tabular data still retain the reference ID for the NWS Public Forecast Zone, it can be used to relate to the zone associated with each alert record.

The NWS Public Forecast Zones can be downloaded in shapefile format[43] and represent the codified areas for which weather alerts are issued by NWS. The Public Forecast Zones shape definitions are predominantly derived from county boundaries. While the Public Forecast Zone boundaries are more refined than those substituted into the Mesonet data, they are not at the same resolution as the current county boundaries derived from Census blocks.

[41] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *Active Alerts* [online dataset]. Retrieved from https://www.weather.gov/.
[42] Department of Agronomy, Iowa State University. (2018). *Iowa Environmental Mesonet* [online database]. Retrieved from https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml.
[43] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *NWS Public Forecast Zones* [online dataset]. Retrieved from https://www.weather.gov/gis/PublicZones.

Utilizing the Public Forecast Zone shapefile in conjunction with the Public Forecast Zone – County Correlation file,[44] a determination was made as to which Public Forecast Zones have single-county coverage and which are either sub-county zones or made of portions of multiple counties. For perspective, the following approximate distribution of forecast zone composition were found:

- 70% of the zones are single-county coverage.
- 20% are cases where a single county is subdivided into multiple zones.
- 10% are zones that breach parts of multiple contiguous counties.

For those Forecast Zones covering a single county, the U.S. Census 2017 county boundaries are substituted. For all other zone shapes, the native NWS Public Forecast Zone shape found in the Mesonet data or correlation file is used. See *Figure 64* for an example of the differences in the spatial resolution of weather alert boundaries.

Another aspect of the NWS Public Forecast Zones is that they can and have changed over time. In the Mesonet data (2005 through 2017), there are 4,364 distinct Forecast Zones referenced that do not exist in the current NWS Public Forecast Zone shapefile. This occurs when an NWS Public Forecast Zone has been modified in shape, renamed, and/or “retired” from use.

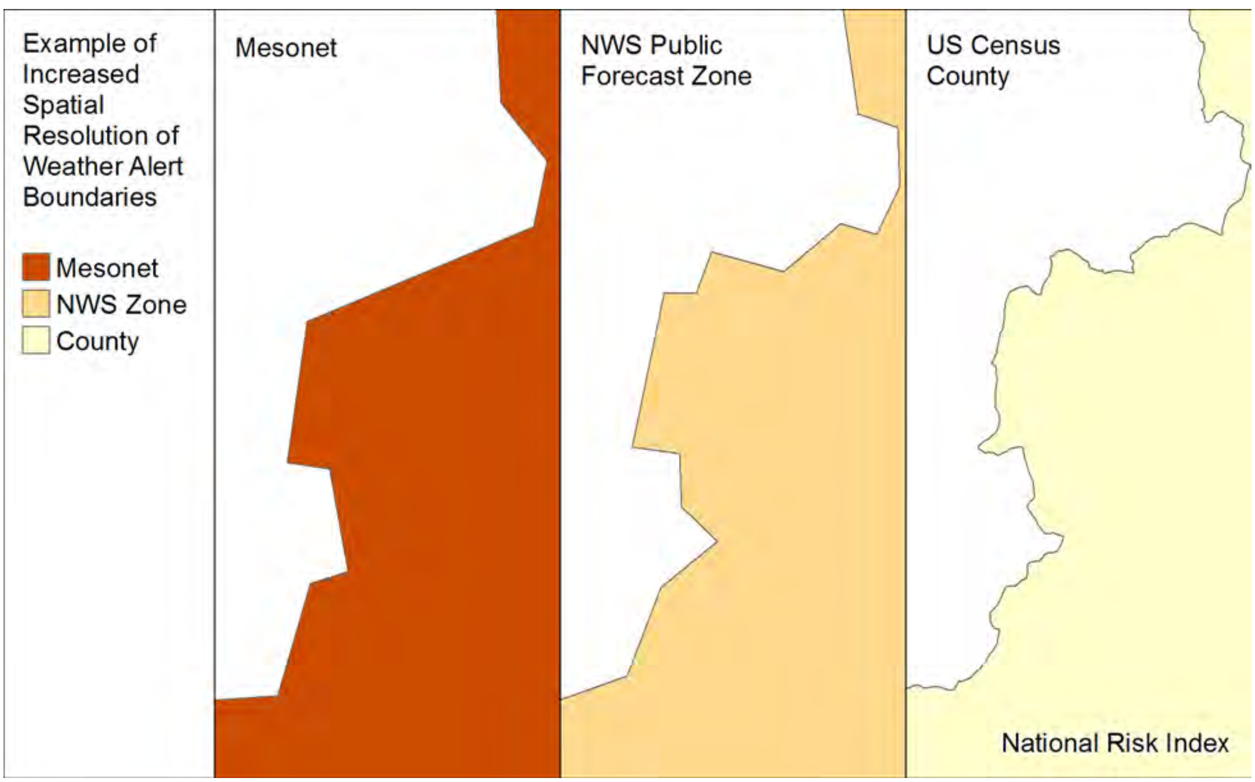

Figure 64: Three Boundary Definitions: Mesonet, Forecast Zone, U.S. Census County

[44] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *Zone-County Correlation File* [online dataset]. Retrieved from https://www.weather.gov/gis/ZoneCounty

Further research found that the NWS maintains a downloadable Change History log of the various changes in Forecast Zone areas since 1997. This text file does not contain the pre- nor post-shape of the altered forecast zone. Archived versions of these changes are likely available via contact with NWS, but the effort to match the NWS issued alert record to the version-controlled shape representation of the forecast zone at the time of alert issue seems to be beyond the scope of the NRI processing effort, though a Mesonet representative was contacted to see if Forecast Zone shapes associated with each year of alert data had been archived. Unfortunately, no such archival information was available. For cases where the more refined NWS Forecast Zone shape is unavailable, the simplified Mesonet boundary version shape is used.

12.1.1 PERIOD OF RECORD

In the 1990s and early 2000s, the NWS's system of recording watch, warnings, and advisories (WWA) made automated processing too difficult. So, in 2005, the Valid Time Extent Code (VTEC) system was implemented, which allowed for the easy automated parsing of alert data. Therefore, NWS weather events data were downloaded for 2005 through 2017. The date range utilized for the NRI is 11/12/2005 to 12/31/2017, so the period of record for which Heat Wave data are utilized is 12.14 years.

12.2 Spatial Processing

With the intended spatial processing goal of intersecting NWS event shapes to determine the Census block area impacted by each event, there are three main preparatory efforts required prior to the intersection of Heat Wave event polygons with Census block polygons for the purposes of calculating Heat Wave exposure and frequency.

Heat Wave weather event alerts are extracted from the dataset based on the VTEC significance code (SIG field) and the phenomena code (PHENOM or TYPE field) values. Only Warning alerts (SIG = 'W') of the Phenomena type "Excessive Heat" (EH) or "Heat" (H) are considered NRI Heat Wave events (see *Table 29*).

To remove unintended error in spatial results due to the use of the simplified event area shapes contained in the Mesonet data, event areas with a higher resolution version are substituted. This substitution uses the NWS Public Forecast Zone shape associated with the alert record or, in cases where the forecast zone is for a single county, a better resolution version of the county boundary area.

Table 29: Original Mesonet Heat Wave Records

WFO	ISSUED	EXPIRED	PHENOM	SIG	NWS_UGC	AREA_KM2
PSR	201706041800	201706080300	EH	W	AZZ554	583.5392
MAF	201706171700	201706180200	EH	W	TXZ045	3894.574
VEF	201706171800	201706270400	EH	W	NVZ017	7555.405

Heat Wave occurrences are measured in event-days as this more accurately represents the variability of Heat Wave event duration. To capture this, each native alert record with a duration greater than a single day is replaced with multiple records, one for each day of the original record's duration.

If a Heat Wave event's duration on any given day is less than 6 hours, then the event is assigned to the day having the greatest duration of the event. This handles cases where the event occurs in the late evening and actually endures for a greater length of time on the next calendar day than on the day the alert was issued.

For cases where the event duration is longer, the following business logic is used: If a weather event's duration is greater than 6 hours, assign the event to all days on which 6 or more hours occur. For example, if a 14-hour weather event was issued for 2 AM until 6 PM on July 1, then the event would be assigned to July 1. If the alert was issued from 11 PM on July 1 to 1 PM on July 2, then the event would be assigned to only July 2. If the alert was issued from 7 PM on July 1 to 9 AM on July 2, then the event would be assigned to both July 1 and July 2.

Additionally, there are some data quality issues with the Mesonet data. For example, some warnings have an expiration date that is prior to the issue date. In these cases, a single record is used and assigned the issue date. To illustrate this concept, the Heat Wave events in *Table 30* are expanded to create the Heat Wave event-day records in *Table 31.*

Table 30: Sample Heat Wave Data after Zone Shape Re-Sourcing

HeatwaveID	WFO	Issued	Expired	PHENOM	SIG	NWS_UGC	AreaKm2	NewShapeSource
47081	PSR	6/4/2017 18:00	6/8/2017 3:00	EH	W	AZZ554	577.2512	NWS Forecast Zone
51174	TWC	6/7/2017 18:00	6/6/2017 21:45	EH	W	AZZ504	5763.599	NWS Forecast Zone

Table 31: Sample Data from the Heat Wave Date Expansion Table

HeatwaveDate Expansion ID	HeatwaveID	Issued	Expired	DateType	HeatwaveHours
2030	47081	6/4/2017 18:00	6/5/2017 0:00	Expanded Dates - Issued	6
2032	47081	6/5/2017 0:00	6/6/2017 0:00	Expanded Dates - New Dates	24
2031	47081	6/6/2017 0:00	6/7/2017 0:00	Expanded Dates - New Dates	24
2034	47081	6/7/2017 0:00	6/8/2017 0:00	Expanded Dates - New Dates	24
1	51174	6/7/2017 18:00	6/7/2017 18:00	Expired before Issued	0

To avoid overestimating the area of influence a “single” distinct weather event has due to multiple NWS alerts being issued for that same weather event, a process to combine all Heat Wave event areas occurring on the same day (Year, Month, Day specific) into one representative event shape is performed. This process results in a single event impact area shape for each day on which a Heat Wave event occurred. These Heat Wave event-day polygons can then be intersected with the Census block polygons to determine Heat Wave exposure and frequency.

12.3 Determination of Possibility of Hazard Occurrence

Heat Waves can occur almost anywhere in the United States as the definition of a Heat Wave is locally defined by the area’s weather forecast office. For example, a forecast office in Texas may define a Heat Wave differently than a forecast office in New York. Therefore, all counties were deemed possible for Heat Wave occurrence.

12.4 Exposure

To identify areas of exposure, the Heat Wave event-day polygons (also referred to as Heat Wave Date Expansions to acknowledge the spatiotemporal processing described in *Section 12.2*) are intersected with the Census block polygons within the NRI processing database. The resulting table contains the Heat Wave event-day’s unique identifier, Census block number, and the intersected area in square kilometers (see *Table 32*).

Table 32: Sample Data from the Heat Wave Expansion Census Block Intersection Table

HeatwaveDateExpansionID	CensusBlock	IntersectedAreaKm2
53297	40131167132017	0.080384
53297	40131167133000	0.313492
53297	40131167133001	0.032176

To determine exposure value, the average coverage of a Heat Wave event-day is found by summing the intersected areas for all Heat Wave event-days that intersected the Census block and dividing this sum by the number of intersecting event-days. This is multiplied by the developed area building value density and the developed area population density of the Census block to model the conservative-case concentration of exposure within the Census block. These developed area Census block building and population densities have been calculated by dividing the total values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers; see *Equation 52*). The VSL was used to express population exposure in terms of dollars.

Equation 52: Census Block Heat Wave Exposure

$$Exposure_{HWAV_{CB_{Bldg}}} = \frac{\sum IntsctArea_{HWAV_{CB}}}{EventCount_{HWAV_{CB}}} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{HWAV_{CB_{Pop}}} = \left(\frac{\sum IntsctArea_{HWAV_{CB}}}{EventCount_{HWAV_{CB}}} \times DevAreaDen_{CB_{Pop}}\right) \times VSL$$

where:

$Exposure_{HWAV_{CB_{Bldg}}}$ is the building value exposed to Heat Wave event-days in a specific Census block (in dollars).

$\sum IntsctArea_{HWAV_{CB}}$ is the sum of the intersected areas of past Heat Wave event-days with the Census block (in square kilometers).

$EventCount_{HWAV_{CB}}$ is the total number of Heat Wave event-days that intersect the Census block.

$DevAreaDen_{CB_{Bldg}}$ is the developed area building value density of the Census block (in dollars per square kilometer).

$Exposure_{HWAV_{CB_{Pop}}}$ is the population value exposed to Heat Wave event-days in a specific Census block (in dollars).

$DevAreaDen_{CB_{Pop}}$ is the developed area population density of the Census block (in people per square kilometer).

VSL is the Value of Statistical Life ($7.4M per person).

It should be noted that, in order for a Heat Wave event-day polygon's intersection with a Census block to be included, the area of the intersection must cover at least 5% of the Census block. This is a spatial modeling technique to correct for the small intersect "slivers" generated by differing versions of county boundary geometry being used.

Because the exposure model uses a conservative-case concentration of exposure and a developed area density value, it is possible to mathematically generate an exposure value that is greater than the total value of the Census block. The Hazus-recorded population and building value are considered ceilings on exposure. For example, if the calculated exposed population exceeds the Hazus-recorded population, then the Hazus-recorded population is used as the population exposure value for the Census block.

12.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 53*).

Equation 53: Census Tract and County Heat Wave Exposure Aggregations

$$Exposure_{HWAV\,CT_{Bldg}} = \sum_{CB}^{CT} Exposure_{HWAV\,CB_{Bldg}}$$

$$Exposure_{HWAV\,Co_{Bldg}} = \sum_{CB}^{Co} Exposure_{HWAV\,CB_{Bldg}}$$

$$Exposure_{HWAV\,CT_{Pop}} = \sum_{CB}^{CT} Exposure_{HWAV\,CB_{Pop}}$$

$$Exposure_{HWAV\,Co_{Pop}} = \sum_{CB}^{Co} Exposure_{HWAV\,CB_{Pop}}$$

where:

$Exposure_{HWAV\,CT_{Bldg}}$	is the building value exposed to Heat Wave event-days in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{HWAV\,CB_{Bldg}}$	is the summed value of all buildings exposed to Heat Wave for each Census block within the Census tract (in dollars).
$Exposure_{HWAV\,Co_{Bldg}}$	is the building value exposed to Heat Wave event-days in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{HWAV\,CB_{Bldg}}$	is the summed value of all buildings exposed to Heat Wave for each Census block within the county (in dollars).
$Exposure_{HWAV\,CT_{Pop}}$	is the population value exposed to Heat Wave event-days in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{HWAV\,CB_{Pop}}$	is the summed value of all population exposed to Heat Wave for each Census block within the Census tract (in dollars).
$Exposure_{HWAV\,Co_{Pop}}$	is the population value exposed to Heat Wave event-days in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{HWAV\,CB_{Pop}}$	is the summed value of all population exposed to Heat Wave for each Census block within the county (in dollars).

12.5 Historic Event-Day Count

The count of historic Heat Wave event-days is computed as the number of distinct Heat Wave event-day polygons that intersect a Census block and have an area of intersection that is at least 5% of the block's total area. This count uses the same Heat Wave expansion Census block intersection table used to calculate exposure and will be used to compute frequency at the Census block level.

Historic Event-Day Counts are also supplied at the Census tract and county levels as the number of distinct Heat Wave event-day polygons that intersect the Census tract and county, respectively.

12.6 Frequency

The number of recorded Heat Wave event-days each year over the period of record (12.14 years) is used to estimate the frequency of Heat Waves in an area. Because a Heat Wave event can occur over several days or a single day, an event-day basis was used to estimate frequency as this method better captures the variability in duration between events. The annualized frequency is calculated at the Census block level, and the Census block-level value is used in the EAL calculations.

Frequency calculations use the same intersection between Heat Wave event-days (or Heat Wave Date Expansion) polygons and Census block polygons that were used to calculate exposure. The count of distinct Heat Wave event-day polygons intersecting each Census block is recorded and used to calculate the annualized frequency of Heat Wave event-days as in *Equation* 54.

Equation 54: Census Block Heat Wave Frequency

$$Freq_{HWAV_{CB}} = \frac{EventCount_{HWAV_{CB}}}{PeriodRecord_{HWAV}}$$

where:

$Freq_{HWAV_{CB}}$	is the annualized frequency of Heat Wave event-days determined for a specific Census block (event-days per year).
$EventCount_{HWAV_{CB}}$	is the number of Heat Wave event-days that intersect the Census block.
$PeriodRecord_{HWAV}$	is the period of record for Heat Wave (12.14 years).

12.6.1 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level. These values may not exactly match that of dividing the number of recorded Heat Wave events at the Census tract and county level by the period of record, as the frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 55*.

Equation 55: Census Tract and County Area-Weighted Heat Wave Frequency Aggregation

$$Freq_{HWAV_{CT}} = \frac{\sum_{CB}^{CT}\left(Freq_{HWAV_{CB}} \times Area_{CB}\right)}{Area_{CT}}$$

$$Freq_{HWAV_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{HWAV_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{HWAV_{CT}}$	is the annualized area-weighted Heat Wave frequency calculated for a specific Census tract (event-days per year).
$Freq_{HWAV_{CB}}$	is the annualized Heat Wave frequency calculated for a specific Census block (event-days per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{HWAV_{Co}}$	is the annualized area-weighted Heat Wave frequency calculated for a specific county (event-days per year).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 65 displays annualized Heat Wave frequency at the county level.

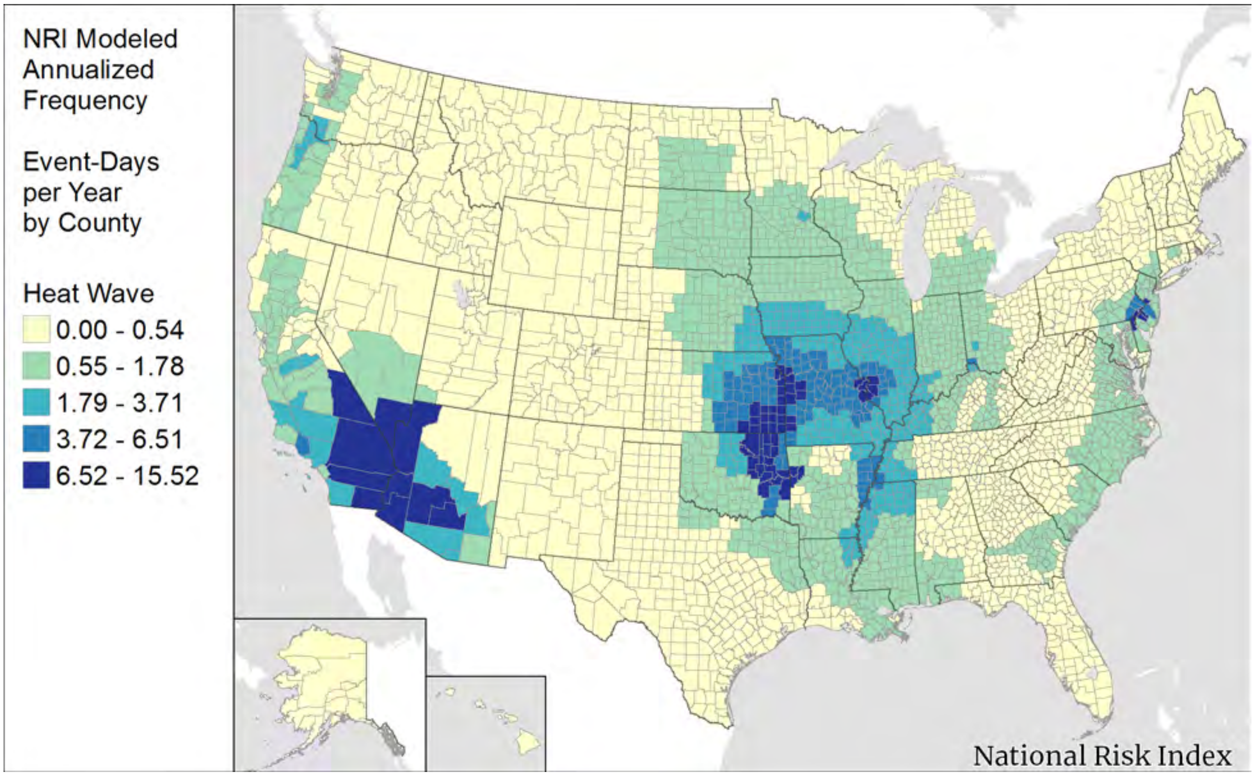

Figure 65: Annualized Heat Wave Frequency by County

12.7 Historic Loss Ratio

The Heat Wave HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Heat Wave event-day, or the average rate of loss associated with the occurrence of a Heat Wave event-day. For a detailed description of the HLR calculation process, see *Section 5.4.* The HLR parameters described below are specific to the Heat Wave hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Two peril types are mapped to the hazard Heat Wave (see *Table 33*). These are expanded on an event-day basis based on the number of event duration days from SHELDUS[45] (see *Section 5.4.1*).

Table 33: Heat Wave Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Heat	3279	25834
HeatWave	543	5042

[45] For Heat Wave loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

The HLR exposure value used in the formula below is a county-level value that represents the dollar value of the total building value or the entire population of a county as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event-day and each consequence type (building and population) is calculated using *Equation 56*.

Equation 56: Loss Ratio per Basis Calculation for a Single Heat Wave Event-Day

$$LRB_{HWAV\,Co_{CnsqType}} = \frac{Loss_{HWAV\,Co_{CnsqType}}}{HLRExposure_{Co_{CnsqType}}}$$

where:

$LRB_{HWAV\,Co_{CnsqType}}$ is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Heat Wave event-day. Calculation is performed for each consequence type (building and population).

$Loss_{HWAV\,Co_{CnsqType}}$ is the loss (by consequence type) experienced from the Heat Wave event-day documented to have occurred in the county (in dollars).

$HLRExposure_{Co_{CnsqType}}$ is the total value (by consequence type) of the county estimated to have been exposed to the Heat Wave event-day (in dollars).

Heat Wave event-days can occur with a high frequency in areas, but often result in no recorded loss to building value or population. SHELDUS does not record events in which no loss occurred, so a number of zero-loss event-days are inserted into the data to align the event count in the HLR calculation to the historic event count experienced within the SHELDUS period of record (1995 to 2016). For Heat Wave, the historic year-month event count is extracted using the intersection between the Heat Wave event-day polygons and the Census block polygons used to calculate exposure and frequency (see *Table 32*). The date when the Heat Wave alert was issued for each Heat Wave event-day polygon is used to sync the event to its year-month. A list of distinct Heat Wave alert issue dates is compiled for the event-day polygon-Census block intersections within the county, and the historic year-month event count is the number of distinct Heat Wave alert issue dates in this list.

If the number of Heat Wave event-day records from SHELDUS is less than the summed historic year-month event-day counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and regional. The regional definition for Heat Wave is derived from the FEMA regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 66 and *Figure 68* display the largest weighting factor contributor in the Bayesian credibility calculation for the Heat Wave HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Heat Wave event-days within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or regional events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing event-days or have widely varying loss ratios get the most influence from regional-level loss data. *Figure 67* and *Figure 69* represent the final county-level HLR values for Heat Wave.

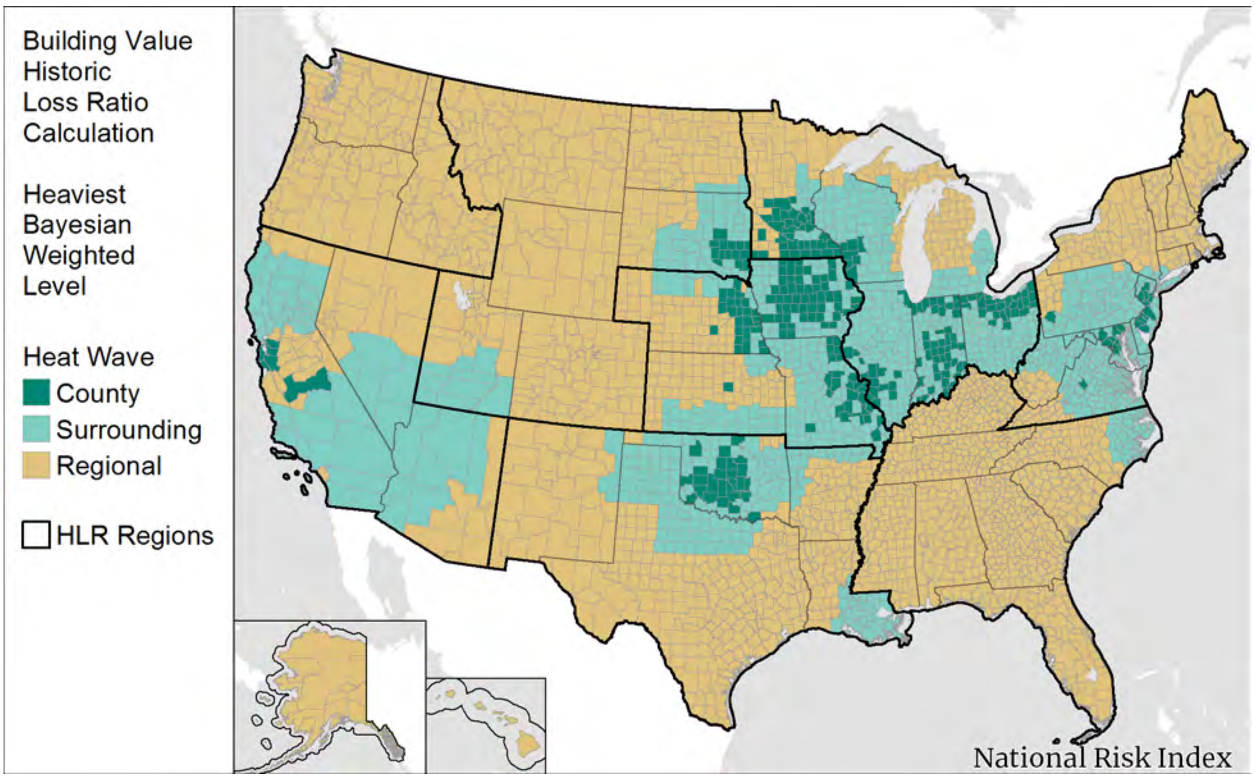

Figure 66: Heat Wave Maximum Weighting Factor Contributor – Building Value

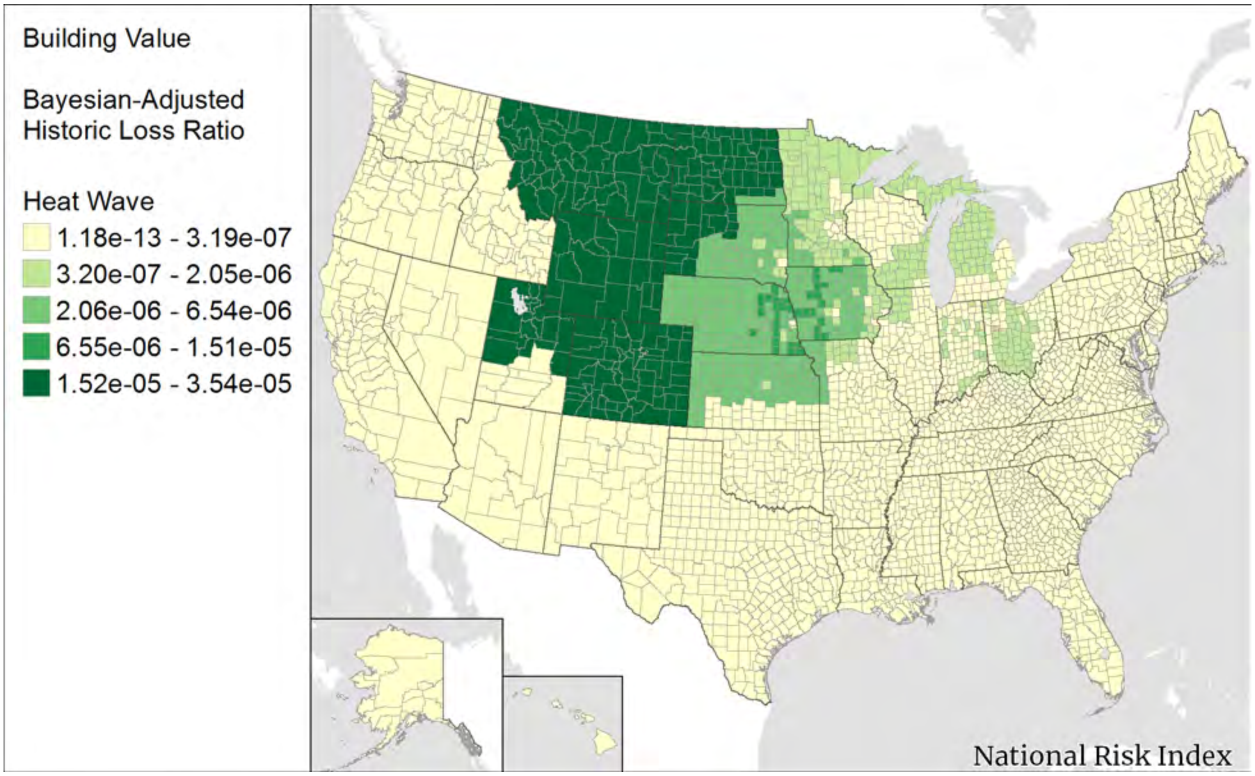

Figure 67: Heat Wave HLR – Building Value

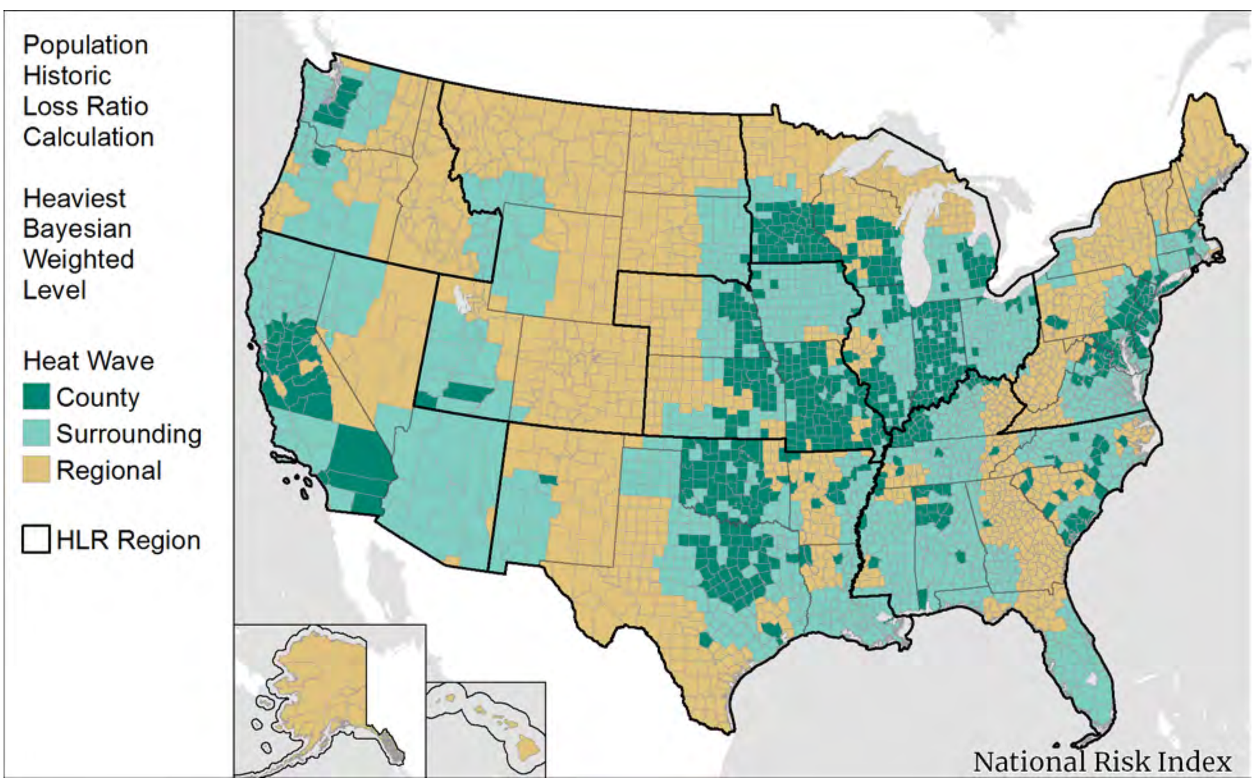

Figure 68: Heat Wave Maximum Weighting Factor Contributor – Population

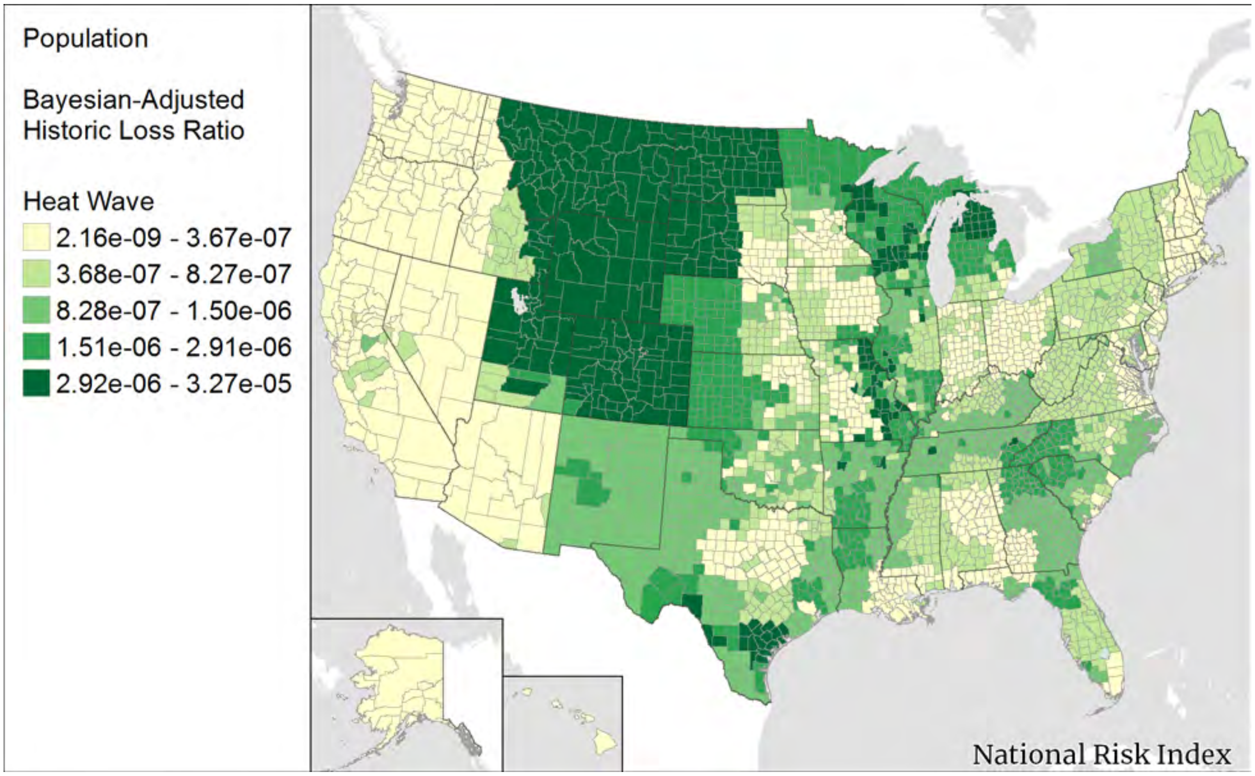

Figure 69: Heat Wave HLR – Population

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

12.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 57*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 57: Census Block Expected Annual Loss to Heat Wave

$$EAL_{HWAV_{CB_{Bldg}}} = Exposure_{HWAV_{CB_{Bldg}}} \times Freq_{HWAV_{CB}} \times HLR_{HWAV_{CB_{Bldg}}}$$

$$EAL_{HWAV_{CB_{Pop}}} = Exposure_{HWAV_{CB_{Pop}}} \times Freq_{HWAV_{CB}} \times HLR_{HWAV_{CB_{Pop}}}$$

where:

$EAL_{HWAV_{CB_{Bldg}}}$ is the Expected Annual Loss to building value due to Heat Wave events for a specific Census block (in dollars).

$Exposure_{HWAV_{CB_{Bldg}}}$	is the building value exposed to Heat Wave events in the Census block (in dollars).
$Freq_{HWAV_{CB}}$	is the annualized Heat Wave frequency calculated for the Census block (event-days per year).
$HLR_{HWAV_{CB_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Heat Wave for the Census block.
$EAL_{HWAV_{CB_{Pop}}}$	is the Expected Annual Loss to population value due to Heat Wave events for a specific Census block (in dollars).
$Exposure_{HWAV_{CB_{Pop}}}$	is the population value exposed to Heat Wave events in the Census block (in dollars).
$HLR_{HWAV_{CB_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Heat Wave for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building and population loss at the Census block level as in *Equation 58*.

Equation 58: Census Tract and County Expected Annual Loss to Heat Wave

$$EAL_{HWAV_{CT}} = \sum_{CB}^{CT} EAL_{HWAV_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{HWAV_{CB_{Pop}}}$$

$$EAL_{HWAV_{Co}} = \sum_{CB}^{Co} EAL_{HWAV_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{HWAV_{CB_{Pop}}}$$

where:

$EAL_{HWAV_{CT}}$	is the total Expected Annual Loss due to Heat Wave events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{HWAV_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Heat Wave events for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{HWAV_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Heat Wave events for all Census blocks in the Census tract (in dollars).
$EAL_{HWAV_{Co}}$	is the total Expected Annual Loss due to Heat Wave events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{HWAV_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Heat Wave events for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{HWAV_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Heat Wave events for all Census blocks in the county (in dollars).

Figure 70 shows the total EAL (building value and population combined) to Heat Wave events.

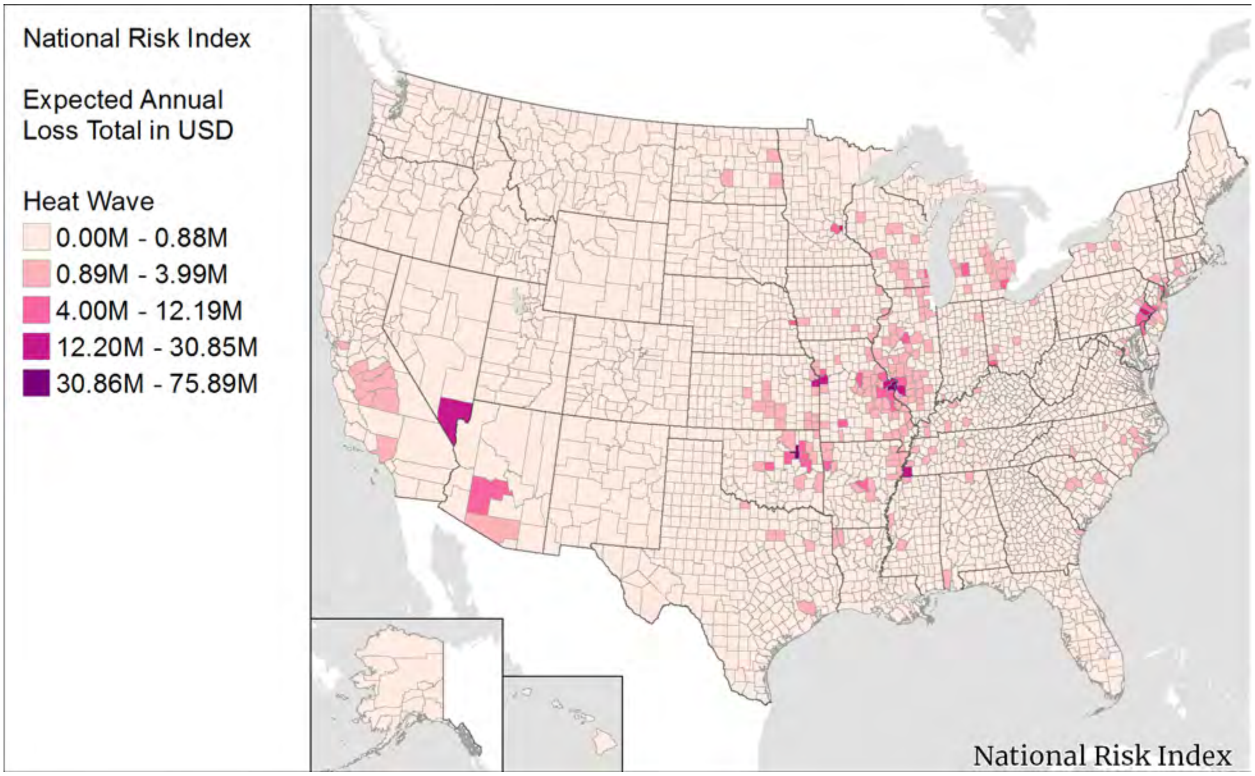

Figure 70: Total Expected Annual Loss by County to Heat Wave

With the Heat Wave total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Heat Wave Risk Index score.

13 Hurricane

A Hurricane is a tropical cyclone or localized, low-pressure weather system that has organized thunderstorms but no front (a boundary separating two air masses of different densities) and maximum sustained winds of at least 74 miles per hour (mph). The NRI Hurricane data also include tropical storms for which wind speeds range from 39 to 74 mph.

13.1 Spatial Source Data

Historical Event Source: NOAA, National Hurricane Center, HURDAT2 Best Track Data[46]

The National Hurricane Center (NHC), a component of NOAA's National Centers for Environmental Prediction, maintains several databases, including the HURDAT2 Best Track Data Archive. The dataset is the most comprehensive source of information on both Atlantic and Pacific tropical and subtropical cyclones.[47] It contains a series of storm observation records at six-hour intervals with location, maximum wind speed, central pressure, and (beginning in 2004) cyclone size. The observation records are organized by storm with a unique identifier and include temporal data (date and time; see *Table 34* and *Figure 71*). The dataset is the result of a post-storm analysis and contains the official assessment of a storm's path and characteristics. It also can include storm observations that were not available in real-time during the storm.

Table 34: Sample Data from HURDAT2

DateObs	Basin	HurricaneNumber	HurricaneName	SystemStatus	Latitude	Longitude	MaxWindKts
10/1/2016 6:00	AL	AL142016	Matthew	HU	13.4	-72.5	140
10/1/2016 12:00	AL	AL142016	Matthew	HU	13.4	-73.1	135
10/1/2016 18:00	AL	AL142016	Matthew	HU	13.4	-73.3	130

[46] National Hurricane Center, National Oceanic and Atmospheric Administration. (2018). HURDAT2 Best Track Data Archive [online dataset]. Retrieved from https://www.nhc.noaa.gov/data/.
[47] Landsea, C. W. & Franklin, J.L. (2013). Atlantic hurricane database uncertainty and presentation of a new database format. Monthly Weather Review, 141, 3576-3592.

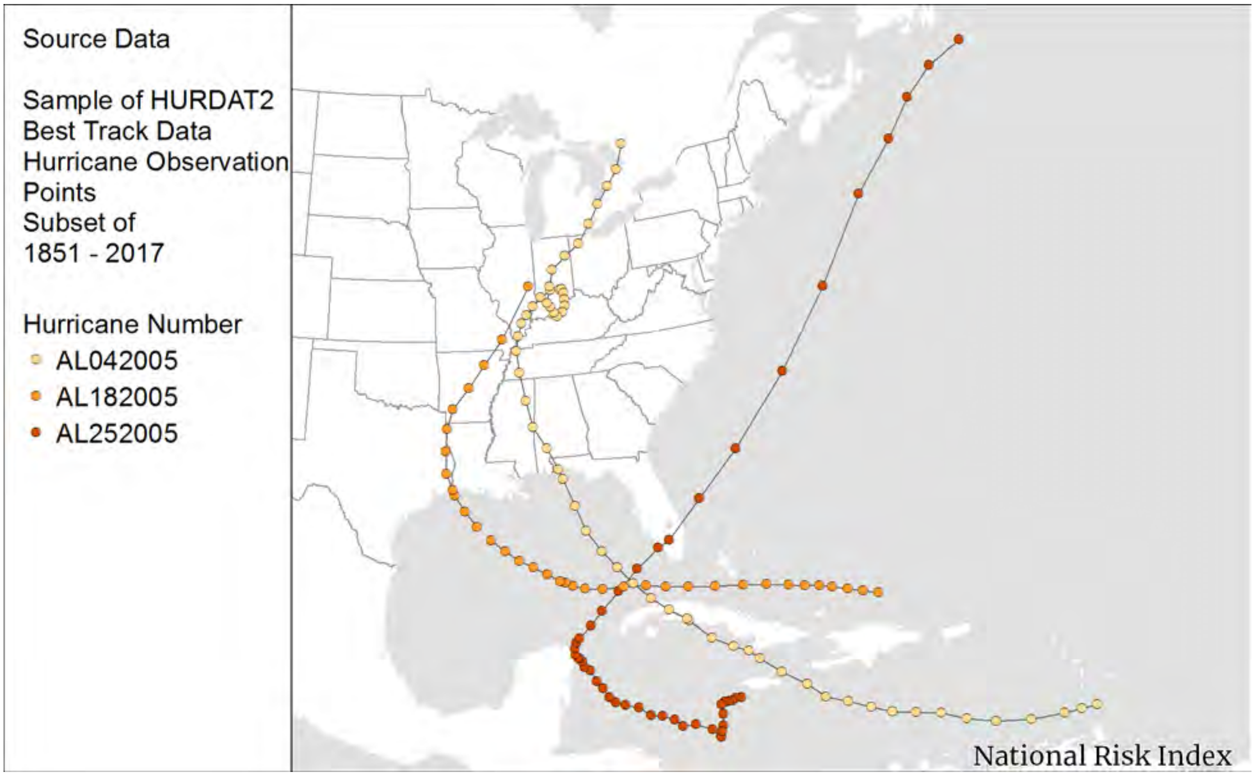

Figure 71: Map of HURDAT2 Points

13.1.1 PERIOD OF RECORD

The HURDAT2 dataset is organized by ocean basins: Atlantic and Pacific. The storms in the Atlantic dataset date from 1851 to 2017 (167.11 years) while those in the Pacific date from 1949 to 2017 (69.04 years).

13.2 Spatial Processing

The HURDAT2 data for both the Pacific and Atlantic basin are downloaded and loaded into the NRI processing database. Upon loading, a record for every storm observation is created and attributed with the StormID to which it is associated. Each storm observation record contains positional and wind speed information. Based on this information, the records are projected as point locations and categorized on the Saffir-Simpson Hurricane Wind Scale. This category is used to assign a buffer radius that represents the average distance from the storm's center that hurricane force (or tropical storm force) winds are likely to reach.

Each storm observation record (point location) is categorized by its associated windspeeds (based on the Saffir-Simpson Hurricane Wind Scale).[48] The storm category is then used to assign a buffer radius (representing the average distance at which storm force winds are found) to each observation

[48] Schott, T., Landsea, C., Hafele, G., Lorens, J., Taylor, A., Thurm, H., Ward, B., Willis, M., & Zaleski, W. (2019). The Saffir-Simpson Hurricane Wind Scale [PDF file]. Retrieved from https://www.nhc.noaa.gov/pdf/sshws.pdf.

location. *Table 35* presents the storm category wind speed definitions and their associated average radius distance of storm force winds. These radii are derived through a process based on research conducted by Bell and Ray (2004).[49]

Table 35: Hurricane Categorization

ID	Storm Category	Minimum Wind Speed (mph)	Maximum Wind Speed (mph)	Minimum Wind Speed (kts)	Maximum Wind Speed (kts)	Average Radius of Hurricane/Tropical Storm Force Winds (miles)
0	Tropical Storm	39	73.9	33	63.9	15
1	Category 1	74	95.9	64	82.9	26.45
2	Category 2	96	110.9	83	95.9	39.1
3	Category 3	111	129.9	96	112.9	43.7
4	Category 4	130	156.9	113	136.9	50.03
5	Category 5	157	9999	137	9999	54.04
6	Other	0	38.9	0	32.9	0

Each storm's associated storm observation points are connected to create a multi-segment line that represents the path of the storm. Each line segment between two consecutive storm observation points is attributed with the lowest storm category value of its endpoint observations (based on the assumption that this would be the minimum expected category along the path segment).

Each storm observation location and line segment are independently buffered by the average radius distance (of storm force winds) associated with its assigned storm category. All the buffered shapes associated with a given storm are then union-dissolved into a single polygon shape representing the area for which hurricane force winds were modeled for that particular storm to create historic Hurricane event path polygons (see *Figure 72*, *Table 36*, and *Figure 73*).

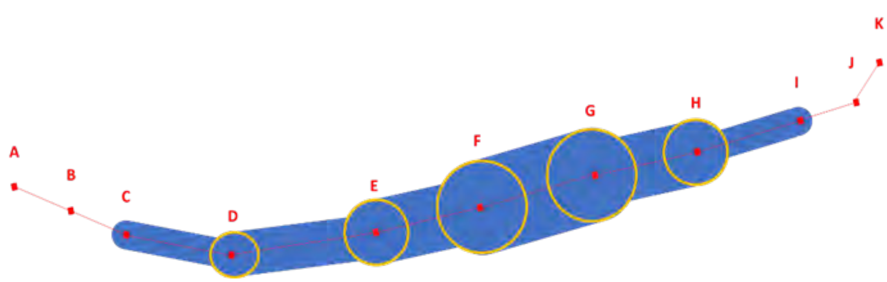

Figure 72: Hurricane Event Path Polygon

[49] Bell, K., & Ray, P.S. (2004). North Atlantic hurricanes 1977-99: Surface hurricane-force wind radii. *Monthly Weather Review, 132*(5), 1167-1189. doi: 10.1175/1520-0493(2004)132<1167:NAHSHW>2.0

Table 36: Notional Example

Observation Point	Wind Speed (kt)	Storm Category
A	15	Other
B	25	Other
C	50	Tropical Storm
D	65	Cat 1
E	85	Cat 2
F	100	Cat 3
G	110	Cat 3
H	90	Cat 2
I	60	Tropical Storm

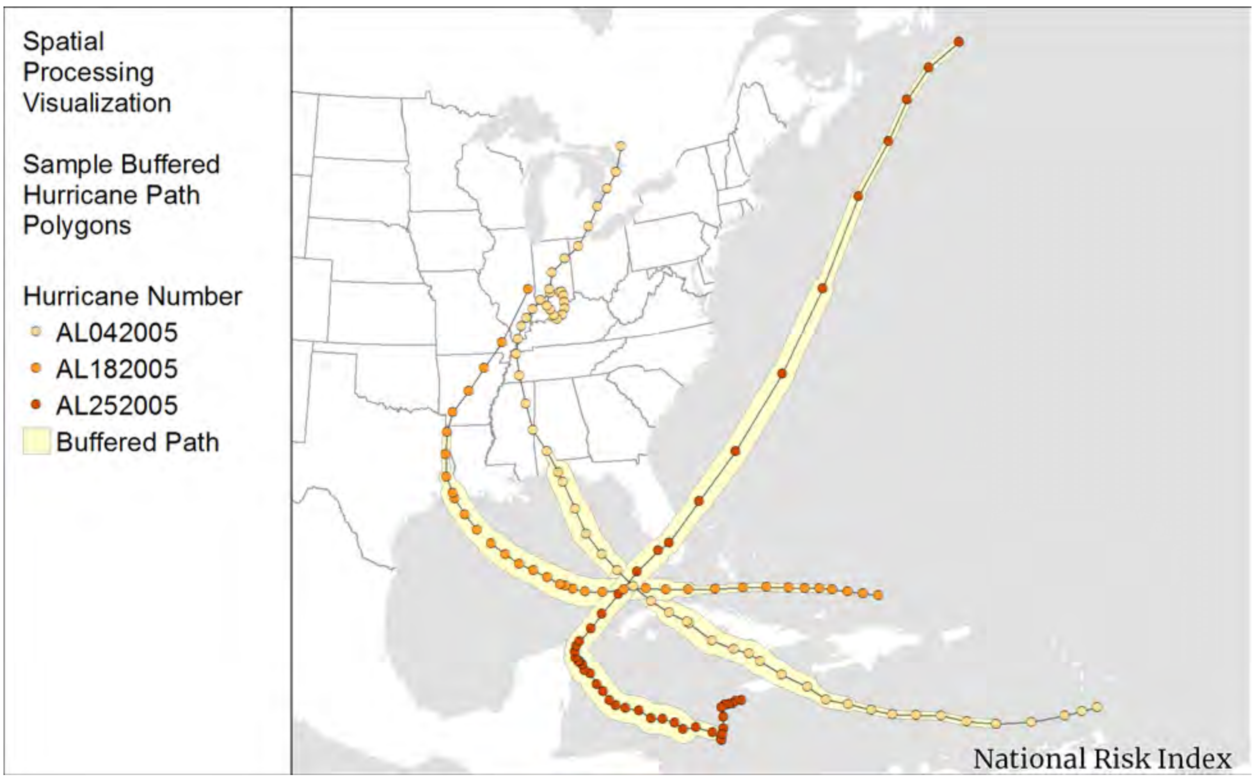

Figure 73: Sample Buffered Hurricane Event Path Polygons

13.3 Determination of Possibility of Hazard Occurrence

To distinguish between areas where no Hurricane events have occurred and those where such events are not deemed possible, a control table was generated to designate which counties have some probability of Hurricane occurrence. The Hurricane event path polygons processed to represent historical storms as described in *Section 13.2* were buffered to an additional 100 miles, and any counties that intersected at least one buffered Hurricane event path polygon were included as counties with some probability of event occurrence. Additionally, a subset of inland counties near the Atlantic basin that had sustained historic economic loss to Hurricanes according to SHELDUS was also included (see *Figure 74*).

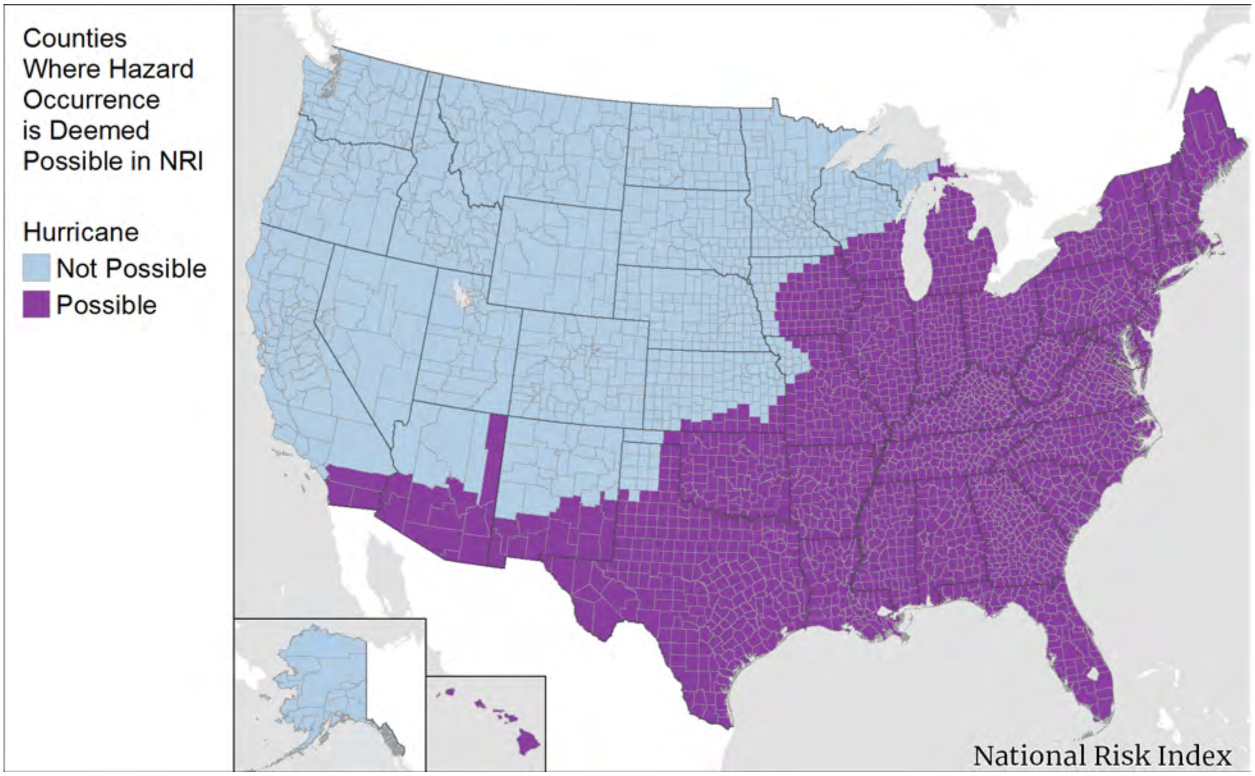

Figure 74: Map of Counties Deemed Possible for Hurricane Occurrence

13.4 Exposure

To identify areas of exposure, the Hurricane event path polygons are intersected with the Census block polygons within the NRI processing database. The resulting table contains the storm's unique identifier, Census block number, and the intersected area in square kilometers (see *Table 37*).

Table 37: Sample Data from the Hurricane Census Block Intersection Table

HurricaneProcessedID	CensusBlock	IntersectedAreaKm2
1561	280870009003030	0.00563004156494141
1561	280870009003031	0.000665592071533203
1561	280870009003032	0.00911474768066406

To determine exposure value, the average coverage of a Hurricane event is found by summing the intersected areas for all buffered Hurricane paths that intersected the Census block and dividing this sum by the number of intersecting Hurricane paths. This is multiplied by the developed area building value density and the developed area population density of the Census block to model the conservative-case concentration of exposure within the Census block. These developed area Census block building and population densities have been calculated by dividing the total values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers; see *Equation 59*). The VSL was used to express population exposure in terms of dollars.

Equation 59: Census Block Hurricane Exposure

$$Exposure_{HRCN_{CB_{Bldg}}} = \frac{\sum IntsctArea_{HRCN_{CB}}}{EventCount_{HRCN_{CB}}} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{HRCN_{CB_{Pop}}} = \left(\frac{\sum IntsctArea_{HRCN_{CB}}}{EventCount_{HRCN_{CB}}} \times DevAreaDen_{CB_{Pop}}\right) \times VSL$$

where:

$Exposure_{HRCN_{CB_{Bldg}}}$	is the building value exposed to Hurricane events in a specific Census block (in dollars).
$\sum IntsctArea_{HRCN_{CB}}$	is the sum of the intersected areas of past Hurricane events with the Census block (in square kilometers).
$EventCount_{HRCN_{CB}}$	is the total number of Hurricane events that intersect the Census block.
$DevAreaDen_{CB_{Bldg}}$	is the developed area building value density of the Census block (in dollars per square kilometer).
$Exposure_{HRCN_{CB_{Pop}}}$	is the population value exposed to Hurricane events in a specific Census block (in dollars).
$DevAreaDen_{CB_{Pop}}$	is the developed area population density of the Census block (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).

In cases where a Census block is deemed potentially at risk for Hurricane damage due to its proximity to areas that have been hit by one or more Hurricanes in the past but has not experienced any historical Hurricane events itself, the exposure value is estimated to be the full Census block building value and population value. These areas will likely have a low HLR and/or frequency, which will diminish the effect of using full Census block exposure values in the final EAL calculation.

Because the exposure model uses a conservative-case concentration of exposure and a developed area density value, it is possible to mathematically generate an exposure value that is greater than the total value of the Census block. The Hazus-recorded population and building value are considered ceilings on exposure. For example, if the calculated exposed population exceeds the Hazus-recorded population, then the Hazus-recorded population is used as the population exposure value for the Census block.

13.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 60*).

Equation 60: Census Tract and County Hurricane Exposure Aggregation

$$Exposure_{HRCN_{CT_{Bldg}}} = \sum_{CB}^{CT} Exposure_{HRCN_{CB_{Bldg}}}$$

$$Exposure_{HRCN_{Co_{Bldg}}} = \sum_{CB}^{Co} Exposure_{HRCN_{CB_{Bldg}}}$$

$$Exposure_{HRCN_{CT_{Pop}}} = \sum_{CB}^{CT} Exposure_{HRCN_{CB_{Pop}}}$$

$$Exposure_{HRCN_{Co_{Pop}}} = \sum_{CB}^{Co} Exposure_{HRCN_{CB_{Pop}}}$$

where:

$Exposure_{HRCN_{CT_{Bldg}}}$	is the building value exposed to Hurricane events in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{HRCN_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Hurricane for each Census block within the Census tract (in dollars).
$Exposure_{HRCN_{Co_{Bldg}}}$	is the building value exposed to Hurricane events in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{HRCN_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Hurricane for each Census block within the county (in dollars).
$Exposure_{HRCN_{CT_{Pop}}}$	is the population value exposed to Hurricane events in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{HRCN_{CB_{Pop}}}$	is the summed value of all population exposed to Hurricane for each Census block within the Census tract (in dollars).
$Exposure_{HRCN_{Co_{Pop}}}$	is the population value exposed to Hurricane events in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{HRCN_{CB}{}_{Pop}}$	is the summed value of all population exposed to Hurricane for each Census block within the county (in dollars).

13.5 Historic Event Count

Historic Event Counts are supplied at the Census tract and county levels as the number of distinct Hurricane event path polygons (see *Section 13.2*) that intersect the Census tract and county, respectively. This count uses the same Hurricane Census block intersection table used to calculate exposure.

13.6 Frequency

The frequency value represents the estimated number of recorded Hurricane events each year for a specific area. This annualized frequency is utilized at the Census block level, and the Census block level value is used in the EAL calculations.

Frequency calculations are determined by intersecting the same buffered Hurricane event path polygons that are used to calculate exposure with a 49-by-49-km fishnet grid. The count of distinct Hurricane event path polygons intersecting each grid cell is recorded, and each Census block inherits this fishnet-aggregated count from the grid cell that encompasses it. If the Census block intersects multiple fishnet grid cells, an area-weighted average count is calculated (see *Appendix D – Fishnet Event Count*).

The Hurricane event count (determined from the fishnet-aggregated count) is then divided by the period of record (depending on the ocean basin of the location) as in *Equation 61*.

Equation 61: Census Block Hurricane Frequency

$$Freq_{HRCN_{CB}} = \frac{EventCount_{HRCN_{CB}}}{PeriodRecord_{HRCN}}$$

where:

$Freq_{HRCN_{CB}}$	is the annualized frequency of Hurricane events determined for a specific Census block (events per year).
$EventCount_{HRCN_{CB}}$	is the number of historic Hurricane events calculated for the Census block.
$PeriodRecord_{HRCN}$	is the period of record for Hurricane events, either 167.11 for Atlantic storms or 69.04 for Pacific storms (in years).

13.6.1 MINIMUM ANNUAL FREQUENCY

If a Census block's historical Hurricane event count (inherited from the fishnet count) is 0, but the Census block is part of a county that was designated as one in which Hurricanes are possible, the

Census block is assigned the minimum annual Hurricane frequency. This minimum frequency is set at 0.01 (1 in 100 years). This was determined by SMEs to be an acceptable assumption.

13.6.2 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level. These values may not exactly match that of dividing the number of recorded Hurricane events at the Census tract and county level by the period of record, as the event count for frequency is a fishnet area-weighted event count including Hurricanes that may have impacted the surrounding area but not the county or Census tract itself. The frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 62*.

Equation 62: Census Tract and County Area-Weighted Hurricane Frequency

$$Freq_{HRCN_{CT}} = \frac{\sum_{CB}^{CT}\left(Freq_{HRCN_{CB}} \times Area_{CB}\right)}{Area_{CT}}$$

$$Freq_{HRCN_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{HRCN_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{HRCN_{CT}}$	is the annualized area-weighted Hurricane frequency calculated for a specific Census tract (events per year).
$Freq_{HRCN_{CB}}$	is the annualized Hurricane frequency calculated for a specific Census block (events per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{HRCN_{Co}}$	is the annualized area-weighted Hurricane frequency calculated for a specific county (events per year).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 75 displays annualized Hurricane frequency at the county level.

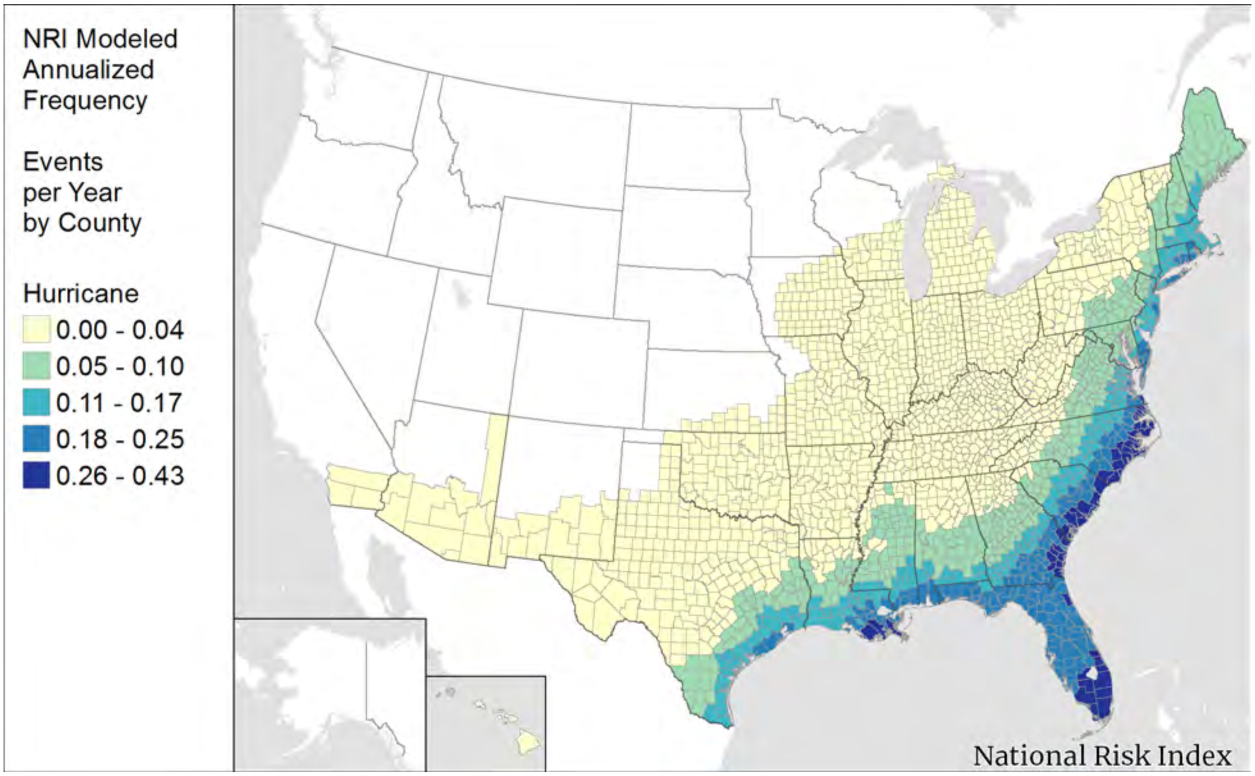

Figure 75: Annualized Hurricane Frequency by County

13.7 Historic Loss Ratio

The Hurricane HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Hurricane event, or the average rate of loss associated with the occurrence of a Hurricane event. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Hurricane hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Eight peril types are mapped to the hazard Hurricane (see *Table 38*). These are expanded on an event basis based on the number of records from SHELDUS[50] (see *Section 5.4.1*). Note that recorded Hurricane events only include those that made landfall as a Tropical Storm or Hurricane.

[50] For Hurricane loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

Table 38: Hurricane Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
CycloneExtratropical	0	0
CycloneSubtropical	0	0
CycloneUnspecified	1	1
HurricaneTropicalStorm	1395	1535
NorEaster	0	0
StormSurge	395	458
TropicalDepression	188	210
TropicalStorm	1596	1854

The HLR exposure value used in the formula below is a county-level value that represents the dollar value of the total building value or the entire population of a county as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event and each consequence type (building and population) is calculated using *Equation 63*.

Equation 63: Loss Ratio per Basis Calculation for a Single Hurricane Event

$$LRB_{HRCN_{Co_{CnsqType}}} = \frac{Loss_{HRCN_{Co_{CnsqType}}}}{HLRExposure_{Co_{CnsqType}}}$$

where:

$LRB_{HRCN_{Co_{CnsqType}}}$ is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Hurricane event. Calculation is performed for each consequence type (building and population).

$Loss_{HRCN_{Co_{CnsqType}}}$ is the loss (by consequence type) experienced from the Hurricane event documented to have occurred in the county (in dollars).

$HLRExposure_{Co_{CnsqType}}$ is the total value (by consequence type) of the county estimated to have been exposed to the Hurricane event (in dollars).

Hurricane events (particularly tropical storms) may occur in areas without resulting in recorded loss to buildings or population. SHELDUS does not record events in which no loss occurred, so a number of zero-loss event records are inserted into the loss data to align the event count in the HLR calculation to the historic event count experienced within the SHELDUS period of record (1995 to 2016). For Hurricane, the historic year-month event count is extracted using the intersection between the Hurricane event path polygons and the Census block polygons used to calculate exposure (see *Table 37*). The observation date of the storm observation point (see *Section 13.1*) used to build the Hurricane event path polygon intersecting the county is used to sync the event to its year-month. A list of distinct Hurricane observation dates is compiled for the Hurricane event path polygon-Census block intersections within the county, and the historic year-month event count is the number of distinct Hurricane observation dates in this list.

If the number of loss-causing Hurricane event records from SHELDUS is less than the summed historic year-month event counts for the county, a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and regional. The regional definition for Hurricane is derived from the FEMA administrative region definitions with Regions I, II, and III merged, but further divides them into coastal regions (for the East and Gulf coasts) and inland regions along a county-level boundary that approximates the hurricane prone regions identified in the American Society of Civil Engineers (ASCE) 7-05, Minimum Design Loads for Buildings and Other Structures[51] (*Figure 14*). This hazard-specific region definition was introduced for Hurricane due to the exaggerated EAL values in certain large inland cities with high exposure value (large population and high property values), low hazard occurrence, and use of national weighting, which can skew the HLR.

Figure 76 and *Figure 78* display the largest weighting factor contributor in the Bayesian credibility calculations for the Hurricane HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Hurricane events within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or regional events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from regional-level loss data. *Figure 77* and *Figure 79* represent the final county-level HLR values for Hurricane.

[51] American Society of Civil Engineers. (2005). Minimum design loads for buildings and other structures (ASCE/SEI 7-05). Reston, VA: American Society of Civil Engineers.

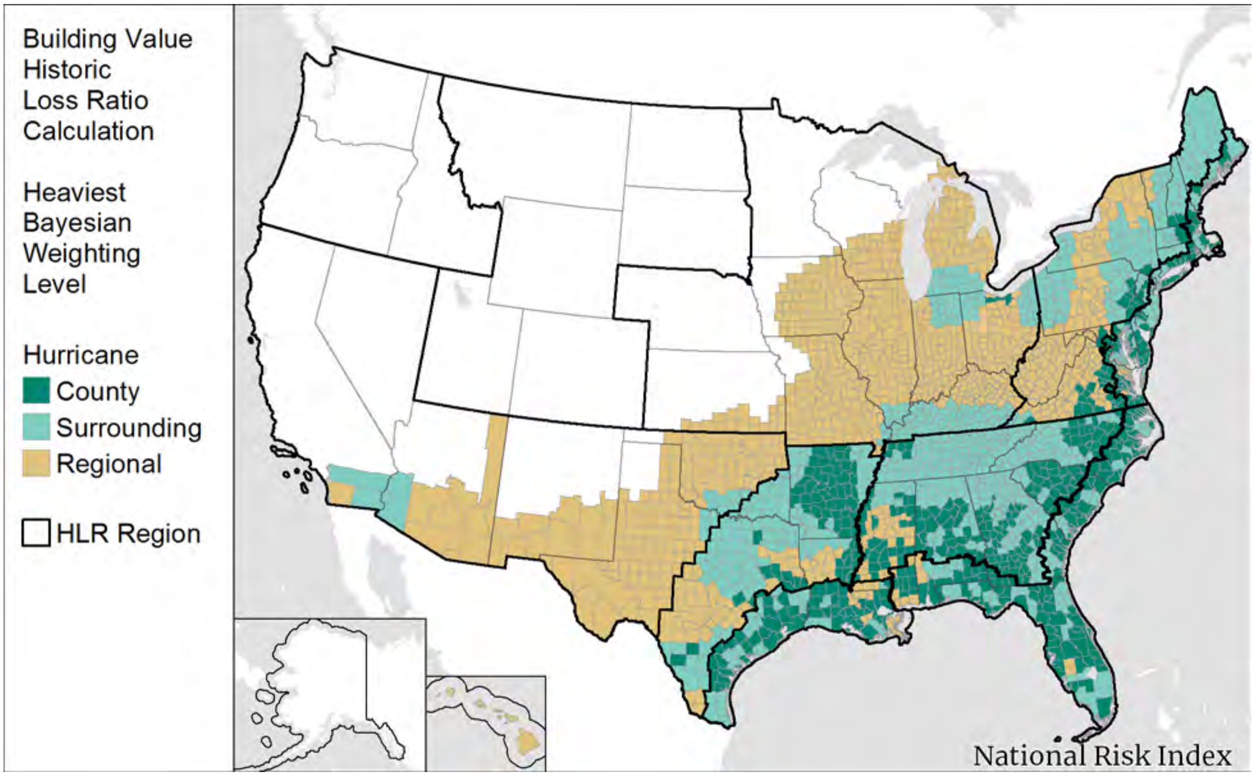

Figure 76: Hurricane Heaviest Bayesian Weighted Level – Building Value

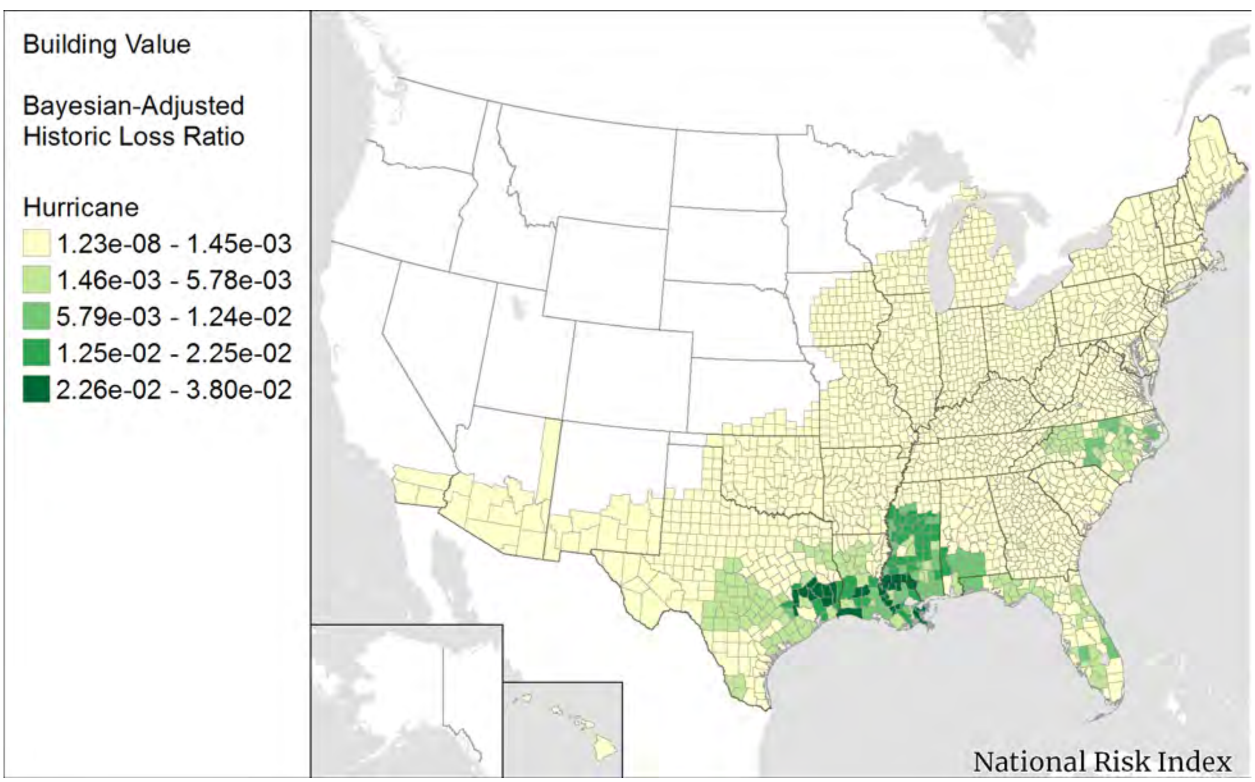

Figure 77: Hurricane HLR – Building Value

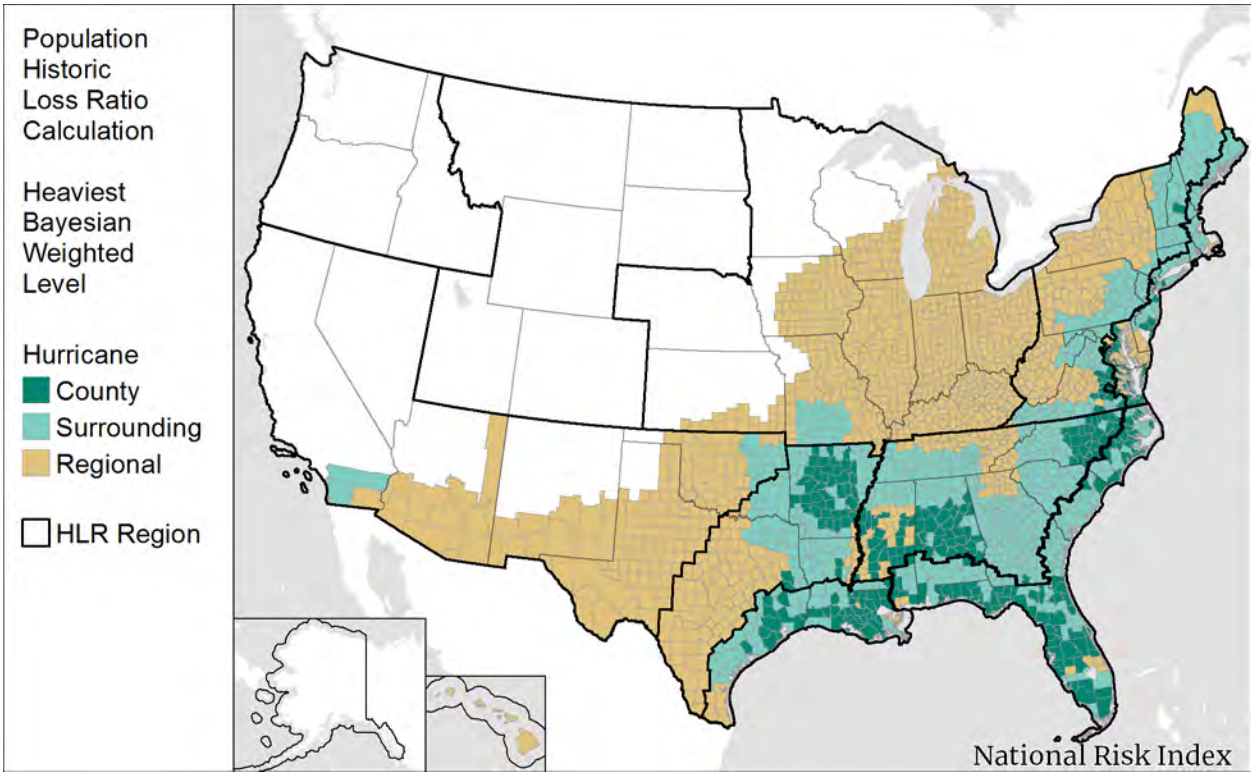

Figure 78: Hurricane Maximum Weighting Factor Contributor – Population

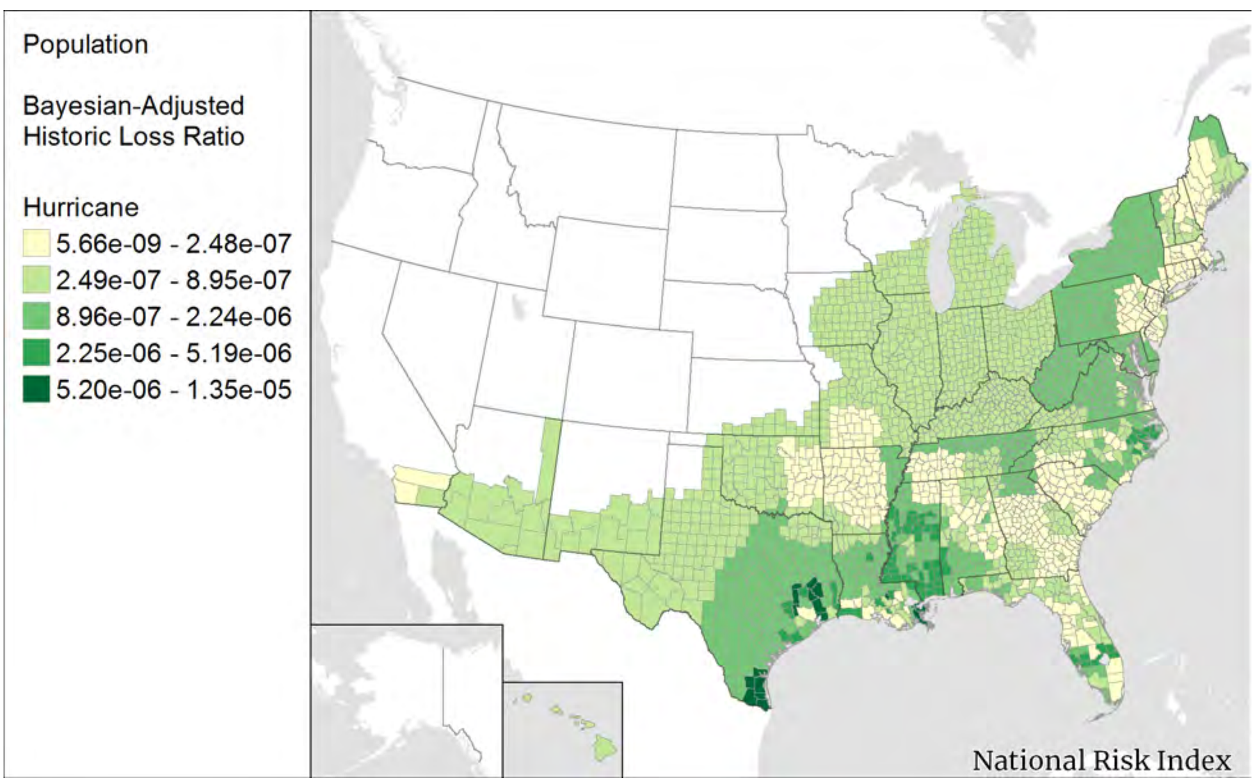

Figure 79: Hurricane HLR – Population

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

13.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 64*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 64: Census Block Expected Annual Loss to Hurricanes

$$EAL_{HRCN_{CB_{Bldg}}} = Exposure_{HRCN_{CB_{Bldg}}} \times Freq_{HRCN_{CB}} \times HLR_{HRCN_{CB_{Bldg}}}$$

$$EAL_{HRCN_{CB_{Pop}}} = Exposure_{HRCN_{CB_{Pop}}} \times Freq_{HRCN_{CB}} \times HLR_{HRCN_{CB_{Pop}}}$$

where:

$EAL_{HRCN_{CB_{Bldg}}}$	is the Expected Annual Loss to building value due to Hurricane events for a specific Census block (in dollars).
$Exposure_{HRCN_{CB_{Bldg}}}$	is the building value exposed to Hurricane events in the Census block (in dollars).
$Freq_{HRCN_{CB}}$	is the annualized Hurricane frequency for the Census block (events per year).
$HLR_{HRCN_{CB_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Hurricane for the Census block.
$EAL_{HRCN_{CB_{Pop}}}$	is the Expected Annual Loss to population value due to Hurricane events for a specific Census block (in dollars).
$Exposure_{HRCN_{CB_{Pop}}}$	is the population value exposed to Hurricane events in the Census block (in dollars).
$HLR_{HRCN_{CB_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Hurricane for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building and population loss at the Census block level as in *Equation 65*.

Equation 65: Census Tract and County Expected Annual Loss to Hurricanes

$$EAL_{HRCN_{CT}} = \sum_{CB}^{CT} EAL_{HRCN_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{HRCN_{CB_{Pop}}}$$

$$EAL_{HRCN_{Co}} = \sum_{CB}^{Co} EAL_{HRCN_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{HRCN_{CB_{Pop}}}$$

where:

$EAL_{HRCN_{CT}}$ is the total Expected Annual Loss due to Hurricane events for a specific Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{HRCN_{CB_{Bldg}}}$ is the summed Expected Annual Loss to building value due to Hurricane events for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{HRCN_{CB_{Pop}}}$ is the summed Expected Annual Loss to population value due to Hurricane events for all Census blocks in the Census tract (in dollars).

$EAL_{HRCN_{Co}}$ is the total Expected Annual Loss due to Hurricane events for a specific county (in dollars).

$\sum_{CB}^{Co} EAL_{HRCN_{CB_{Bldg}}}$ is the summed Expected Annual Loss to building value due to Hurricane events for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{HRCN_{CB_{Pop}}}$ is the summed Expected Annual Loss to population value due to Hurricane events for all Census blocks in the county (in dollars).

Figure 80 shows the total EAL (building value and population combined) to Hurricane events.

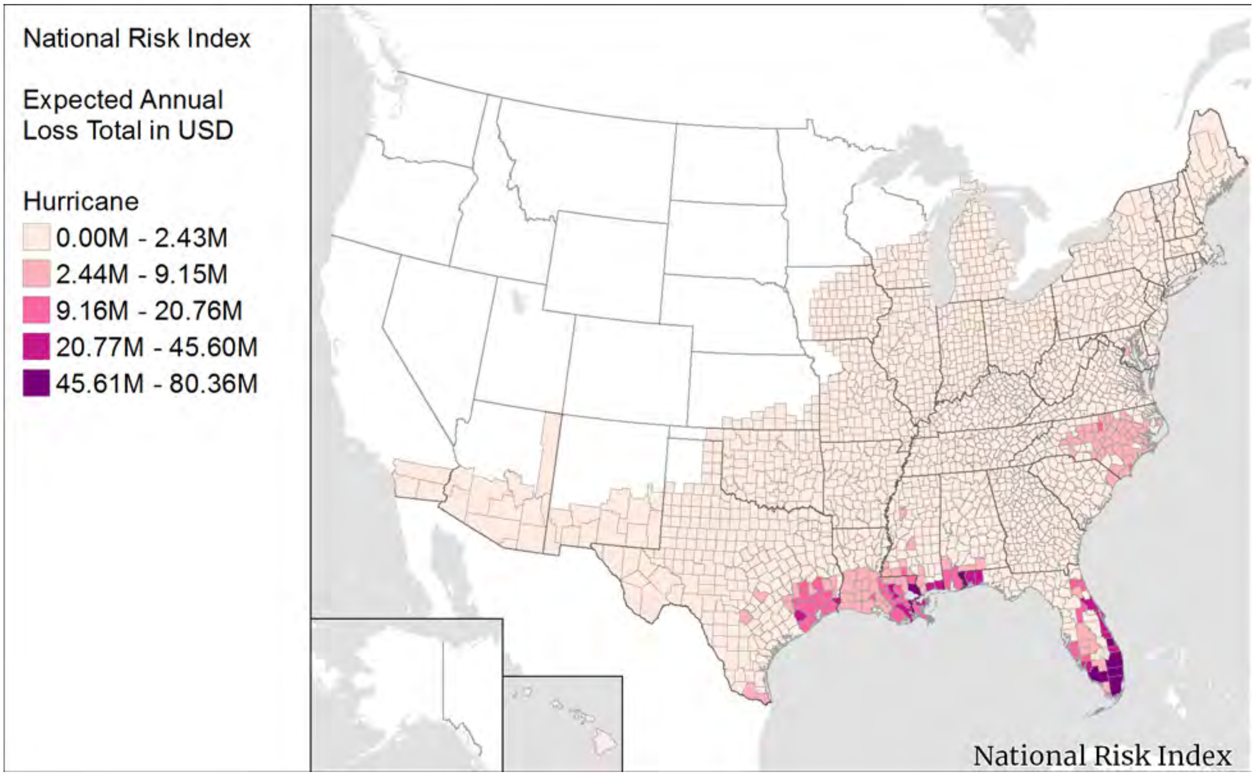

Figure 80: Total Expected Annual Loss by County to Hurricane

With the Hurricane total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Hurricane Risk Index score.

14 Ice Storm

An Ice Storm is a freezing rain situation (rain that freezes on surface contact) with significant ice accumulations of 0.25 inches or greater.

14.1 Spatial Source Data

Historical Event Source: *U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), Damaging Ice Storm GIS*[52]

The CRREL Damaging Ice Storm GIS database includes footprint polygons representing the area where ice-sensitive structures (i.e., overhead power, phone and cable TV lines, communication towers, and trees) were damaged by freezing rain storms in a subset of storms between 1940 and the spring of 2014, with modeled ice thicknesses designated as significant based on an established 50-year mean recurrence interval (see *Figure 81*). Start and end dates for Ice Storm events are also included in the data. Ice Storms that cause only slippery roads are not included. This data source is not complete for all years in the period of record, as many weather stations did not begin storing electronic records until the early 1970s.

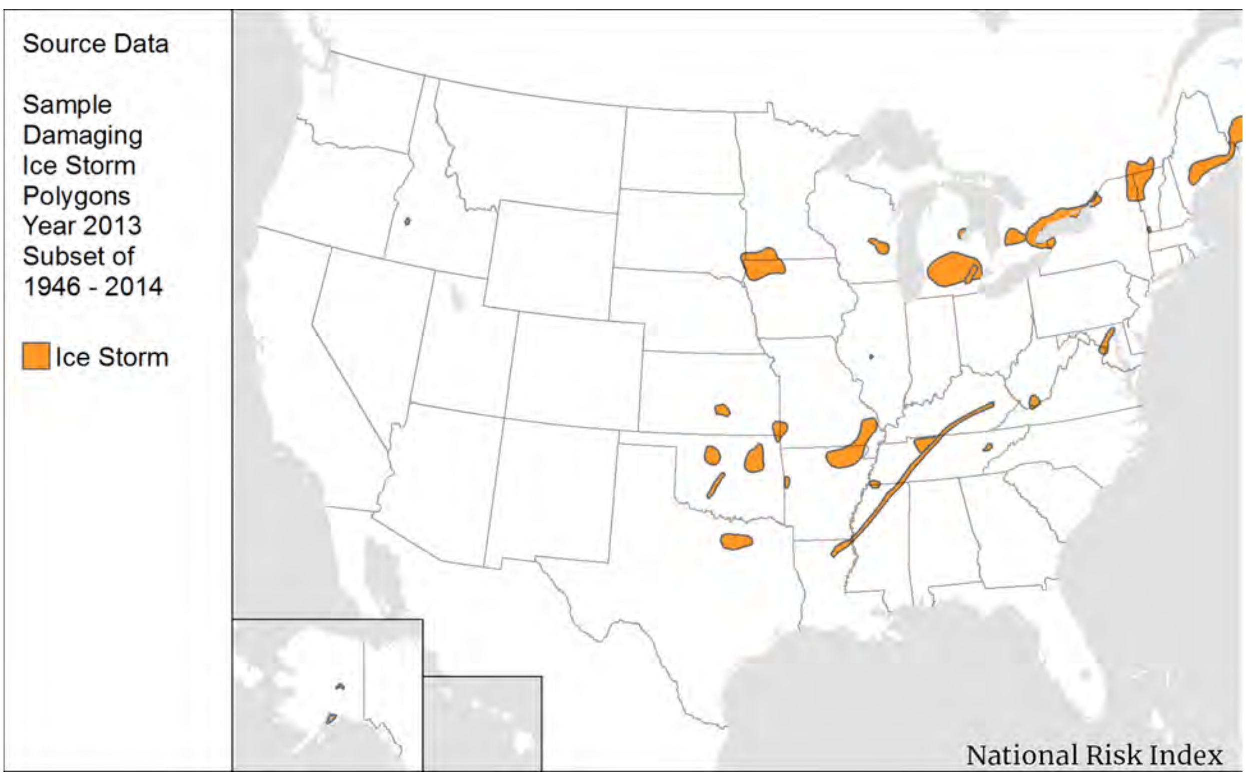

Figure 81: Map of Sample Damaging Ice Storm Polygons

[52] Cold Regions Research and Engineering Laboratory, US Army Corps of Engineers. (2014). Damaging Ice Storm Geographic Information System [online dataset]. Retrieved from https://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/490684/damaging-ice-storm-gis/.

14.1.1 PERIOD OF RECORD

To capture the largest extent of credible data, records from 12/31/1946 to 2/12/2014 are analyzed. The period of record for which Ice Storm data are utilized is 67.16 years.

14.2 Data Pre-Processing

Because the source data provide Ice Storm footprint polygons that work well for the purposes of the NRI, no spatial pre-processing is necessary beyond projecting the data to the North America Albers Equal Area Conic projection. However, some inaccuracies can be found in the storm event start and end dates, such as end dates that precede their start dates or exceptionally long storms that were deemed suspect. Once Ice Storm durations are calculated, any negative or zero-day durations are set to 1, while any storms longer than 30 days are capped at 30. These durations will be used to estimate exposure and frequency.

14.3 Determination of Possibility of Hazard Occurrence

To distinguish between areas where no Ice Storm events have occurred and those where such events are not deemed possible, a control table was generated to designate which counties have some probability of Ice Storm occurrence. This was initially determined by selecting only counties that intersected a past Ice Storm footprint polygon. However, this selection was widened to include all counties in states that intersected a past Ice Storm footprint polygon, excepting Florida. Counties in Florida that intersected past Ice Storm footprint polygons were included as possible; however, the southern parts of the state that had not experienced an Ice Storm were not included. Any county that had sustained economic loss due to an Ice Storm as reported in SHELDUS was also included as one in which Ice Storm occurrence is possible. (See *Figure 82*).

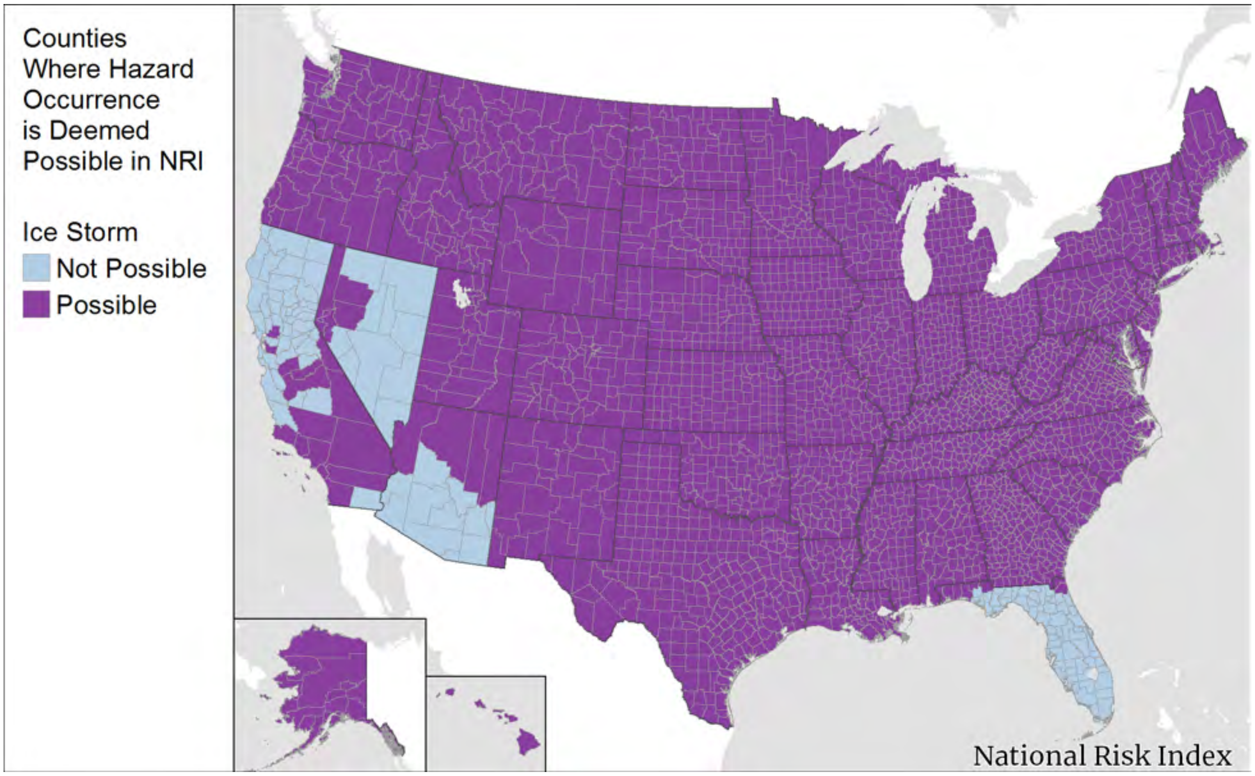

Figure 82: Map of Counties Deemed Possible for Ice Storm Occurrence

14.4 Exposure

To identify areas of exposure, the Ice Storm event-day polygons are intersected with the Census block polygons within the NRI processing database. The resulting table contains the storm's unique identifier, Census block number, and the intersected area in square kilometers (see *Table 39*).

Table 39: Sample Data from the Ice Storm Census Block Intersection Table

IceStormID	CensusBlock	IntersectedAreaKm^2
568	511610308024005	0.087504
568	511610308024006	0.035518
568	511610308024007	0.287145

Because an Ice Storm event can occur over several days or a single day, an event-day basis was used to estimate exposure and frequency as this method better captures the variability in duration between events. To determine exposure value, the average coverage of an Ice Storm event-day is found by taking the sum of the products of the intersected areas for all storms multiplied by their event-day durations and dividing this sum by the total number of Ice Storm event-days for the Census block. This is multiplied by the developed area building value density and the developed area population density of the Census block to model the conservative-case concentration of exposure within the Census block. These developed area Census block building and population densities have been calculated by dividing the total values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers; see *Equation 66*). The VSL was used to express population exposure in terms of dollars.

Equation 66: Census Block Ice Storm Exposure

$$Exposure_{ISTM\,CB\,Bldg} = \frac{\sum_{ISTM}^{CB}\left(IntsctArea_{ISTM\,CB} \times Days_{ISTM}\right)}{Days_{ISTM\,CB}} \times DevAreaDen_{CB\,Bldg}$$

$$Exposure_{ISTM\,CB\,Pop} = \left(\frac{\sum_{ISTM}^{CB}\left(IntsctArea_{ISTM\,CB} \times Days_{ISTM}\right)}{EventCount_{ISTM\,CB}} \times DevAreaDen_{CB\,Pop}\right) \times VSL$$

where:

$Exposure_{ISTM\,CB\,Bldg}$	is the building value exposed to Ice Storm events for a specific Census block (in dollars).
$IntsctArea_{ISTM\,CB}$	is the intersected areas of the Ice Storm event polygon with the Census block (in square kilometers).
$Days_{ISTM}$	is the event-day duration of the Ice Storm event (in days).
$EventCount_{ISTM\,CB}$	is the total number of Ice Storm event polygons that intersect the Census block.
$\sum_{ISTM}^{CB}$	is the sum for all Ice Storm event polygons intersecting the Census block.
$DevAreaDen_{CB\,Bldg}$	is the developed area building value density of the Census block (in dollars per square kilometer).
$Exposure_{ISTM\,CB\,Pop}$	is the population value exposed to Ice Storm events for a specific Census block (in dollars).
$DevAreaDen_{CB\,Pop}$	is the developed area population density of the Census block (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).

In cases where a Census block is deemed potentially at risk for Ice Storm damage, but has had no historical Ice Storm events, the exposure value is estimated to be the full Census block building value and population value. A low HLR and low frequency of Ice Storm event-days will diminish the effect of using full Census block values in the final EAL calculation.

Because the exposure model uses a conservative-case concentration of exposure and a developed area density value, it is possible to mathematically generate an exposure value that is greater than the total value of the Census block. The Hazus-recorded population and building value are considered ceilings on exposure. For example, if the calculated exposed population exceeds the Hazus-recorded population, then the Hazus-recorded population is used as the population exposure value for the Census block.

14.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 67*).

Equation 67: Census Tract and County Ice Storm Exposure

$$Exposure_{ISTM_{CT_{Bldg}}} = \sum_{CB}^{CT} Exposure_{ISTM_{CB_{Bldg}}}$$

$$Exposure_{ISTM_{Co_{Bldg}}} = \sum_{CB}^{Co} Exposure_{ISTM_{CB_{Bldg}}}$$

$$Exposure_{ISMT_{CT_{Pop}}} = \sum_{CB}^{CT} Exposure_{ISTM_{CB_{Pop}}}$$

$$Exposure_{ISTM_{Co_{Pop}}} = \sum_{CB}^{Co} Exposure_{ISTM_{CB_{Pop}}}$$

where:

$Exposure_{ISTM_{CT_{Bldg}}}$	is the building value exposed to Ice Storm event-days in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{ISTM_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Ice Storms for each Census block within the Census tract (in dollars).
$Exposure_{ISTM_{Co_{Bldg}}}$	is the building value exposed to Ice Storm event-days in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{ISTM_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Ice Storms for each Census block within the county (in dollars).
$Exposure_{ISMT_{CT_{Pop}}}$	is the population value exposed to Ice Storm event-days in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{ISTM\,CB_{Pop}}$	is the summed value of all population exposed to Ice Storms for each Census block within the Census tract (in dollars).
$Exposure_{ISTM\,Co_{Pop}}$	is the population value exposed to Ice Storm event-days in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{ISTM\,CB_{Pop}}$	is the summed value of all population exposed to Ice Storms for each Census block within the county (in dollars).

14.5 Historic Event-Day Count

The count of historic Ice Storm event-days is computed as the number of distinct Ice Storm event polygons that intersect a 49-by-49-km fishnet grid cell multiplied by the number of duration days associated with each Ice Storm event (see *Equation 68*).

Equation 68: Fishnet Ice Storm Event-Day Count

$$EventDayCount_{ISTM\,Fish} = EventCount_{ISTM\,Fish} \times \sum_{ISTM}^{Fish} Days_{ISTM}$$

where:

$EventDayCount_{ISTM\,Fish}$	is the count of Ice Storm event-days calculated for a specific fishnet grid cell (in days).
$EventCount_{ISTM\,Fish}$	is the count of distinct Ice Storm event polygons that intersect the fishnet grid cell.
$\sum_{ISTM}^{Fish} Days_{ISTM}$	is the sum of the duration days for each Ice Storm event polygon that intersects the fishnet grid cell (in days),

Historic Event-Day Counts are supplied at the Census tract and county levels as the area-weighted Ice Storm event-day count of the fishnet grid cells that intersect the Census tract and county, respectively.

14.6 Frequency

The frequency value represents the estimated number of recorded Ice Storm event-days each year for a specific area. This annualized frequency is calculated at the Census block level, and the Census block level value is used in the EAL calculations.

Frequency calculations use the Ice Storm footprint polygons from the source data as well as their corresponding computed duration days from the pre-processing of the data. The footprint polygons are intersected with a 49-by-49-km fishnet grid. The sum of Ice Storm event-days for the polygons intersecting each grid cell is recorded, and the Census block inherits this aggregated event-day count from the grid cell that encompasses it (see *Equation 68*). If the Census block intersects multiple fishnet grid cells, an area-weighted average count is calculated (see *Appendix D – Fishnet Event Count*). Using this count, the Census block frequency is calculated as in *Equation 69*.

Equation 69: Census Block Ice Storm Frequency

$$Freq_{ISTM_{CB}} = \frac{EventCount_{ISTM_{CB}}}{PeriodRecord_{ISTM}}$$

where:

$Freq_{ISTM_{CB}}$	is the annualized area-weighted frequency of Ice Storm event-days determined for a specific Census block (event-days per year).
$EventCount_{ISTM_{CB}}$	is the number of historic Ice Storm event-days calculated for the Census block.
$PeriodRecord_{ISTM}$	is the period of record for Ice Storm (67.14 years).

14.6.1 MINIMUM ANNUAL FREQUENCY

If a Census block's historical Ice Storm event-day count is 0, but the Census block is part of a county that was designated as one in which Ice Storms are possible, the Census block is assigned the minimum annual Ice Storm frequency. This minimum frequency is set at 0.01489, or once in the period of record (1 in 67.14 years).

14.6.2 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level. These values may not exactly match that of dividing the number of recorded Ice Storm event-days at the Census tract and county level by the period of record, as the event count for frequency is a fishnet area-weighted event count including Ice Storms that may have impacted the surrounding area but not the county or Census tract itself. The frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 70*.

Equation 70: Census Tract and County Area-Weighted Ice Storm Frequency Aggregation

$$Freq_{ISTM_{CT}} = \frac{\sum_{CB}^{CT}\left(Freq_{ISTM_{CB}} \times Area_{CB}\right)}{Area_{CT}}$$

$$Freq_{ISTM_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{ISTM_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{ISTM_{CT}}$ is the annualized area-weighted frequency of Ice Storm event-days determined for a specific Census tract (event-days per year).

$Freq_{ISTM_{CB}}$ is the annualized Ice Storm frequency determined for a specific Census block (event-days per year).

$Area_{CB}$ is the total area of the Census block (in square kilometers).

$\sum_{CB}^{CT}$ is the sum for all Census blocks in the Census tract.

$Area_{CT}$ is the total area of the Census tract (in square kilometers).

$Freq_{ISTM_{Co}}$ is the annualized area-weighted Ice Storm frequency determined for a specific county (event-days per year).

$\sum_{CB}^{Co}$ is the sum for all Census blocks in the county.

$Area_{Co}$ is the total area of the county (in square kilometers).

Figure 83 displays annualized Ice Storm frequency at the county level.

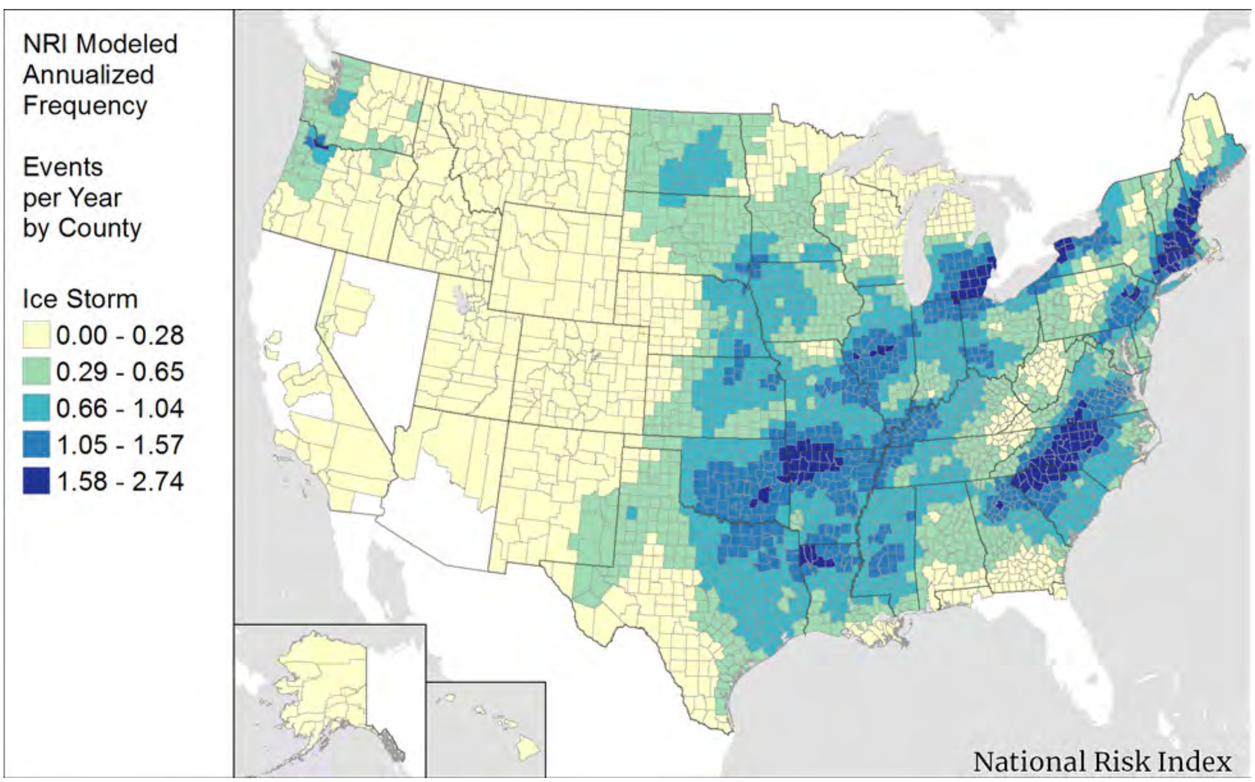

Figure 83: Annualized Ice Storm Frequency by County

14.7 Historic Loss Ratio

The Ice Storm HLR is the representative percentage of a location's hazard exposure area that experiences loss due to an Ice Storm event-day, or the average rate of loss associated with the occurrence of an Ice Storm event-day. For a detailed description of the HLR calculation process, see Section 5.4. The HLR parameters described below are specific to the Ice Storm hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. One peril type is mapped to the hazard Ice Storm (see Table 40). These are expanded on an event-day basis based on the number of event duration days from SHELDUS[53] (see Section 5.4.1).

Table 40: Ice Storm Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Ice	3,645	6,647

The HLR exposure value used in the formula below is a county-level value that represents the dollar value of the total building value or the entire population of a county as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event-day and each consequence type (building and population) is calculated using Equation 71.

Equation 71: Loss Ratio per Basis Calculation for a Single Ice Storm Event-Day

$$LRB_{ISTM_{Co_{CnsqType}}} = \frac{Loss_{ISTM_{Co_{CnsqType}}}}{HLRExposure_{Co_{CnsqType}}}$$

where:

$LRB_{ISTM_{Co_{CnsqType}}}$ is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Ice Storm event-day. Calculation is performed for each consequence type (building and population).

$Loss_{ISTM_{Co_{CnsqType}}}$ is the loss (by consequence type) experienced from the Ice Storm event-day documented to have occurred in the county (in dollars).

[53] For Ice Storm loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

$HLRExposure_{Co_{CnsqType}}$ is the total value (by consequence type) of the county estimated to have been exposed to the Ice Storm event-day (in dollars).

Ice Storm event-days may occur in areas without resulting in recorded loss to buildings or population. SHELDUS does not record events in which no loss occurred, so a number of zero-loss event-day records are inserted into the loss data to align the event count in the HLR calculation to the historic event count experienced within the SHELDUS period of record (1995 to 2016). For Ice Storm, a historic year-month event-day count is extracted using an intersection between the Ice Storm event-day polygons and the Census blocks. The begin date of each Ice Storm event-day polygon is used to sync the event to its year-month. A list of distinct Ice Storm start dates is compiled for the event-day polygon-Census block intersections that intersect the county, and the historic year-month event count is the number of distinct Ice Storm start dates in this list.

If the number of loss-causing Ice Storm event-day records from SHELDUS is less than the summed historic year-month event-day counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, regional, and national. The regional definition for Ice Storm is derived from the FEMA regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 84 and *Figure 86* display the largest weighting factor contributor in the Bayesian credibility calculation for the Ice Storm HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Ice Storm event-days within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local, regional, or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing event-days or have widely varying loss ratios get the most influence from regional- or national-level loss data. *Figure 85* and *Figure 87* represent the final county-level HLR values for Ice Storm.

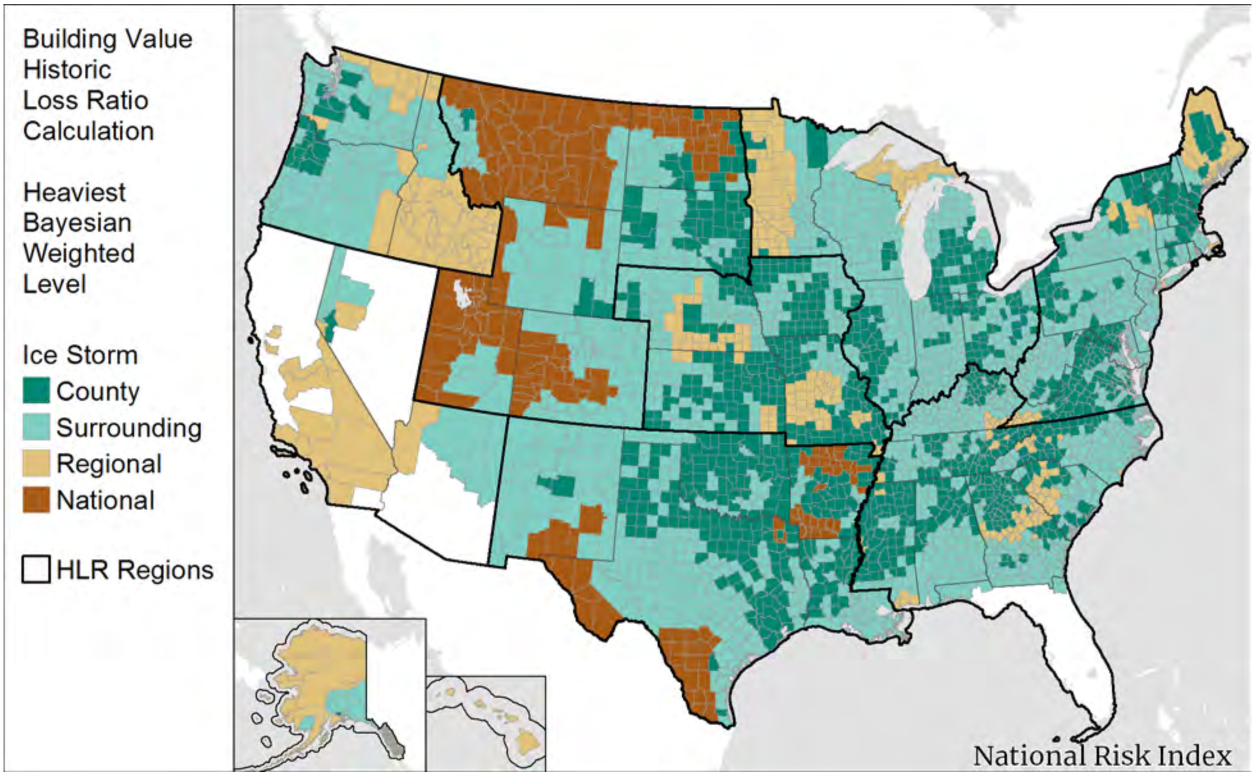

Figure 84: Ice Storm Heaviest Bayesian Weighted Level – Building Value

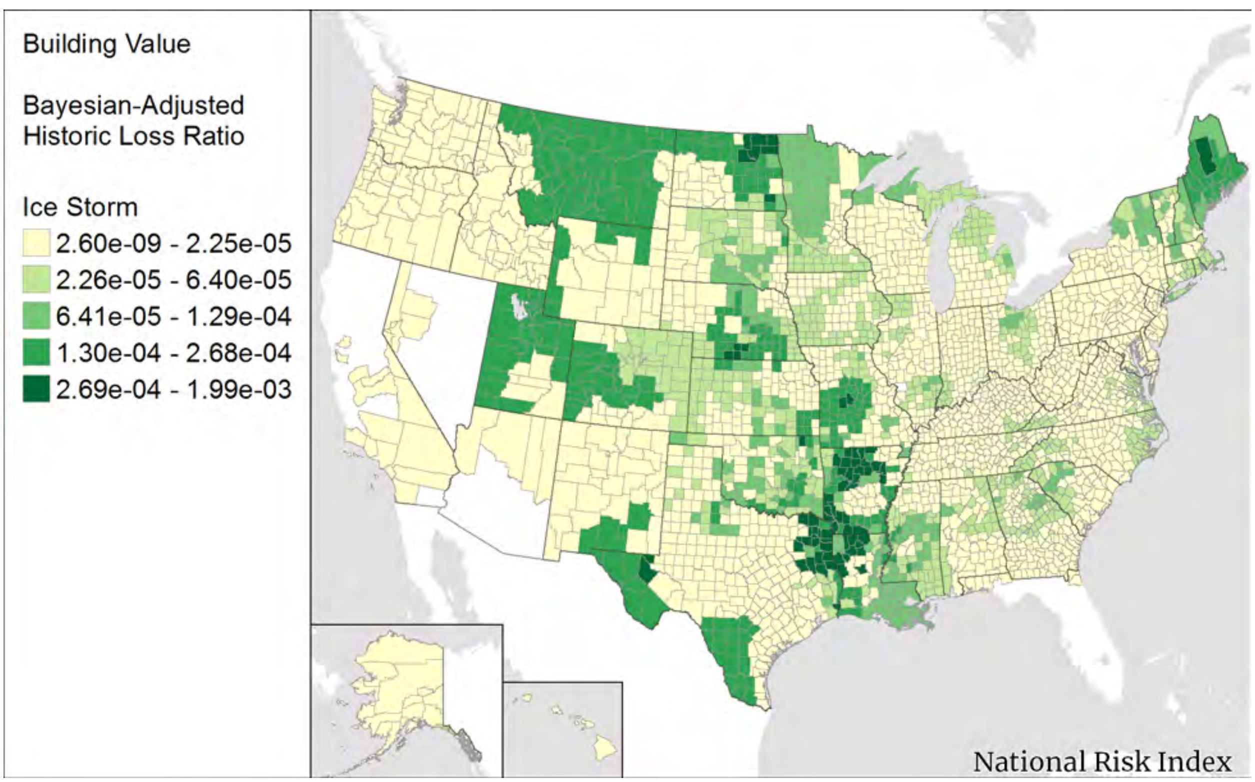

Figure 85: Ice Storm HLR – Building Value

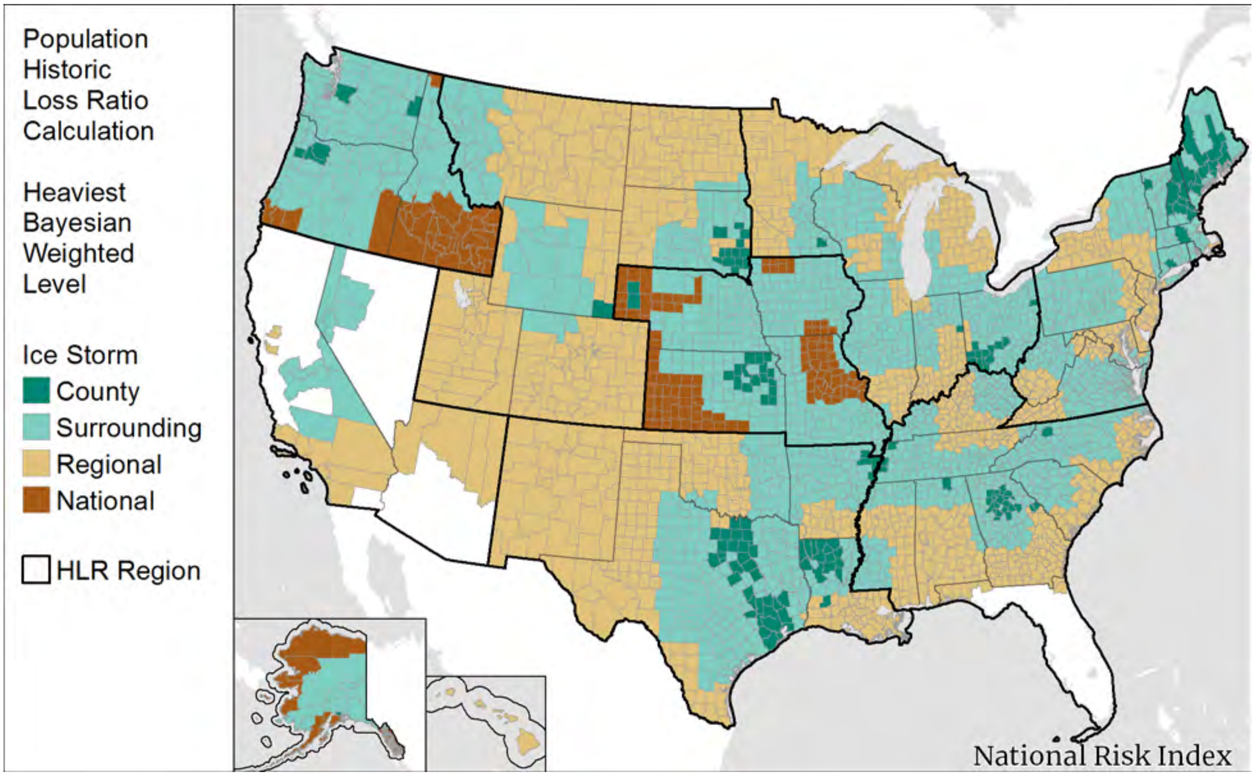

Figure 86: Ice Storm Heaviest Bayesian Weighted Level – Population

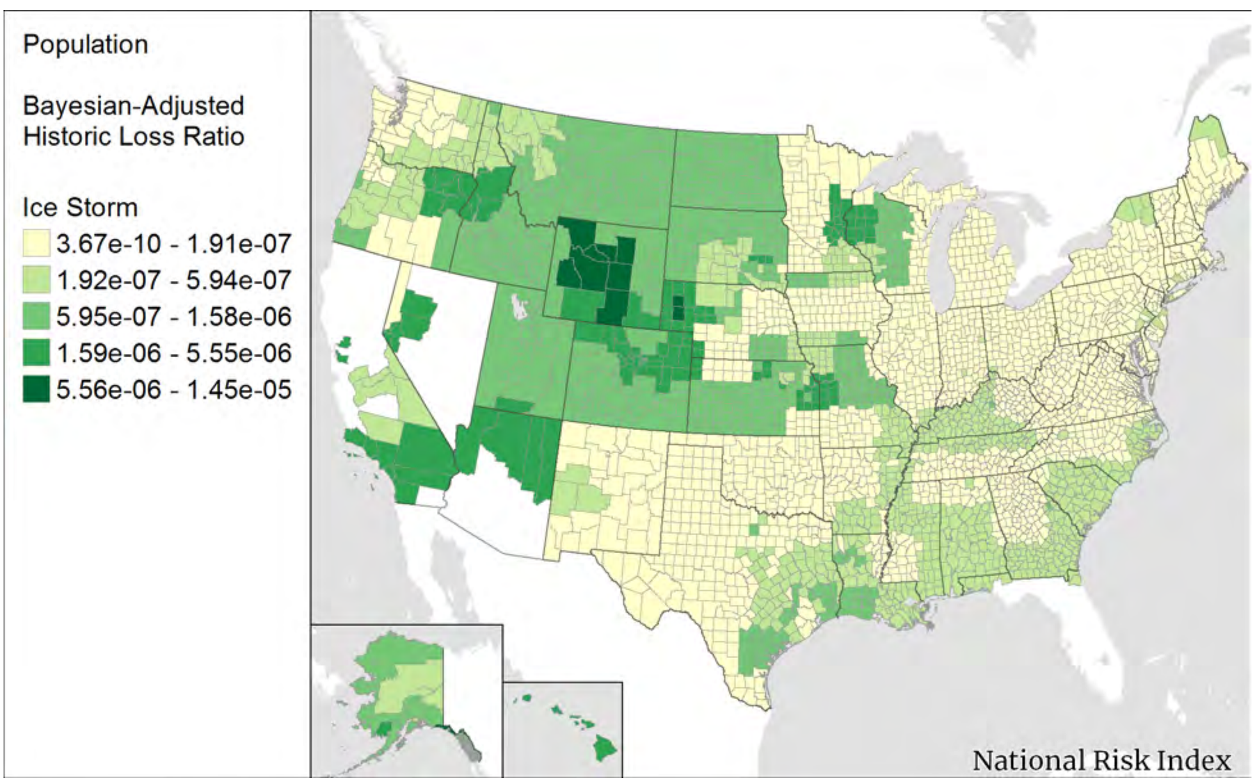

Figure 87: Ice Storm HLR – Population

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

14.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 72*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of Expected Annual Loss at higher levels.

Equation 72: Census Block Expected Annual Loss to Ice Storms

$$EAL_{ISTM_{CB_{Bldg}}} = Exposure_{ISTM_{CB_{Bldg}}} \times Freq_{ISTM_{CB}} \times HLR_{ISTM_{CB_{Bldg}}}$$

$$EAL_{ISTM_{CB_{Pop}}} = Exposure_{ISTM_{CB_{Pop}}} \times Freq_{ISTM_{CB}} \times HLR_{ISTM_{CB_{Pop}}}$$

where:

$EAL_{ISTM_{CB_{Bldg}}}$	is the expected Annual Loss to building value due to Ice Storm events for a specific Census block (in dollars).
$Exposure_{ISTM_{CB_{Bldg}}}$	is the building value exposed to Ice Storm events in the Census block (in dollars).
$Freq_{ISTM_{CB}}$	is the annualized Ice Storm frequency for the Census block (event-days per year).
$HLR_{ISTM_{CB_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Ice Storm for the Census block.
$EAL_{ISTM_{CB_{Pop}}}$	is the Expected Annual Loss to population value due to Ice Storm events for a specific Census block (in dollars).
$Exposure_{ISTM_{CB_{Pop}}}$	is the population value exposed to Ice Storm events in the Census block (in dollars).
$HLR_{ISTM_{CB_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Ice Storm for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building and population loss at the Census block level as in *Equation 73*.

Equation 73: Census Tract and County Expected Annual Loss to Ice Storms

$$EAL_{ISTM_{CT}} = \sum_{CB}^{CT} EAL_{ISTM_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{ISTM_{CB_{Pop}}}$$

$$EAL_{ISTM_{Co}} = \sum_{CB}^{Co} EAL_{ISTM_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{ISTM_{CB_{Pop}}}$$

where:

$EAL_{ISTM_{CT}}$	is the total Expected Annual Loss due to Ice Storm events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{ISTM_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Ice Storm events for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{ISTM_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Ice Storm events for all Census blocks in the Census tract (in dollars).
$EAL_{ISTM_{Co}}$	is the total Expected Annual Loss due to Ice Storm events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{ISTM_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Ice Storm events for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{ISTM_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Ice Storm events for all Census blocks in the county (in dollars).

Figure 88 shows the total EAL (building value and population combined) to Ice Storm events.

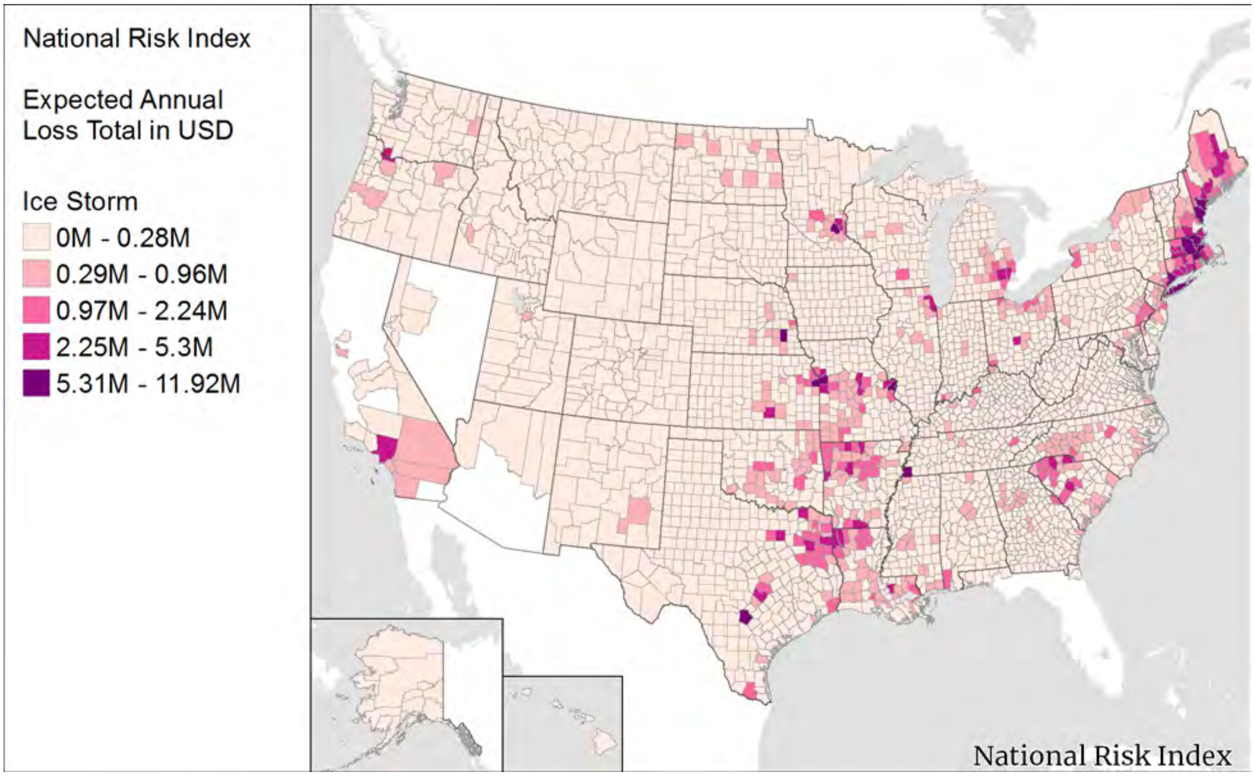

Figure 88: Total Expected Annual Loss by County to Ice Storm

With the Ice Storm total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Ice Storm Risk Index score.

15 Landslide

A Landslide is the movement of a mass of rock, debris, or earth down a slope.

15.1 Spatial Source Data

Susceptible Area Source: *Dr. Jonathan Godt, Landslide Hazards Program Coordinator, USGS, Landslide Hazard Map*[54]

A conterminous United States 1-km grid classified into "Some" or "Negligible" landslide hazard categories was obtained directly from Dr. Jonathan Godt at the USGS. The classified grid was created using conterminous United States slope and relief datasets and past landslide inventories from Oregon, New Jersey, New Mexico, the San Francisco Bay region, and parts of North Carolina. Slope and relief ranges associated with "Some" landslide susceptibility were derived using the cumulative frequencies of slope and relief values at past landslide locations in each state inventory. The raster cell values are either 0 or 10. Grid cells with slope and relief values within the ranges most frequently associated with past landslides were classified as "Some" landslide susceptibility, or a cell value of 10. All other grid cells were classified as "Negligible" landslide susceptibility with a cell value of 0. (See *Figure 89*.)

Note: Because Landslide susceptibility data are not available for Alaska and Hawaii, exposure and, therefore, EAL values cannot be computed within the NRI for these states.

[54] Godt, J.W., Coe, J.A., Baum, R.L., Highland, L.M., Keaton, J.R., & Roth, R.J, Jr. (2012). Prototype landslide hazard map of the conterminous United States. In E. Eberhardt, C. Froese, K. Turner, & S. Leroueil (Eds.), *Landslides and Engineered Slopes: Protecting Society through Improved Understanding: Proceedings of the 11th International and 2nd North American Symposium on Landslides and Engineered Slopes* (pp. 245-250). London: Taylor & Francis Group.

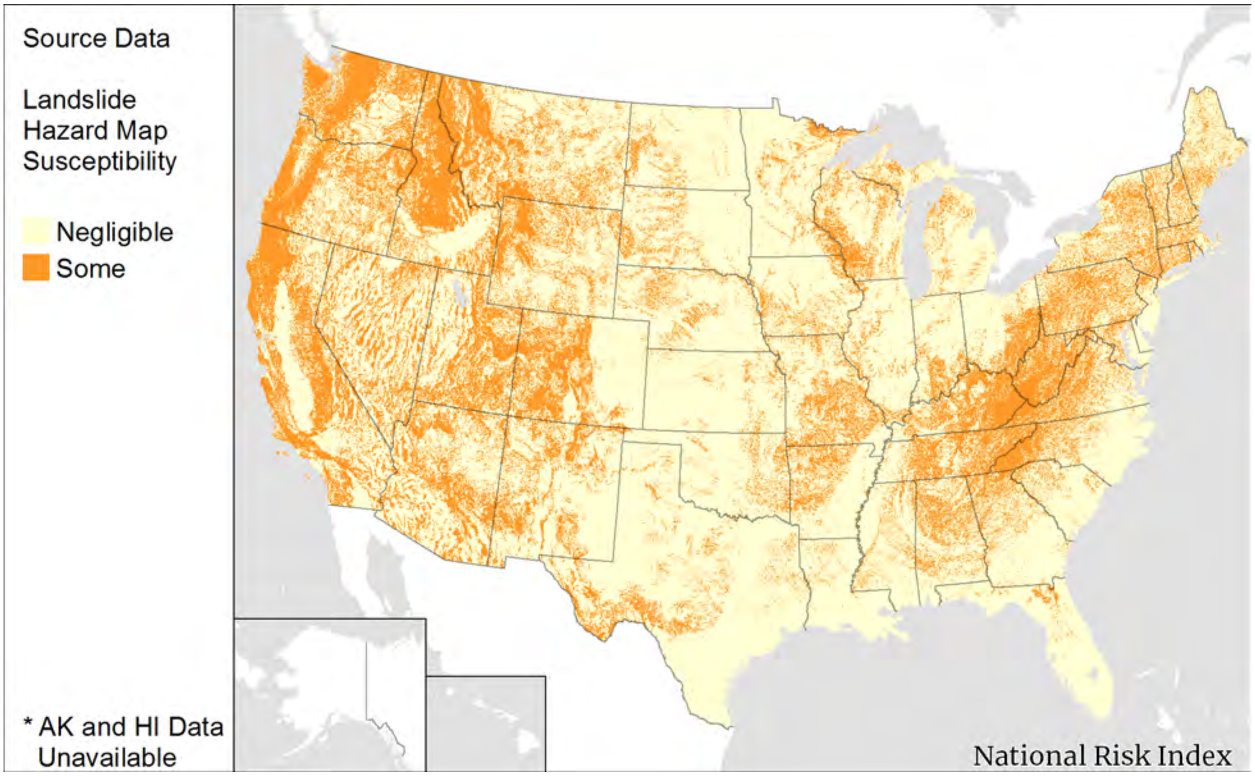

Figure 89: Map of Landslide Raster

Historical Event Source: [National Aeronautics and Space Administration (NASA)](), [Global Landslide Catalog]()[55]

Landslide source data provided by NASA through its Open Data Portal include spatiotemporal data of individual historical Landslide event occurrences dating from 2010 to 2018. Data were available for download in multiple formats, including shapefile format (see *Figure 90*). Records contain coordinates of the Landslide event, date of observation, Landslide type and trigger, any fatalities or injuries, and links to source documentation of the event, typically local news stories.

[55] National Aeronautics and Space Administration. (2018). *Global Landslide Catalog* [online dataset]. Retrieved from *https://data.nasa.gov/Earth-Science/Global-Landslide-Catalog/h9d8-neg4*.

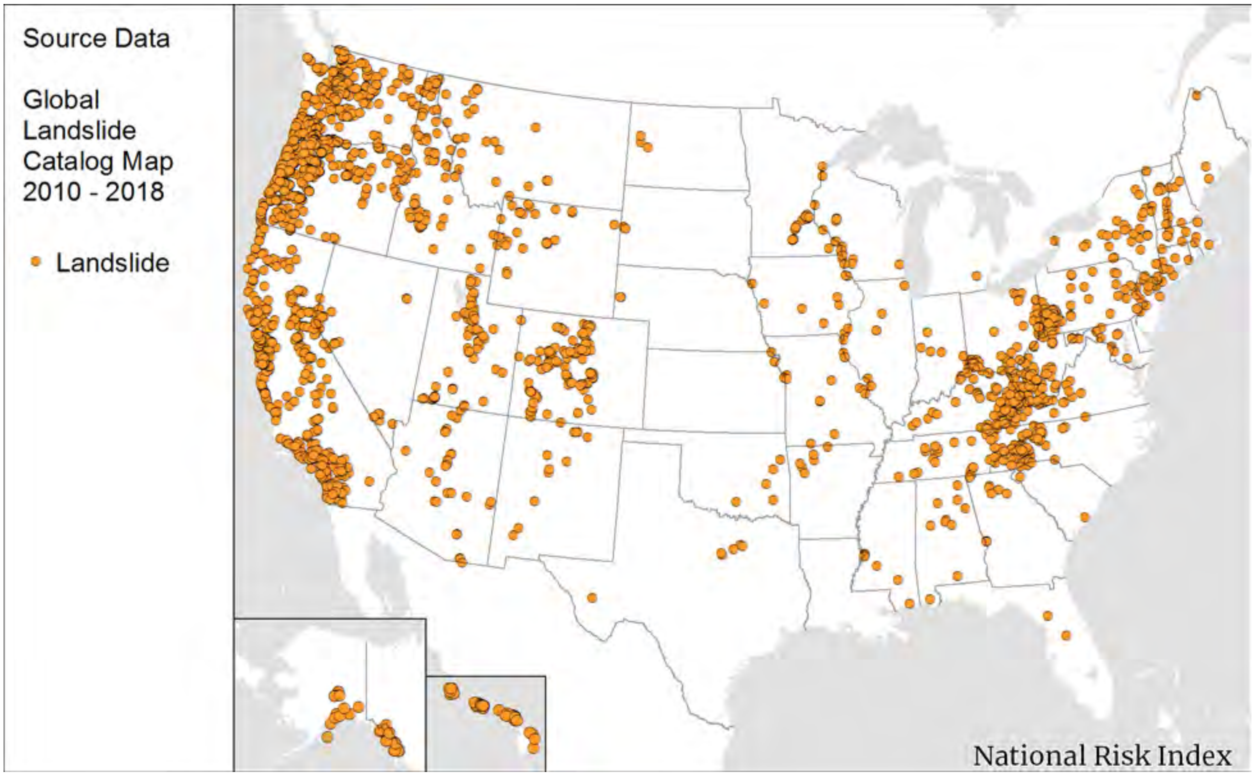

Figure 90: Map of Landslide Points

15.1.1 PERIOD OF RECORD

All Landslide records in the conterminous United States between 1/1/2010 and 11/20/2018 are included in the calculation of frequency, so the period of record for which Landslide data are utilized is 8.89 years.

15.2 Spatial Processing

To determine the intersections of the Landslide susceptibility raster cells (i.e., any cells with a value of 10 denoting "Some" Landslide susceptibility) with Census blocks, the raster formatted data are converted to a vector format (i.e., polygons). Converting the raster dataset to vector format greatly improves the processing speed and repeatability of resource-intensive intersection functions performed within the NRI processing database. A polygon fishnet for which the dimensions (1-by-1-km) and coverage match the raster datasets was created to make the conversion. Because these polygons matched the cells of the raster datasets, the coordinates of each polygon's centroid could be used to query each raster and return its associated value for the corresponding raster cell. The result is that the cell value of the raster is now tabularly related to a single cell Landslide-susceptibility fishnet polygon that can then be intersected with the Census blocks to determine Landslide exposure.

15.3 Determination of Possibility of Hazard Occurrence

Initially, any county that intersected a Landslide-susceptibility fishnet cell polygon or a historical Landslide event as recorded in the Global Landslide Catalog, or that had sustained economic loss due to a Landslide as reported in SHELDUS was included as one in which Landslide occurrence is possible. However, because only 35 counties in the United States were found to have no risk of Landslide according to these criteria, the decision was made to include all counties as those in which Landslides are possible. While the current data source does not supply information for Alaska and Hawaii, these states are still included as possible for Landslide occurrence. In the NRI application, no risk scoring for Alaska and Hawaii will be available as the data are insufficient.

15.4 Exposure

To identify areas of exposure, the Landslide-susceptibility fishnet polygons are intersected with the Census block polygons within the NRI processing database. The resulting table contains the fishnet polygon's unique identifier, Census block number, and the intersected area in square kilometers (see *Table 41*).

Table 41: Sample Data from the Landslide Fishnet Census Block Intersection Table

LandslideFishnetID	CensusBlock	IntersectedAreaKm2
12018935	490230102003288	0.875497717376709
12018937	490230102003288	0.875497717376709
12018944	490399722001306	0.875497717376709

To find exposure value, the sum of the intersection areas of the Landslide-susceptibility fishnet polygons for each Census block is multiplied by the developed area building value density and the developed area population density of the Census block to model the conservative-case concentration of exposure within the Census block. These developed area Census block building and population densities have been calculated by dividing the total county values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers; see *Equation 74*). The VSL was used to express population exposure in terms of dollars.

Equation 74: Census Block Landslide Exposure

$$Exposure_{LNDS_{CB_{Bldg}}} = \sum_{Fish}^{CB} IntsctArea_{LNDS_{Fish_{CB}}} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{LNDS_{CB_{Pop}}} = \left(\sum_{Fish}^{CB} IntsctArea_{LNDS_{Fish_{CB}}} \times DevAreaDen_{CB_{Pop}}\right) \times VSL$$

where:

$Exposure_{LNDS_{CB_{Bldg}}}$	is the building value exposed to Landslide susceptibility in a specific Census block (in dollars).
$\sum_{Fish}^{CB} IntsctArea_{LNDS_{Fish_{CB}}}$	is the sum of the intersected areas of Landslide-susceptibility fishnet polygons with the Census block (in square kilometers).
$DevAreaDen_{CB_{Bldg}}$	is the developed area building value density of the Census block (in dollars per square kilometer).
$Exposure_{LNDS_{CB_{Pop}}}$	is the population value exposed to Landslide susceptibility in a specific Census block (in dollars).
$DevAreaDen_{CB_{Pop}}$	is the developed area population density of the Census block (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).

Because the exposure model uses a conservative-case concentration of exposure and a developed area density value, it is possible to mathematically generate an exposure value that is greater than the total value of the Census block. The Hazus-recorded population and building value are considered ceilings on exposure. For example, if the calculated exposed population exceeds the Hazus-recorded population, then the Hazus-recorded population is used as the population exposure value for the Census block.

15.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 75*).

Equation 75: Census Tract and County Landslide Aggregation

$$Exposure_{LNDS_{CT_{Bldg}}} = \sum_{CB}^{CT} Exposure_{LNDS_{CB_{Bldg}}}$$

$$Exposure_{LNDS_{Co_{Bldg}}} = \sum_{CB}^{Co} Exposure_{LNDS_{CB_{Bldg}}}$$

$$Exposure_{LNDS_{CT_{Pop}}} = \sum_{CB}^{CT} Exposure_{LNDS_{CB_{Pop}}}$$

$$Exposure_{LNDS_{Co_{Pop}}} = \sum_{CB}^{Co} Exposure_{LNDS_{CB_{Pop}}}$$

where:

$Exposure_{LNDS_{CT_{Bldg}}}$ is the building value exposed to Landslide susceptibility in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{LNDS_{CB_{Bldg}}}$ is the summed value of all buildings exposed to Landslide susceptibility for each Census block within the Census tract (in dollars).

$Exposure_{LNDS_{Co_{Bldg}}}$ is the building value exposed to Landslide susceptibility in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{LNDS_{CB_{Bldg}}}$ is the summed value of all buildings exposed to Landslide susceptibility for each Census block within the county (in dollars).

$Exposure_{LNDS_{CT_{Pop}}}$ is the population value exposed to Landslide susceptibility in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{LNDS_{CB_{Pop}}}$ is the summed value of all population exposed to Landslide susceptibility for each Census block within the Census tract (in dollars).

$Exposure_{LNDS_{Co_{Pop}}}$ is the population value exposed to Landslide susceptibility in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{LNDS_{CB_{Pop}}}$ is the summed value of all population exposed to Landslide susceptibility for each Census block within the county (in dollars).

15.5 Historic Event Count

The count of historic Landslide events is computed as the number of distinct Landslide event points (from the Global Landslide Catalog, see *Section 15.1*) that intersect a Census tract. A Historic Event Count is also supplied at the county level as the number of distinct Landslide event points that intersect the county.

15.6 Frequency

The frequency value represents the estimated number of recorded Landslide events each year for a specific area. Because the period of record is so small, this annualized frequency is calculated at the Census tract level (see *Equation 76*), and the Census block inherits this value. The Census block value is used in the EAL calculations.

Frequency calculations use the source data points from the Global Landslide Catalog. The Landslide event count is the total number of Landslide points that intersect the Census tract.

Equation 76: Census Tract Landslide Frequency

$$Freq_{LNDS_{CT}} = \frac{EventCount_{LNDS_{CT}}}{PeriodRecord_{LNDS}}$$

where:

$Freq_{LNDS_{CT}}$	is the annualized frequency of Landslide events determined for a specific Census tract (events per year).
$EventCount_{LNDS_{CT}}$	is the number of Landslide events that intersect the Census tract.
$PeriodRecord_{LNDS}$	is the period of record for Landslide (8.89 years).

15.6.1 MINIMUM ANNUAL FREQUENCY

If a Census tract's historical Landslide event count is 0, but the Census tract is part of a county that was designated as one in which Landslides are possible according to the determination above, the Census tract is assigned the minimum annual Landslide frequency. This minimum frequency is set at 0.02 (1 in 50 years).

15.6.2 FREQUENCY INHERITANCE AND AGGREGATION

The Census block inherits its frequency value from the Census tract that contains it as in *Equation 77*.

Equation 77: Census Block Landslide Inheritance

$$Freq_{LNDS_{CB}} = Freq_{LNDS_{CT}}$$

where:

$Freq_{LNDS_{CB}}$	is the annualized frequency of Landslide events determined for a specific Census block (events per year).
$Freq_{LNDS_{CT}}$	is the annualized frequency of Landslide events determined for a specific Census tract (events per year).

The NRI application provides an area-weighted average frequency value at the county level. This value may not exactly match that of dividing the number of recorded Landslide events at the county level by the period of record. The frequency values at the Census block level are rolled up to the county level using area-weighted aggregations as in *Equation 78*.

Equation 78: County Area-Weighted Landslide Frequency Aggregation

$$Freq_{LNDS_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{LNDS_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{LNDS_{Co}}$	is the annualized area-weighted frequency of Landslide events determined for a specific county (events per year).
$Freq_{LNDS_{CB}}$	is the annualized frequency of Landslide events determined for a specific Census block (events per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 91 displays annualized Landslide frequency at the county level.

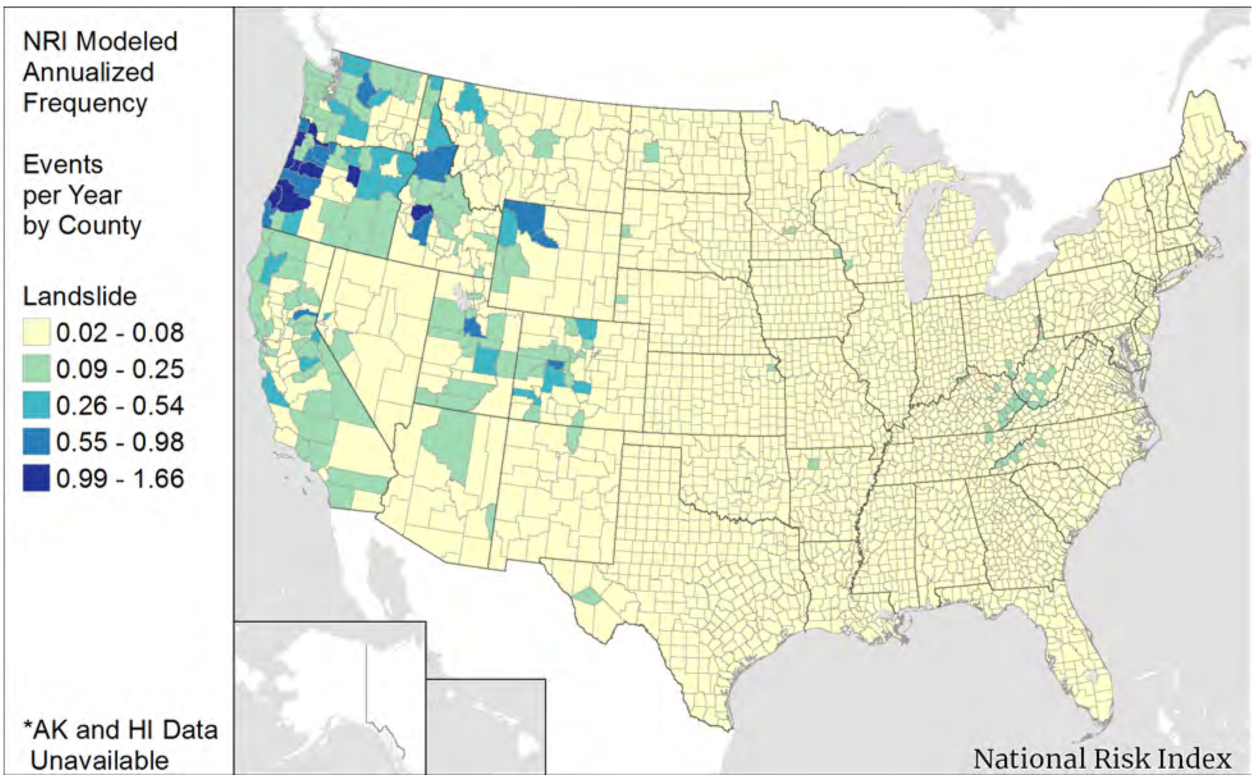

Figure 91: Annualized Landslide Frequency by County

15.7 Historic Loss Ratio

The Landslide HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Landslide event, or the average rate of loss associated with the occurrence of a Landslide event. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Landslide hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Five peril types are mapped to the hazard Landslide (see *Table 42*). These are expanded on an event basis based on the number of records from SHELDUS[56] (see *Section 5.4.1*).

Table 42: Landslide Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Landslide	454	541
LandslideSlump	1	1
MudFlow	0	0
Mudslide	173	179
RockSlide	60	61

The HLR exposure value for Landslide is a county-level value that represents the dollar value of the total building value or the entire population of a county as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event and each consequence type (building and population) is calculated using *Equation 79*.

Equation 79: Loss Ratio per Basis Calculation for a Single Landslide Event

$$LRB_{LNDS_{Co_{CnsqType}}} = \frac{Loss_{LNDS_{Co_{CnsqType}}}}{HLRExposure_{LNDS_{Co_{CnsqType}}}}$$

where:

$LRB_{LNDS_{Co_{CnsqType}}}$	is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Landslide event. Calculation is performed for each consequence type (building and population).
$Loss_{LNDS_{Co_{CnsqType}}}$	is the loss (by consequence type) experienced from the Landslide event documented to have occurred in the county (in dollars).
$HLRExposure_{LNDS_{Co_{CnsqType}}}$	is the total value (by consequence type) of the county estimated to have been exposed to the Landslide event (in dollars).

For counties that have never experienced a Landslide event, an artificial LRB record is created with the county-level exposure and a default loss value of either one person for population loss or, for property loss, a dollar amount based on the total building value of the county (see *Table 43*). This

[56] For Landslide loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information, USGS Landslide News & Info, the USDA's Cost Estimating Guide for Road Construction, NASA's Global Landslide Catalog, and the Oregon Department of Geology and Mineral Industries' Statewide Landslide Information Layer for Oregon

artificial loss creation is an attempt to supplement the historic event data, which only exist for the eight (8) years from 2010 to 2018. Prior to the addition of these artificial loss records, the resulting HLR ratios did not translate well to all county sizes. The use of these artificial loss records allows for a more representative estimation of HLR.

Table 43: Default Landslide Property Loss

Default Loss	Total County Building Value Range
$1M	$0-$500M
$5M	$500,000,001-$1B
$25M	$1,000,000,001+

Because loss ratios representing modeled loss are inserted for counties with no recorded Landslide occurrence, no Bayesian credibility weighting is applied to the county-level HLR values, and each county's HLR represents its average LRB. The resulting county-specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county. *Figure 92* and *Figure 93* represent the final county-level HLR values for Landslide.

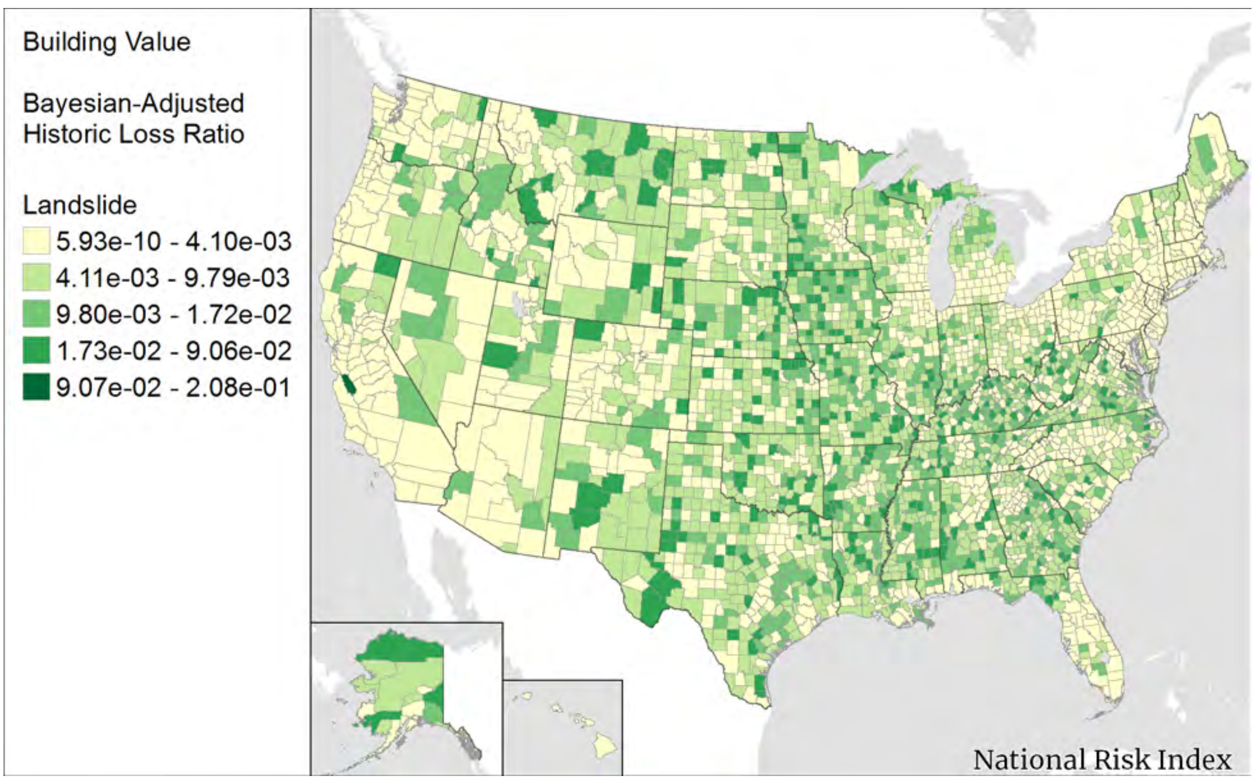

Figure 92: Landslide HLR – Building Value

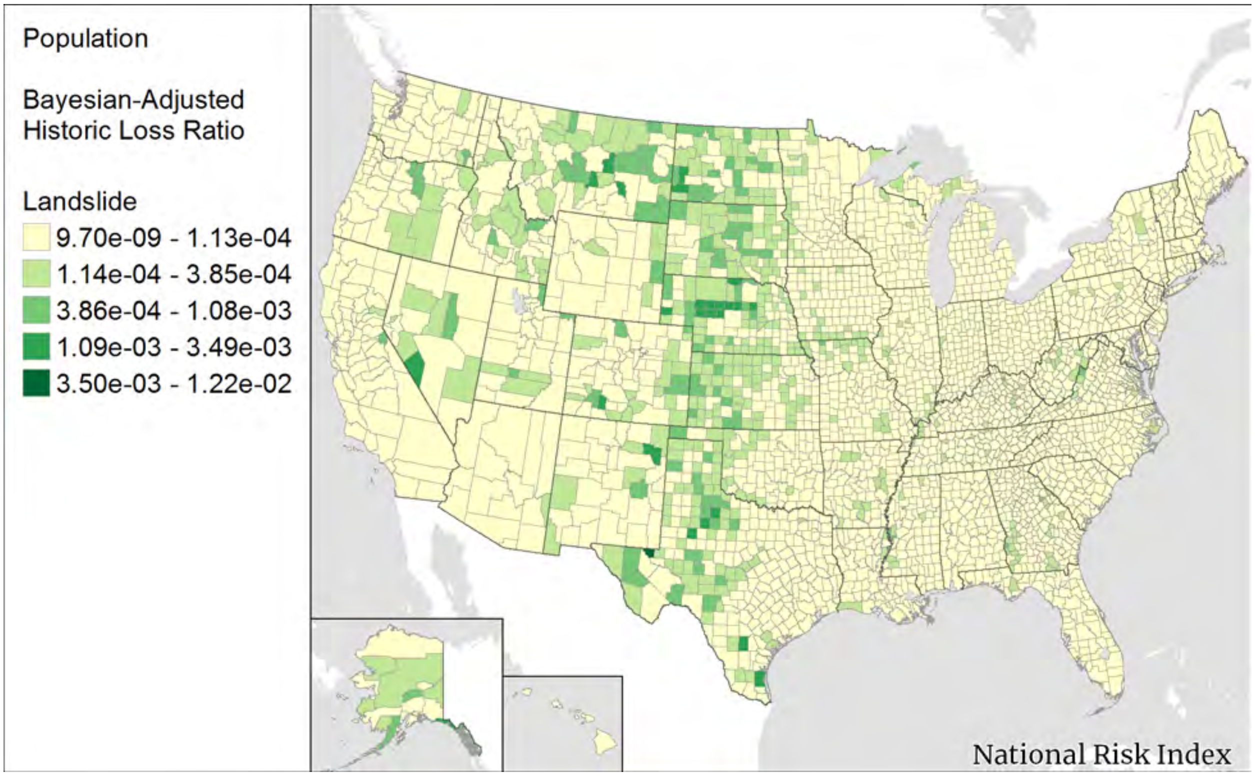

Figure 93: Landslide HLR – Population

15.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 80*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of Expected Annual Loss at higher levels.

Equation 80: Census Block Expected Annual Loss to Landslide

$$EAL_{LNDS_{CB_{Bldg}}} = Exposure_{LNDS_{CB_{Bldg}}} \times Freq_{LNDS_{CB}} \times HLR_{LNDS_{CB_{Bldg}}}$$

$$EAL_{LNDS_{CB_{Pop}}} = Exposure_{LNDS_{CB_{Pop}}} \times Freq_{LNDS_{CB}} \times HLR_{LNDS_{CB_{Pop}}}$$

where:

$EAL_{LNDS_{CB_{Bldg}}}$	is the Expected Annual Loss to building value due to Landslide events for a specific Census block (in dollars).
$Exposure_{LNDS_{CB_{Bldg}}}$	is the building value exposed to Landslide susceptibility in the Census block (in dollars).

$Freq_{LNDS_{CB}}$	is the annualized Landslide frequency for the Census block (events per year).
$HLR_{LNDS_{CB_{Bldg}}}$	is the building Historic Loss Ratio for Landslide for the Census block.
$EAL_{LNDS_{CB_{Pop}}}$	is the Expected Annual Loss to population value due to Landslide events for a specific Census block (in dollars).
$Exposure_{LNDS_{CB_{Pop}}}$	is the population value exposed to Landslide susceptibility in the Census block (in dollars).
$HLR_{LNDS_{CB_{Pop}}}$	is the population Historic Loss Ratio for Landslide for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building and population loss at the Census block level as in *Equation 81*.

Equation 81: Census Tract and County Expected Annual Loss to Landslide

$$EAL_{LNDS_{CT}} = \sum_{CB}^{CT} EAL_{LNDS_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{LNDS_{CB_{Pop}}}$$

$$EAL_{LNDS_{Co}} = \sum_{CB}^{Co} EAL_{LNDS_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{LNDS_{CB_{Pop}}}$$

where:

$EAL_{LNDS_{CT}}$	is the total Expected Annual Loss due to Landslide events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{LNDS_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Landslide events for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{LNDS_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Landslide events for all Census blocks in the Census tract (in dollars).
$EAL_{LNDS_{Co}}$	is the total Expected Annual Loss due to Landslide events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{LNDS_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Landslide events for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{LNDS_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Landslide events for all Census blocks in the county (in dollars).

Figure 94 shows the total EAL (building value and population combined) to Landslide events.

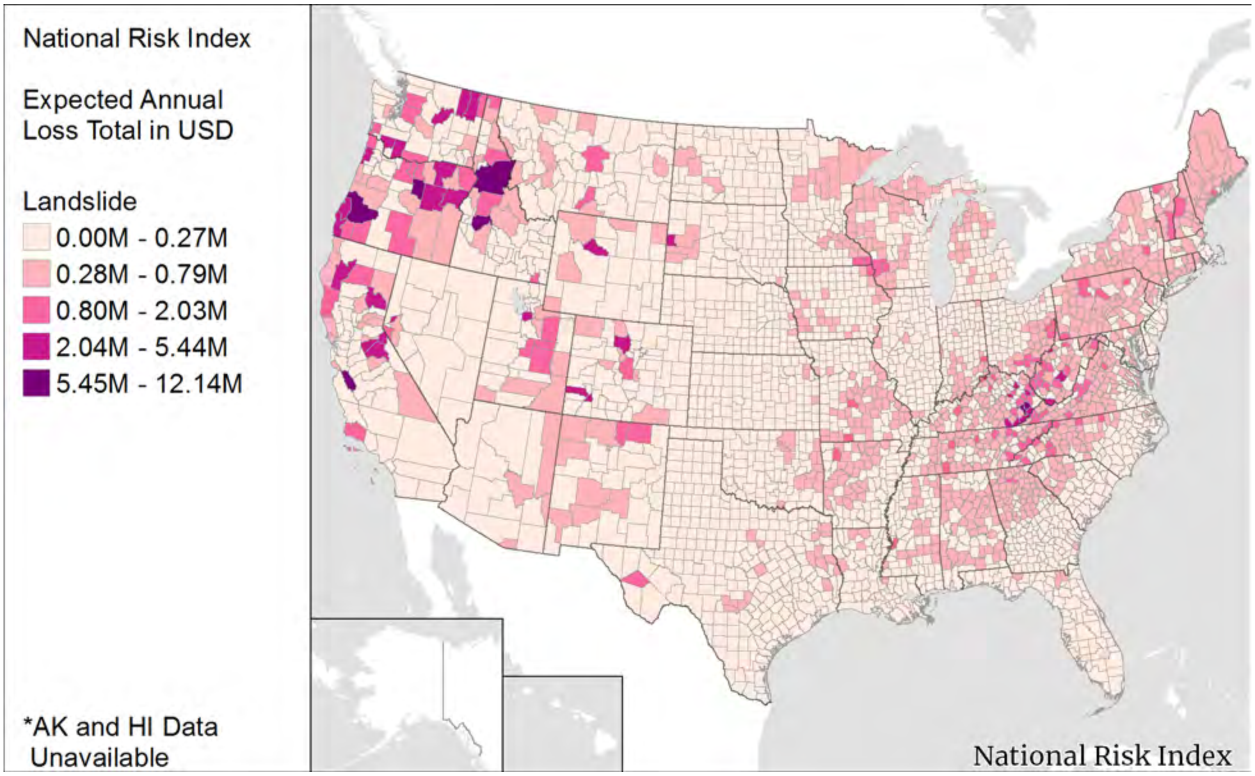

Figure 94: Total Expected Annual Loss by County to Landslide

With the Landslide total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Landslide Risk Index score.

16 Lightning

Lightning is a visible electrical discharge or spark of electricity in the atmosphere between clouds, the air, and/or the ground often produced by a thunderstorm.

16.1 Spatial Source Data

Historical Event Source: *NOAA, National Centers for Environmental Information (NCEI), Cloud-to-Ground Lightning Strikes*[57]

NCEI currently maintains a prototype dataset with all recorded cloud-to-ground Lightning strikes in the conterminous United States from 1986 to 2012. Spatiotemporal records are available in NetCDF (Network Common Data Form) format to authorized NOAA employees and contractors. Each file, organized by time-period aggregation, is a grid of 4-by-4-km cells in the Albers Equal Area projection (see *Figure 95*). Each cell summarizes Lightning strikes for each hour, day, month, or year. The files aggregating Lightning strikes per year are used by the NRI to calculate frequency at the Census block level.

Note: Because Lightning strike data are not available for Alaska and Hawaii, frequency and, therefore, EAL cannot be computed for these states.

[57] National Centers for Environmental Information, National Oceanic and Atmospheric Administration. (2017). *Cloud-to-ground lightning strikes, Prototype* [online dataset]. Retrieved from https://www.ncdc.noaa.gov/data-access/severe-weather/lightning-products-and-services.

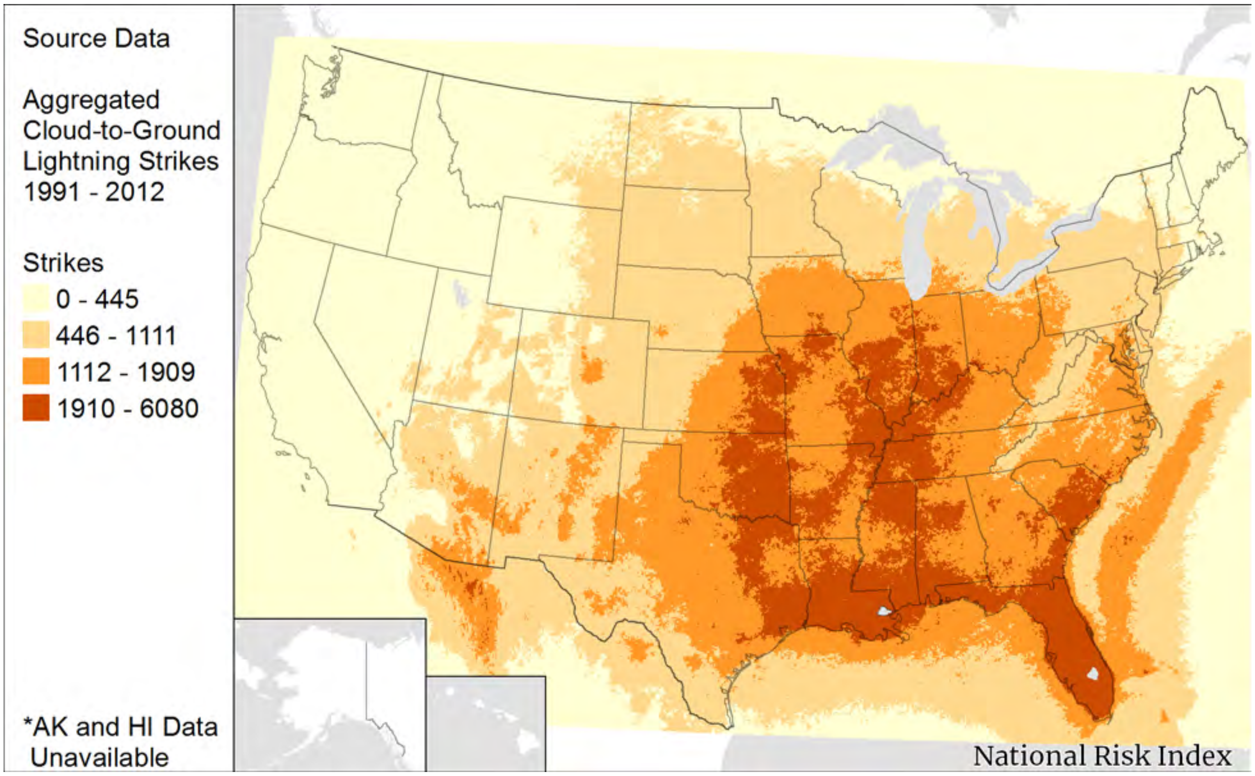

Figure 95: Map of Lightning Strikes

16.1.1 PERIOD OF RECORD

To use only the most accurate data, Lightning strikes between 1/1/1991 and 12/31/2012 are analyzed, so the period of record for which Lightning data are utilized is 22 years.

16.2 Spatial Processing

The NetCDF files containing Lightning strike data are converted to raster files via ArcGIS's Make NetCDF Raster Layer tool, and then converted to points using the Raster to Point tool. A series of spatial joins are performed to combine all 22 years of data into a single layer, and these points are then merged with a layer of 4-by-4-km fishnet polygons for which the extent and dimensions match those of the source data files. Converting the raster dataset to vector format greatly improves the processing speed and repeatability of resource-intensive intersection functions performed within the NRI processing database. An additional field is calculated that aggregates the number of Lightning strikes over all years. The result is a set of 4-by-4-km polygons for which the attribute table contains a field for each year with the total number of Lightning strikes for that year and the cumulative total of all Lightning strikes within the polygon (see *Table 44*). Polygons imported into the NRI processing database can then be intersected with the Census-block polygons.

Table 44: Sample Data from the Lightning Fishnet table

LightningFishnetID	F_AllYear	F1991	F1992	F2008	F2009	F2010	F2011	F2012
341	85	1	0	6	23	9	19	27
350	86	0	1	4	19	12	22	28
266	6	0	0	3	0	2	0	1

16.3 Determination of Possibility of Hazard Occurrence

Lightning can occur almost anywhere under the right conditions, so all counties were deemed possible for Lightning strike occurrence. While the current data source does not supply information for Alaska and Hawaii, these states are still included as possible for Lightning occurrence. In the NRI application, no risk scoring will be available for Alaska and Hawaii as the data are insufficient.

16.4 Exposure

Because Lightning strikes can occur anywhere, the entire building and population value of a Census block, Census tract, and county are considered exposed to Lightning.

16.5 Historic Event Count

The count of historic Lightning strikes is computed as an area-weighted sum of the total Lightning strike count of the Lightning fishnet polygons that intersect the Census block (see *Equation 82*). Historic Event-Day Counts are supplied at the Census tract and county levels as the area-weighted Lightning strike count of the fishnet grid cells that intersect the Census tract and county, respectively.

Equation 82: Census Tract and County Area-Weighted Lightning Strike Event Count

$$EventCount_{LTNG_{CT}} = \frac{\sum_{CB}^{CT}\left(EventCount_{LTNG\,Fish_{AllYears}} \times IntsctArea_{LTNG\,Fish_{CB}}\right)}{Area_{CT}}$$

$$EventCount_{LTNG_{Co}} = \frac{\sum_{CB}^{Co}\left(EventCount_{LTNG\,Fish_{AllYears}} \times IntsctArea_{LTNG\,Fish_{CB}}\right)}{Area_{Co}}$$

where:

$EventCount_{LTNG_{CT}}$	is the count of past Lightning strikes calculated for a specific Census tract.
$EventCount_{LTNG\,Fish_{AllYears}}$	is the cumulative total of all past Lightning strikes for a specific fishnet grid cell.

$IntsctArea_{LTNG_{Fish_{CB}}}$	is the intersected area of the Lightning fishnet grid cell with a specific Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$EventCount_{LTNG_{Co}}$	is the count of past Lightning strikes calculated for a specific county.
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

16.6 Frequency

The frequency value represents the estimated number of recorded Lightning strikes each year for a specific area. The annualized frequency is calculated initially at the resolution of the source data (a 4-by-4-km cell), and the Census block-level value is an area-weighted aggregation of the frequencies of its intersecting fishnet cells. The Census block value is used in the EAL calculations.

Frequency is first calculated at the 4-by-4-km fishnet level as the cumulative total of Lightning strikes divided by the period of record as in *Equation 83*.

Equation 83: Fishnet Cell Lightning Frequency

$$Freq_{LTNG_{Fish}} = \frac{EventCount_{LTNG_{AllYears}}}{PeriodRecord_{LTNG}}$$

where:

$Freq_{LTNG_{Fish}}$	is the annualized frequency of Lightning strikes determined for the specific 4x4-km fishnet grid cell (events per year).
$EventCount_{LTNG_{AllYears}}$	is the cumulative total of all past Lightning strikes associated with the fishnet grid cell.
$PeriodRecord_{LTNG}$	is the period of record for Lightning (22 years).

To calculate frequency at the Census block level, the Lightning fishnet polygons are first intersected with the Census block polygons within the NRI processing database. The resulting table contains the polygon's unique identifier, Census block number, and the intersected area in square kilometers (see *Table 45*).

Table 45: Sample Data from the Lightning Fishnet Census Block Intersection table

LightningFishnetID	CensusBlock	IntersectedAreaKm2
815373	481130020001002	0.0732602925796509
815373	481130020001003	0.0534260125160217
815373	481130020001004	0.048496762966156

An area-weighted annualized frequency value is then calculated at the Census block level using the intersection between the Lightning fishnet polygons and the Census block as in *Equation 84*.

Equation 84: Census Block Area-Weighted Fishnet Lightning Frequency

$$Freq_{LTNG_{CB}} = \frac{\sum_{Fish}^{CB}\left(Freq_{LTNG_{Fish}} \times IntsctArea_{LTNG_{Fish_{CB}}}\right)}{Area_{CB}}$$

where:

$Freq_{LTNG_{CB}}$	is the annualized area-weighted frequency of Lightning strikes determined for the specific Census block (events per year).
$Freq_{LTNG_{Fish}}$	is the annualized frequency of Lightning strikes determined for the specific 4-by-4-km fishnet grid cell (events per year).
$IntsctArea_{LTNG_{Fish_{CB}}}$	is the intersected area of the Lightning fishnet grid cell with the Census block (in square kilometers).
$\sum_{Fish}^{CB}$	is the sum for all 4-by-4-km fishnet grid cells that intersect the Census block.
$Area_{CB}$	Is the total area of the Census block (in square kilometers).

16.6.1 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level as well. These values may not exactly match that of dividing the number of recorded Lightning strikes at the Census tract and county level by the period of record. The frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 85*.

Equation 85: Census Tract and County Area-Weighted Lightning Frequency

$$Freq_{LTNG_{CT}} = \frac{\sum_{CB}^{CT}(Freq_{LTNG_{CB}} \times Area_{CB})}{Area_{CT}}$$

$$Freq_{LTNG_{Co}} = \frac{\sum_{CB}^{Co}(Freq_{LTNG_{CB}} \times Area_{CB})}{Area_{Co}}$$

where:

$Freq_{LTNG_{CT}}$	is the annualized area-weighted Lightning frequency for a specific Census tract.
$Freq_{LTNG_{CB}}$	is the annualized Lightning frequency associated with a specific Census block.
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{LTNG_{Co}}$	is the annualized area-weighted Lightning frequency for a specific county.
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 96 displays annualized Lightning frequency at the county level.

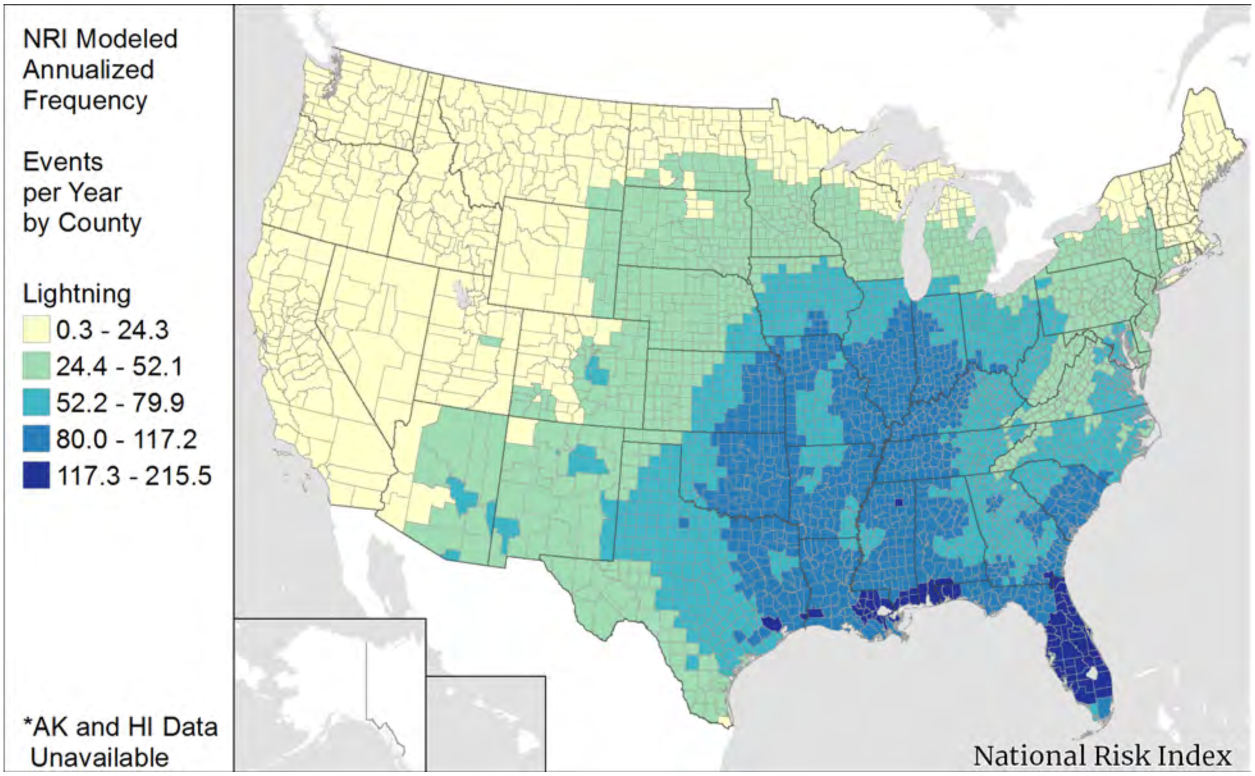

Figure 96: Annualized Lightning Frequency by County

16.7 Historic Loss Ratio

The Lightning HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Lightning strike event, or the average rate of loss associated with the occurrence of a Lightning strike event. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Lightning hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. To ensure that the loss data align with the historic count computed from the spatial source data, SHELDUS events from 1995 to 2012 are included in the HLR calculation. Two peril types are mapped to the hazard Lightning (see *Table 46*). These are expanded on an event basis based on the number of records from SHELDUS[58] (see *Section 5.4.1*).

[58] For Lightning loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

Table 46: Lightning Peril Types and Recorded Events from 1995-2012

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
FireStElmos	0	0
Lightning	10347	12307

The HLR exposure value used in the formula below is a county-level value that represents the dollar value of the total building value or the entire population of a county as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event and each consequence type (building and population) is calculated using *Equation 86*.

Equation 86: Loss Ratio per Basis Calculation for a Single Lightning Strike Event

$$LRB_{LTNG_{Co_{CnsqType}}} = \frac{Loss_{LTNG_{Co_{CnsqType}}}}{HLRExposure_{Co_{CnsqType}}}$$

where:

$LRB_{LTNG_{Co_{CnsqType}}}$	is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Lightning strike event. Calculation is performed for each consequence type (building and population).
$Loss_{LTNG_{Co_{CnsqType}}}$	is the loss (by consequence type) experienced from the Lightning strike event documented to have occurred in the county (in dollars).
$HLRExposure_{Co_{CnsqType}}$	is the total value (by consequence type) of the county estimated to have been exposed to the Lightning strike event (in dollars).

Lightning strikes can occur with a high frequency in areas, but often result in no recorded loss to buildings or population. SHELDUS does not record events in which no loss occurred, so a number of zero-loss event-days are inserted into the data to align the event count in the HLR calculation to the historic event count experienced within the period of record (1995 to 2012). The best available source data for Lightning strike events do not record the actual date of the Lightning strike, only the total strikes for the year. An annual historic event count is extracted using the intersection between the Lightning fishnet polygons and the Census block polygons used to calculate frequency (see *Table 45*). The area-weighted annual count of all Lightning fishnet-Census block polygon intersections within the county for each record year is used as the annual historic event count.

If the number of loss-causing Lightning event records from SHELDUS is less than the summed annual historic event counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and national.

Figure 97 and *Figure 99* display the largest weighting factor contributor in the Bayesian credibility calculation for the Lightning HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Lightning events within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from national-level loss data. *Figure 98* and *Figure 100* represent the final county-level HLR values for Lightning.

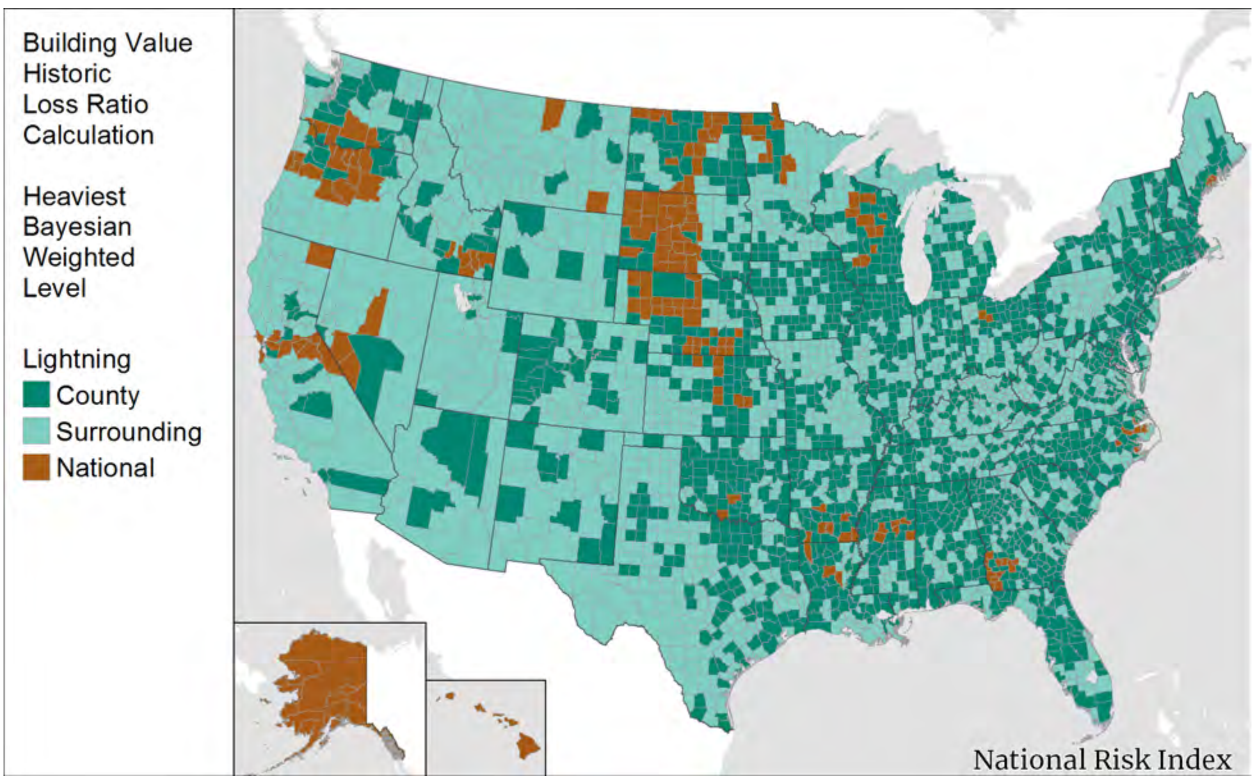

Figure 97: Lightning Heaviest Bayesian Weighted Level – Building Value

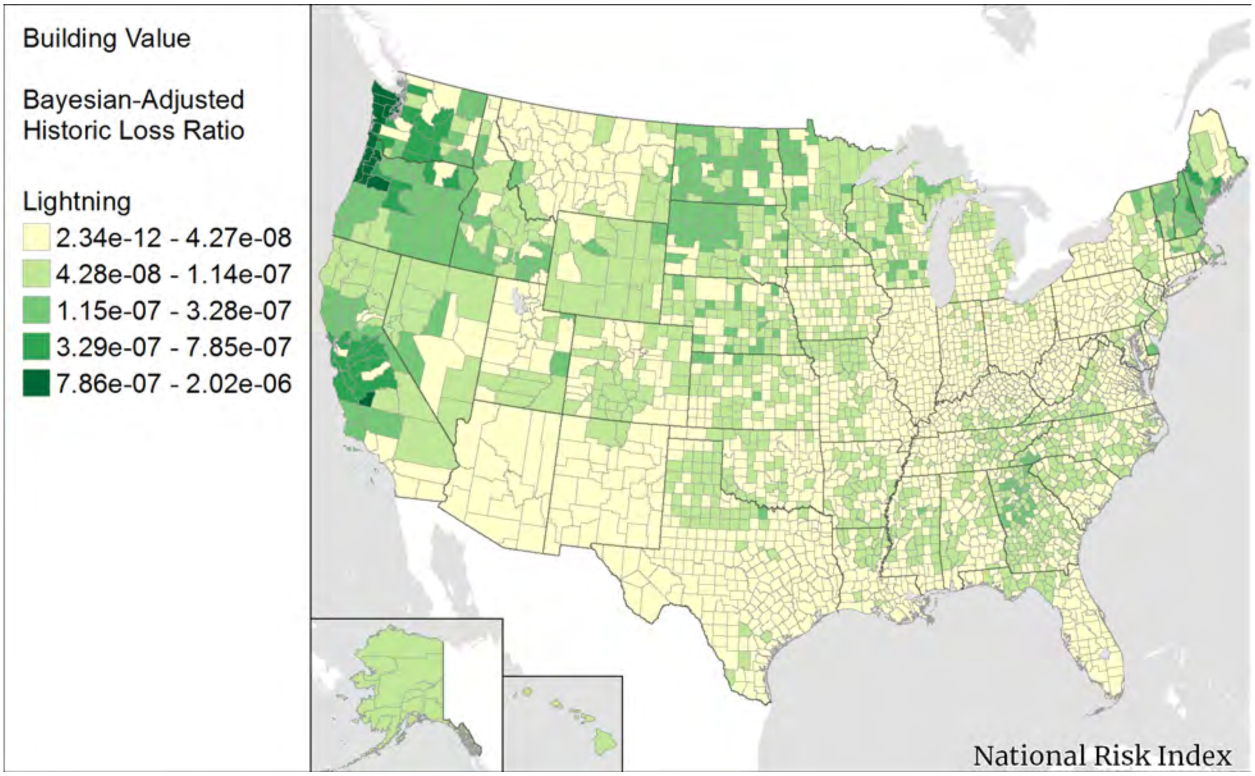

Figure 98: Lightning HLR – Building Value

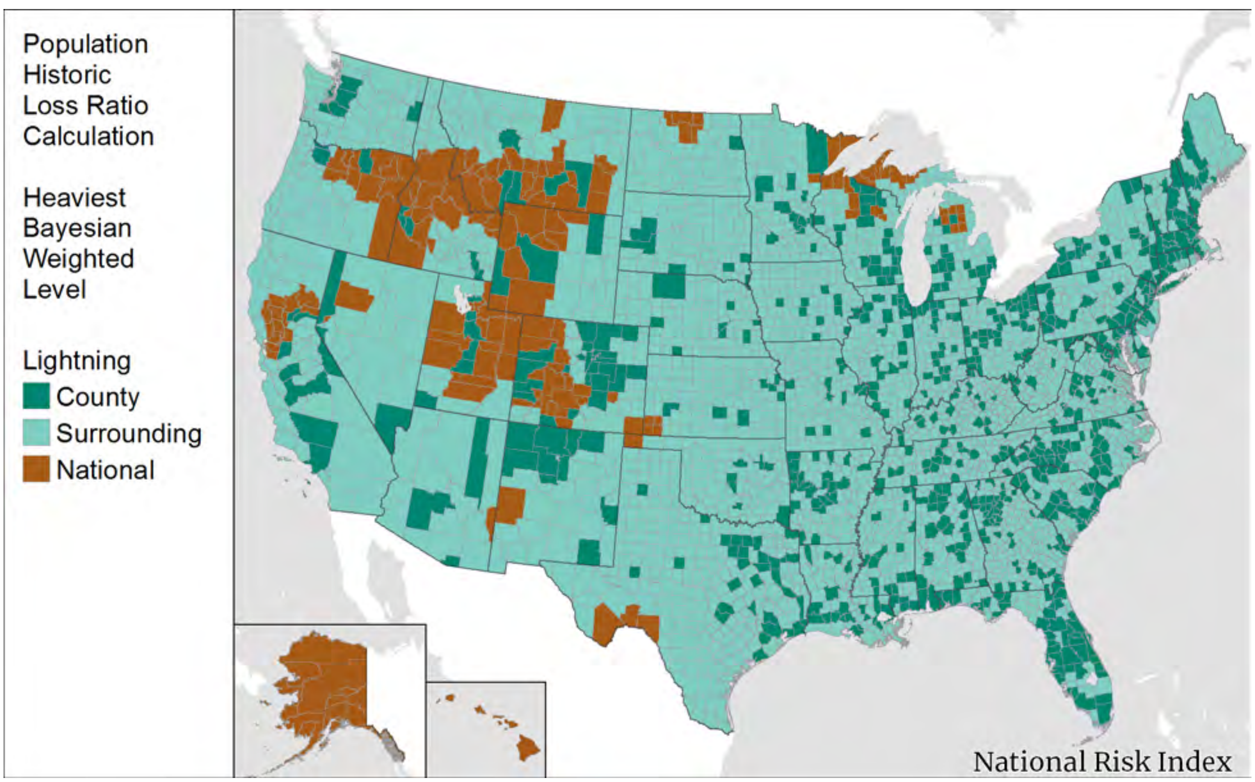

Figure 99: Lightning Heaviest Bayesian Weighted Level – Population

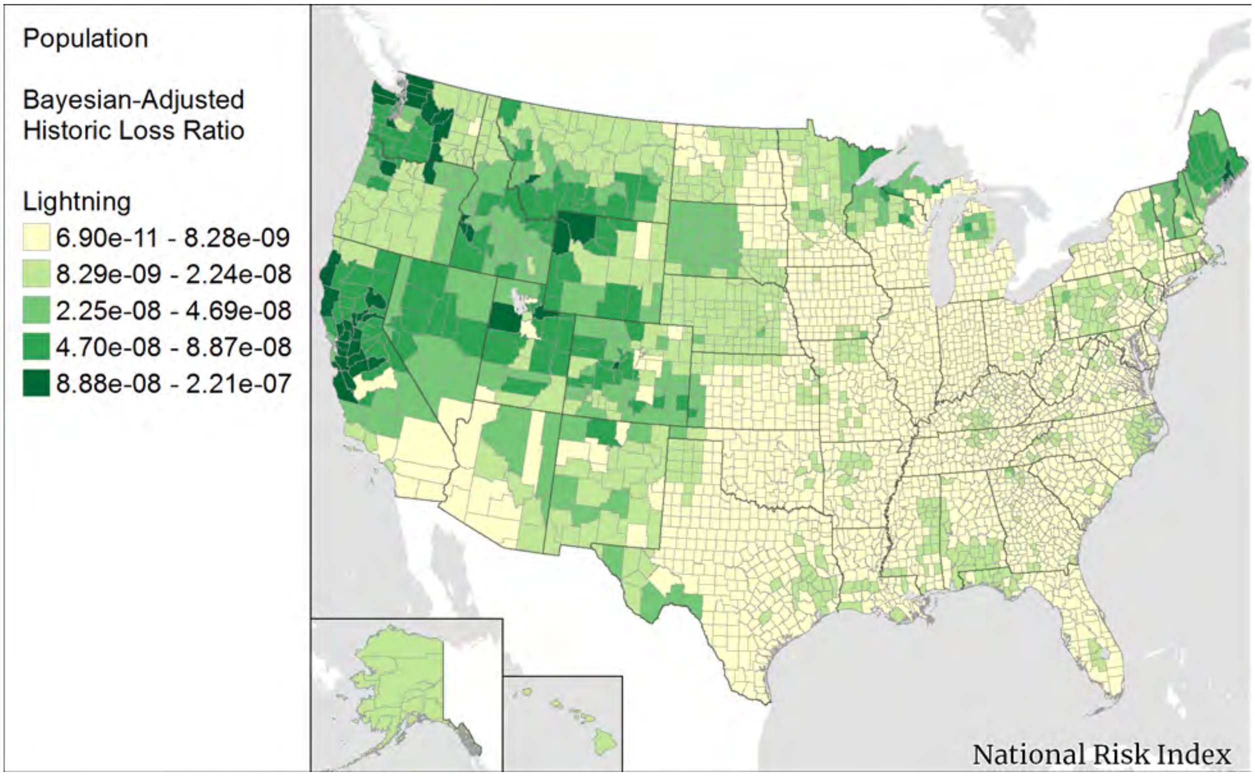

Figure 100: Lightning HLR – Population

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

16.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 87*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 87: Census Block Expected Annual Loss to Lightning

$$EAL_{LTNG_{CB_{Bldg}}} = Exposure_{LTNG_{CB_{Bldg}}} \times Freq_{LTNG_{CB}} \times HLR_{LTNG_{CB_{Bldg}}}$$

$$EAL_{LTNG_{CB_{Pop}}} = Exposure_{LTNG_{CB_{Pop}}} \times Freq_{LTNG_{CB}} \times HLR_{LTNG_{CB_{Pop}}}$$

where:

$EAL_{LTNG_{CB_{Bldg}}}$	is the Expected Annual Loss to building value due to Lightning events for a specific Census block (in dollars).
$Exposure_{LTNG_{CB_{Bldg}}}$	is the building value exposed to Lightning events in the Census block (in dollars).

$Freq_{LTNG_{CB}}$	is the annualized Lightning frequency for the Census block (events per year).
$HLR_{LTNG_{CB_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Lightning for the Census block.
$EAL_{LTNG_{CB_{Pop}}}$	is the Expected Annual Loss to population value due to Lightning events for a specific Census block (in dollars).
$Exposure_{LTNG_{CB_{Pop}}}$	is the population value exposed to Lightning events in the Census block (in dollars).
$HLR_{LTNG_{CB_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Lightning for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building and population loss at the Census block level as in *Equation 88*.

Equation 88: Census Tract and County Expected Annual Loss to Lightning

$$EAL_{LTNG_{CT}} = \sum_{CB}^{CT} EAL_{LTNG_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{LTNG_{CB_{Pop}}}$$

$$EAL_{LTNG_{Co}} = \sum_{CB}^{Co} EAL_{LTNG_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{LTNG_{CB_{Pop}}}$$

where:

$EAL_{LTNG_{CT}}$	is the total Expected Annual Loss due to Lightning events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{LTNG_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Lightning events for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{LTNG_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Lightning events for all Census blocks in the Census tract (in dollars).
$EAL_{LTNG_{Co}}$	is the total Expected Annual Loss due to Lightning events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{LTNG_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Lightning events for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{LTNG_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Lightning events for all Census blocks in the county (in dollars).

Figure 101 shows the total EAL (building value and population combined) to Lightning events.

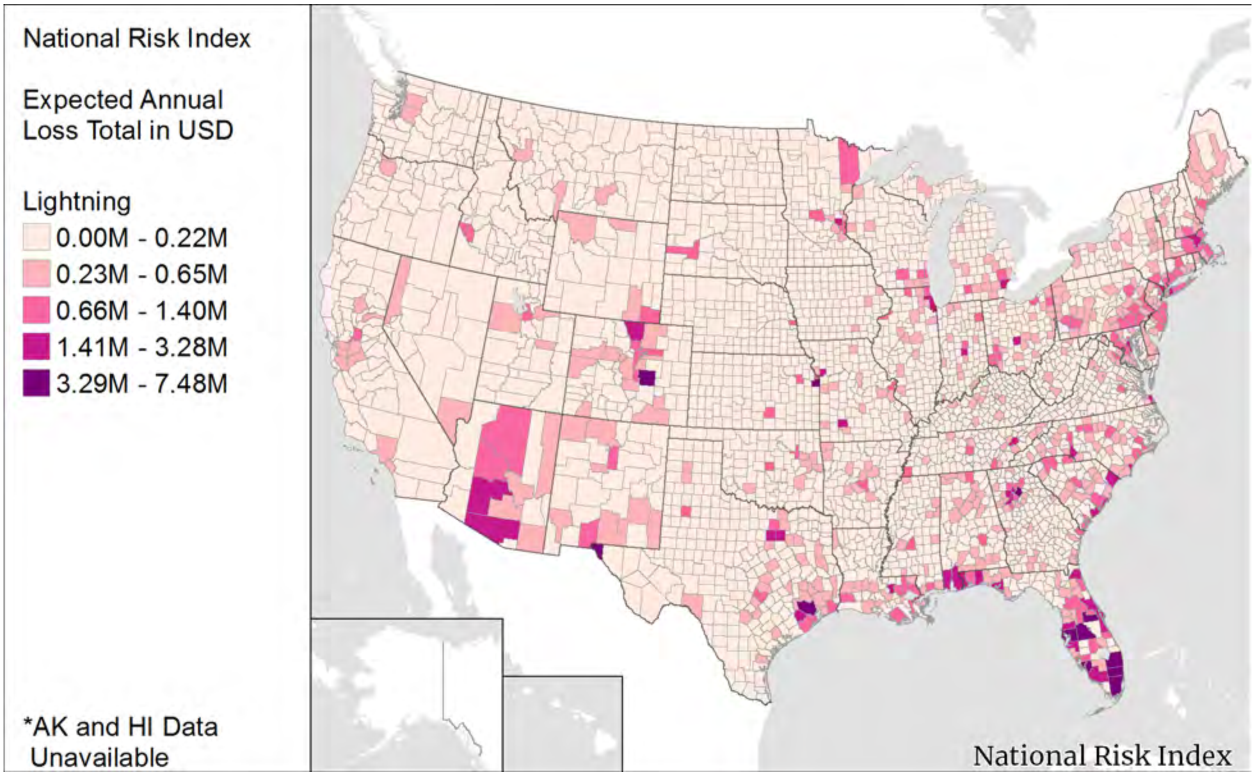

Figure 101: Total Expected Annual Loss by County to Lightning

With the Lightning total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Lightning Risk Index score.

17 Riverine Flooding

Riverine Flooding is when streams and rivers exceed the capacity of their natural or constructed channels to accommodate water flow and water overflows the banks, spilling into adjacent low-lying, dry land.

17.1 Spatial Source Data

Susceptible Area Source: *Federal Emergency Management Agency, National Flood Insurance Program, National Flood Hazard Layer*[59]

The National Flood Hazard Layer (NFHL) contains several layers depicting flood information, including levee locations, Flood Insurance Rate Map (FIRM) boundaries, and floodplain polygons. The polygons for the 1% annual chance floodplain were downloaded in shapefile format (see *Figure 102*) for use in the calculation of Riverine Flooding exposure.

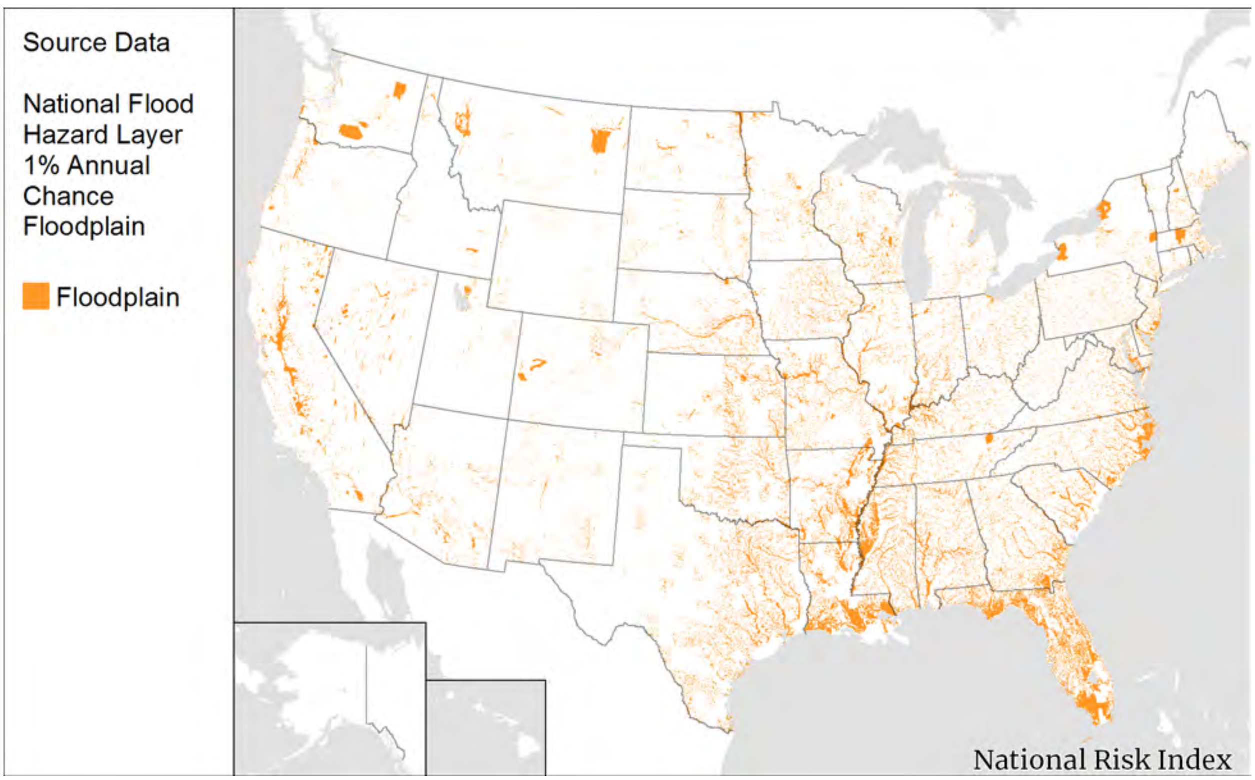

Figure 102: Map of 1% Annual Chance Floodplain

Susceptible Area Source: CoreLogic Special Flood Hazard Area Layer

[59] National Flood Insurance Program, Federal Emergency Management Agency. (2018). *National Flood Hazard Layer* [online dataset]. Retrieved from https://www.fema.gov/national-flood-hazard-layer-nfhl

The CoreLogic digitized floodplain boundaries supplement FEMA's official digital NFHL data in areas where only paper FIRMs exist. These boundaries have been compiled by CoreLogic through the digitization of existing paper flood maps and the use of legacy paper FEMA products. FEMA has licensed this data from CoreLogic to supplement its NFHL data while FEMA engages with communities where digital data-coverage gaps exist in FEMA's NFHL.

Historical Event Source: *National Weather Service, Storm Events Database*[60]

The NWS Storm Events Database contains records of the occurrence of storms and other significant weather phenomena, including flooding events, from January 1950 to August 2019. Each flooding event record includes the affected counties, the dates of the event occurrence, and any reported loss. These records are used to calculate frequency for Riverine Flooding.

17.1.1 PERIOD OF RECORD

The Riverine Flooding frequency calculation is based on the number of recorded Riverine Flooding events in the NWS Storm Events Database from 1/1/1995 to 12/31/2016, so the period of record is 22.01 years.

17.2 Spatial Processing

The flood hazard areas in which the Flood Zone Category begins with "A" are extracted from the CoreLogic data and the NFHL data. This selection criteria extracts the 1% annual chance flood hazard areas associated with possible Riverine Flooding, as well as coastal hazard areas that experience shallow flow or ponding with water depths of 1 to 3 feet ("AH"). These two selections from the source data are then combined to form a single layer of polygons for the 1% annual chance Riverine Flood hazard.

17.3 Determination of Possibility of Hazard Occurrence

On examining the economic loss records in SHELDUS, it was found that almost every county in the United States had sustained some form of loss due to Riverine Flooding events, so all counties were deemed possible for Riverine Flooding occurrence.

17.4 Exposure

To identify areas of exposure, the riverine floodplain polygons were intersected with the Census block polygons within the NRI processing database. The resulting table contains the floodplain polygon's unique identifier, Census block number, the intersected area, the developed area of intersection, and the area of intersection containing crop or pastureland (see *Table 47*). All area values are in square kilometers.

[60] National Weather Service. (2017). *Storm Events Database, Version 3.0.* [online database]. Retrieved from https://www.ncdc.noaa.gov/stormevents/.

Table 47: Sample Data from the Riverine Flood Zone Census Block Intersection Table

FloodZoneRiverine 100yrID	CensusBlock	AreaDevelopedKm2	IntersectedAreaKm2	AreaCropPastureKm2
413	150010202021103	0.005357	0.005357	0
2805	150010202021103	0.003001	0.003013	0
8069	150010203001007	0.05579	0.05579	0.000463

To determine exposure value for buildings and population, the sum of the developed areas of the riverine floodplain polygons for each Census block is multiplied by the developed area building value density and the developed area population density of the Census block to model the conservative-case concentration of exposure within the Census block. To determine exposure value for agriculture, the sum of the agricultural area intersecting the riverine floodplain polygons for each Census block is multiplied by the total agricultural value density. These Census block building, population, and agricultural value densities have been calculated by dividing the total values (as recorded in Hazus 4.2 SP1) by the developed or agricultural land area (in square kilometers; see *Equation 89*). The VSL was used to express population exposure in terms of dollars.

Equation 89: Census Block Riverine Flooding Exposure

$$Exposure_{RFLD\,CB_{Bldg}} = \sum IntsctArea_{RFLD\,Dev_{CB}} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{RFLD\,CB_{Pop}} = \left(\sum IntsctArea_{RFLD\,Dev_{CB}} \times DevAreaDen_{CB_{Pop}}\right) \times VSL$$

$$Exposure_{RFLD\,CB_{Ag}} = \sum IntsctArea_{RFLD\,Ag_{CB}} \times AgValueDen_{CB}$$

where:

$Exposure_{RFLD\,CB_{Bldg}}$	is the building value exposed to Riverine Flooding in a specific Census block (in dollars).
$\sum IntsctArea_{RFLD\,Dev_{CB}}$	is the sum of the intersected developed areas of riverine floodplain polygons with the Census block (in square kilometers).
$DevAreaDen_{CB_{Bldg}}$	is the developed area building value density of the Census block (in dollars per square kilometer).
$Exposure_{RFLD\,CB_{Pop}}$	is the population value exposed to Riverine Flooding in a specific Census block (in dollars).

$DevAreaDen_{CB_{Pop}}$	is the developed area population density of the Census block (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).
$Exposure_{RFLD_{CB_{Ag}}}$	is the agricultural value exposed to Riverine Flooding in a specific Census block (in dollars).
$\sum IntsctArea_{RFLD_{Ag_{CB}}}$	is the sum of the intersected agricultural areas of riverine floodplain polygons with the Census block (in square kilometers).
$AgValueDen_{CB}$	is the agriculture value density of the Census block (in dollars per square kilometer).

Because the exposure model uses a conservative-case concentration of exposure, it is possible to mathematically generate an exposure value that is greater than the total value of the Census block. The Hazus-recorded population and building value and the Census of Agriculture-reported crop and livestock value for the Census block are considered ceilings on exposure. For example, if the calculated exposed population exceeds the Hazus-recorded population, then the Hazus-recorded population is used as the population exposure value for the Census block.

17.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 90*).

Equation 90: Census Tract and County Riverine Flooding Exposure Aggregation

$$Exposure_{RFLD_{CT_{Bldg}}} = \sum_{CB}^{CT} Exposure_{RFLD_{CB_{Bldg}}}$$

$$Exposure_{RFLD_{Co_{Bldg}}} = \sum_{CB}^{Co} Exposure_{RFLD_{CB_{Bldg}}}$$

$$Exposure_{RFLD_{CT_{Pop}}} = \sum_{CB}^{CT} Exposure_{RFLD_{CB_{Pop}}}$$

$$Exposure_{RFLD_{Co_{Pop}}} = \sum_{CB}^{Co} Exposure_{RFLD_{CB_{Pop}}}$$

$$Exposure_{RFLD_{CT_{Ag}}} = \sum_{CB}^{CT} Exposure_{RFLD_{CB_{Ag}}}$$

$$Exposure_{RFLD_{Co_{Ag}}} = \sum_{CB}^{Co} Exposure_{RFLD_{CB_{Ag}}}$$

where:

$Exposure_{RFLD_{CT_{Bldg}}}$	is the building value exposed to Riverine Flooding in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{RFLD_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Riverine Flooding for each Census block within the Census tract (in dollars).
$Exposure_{RFLD_{Co_{Bldg}}}$	is the building value exposed to Riverine Flooding in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{RFLD_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Riverine Flooding for each Census block within the county (in dollars).
$Exposure_{RFLD_{CT_{Pop}}}$	is the population value exposed to Riverine Flooding in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{RFLD_{CB_{Pop}}}$	is the summed value of all population exposed to Riverine Flooding for each Census block within the Census tract (in dollars).
$Exposure_{RFLD_{Co_{Pop}}}$	is the population value exposed to Riverine Flooding in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{RFLD\,CB_{Pop}}$	is the summed value of all population exposed to Riverine Flooding for each Census block within the county (in dollars).
$Exposure_{RFLD\,CT_{Ag}}$	is the agricultural value exposed to Riverine Flooding in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{RFLD\,CB_{Ag}}$	is the summed value of all agricultural value exposed to Riverine Flooding for each Census block within the Census tract (in dollars).
$Exposure_{RFLD\,Co_{Ag}}$	is the agricultural value exposed to Riverine Flooding in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{RFLD\,CB_{Ag}}$	is the summed value of all agricultural value exposed to Riverine Flooding for each Census block within the county (in dollars).

17.5 Historic Event Count

The count of historic Riverine Flooding events is computed as the number of Riverine Flooding events (defined as having an Event Type of Flash Flood, Flood, Hail Flooding, Lakeshore Flood, Thunderstorm Winds/Flood, or Thunderstorm Winds/Flash Flood) recorded in the NWS Storm Events Database that have occurred within the county from January 1995 to December 2016. Multiple event records that occur on the same day in the same county are counted as a single Riverine Flooding event as these recorded events are likely due to the same cause (heavy rain, for example), but occur in different parts of the county. This count is only performed for counties that intersect the 1% annual chance riverine floodplain. Historic Event Counts are also supplied at the Census tract level. These values are inherited from the county that contains them as the exact location of the event within the county cannot be determined from the NWS Storm Events Database record.

17.6 Frequency

The frequency value represents the number of Riverine Flooding events each year over the period of record (22.01 years). Annualized frequency is initially calculated at the county level. The Census tracts and blocks inherit frequency values from the counties that contain them, and the Census block-level value is used in the EAL calculations.

Frequency calculations use the NWS Storm Events Database Riverine Flooding events for the county (see *Section 17.5*) and divide by the period of record as in *Equation 91*. Multiple event records that occur on the same day in the same county are counted as a single Riverine Flooding event.

Equation 91: County Riverine Flooding Frequency

$$Freq_{RFLD\,Co} = \frac{EventCount_{RFLD\,Co}}{PeriodRecord_{RFLD}}$$

where:

$Freq_{RFLD\,Co}$	is the annualized frequency of Riverine Flooding events determined for a specific county (events per year).
$EventCount_{RFLD\,Co}$	is the total number of Riverine Flooding events (from the NWS Storm Events Database) that have impacted the county.
$PeriodRecord_{RFLD}$	is the period of record for Riverine Flooding (22.01 years).

17.6.1 MINIMUM ANNUAL FREQUENCY

If a county intersects the 100-year riverine floodplain but has not experienced a Riverine Flooding event, it is assigned a minimum annual frequency of 0.01 or once in 100 years.

17.6.2 FREQUENCY INHERITANCE

The Census tracts and blocks inherit their frequency values from the counties that contain them as in *Equation 92*.

Equation 92: Census Block and Tract Riverine Flooding Frequency Inheritance

$$Freq_{RFLD\,CB} = Freq_{RFLD\,CT} = Freq_{RFLD\,Co}$$

where:

$Freq_{RFLD\,CB}$	is the inherited annualized frequency of Riverine Flooding events for a specific Census block within the county.
$Freq_{RFLD\,CT}$	is the inherited annualized frequency of Riverine Flooding events for a specific Census tract within the county.
$Freq_{RFLD\,Co}$	is the annualized frequency of Riverine Flooding events associated with a specific county.

Figure 103 displays annualized Riverine Flooding frequency at the county level.

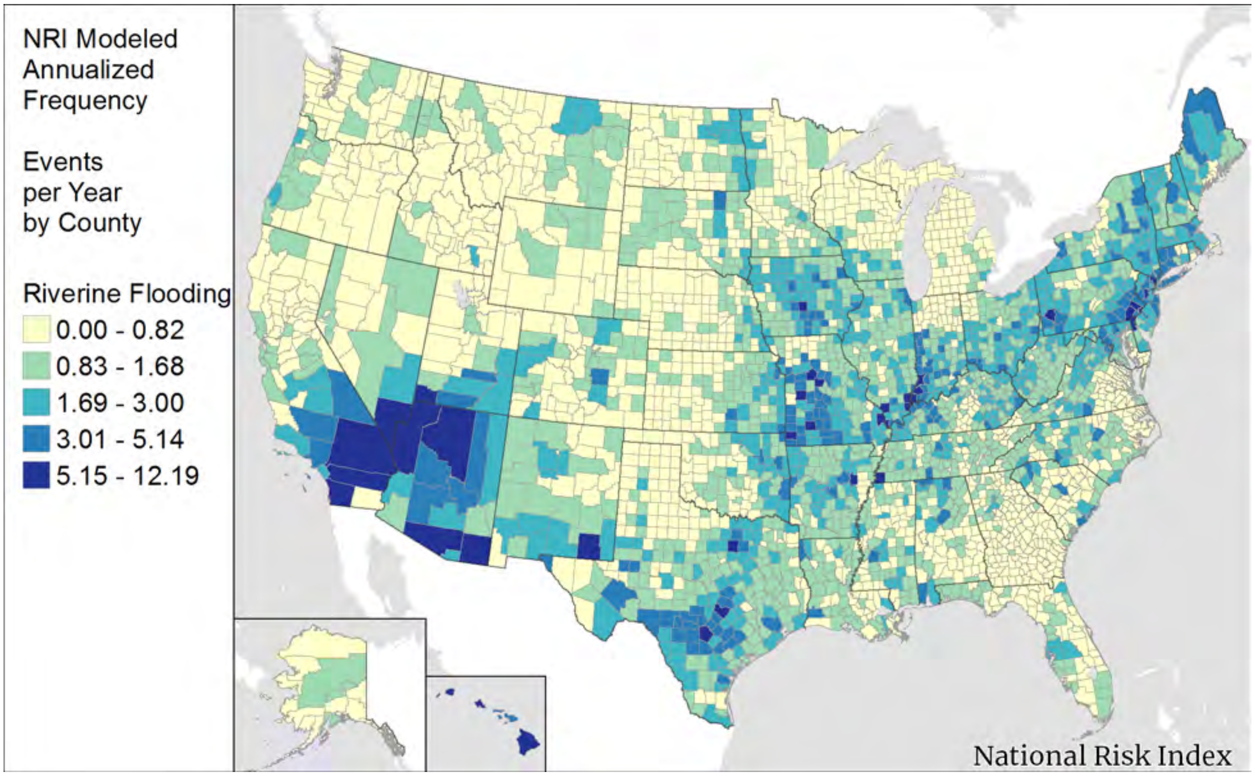

Figure 103: Annualized Riverine Flooding Frequency by County

17.7 Historic Loss Ratio

The Riverine Flooding HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Riverine Flooding event, or the average rate of loss associated with the occurrence of a Riverine Flooding event. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Riverine Flooding hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Eight peril types are mapped to the hazard Riverine Flooding (see *Table 48*). These are expanded on an event basis based on the number of records from SHELDUS[61] (see *Section 5.4.1*).

[61] For Riverine Flooding loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

Table 48: Riverine Flooding Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
FloodFlash	13,763	20,436
FloodIceJam	22	22
Flooding	19,260	24,900
FloodLakeshore	23	28
FloodLowland	0	0
FloodRiverine	149	174
FloodSmallStream	261	326
FloodSnowmelt	0	0

The HLR exposure value used in the LRB calculation is the value of the county's area that is susceptible to Riverine Flooding. This value is determined by summing the developed area density or crop area density exposure values of the Census blocks that intersect the layer of the 1% annual chance Floodplain (see *Section 17.4*). To prevent inflating the LRBs of counties for which the areas of intersection with the floodplain were very small, counties with a calculated building value or crop value exposure less than $10,000 or a calculated population exposure less than one person were given an LRB of 0 for the consequence types that did not meet its respective threshold. The LRB for each SHELDUS-documented event and each consequence type (building, population, and agriculture) is calculated using *Equation 93*.

Equation 93: Loss Ratio per Basis Calculation for a Single Riverine Flooding Event

$$LRB_{RFLD\,Co_{CnsqType}} = \frac{Loss_{RFLD\,Co_{CnsqType}}}{HLRExposure_{RFLD\,Co_{CnsqType}}}$$

where:

$LRB_{RFLD\,Co_{CnsqType}}$	is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Riverine Flooding event. Calculation is performed for each consequence type (building, population, and agriculture).
$Loss_{RFLD\,Co_{CnsqType}}$	is the loss (by consequence type) experienced from the Riverine Flooding event documented to have occurred in the county (in dollars).
$HLRExposure_{RFLD\,Co_{CnsqType}}$	is the value (by consequence type) of the susceptible area estimated to have been exposed to the Riverine Flooding event (in dollars).

Riverine Flooding events may occur in areas without resulting in recorded loss to buildings, population, or agriculture. SHELDUS does not record events in which no loss occurred, so a number of zero-loss events are inserted into the data to align the event count in the HLR calculation to the historic event count experienced within the SHELDUS period of record (1995 to 2016). For Riverine Flooding, a historic year-month event count is computed as the number of Riverine Flooding events recorded in the NWS Storm Events Database that have occurred within the county. (Multiple event records that occur on the same day in the same county are counted as a single event.) The observation date of each Riverine Flooding event is used to sync the event to its year-month. A list of distinct Riverine Flooding observation dates is compiled for the counties, and the historic year-month event count is the number of distinct Riverine Flooding observation dates in this list.

If the number of loss-causing Riverine Flooding event records from SHELDUS is less than the summed historic year-month event counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and national.

Figure 104, *Figure 106*, and *Figure 108* display the largest weighting factor contributor in the Bayesian calculation for the Riverine Flooding HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Riverine Flooding events within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from national-level loss data. *Figure 105*, *Figure 107*, and *Figure 109* represent the final county-level HLR values for Riverine Flooding.

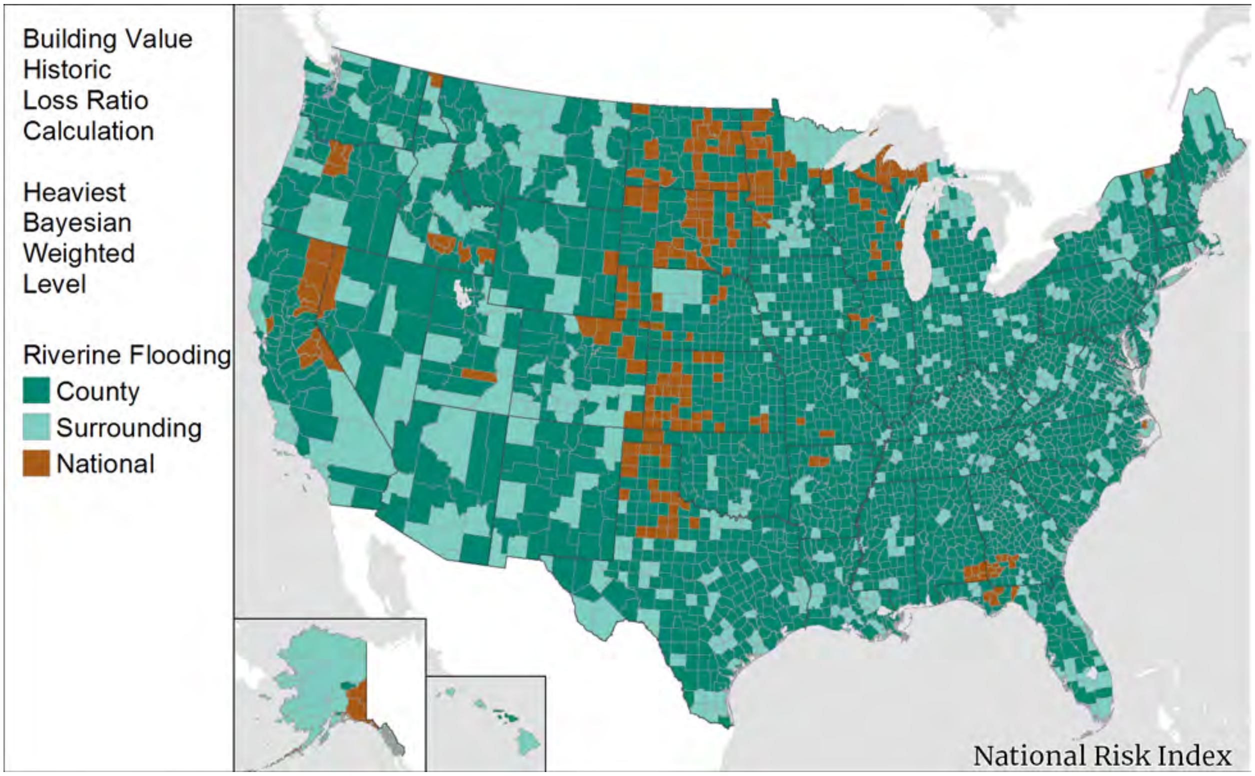

Figure 104: Riverine Flooding Heaviest Bayesian Influence Level – Building Value

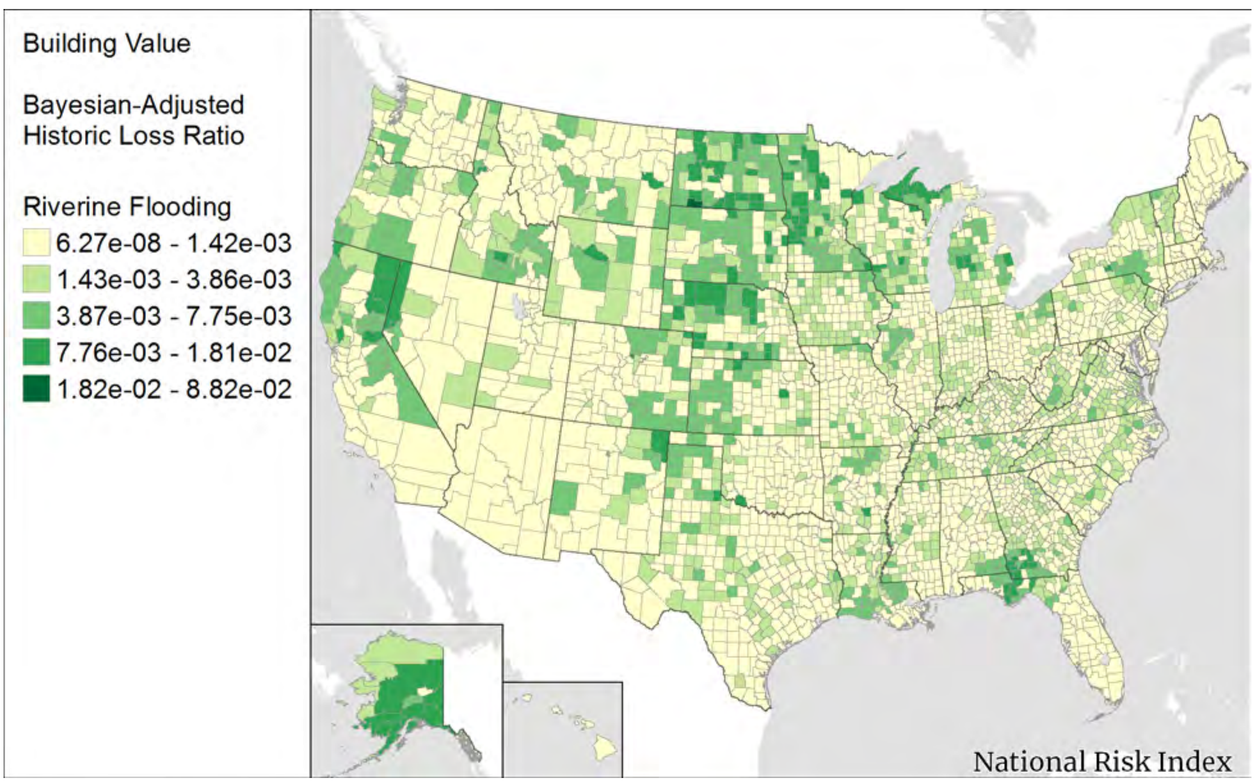

Figure 105: Riverine Flooding HLR – Building Value

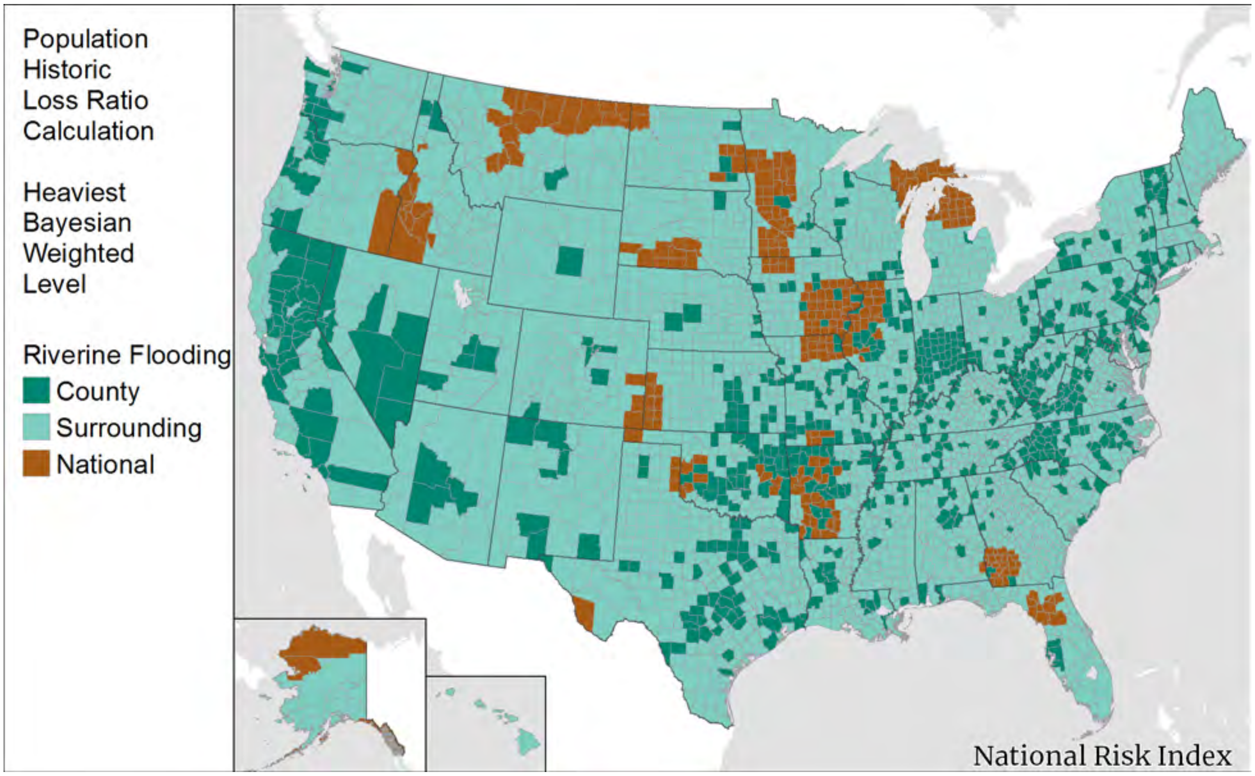

Figure 106: Riverine Flooding Heaviest Bayesian Influence Level – Population

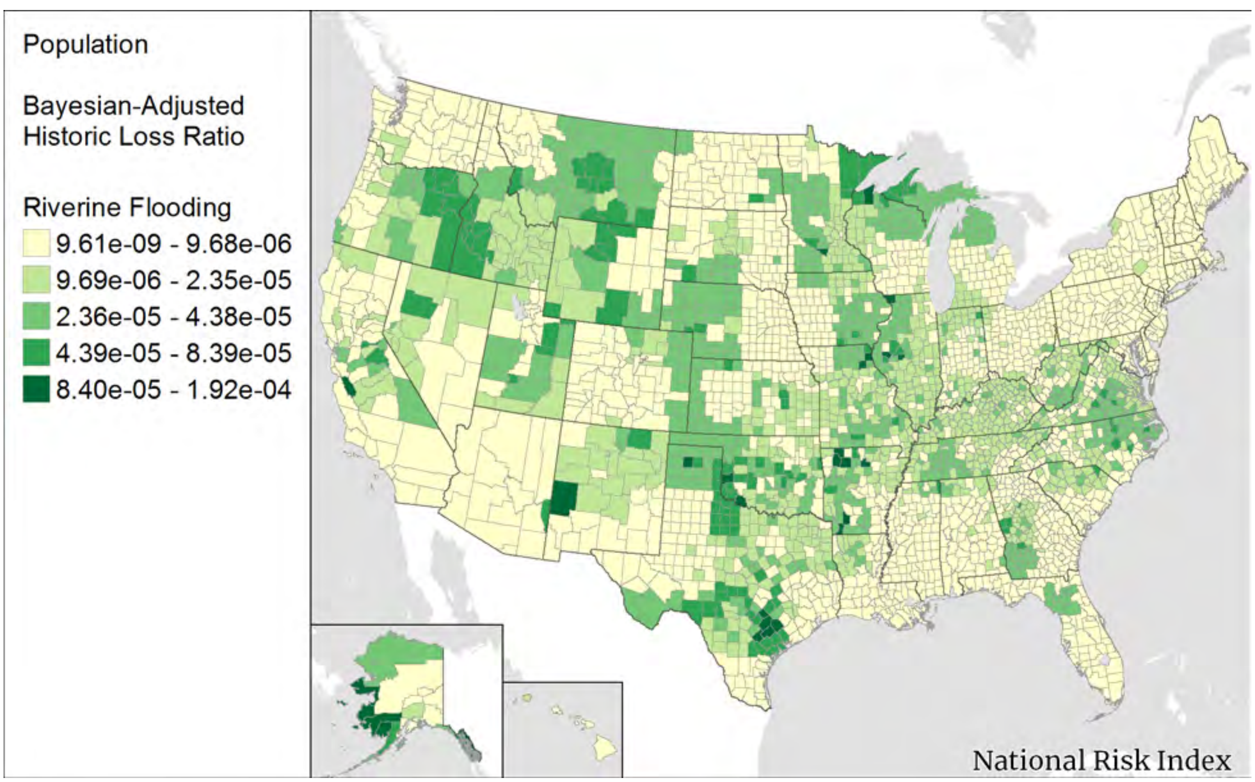

Figure 107: Riverine Flooding HLR – Population

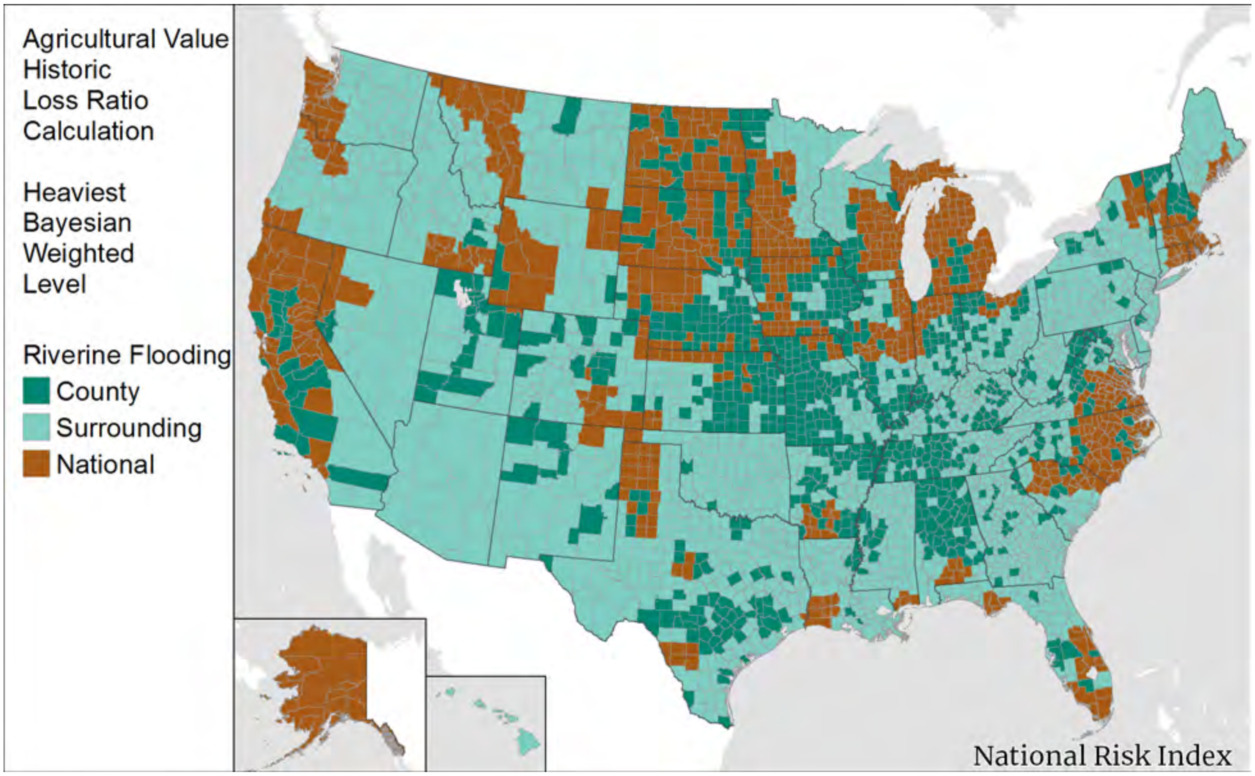

Figure 108: Riverine Flooding Heaviest Bayesian Influence Level – Agriculture Value

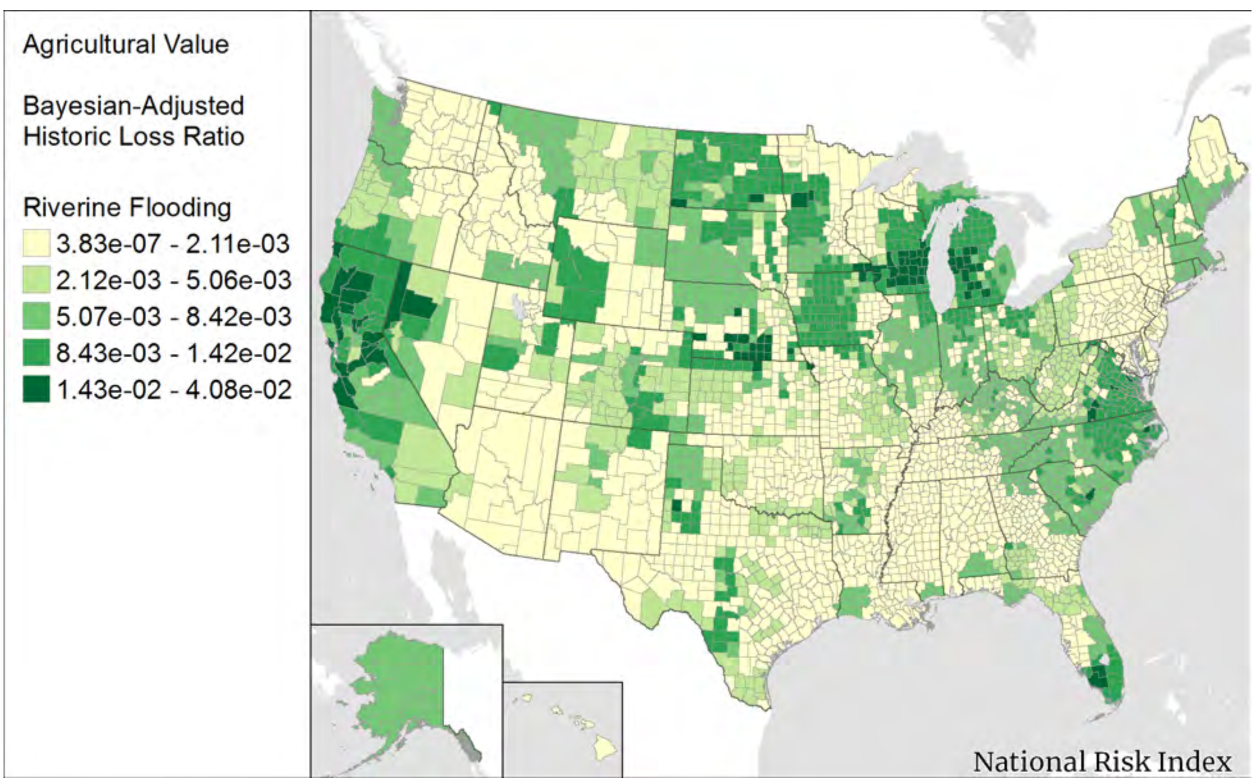

Figure 109: Riverine Flooding HLR – Agriculture Value

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

17.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 94*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 94: Census Block Expected Annual Loss to Riverine Flooding

$$EAL_{RFLD\,CB_{Bldg}} = Exposure_{RFLD\,CB_{Bldg}} \times Freq_{RFLD\,CB} \times HLR_{RFLD\,CB_{Bldg}}$$

$$EAL_{RFLD\,CB_{Pop}} = Exposure_{RFLD\,CB_{Pop}} \times Freq_{RFLD\,CB} \times HLR_{RFLD\,CB_{Pop}}$$

$$EAL_{RFLD\,CB_{Ag}} = Exposure_{RFLD\,CB_{Ag}} \times Freq_{RFLD\,CB} \times HLR_{RFLD\,CB_{Ag}}$$

where:

$EAL_{RFLD\,CB_{Bldg}}$	is the Expected Annual Loss to building value due to Riverine Flooding events for a specific Census block (in dollars).
$Exposure_{RFLD\,CB_{Bldg}}$	is the building value exposed to Riverine Flooding events in the Census block (in dollars).
$Freq_{RFLD\,CB}$	is the annualized Riverine Flooding frequency for the Census block.
$HLR_{RFLD\,CB_{Bldg}}$	is the Bayesian-adjusted building Historic Loss Ratio for Riverine Flooding for the Census block.
$EAL_{RFLD\,CB_{Pop}}$	is the Expected Annual Loss to population value due to Riverine Flooding events for a specific Census block (in dollars).
$Exposure_{RFLD\,CB_{Pop}}$	is the population value exposed to Riverine Flooding events in the Census block (in dollars).
$HLR_{RFLD\,CB_{Pop}}$	is the Bayesian-adjusted population Historic Loss Ratio for Riverine Flooding for the Census block.
$EAL_{RFLD\,CB_{Ag}}$	is the Expected Annual Loss to agricultural value due to Riverine Flooding events for a specific Census block (in dollars).
$Exposure_{RFLD\,CB_{Ag}}$	is the agriculture value exposed to Riverine Flooding events in the Census block (in dollars).

$HLR_{RFLD_{CB_{Ag}}}$	is the Bayesian-adjusted agriculture Historic Loss Ratio for Riverine Flooding for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building, population, and agricultural loss at the Census block level as in *Equation 95*.

Equation 95: Census Tract and County Expected Annual Loss to Riverine Flooding

$$EAL_{RFLD_{CT}} = \sum_{CB}^{CT} EAL_{RFLD_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{RFLD_{CB_{Pop}}} + \sum_{CB}^{CT} EAL_{RFLD_{CB_{Ag}}}$$

$$EAL_{RFLD_{Co}} = \sum_{CB}^{Co} EAL_{RFLD_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{RFLD_{CB_{Pop}}} + \sum_{CB}^{Co} EAL_{RFLD_{CB_{Ag}}}$$

where:

$EAL_{RFLD_{CT}}$	is the total Expected Annual Loss due to Riverine Flooding events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{RFLD_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Riverine Flooding for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{RFLD_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Riverine Flooding for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{RFLD_{CB_{Ag}}}$	is the summed Expected Annual Loss to agricultural value due to Riverine Flooding for all Census blocks in the Census tract (in dollars).
$EAL_{RFLD_{Co}}$	is the total Expected Annual Loss due to Riverine Flooding events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{RFLD_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Riverine Flooding for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{RFLD_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Riverine Flooding for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{RFLD_{CB_{Ag}}}$	is the summed Expected Annual Loss to agricultural value due to Riverine Flooding for all Census blocks in the county (in dollars).

Figure 110 shows the total EAL (building value, population, and agriculture value combined) to Riverine Flooding events.

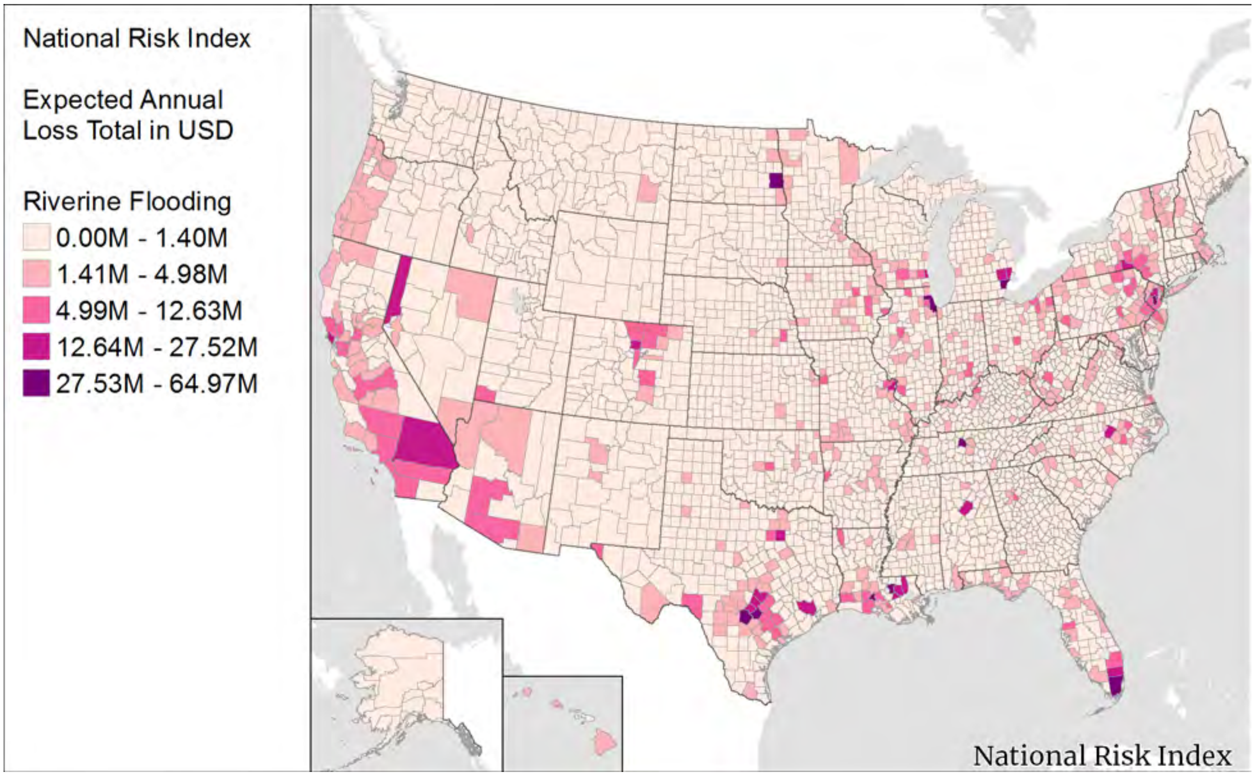

Figure 110: Total Expected Annual Loss by County to Riverine Flooding

With the Riverine Flooding total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Riverine Flooding Risk Index score.

18 Strong Wind

Strong Wind consists of damaging winds, often originating from thunderstorms, that are classified as exceeding 58 mph.

18.1 Spatial Source Data

Historical Event Source: *National Weather Service, Storm Prediction Center, Severe Weather Database Files*[62]

The Storm Prediction Center compiles all records of damaging Wind from the NWS's monthly Storm Data publication and makes them available in CSV format on the Warning Coordination Meteorologist's (WCM) website. These files record spatiotemporal information (start and end coordinates, date, time) as well as economic loss, wind speed in knots, and, from 2006 on, whether the wind speed was measured or estimated and whether the speed denotes a gust wind speed or a sustained wind speed (see *Table 49* and *Figure 111*). Many fields are empty for older records, especially those before 1985.

Table 49: Sample Strong Wind Data from the SPC

om (Wind ID)	date	st (State)	mag (Wind Speed [kt])	slon (Start Longitude)	slat (Start Latitude)	elon (End Longitude)	elat (End Latitude)
400	10/23/1955 19:00	MT	0	-84.58	43.28	0	0
553	2/6/1999 22:37	AR	52	-93.92	33.93	0	0
636896	6/9/2017 1:59	MI	100	-111.86	48.85	-111.86	48.85

62 National Weather Service – Storm Prediction Center, National Oceanic and Atmospheric Administration. (2017). Severe Weather Database files, Damaging Wind, 1955-2017 [online dataset]. Retrieved from https://www.spc.noaa.gov/wcm/.

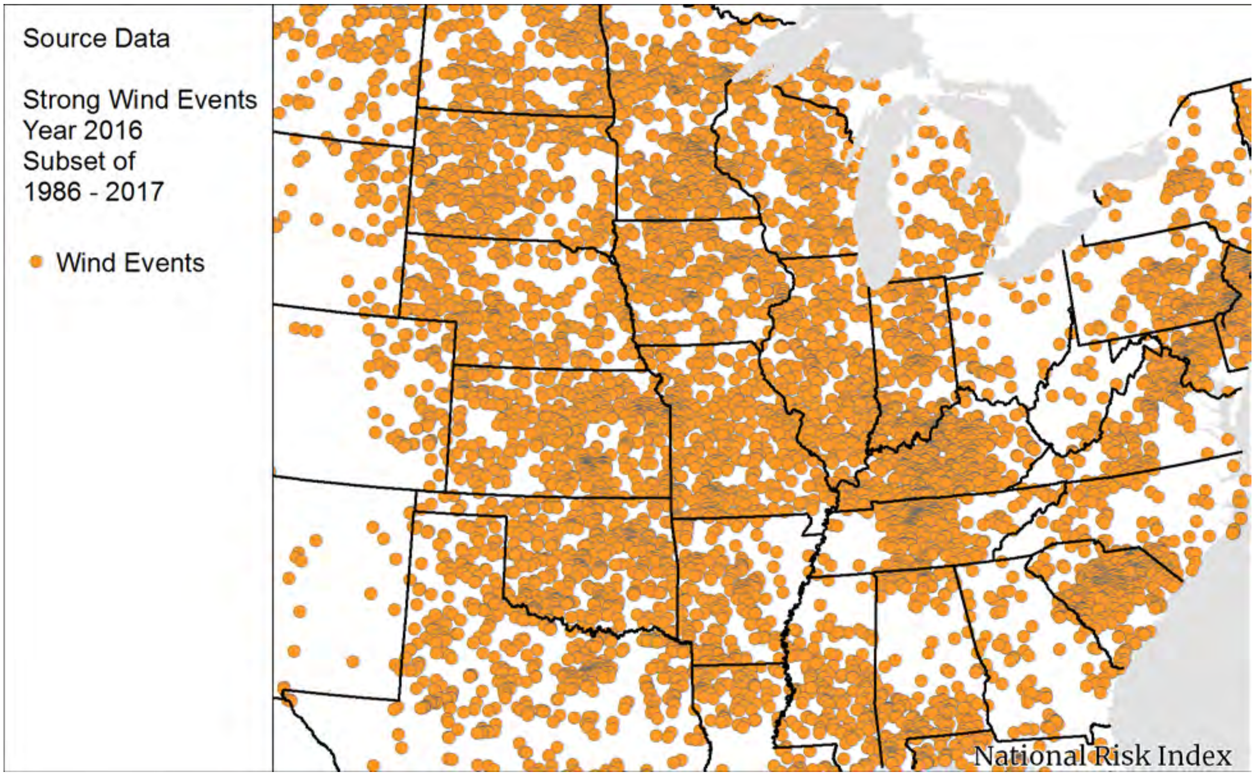

Figure 111: Map of Wind Points

18.1.1 PERIOD OF RECORD

To use only the most accurate data, wind speed data between 1/1/1986 and 12/31/2017 are analyzed, so the period of record for which Strong Wind data are utilized is 32 years.

18.2 Spatial Processing

The source data include fields for two sets of coordinates, a start and an end. This is mainly because the data share its format with the data for tornadoes. Most Wind events only have start coordinates (or the end coordinates match the start coordinates), so the points are projected from these coordinates. Any events outside of the period of record or with wind speeds of less than 50.4 knots (58 mph)[63] are filtered out. An 80-km buffer was created from the remaining points and, because multiple records were often recorded for a single date, the buffer polygons were dissolved on date to produce a layer of Strong Wind event-day polygons (see *Figure 112*). The buffer is not an attempt to represent the area of impact by a Strong Wind event, but rather an effort to estimate the area where Strong Winds may have been present. The Wind event-day polygons can then be used to estimate frequency at the Census block level.

[63] This threshold is used by NOAA and the National Weather Service as the minimum wind gust criterion for a Severe Thunderstorm Watch.

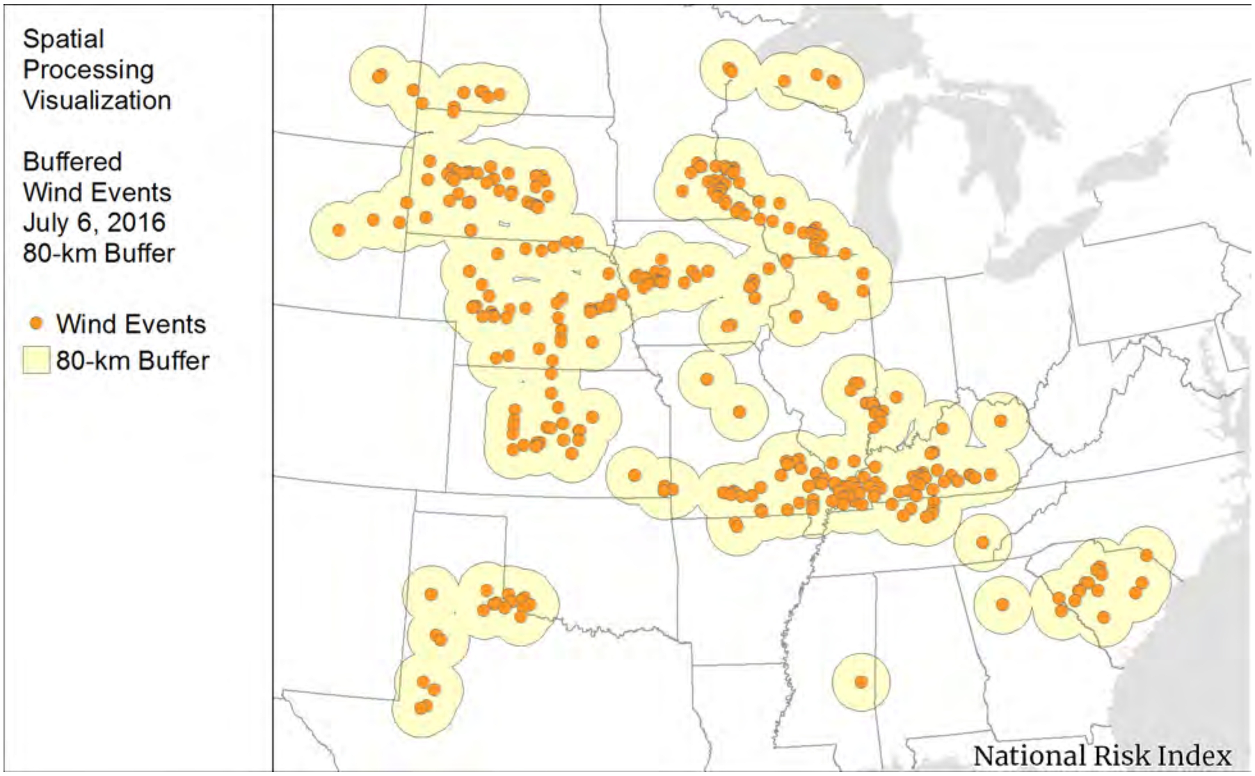

Figure 112: Map of Buffered Wind Points

18.3 Determination of Possibility of Hazard Occurrence

Strong Winds can occur almost anywhere under the right conditions, so all counties were deemed possible for Strong Wind occurrence.

18.4 Exposure

Because Strong Wind can occur anywhere, the entire building, population, and crop value of a Census block, Census tract, and county is considered exposed to Strong Wind. Crop value is included as a consequence type for Strong Wind because more than 10% of economic loss due to Strong Wind recorded in SHELDUS impacted crops and agriculture.

18.5 Historic Event-Day Count

The count of historic Strong Wind event-days is computed as the number of distinct Strong Wind event-day polygons that intersect a 49-by-49-km fishnet grid cell that encompasses the Census block, or an area-weighted count of the cells that intersect the Census block if it intersects multiple fishnet grid cells (see *Appendix D – Fishnet Event Count*). This count is used to compute Strong Wind event-day frequency.

Historic Event-Day Counts are also supplied at the Census tract and county levels as the area-weighted number of Strong Wind event-days that intersect the Census tract and county, respectively.

18.6 Frequency

The number of recorded Strong Wind event-days each year over the period of record (32 years) is used to estimate the frequency of Strong Wind event-days in an area. This annualized frequency is calculated at the Census block level, and the Census block-level value is used in the EAL calculations.

Frequency calculations use the Strong Wind event-day polygons created from the source data (as described in *Section 18.2*), as well as their corresponding computed duration days from the pre-processing of the data. The footprint polygons are intersected with a 49-by-49-km fishnet grid. The sum of Strong Wind event-days for the polygons intersecting each grid cell is recorded, and the Census block inherits this aggregated event-day count from the grid cell that encompasses it. If the Census block intersects multiple fishnet grid cells, an area-weighted average count is calculated (see *Appendix D – Fishnet Event Count*). The Strong Wind event-day count is then divided by the period of record as in *Equation 96*.

Equation 96: Census Block Strong Wind Frequency

$$Freq_{SWND\,CB} = \frac{EventDayCount_{SWND\,CB}}{PeriodRecord_{SWND}}$$

where:

$Freq_{SWND\,CB}$	is the annualized frequency of Strong Wind event-days determined for a specific Census block (event-days per year).
$EventDayCount_{SWND\,CB}$	is the number of Strong Wind event-days calculated for the Census block.
$PeriodRecord_{SWND}$	is the period of record for Strong Wind (32 years).

18.6.1 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level. These values may not exactly match that of dividing the number of recorded Strong Wind events at the Census tract and county level by the period of record, as the event count for frequency is a fishnet area-weighted event count including Strong Wind events that may have impacted the surrounding area but not the county or Census tract itself. The frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 97*.

Equation 97: Census Tract and County Area-Weighted Strong Wind Frequency Aggregation

$$Freq_{SWND_{CT}} = \frac{\sum_{CB}^{CT}\left(Freq_{SWND_{CB}} \times Area_{CB}\right)}{Area_{CT}}$$

$$Freq_{SWND_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{SWND_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{SWND_{CT}}$	is the annualized area-weighted Strong Wind frequency for a specific Census tract (event-days per year).
$Freq_{SWND_{CB}}$	is the annualized Strong Wind frequency associated with a specific Census block (event-days per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{SWND_{Co}}$	is the annualized area-weighted Strong Wind frequency for a specific county (event-days per year).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 113 displays annualized Strong Wind frequency at the county level.

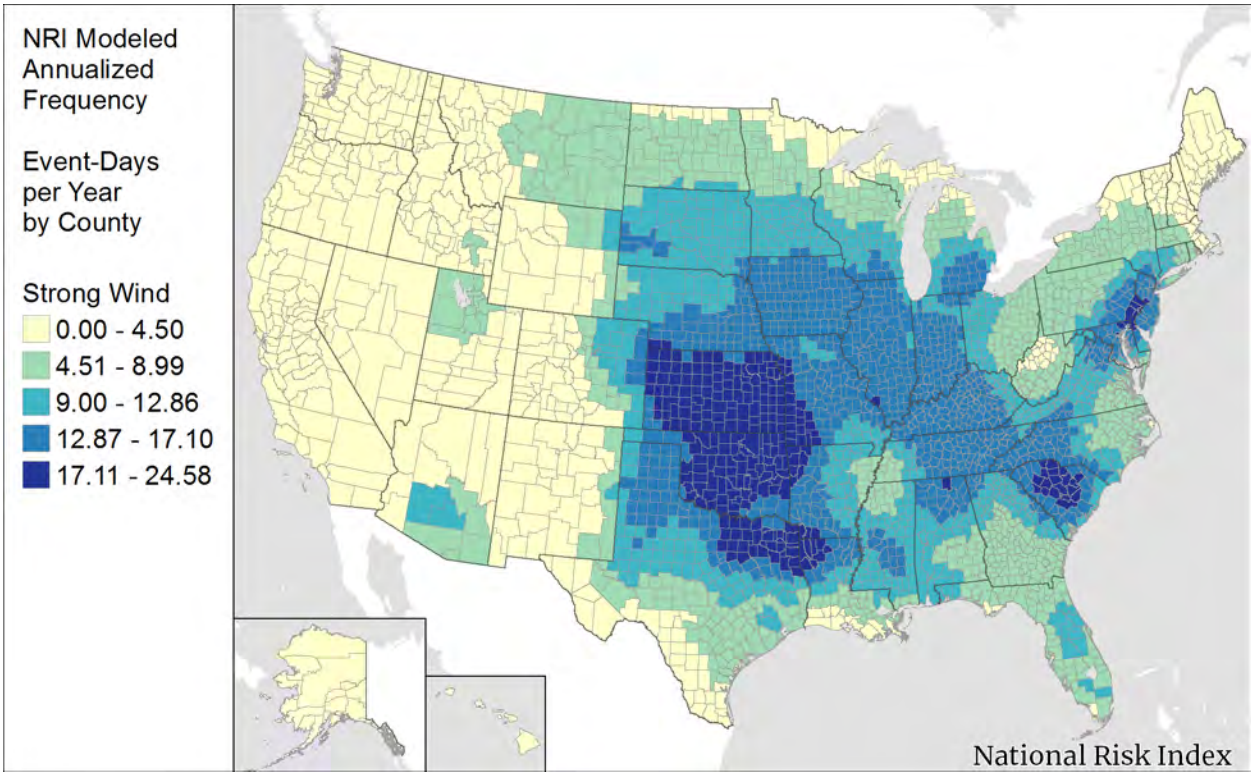

Figure 113: Annualized Strong Wind Frequency by County

18.7 Historic Loss Ratio

The Strong Wind HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Strong Wind event-day, or the average rate of loss associated with the occurrence of a Strong Wind event-day. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Strong Wind hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Three peril types are mapped to the hazard Strong Wind (see *Table 50*). These are expanded on an event-day basis based on the number of event duration days from SHELDUS[64] (see *Section 5.4.1*).

Table 50: Strong Wind Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Derecho	6	6
Wind	110,357	121,028
WindStraightLine	0	0

[64] For Strong Wind loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

The HLR exposure value for Strong Wind is a county-level value that represents the dollar value of the total building value or the entire population of a county as recorded in Hazus 4.2 SP1, or the total crop and livestock value of the county as estimated in the USDA 2017 Census of Agriculture data. The LRB for each SHELDUS-documented event and each consequence type (building, population, and agriculture) is calculated using *Equation 98*.

Equation 98: Loss Ratio per Basis Calculation for a Single Strong Wind Event-Day

$$LRB_{SWND_{Co_{CnsqType}}} = \frac{Loss_{SWND_{Co_{CnsqType}}}}{HLRExposure_{Co_{CnsqType}}}$$

where:

$LRB_{SWND_{Co_{CnsqType}}}$ is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Strong Wind event-day. Calculation is performed for each consequence type (building, population, and agriculture).

$Loss_{SWND_{Co_{CnsqType}}}$ is the loss (by consequence type) experienced from the Strong Wind event-day documented to have occurred in the county (in dollars).

$HLRExposure_{Co_{CnsqType}}$ is the total value (by consequence type) of the county estimated to have been exposed to the Strong Wind event-day (in dollars).

Strong Wind event-days can occur with a high frequency in areas, but often result in no recorded loss to buildings, population, or agriculture. SHELDUS does not record events in which no loss occurred, so a number of zero-loss event-days are inserted into the data to align the event-day count in the HLR calculation to the historic event-day count experienced within the SHELDUS period of record (1995 to 2016). For Strong Wind, a historic year-month event count is extracted using an intersection between the Strong Wind event-day polygons and the Census blocks. The observation date of each Strong Wind event-day polygon is used to sync the event to its year-month. A list of distinct Strong Wind observation dates is compiled for the event-day polygon-Census block intersections within the county, and the historic year-month event count is the number of distinct Strong Wind observation dates in this list.

If the number of loss-causing Strong Wind event-day records from SHELDUS is less than the summed historic year-month event-day counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, regional, and national. The regional definition for Strong Wind is derived from the FEMA regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 114, *Figure 116*, and *Figure 118* display the largest weighting factor contributor in the Bayesian credibility calculation for the Strong Wind HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Strong Wind event-days within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local, regional, or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing event-days or have widely varying loss ratios get the most influence from regional- or national-level loss data. *Figure 115*, *Figure 117*, and *Figure 119* represent the final county-level HLR values for Strong Wind.

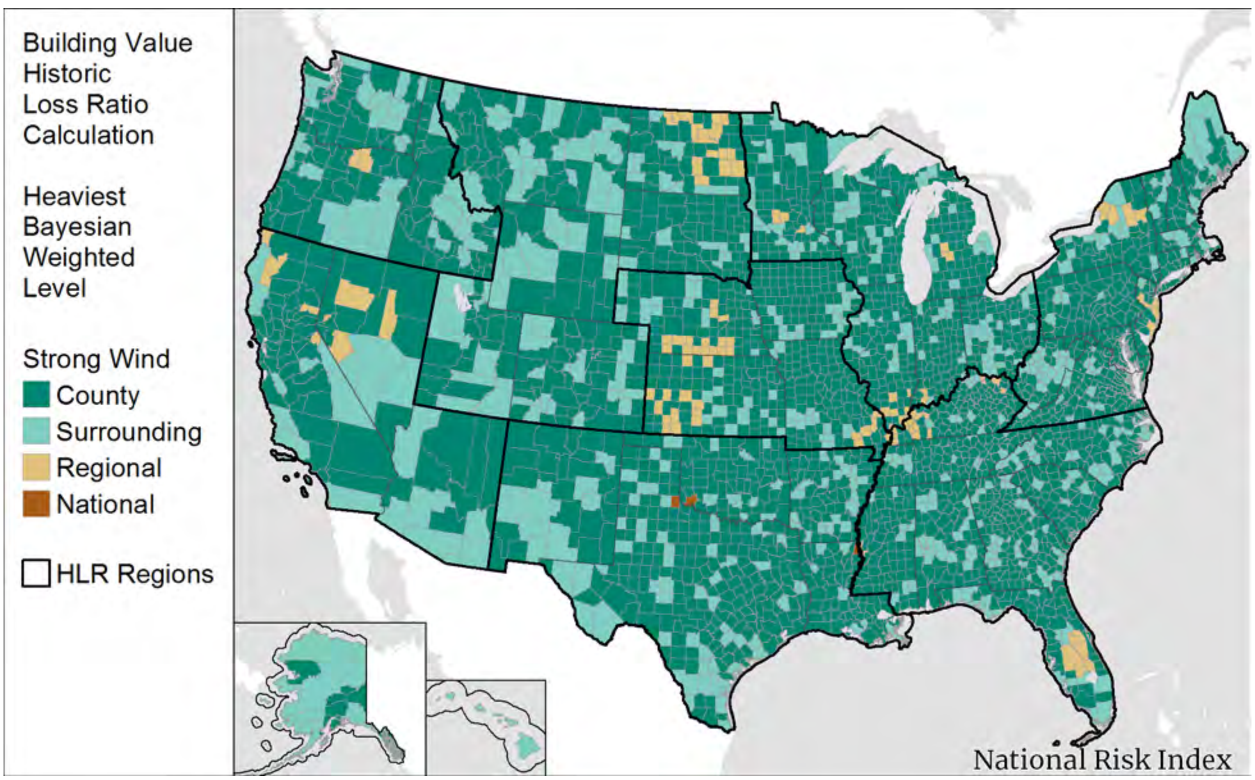

Figure 114: Strong Wind Heaviest Bayesian Influence Level – Building Value

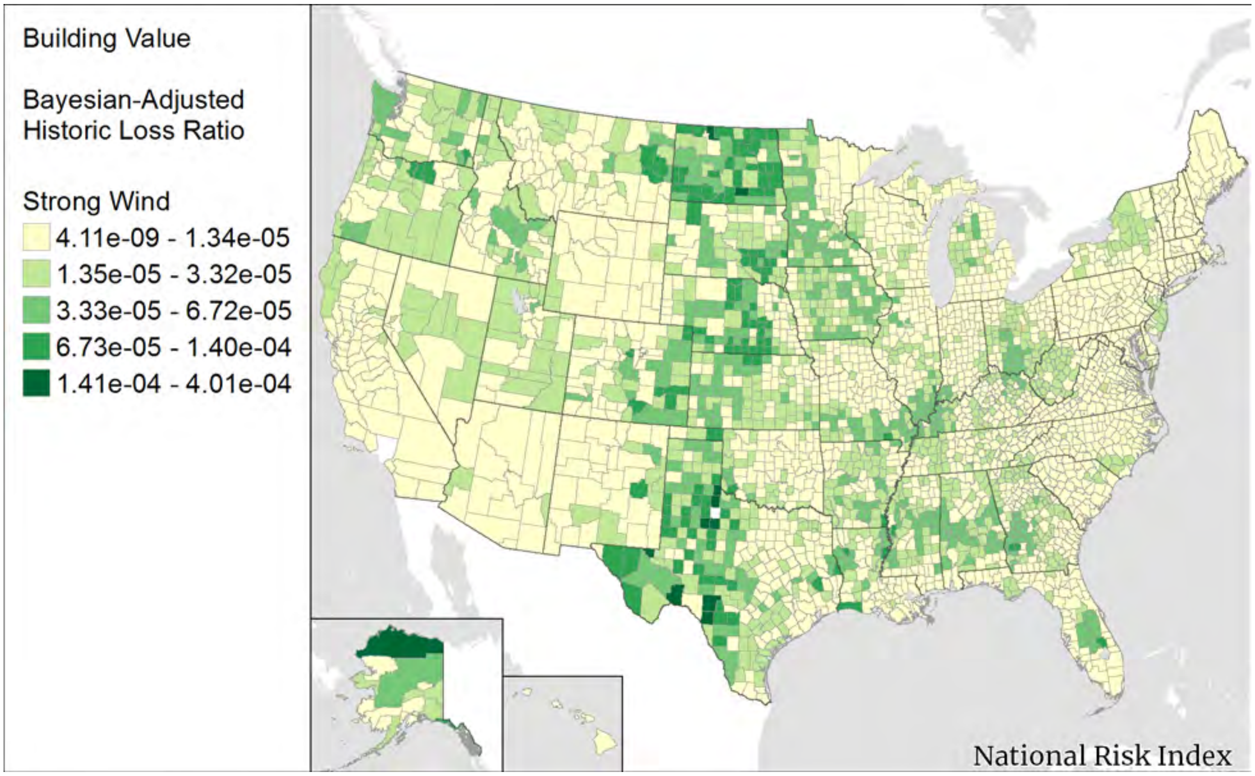

Figure 115: Strong Wind HLR – Building Value

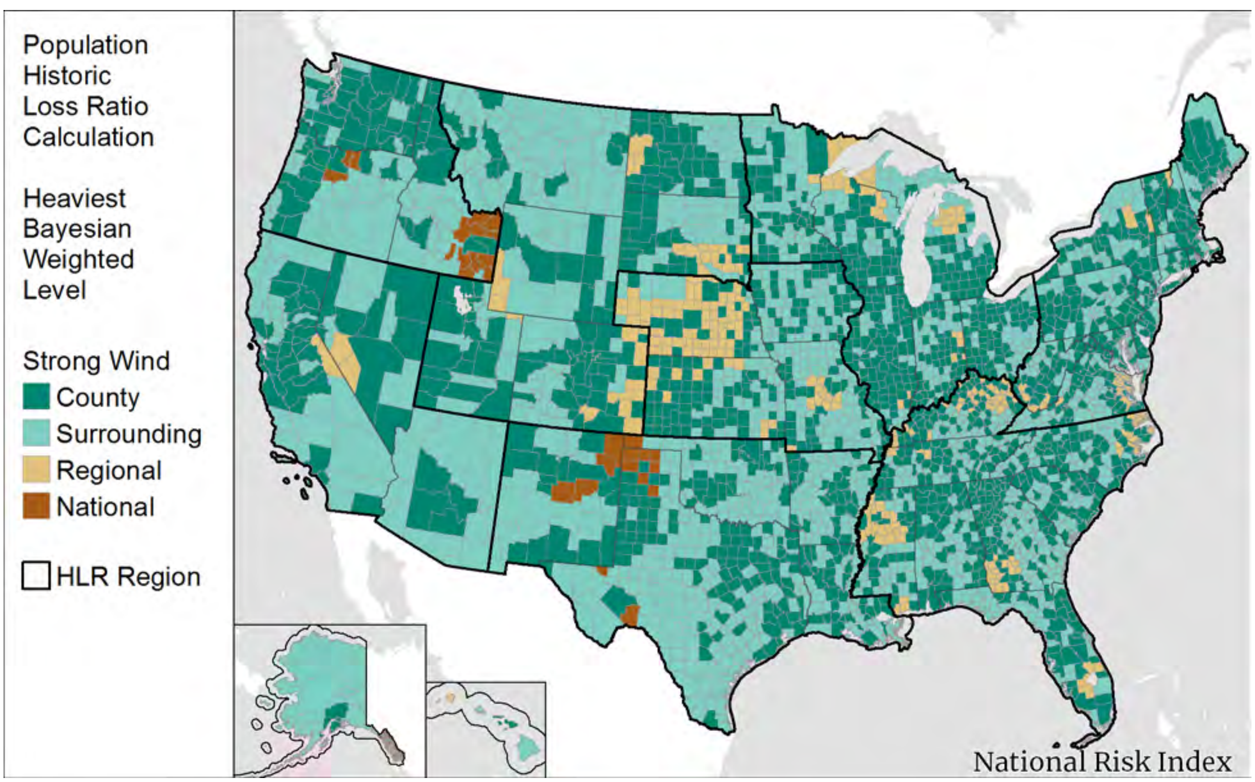

Figure 116: Strong Wind Heaviest Bayesian Influence Level – Population

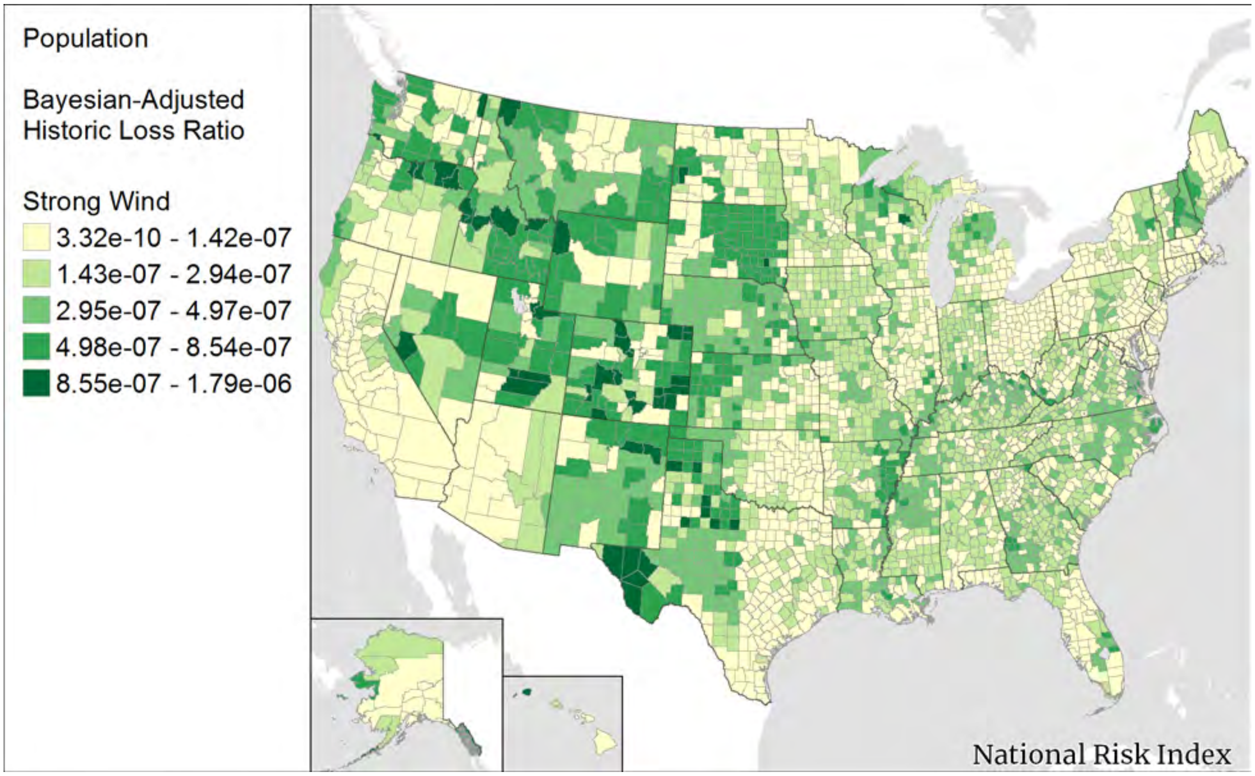

Figure 117: Strong Wind HLR – Population

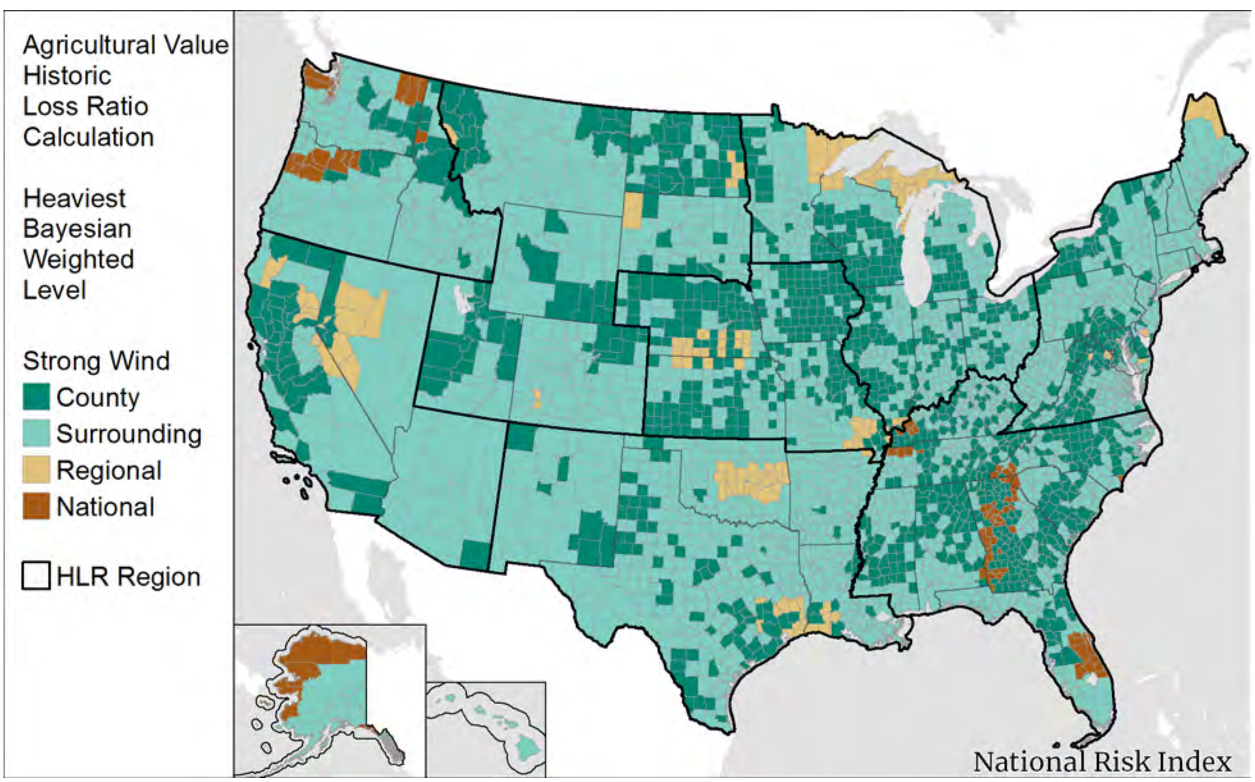

Figure 118: Strong Wind Heaviest Bayesian Influence Level – Agriculture Value

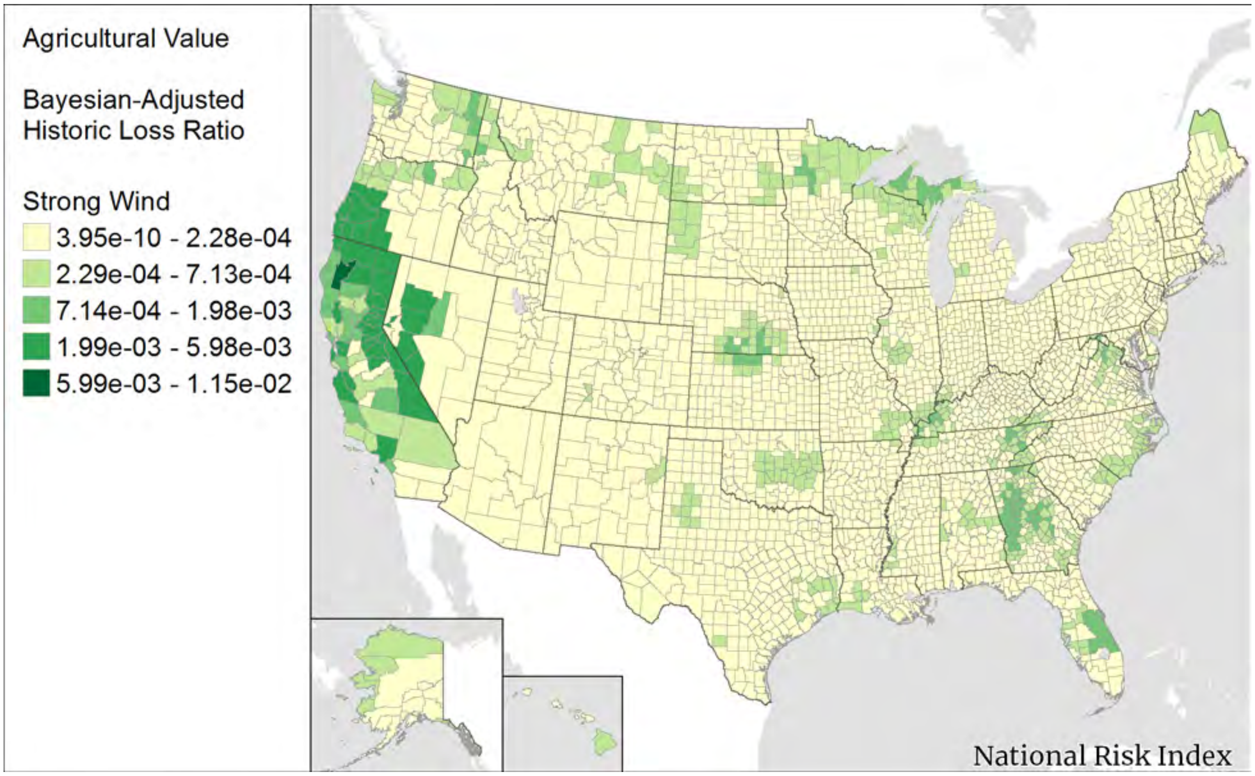

Figure 119: Strong Wind HLR – Agriculture Value

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

18.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 99*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 99: Census Block Expected Annual Loss to Strong Wind

$$EAL_{SWND_{CB_{Bldg}}} = Exposure_{SWND_{CB_{Bldg}}} \times Freq_{SWND_{CB}} \times HLR_{SWND_{CB_{Bldg}}}$$

$$EAL_{SWND_{CB_{Pop}}} = Exposure_{SWND_{CB_{Pop}}} \times Freq_{SWND_{CB}} \times HLR_{SWND_{CB_{Pop}}}$$

$$EAL_{SWND_{CB_{Ag}}} = Exposure_{SWND_{CB_{Ag}}} \times Freq_{SWND_{CB}} \times HLR_{SWND_{CB_{Ag}}}$$

where:

$EAL_{SWND_{CB_{Bldg}}}$ is the Expected Annual Loss to building value due to Strong Wind events for a specific Census block (in dollars).

$Exposure_{SWND_{CB_{Bldg}}}$	is the building value exposed to Strong Wind events in the Census block (in dollars).
$Freq_{SWND_{CB}}$	is the annualized Strong Wind frequency for the Census block (event-days per year).
$HLR_{SWND_{CB_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Strong Wind for the Census block.
$EAL_{SWND_{CB_{Pop}}}$	is the Expected Annual Loss to population value due to Strong Wind events for a specific Census block (in dollars).
$Exposure_{SWND_{CB_{Pop}}}$	is the population value exposed to Strong Wind events in the Census block (in dollars).
$HLR_{SWND_{CB_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Strong Wind for the Census block.
$EAL_{SWND_{CB_{Ag}}}$	is the Expected Annual Loss to agricultural value due to Strong Wind events for a specific Census block (in dollars).
$Exposure_{SWND_{CB_{Ag}}}$	is the agriculture value exposed to Strong Wind events in the Census block (in dollars).
$HLR_{SWND_{CB_{Ag}}}$	is the Bayesian-adjusted agriculture Historic Loss Ratio for Strong Wind for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building, crop, and population loss at the Census block level as in *Equation 100*.

Equation 100: Census Tract and County Expected Annual Loss to Strong Wind

$$EAL_{SWND_{CT}} = \sum_{CB}^{CT} EAL_{SWND_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{SWND_{CB_{Pop}}} + \sum_{CB}^{CT} EAL_{SWND_{CB_{Ag}}}$$

$$EAL_{SWND_{Co}} = \sum_{CB}^{Co} EAL_{SWND_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{SWND_{CB_{Pop}}} + \sum_{CB}^{Co} EAL_{SWND_{CB_{Ag}}}$$

where:

$EAL_{SWND_{CT}}$	is the total Expected Annual Loss due to Strong Wind events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{SWND_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Strong Wind for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{SWND_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Strong Wind for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{SWND\,CB_{Ag}}$	is the summed Expected Annual Loss to agricultural value due to Strong Wind for all Census blocks in the Census tract (in dollars).
$EAL_{SWND_{Co}}$	is the total Expected Annual Loss due to Strong Wind events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{SWND\,CB_{Bldg}}$	is the summed Expected Annual Loss to building value due to Strong Wind for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{SWND\,CB_{Pop}}$	is the summed Expected Annual Loss to population value due to Strong Wind for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{SWND\,CB_{Ag}}$	is the summed Expected Annual Loss to agricultural value due to Strong Wind for all Census blocks in the county (in dollars).

Figure 120 shows the total EAL (building value, population, and agriculture value combined) to Strong Wind events.

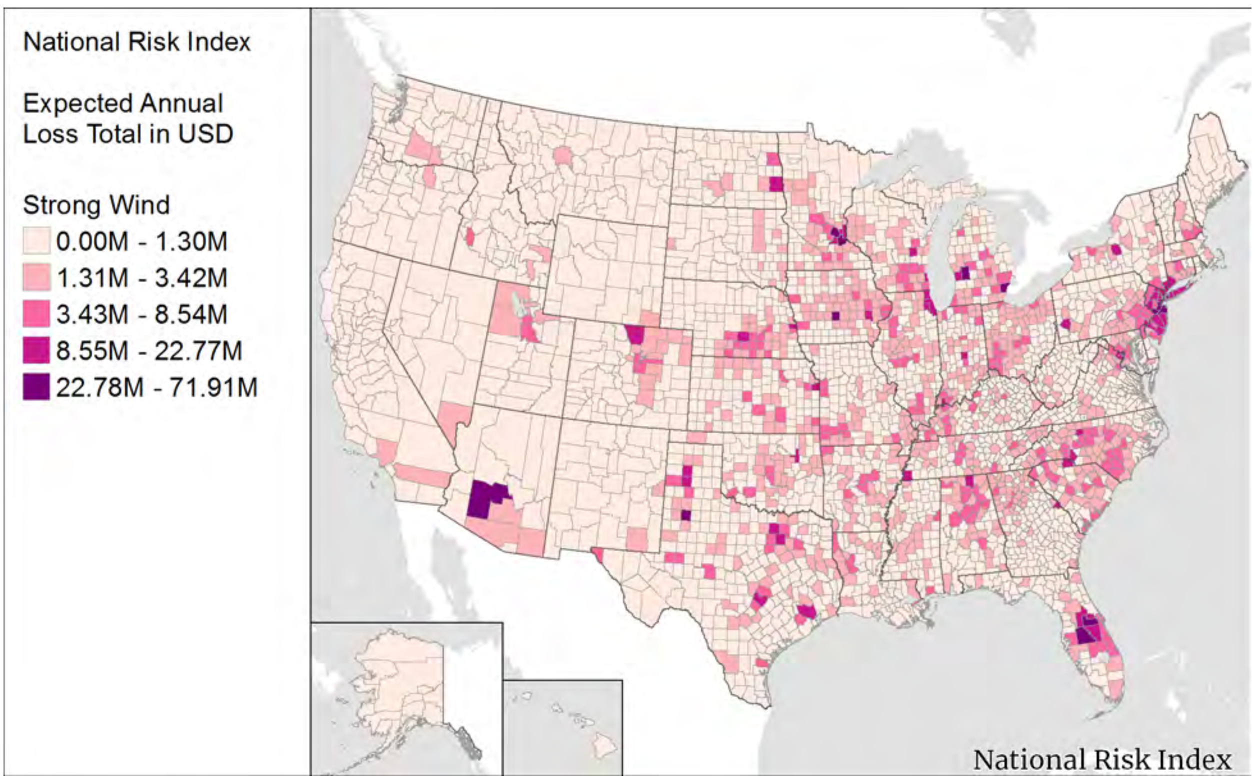

Figure 120: Total Expected Annual Loss by County to Strong Wind

With the Strong Wind total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Strong Wind Risk Index score.

19 Tornado

A Tornado is a narrow, violently rotating column of air that extends from the base of a thunderstorm to the ground and is visible only if it forms a condensation funnel made up of water droplets, dust, and debris.

19.1 Spatial Source Data

Historical Event Source: *National Weather Service, Storm Prediction Center, Severe Weather Database Files*[65]

The Storm Prediction Center compiles all records of Tornadoes from the NWS's monthly Storm Data publication and makes them available in CSV format on the Warning Coordination Meteorologist's (WCM) website. These files record spatiotemporal information (start and end coordinates, date, time) as well as economic loss, injuries, fatalities, and, depending on the date of the Tornado, Fujita (F-) or Enhanced Fujita (EF-) scale category (see *Table 51* and *Figure 121*). Tornado records with two distinct sets of start and end coordinates represent a Tornado path. A record with identical start and end coordinates or with no end coordinates represents a Tornado touchdown.

Table 51: Sample Tornado Data from SPC

om (Tornado Number [before 2007])	Date	St (State)	Mag (F/EF Scale)	Inj (Injuries)	Fat (Fatalities)	loss (Loss Category or $)	slon (Start Longitude)	slat (Start Latitude)	elon (End Longitude)	elat (End Latitude)
1	1/3/1950 11:00	MO	3	3	0	6	-90.22	38.77	-90.03	38.83
241	5/15/1989 15:35	TX	1	3	0	5	-101.57	34.05	-101.48	34.07
0	12/20/2017 12:15	GA	0	0	0	30000	-84.5904	33.0245	-84.536	33.0195

[65] Storm Prediction Center, National Weather Service. (2017). Severe Weather Database files, Tornado, 1950-2017 [online dataset]. Retrieved from http://www.spc.noaa.gov/wcm/.

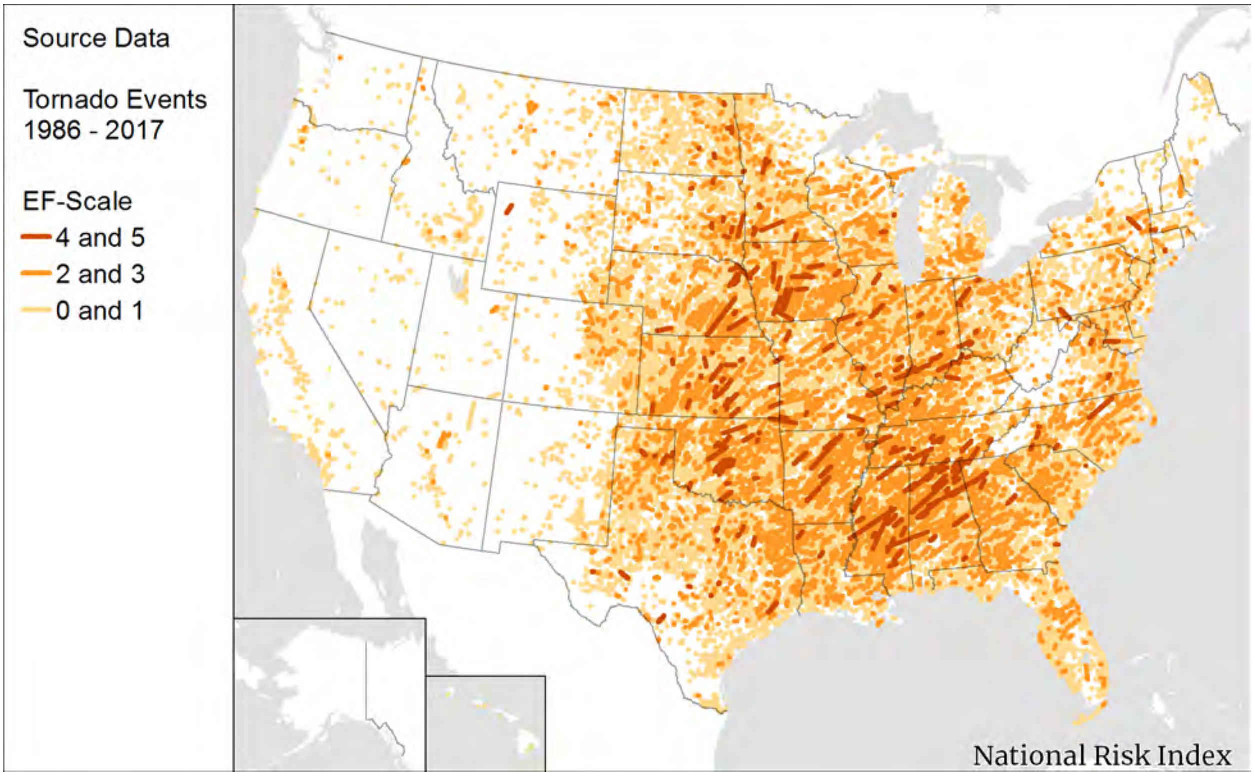

Figure 121: Map of Tornado Source Data

19.1.1 PERIOD OF RECORD

To use only the most accurate data, Tornado data between 1/1/1986 and 12/31/2017 are analyzed, so the period of record for which Tornado data are utilized is 32 years.

19.2 Spatial Processing

The source data include fields for two sets of coordinates, a start and an end. If the two sets of coordinates are non-zero and distinct, a Tornado path is represented in the NRI database as a line between the start and end coordinates. Otherwise, the start coordinates are projected as a Tornado touchdown point. Any Tornado events outside the period of record or that have an F- or EF-scale of -9 to signify insufficient data are filtered out. A buffer is created based on F- or EF-scale category according to *Table 52*. The distances used represent the average radius of impact for a storm of that magnitude.

Table 52: Tornado Categories

F-Scale Category	Tornado Touchdown Point Buffer (meter)	Tornado Path Line Buffer (meter)
0	27	48
1	54	134
2	110	269
3	172	535
4	249	776
5	249	1233

Because Tornado events are recorded at distinct locations and multiple Tornadoes are often reported on the same day in near proximity, it was necessary for frequency estimation to spread the influence of the reported historical event. Thus, an additional 80-km buffer was created from these category-buffered polygons (see *Figure 122*). This 80-km buffer radius is not an attempt to represent the Tornado's impact area. Rather, it is to better represent the area where the event could possibly have occurred. The 80-km buffered Tornado event path polygons can then be used to estimate frequency at the Census tract level.

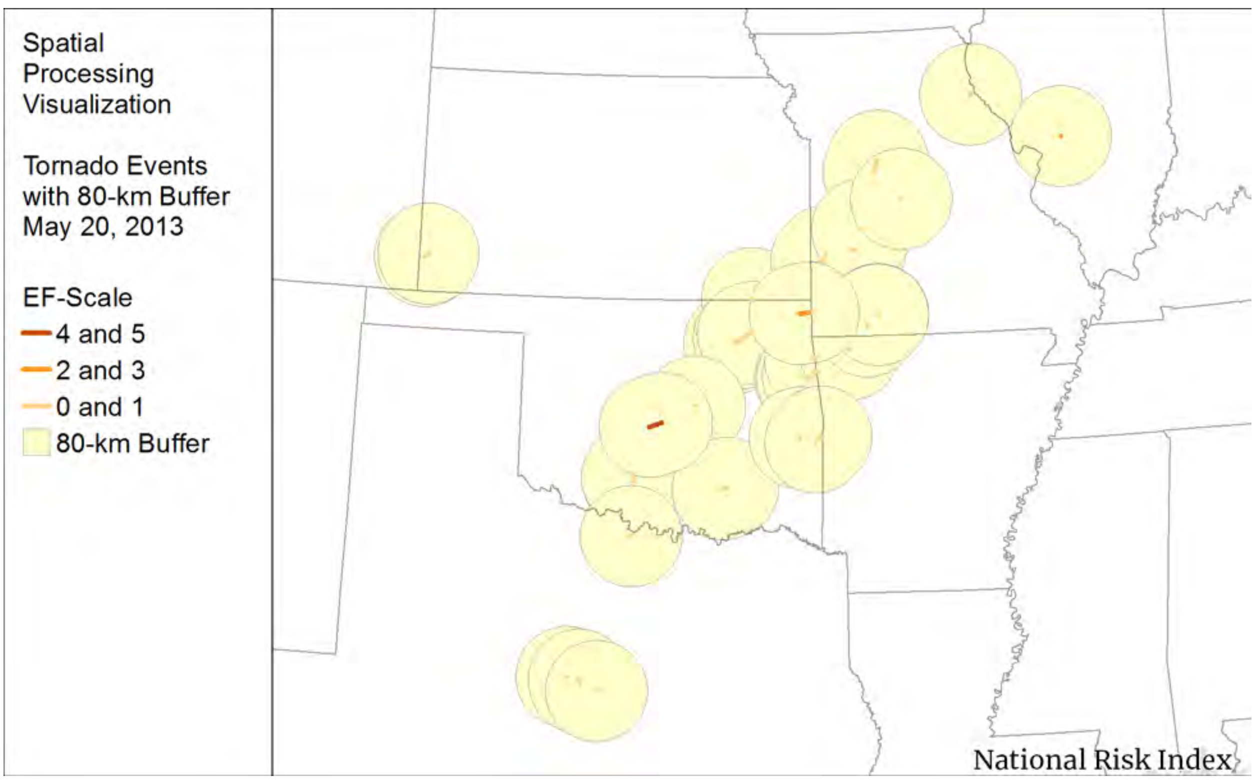

Figure 122: Map of Buffered Tornadoes

19.3 Determination of Possibility of Hazard Occurrence

Tornadoes are capable of occurring almost anywhere under the right conditions, so all counties were deemed possible for Tornado occurrence.

19.4 Exposure

A review of the source data found that 98% of historical Tornado events impact an area of 50 km² or less, with the average damage area being 2.07 km². Thus, a 2 km² area was used to estimate an average area impacted by a Tornado. Because a Tornado could occur anywhere in the Census tract, the tract average density (the tract's total building value or population divided by the total area of the tract) is applied. Therefore, the exposure area of a Census tract is calculated using *Equation 101* and the exposure area of a county is calculated using *Equation 102*.

Equation 101: Census Tract Tornado Exposure

$$Exposure_{TRND\,CT_{Bldg}} = DamageArea_{TRND} \times AvgDen_{CT_{Bldg}}$$

$$Exposure_{TRND\,CT_{Pop}} = \left(DamageArea_{TRND} \times AvgDen_{CT_{Pop}}\right) \times VSL$$

where:

$Exposure_{TRND\,CT_{Bldg}}$	is the building value exposed to Tornadoes in a specific Census tract (in dollars).
$DamageArea_{TRND}$	is the average area of Tornado impact (estimated at 2 km²).
$AvgDen_{CT_{Bldg}}$	is the average building value density of the Census tract (in dollars per square kilometer).
$Exposure_{TRND\,CT_{Pop}}$	is the population exposed to Tornadoes in a specific Census tract (in dollars).
$AvgDen_{CT_{Pop}}$	is the average population density of the Census tract (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).

Equation 102: County Tornado Exposure

$$Exposure_{TRND\,Co_{Bldg}} = DamageArea_{TRND} \times AvgDen_{Co_{Bldg}}$$

$$Exposure_{TRND\,Co_{Pop}} = \left(DamageArea_{TRND} \times AvgDen_{Co_{Pop}}\right) \times VSL$$

where:

$Exposure_{TRND_{Co_{Bldg}}}$	is the building value exposed to Tornadoes in a specific county (in dollars).
$DamageArea_{TRND}$	is the average area of Tornado impact (estimated at 2 km^2).
$AvgDen_{Co_{Bldg}}$	is the average building value density of the county (in dollars per square kilometer).
$Exposure_{TRND_{Co_{Pop}}}$	is the population value exposed to Tornadoes in a specific county (in dollars).
$AvgDen_{Co_{Pop}}$	is the average population density of the county (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).

19.5 Historic Event Count

The count of historic Tornado events is computed as the number of distinct Tornado event path polygons that intersect a Census block. Historic Event-Day Counts are supplied at the Census tract and county levels as the number of distinct Tornado event path polygons that intersect the Census tract and county, respectively. Note that this historic event count is displayed in the NRI application but that this count is not used to calculate frequency.

19.6 Frequency

The frequency value represents the estimated number of recorded Tornado events each year for a specific area. Annualized frequency is calculated at the Census tract level, and the Census tract-level value is used in the EAL calculations.

Frequency calculations are determined by intersecting the 80-km buffered Tornado event path polygons generated in *Section 19.2* with a 49-by-49-km fishnet grid. The count of distinct Tornado event path polygons intersecting each grid cell is recorded (see *Appendix D – Fishnet Event Count*), and the Census tract inherits this count from the grid cell that encompasses it.

If the Census tract intersects multiple grid cells, an area-weighted average count is calculated (see *Appendix D – Fishnet Event Count*). The Tornado event count is then divided by the period of record as in *Equation 103*.

Equation 103: Census Tract Tornado Frequency

$$Freq_{TRND_{CT}} = \frac{EventCount_{TRND_{CT}}}{PeriodRecord_{TRND}}$$

where:

$Freq_{TRND_{CT}}$	is the annualized frequency of Tornado events determined for a specific Census tract (events per year).
$EventCount_{TRND_{CT}}$	is the number of Tornado events calculated for the Census tract (estimated based on the counts of intersecting fishnet cells).
$PeriodRecord_{TRND}$	is the period of record for Tornado (32 years).

19.6.1 MINIMUM ANNUAL FREQUENCY

If a Census tract's historical Tornado event count and fishnet event count is 0, the Census tract is assigned the minimum annual Tornado frequency. This minimum frequency is set at 0.03125, or once in the period of record (1 in 32 years).

19.6.2 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at the county level. These values may not exactly match that of dividing the number of recorded historic Tornado events at the county level by the period of record, as the event count for frequency is a fishnet area-weighted event count including Tornadoes that may have impacted the surrounding area but not the county itself. The frequency values at the Census tract level are rolled up to the county level using area-weighted aggregations as in *Equation 104*.

Equation 104: County Area-Weighted Tornado Frequency Aggregation

$$Freq_{TRND_{Co}} = \frac{\sum_{CT}^{Co}\left(Freq_{TRND_{CT}} \times Area_{CT}\right)}{Area_{Co}}$$

where:

$Freq_{TRND_{Co}}$	is the annualized Tornado frequency calculated for a specific county (events per year).
$Freq_{TRND_{CT}}$	is the annualized Tornado frequency calculated for a specific Census tract (events per year).
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$\sum_{CT}^{Co}$	is the sum for all Census tracts in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 123 displays annualized Tornado frequency at the county level.

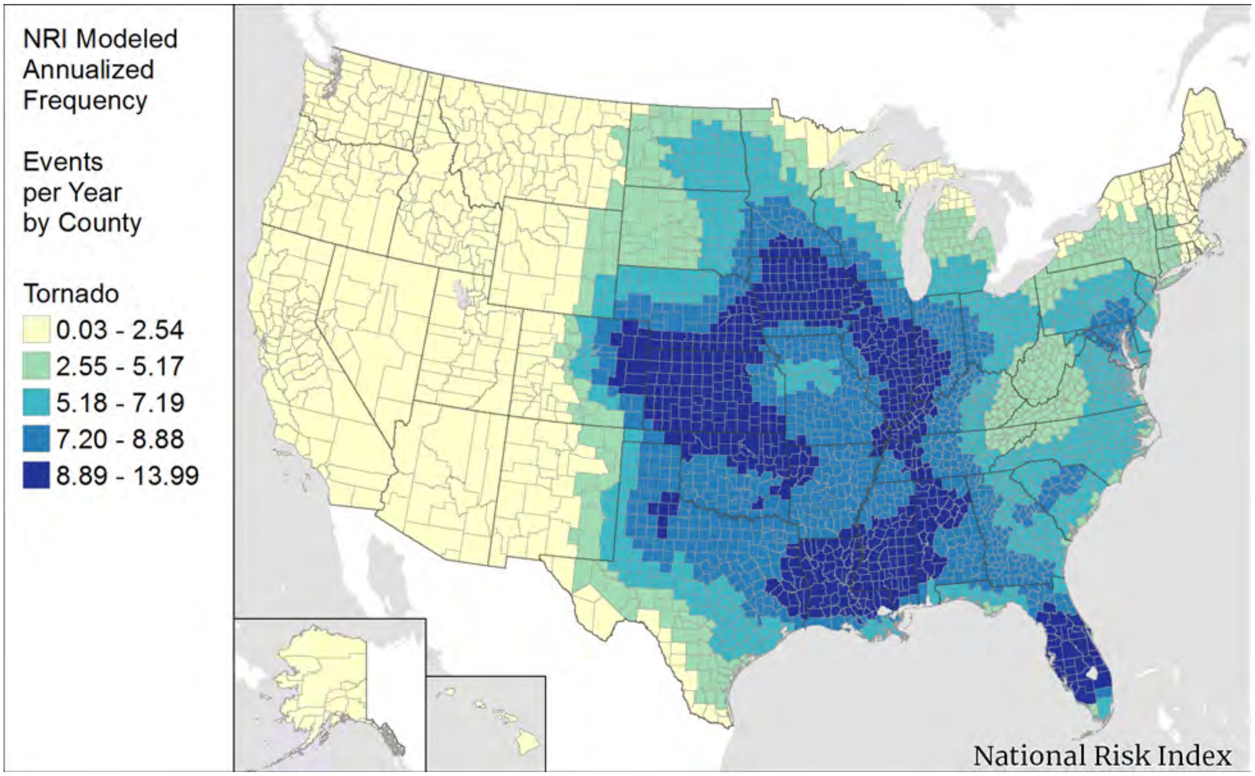

Figure 123: Annualized Tornado Frequency by County

19.7 Historic Loss Ratio

The Tornado HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Tornado event, or the average rate of loss associated with the occurrence of a Tornado event. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Tornado hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Five peril types are mapped to the hazard Tornado (see *Table 53*). These are expanded on an event basis based on the number of records from SHELDUS[66] (see *Section 5.4.1*).

[66] For Tornado loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

Table 53: Tornado Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
FireTornado	0	0
Tornado	12,162	15,549
Waterspout	10	10
WindTornadic	0	0
WindVortex	1	2

The HLR exposure value used in the LRB calculation is based on the historic Tornado paths that have occurred within the county for the year-month in which the SHELDUS-documented loss occurred. The goal is to match the economic loss caused by the specific Tornado directly to the building value and population that were in the Tornado's path. This HLR exposure is calculated by summing the total values of Census blocks that intersect the F-scale buffered Tornado path within the county.

Because an attempt was made to match all loss-causing Tornado events to the estimated footprint of their historic paths (according to the spatial source data), any SHELDUS record for which the year-month count was greater than the count of past Tornado events for that month was discarded. If more than one Tornado has impacted the county during the month in which the loss was recorded, the loss values for each event will be the total loss value divided by the number of Tornado events (via the event basis record expansion), and the HLR exposure value will be the total year-month's HLR exposure value divided by the number of Tornado events as in *Equation 105*.

Equation 105: Loss Ratio per Basis Calculation for a Single Tornado Event

$$LRB_{TRND\,Co_{CnsqType}} = \frac{Loss_{TRND\,Co_{CnsqType}}}{HLRExposure_{TRND\,Co_{CnsqType}}}$$

where:

$LRB_{TRND\,Co_{CnsqType}}$	is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Tornado event. Calculation is performed for each consequence type (building and population).
$Loss_{TRND\,Co_{CnsqType}}$	is the loss (by consequence type) experienced from the Tornado event documented to have occurred in the county (in dollars).
$HLRExposure_{TRND\,Co_{CnsqType}}$	is the value (by consequence type) of the area estimated to have been exposed to the Tornado event based on the path of the historic Tornado during the month in which the loss occurred (in dollars).

Tornado events may occur in areas without resulting in recorded loss to buildings or population. SHELDUS does not record events in which no loss occurred, so a number of zero-loss events are inserted into the data to align the event count in the HLR calculation to the historic event count experienced within the SHELDUS period of record (1995 to 2016). For Tornado, the historic year-month event count is extracted using an intersection between the Tornado event path polygons (buffered by F-scale, but not the additional 80-km buffer; see *Section 19.2*) and the Census blocks. The observation date of each Tornado event path polygon is used to sync the event to its year-month. A list of distinct Tornado observation dates is compiled for the path polygon-fishnet intersections that intersect the county, and the historic year-month event count is the number of distinct Tornado observation dates in this list.

If the number of loss-causing Tornado event records from SHELDUS is less than the summed historic year-month event counts for the county, then a number of zero-loss records equal to the difference is inserted into the Loss Ratio per Basis table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, regional, and national. The regional definition for Tornado is derived from the FEMA regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 124 and *Figure 126* display the largest weighting factor contributor in the Bayesian credibility calculation for the Tornado HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Tornado events within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local, regional, or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from regional- or national-level loss data. *Figure 125* and *Figure 127* represent the final county-level HLR values for Tornado.

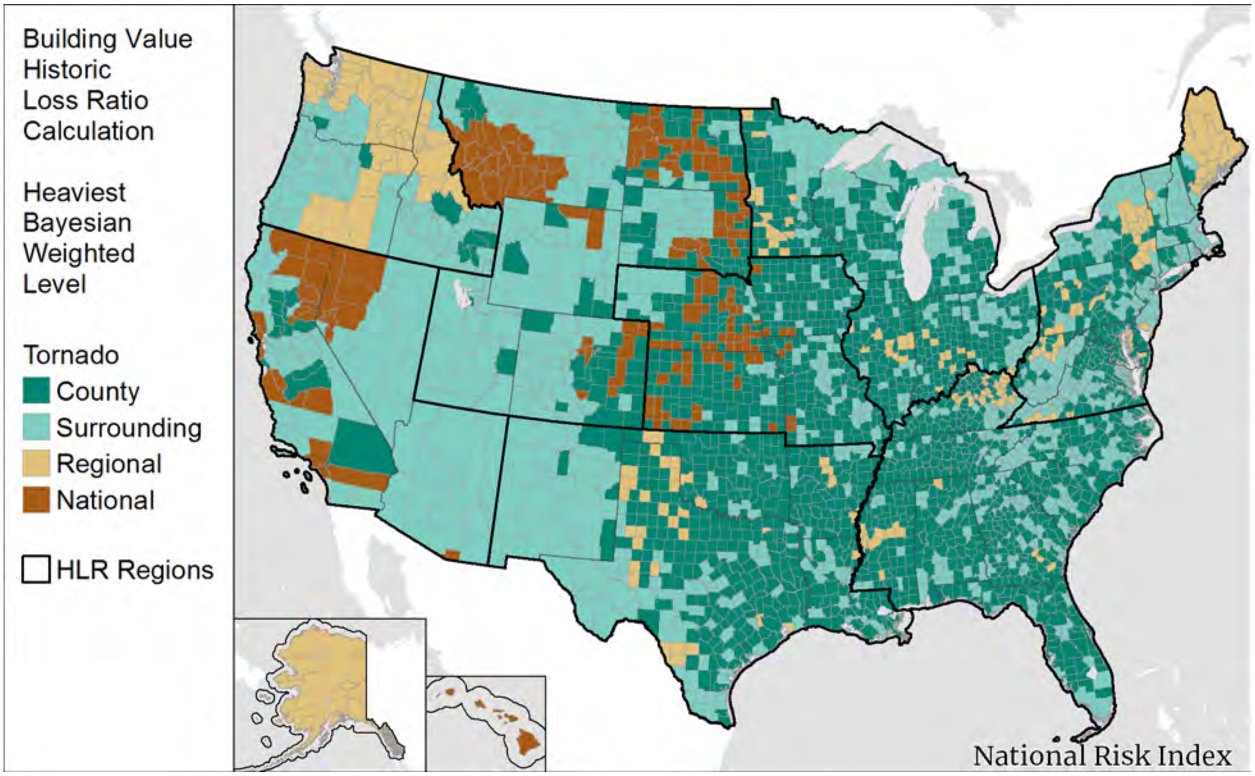

Figure 124: Tornado Heaviest Bayesian Influence Level – Building Value

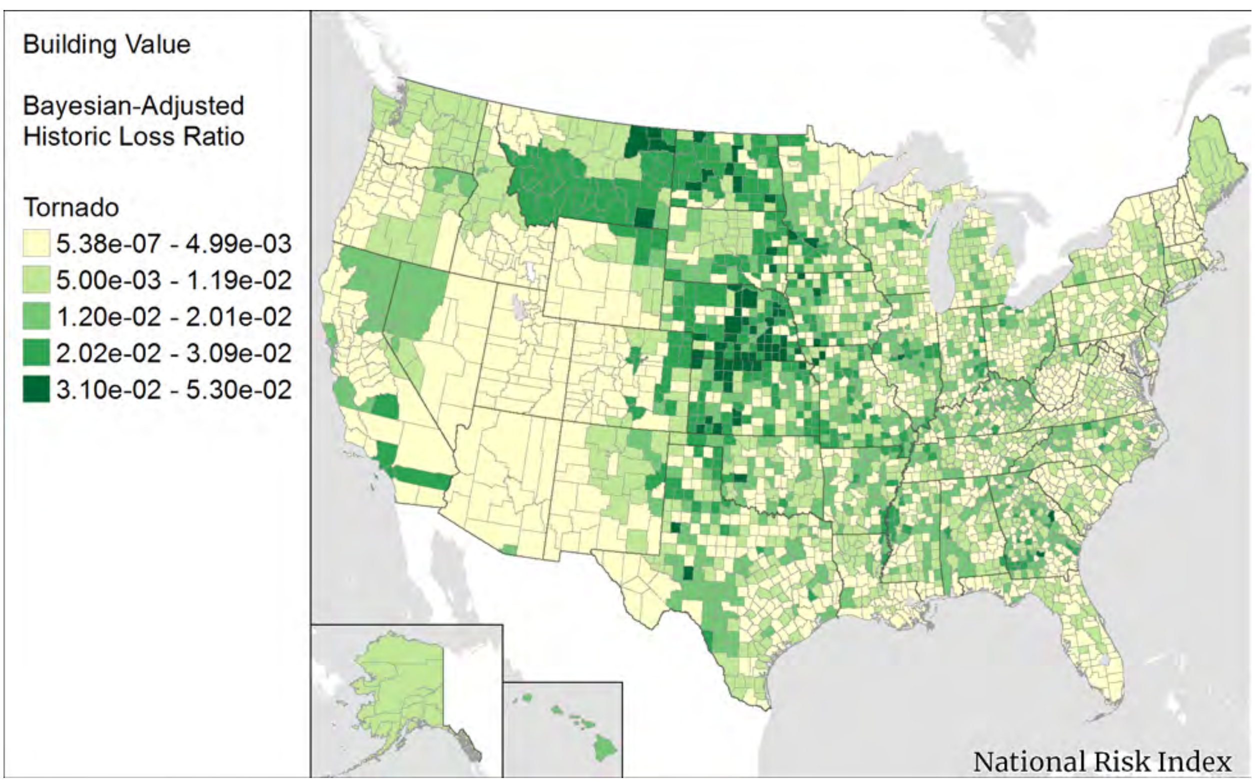

Figure 125: Tornado HLR – Building Value

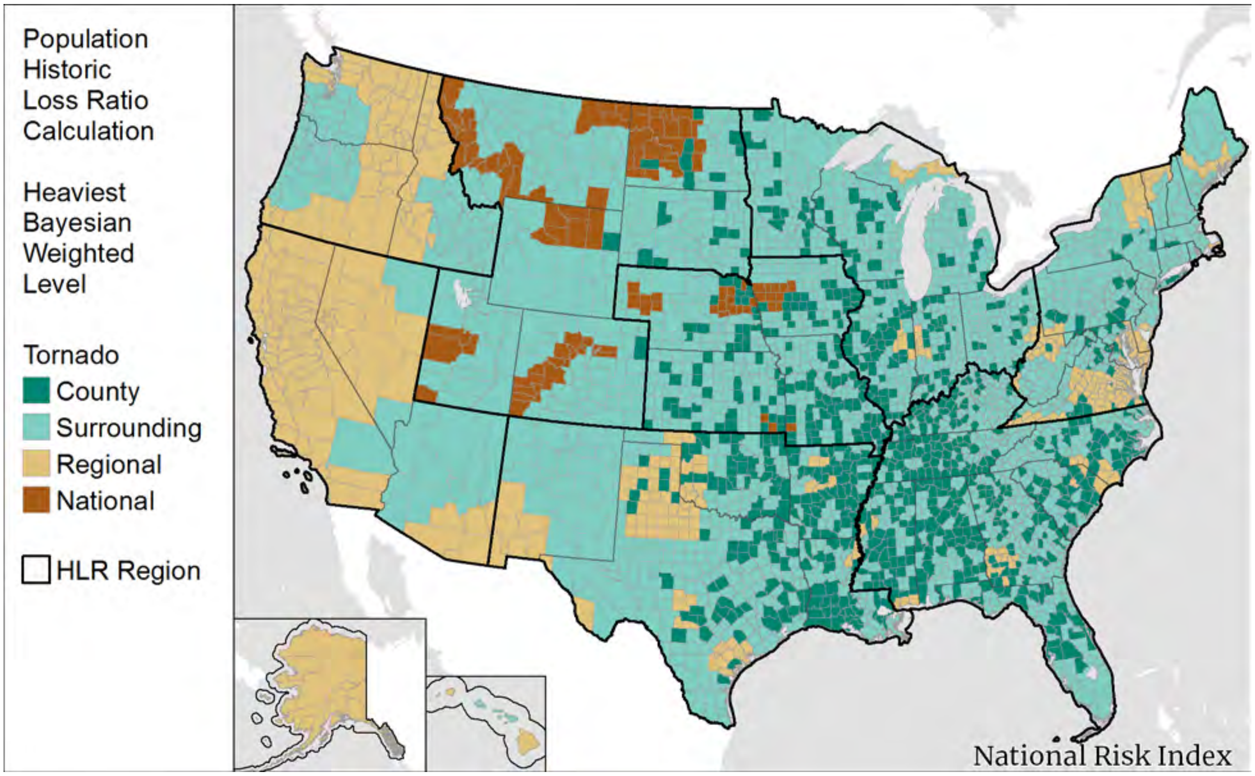

Figure 126: Tornado Heaviest Bayesian Influence Level – Population

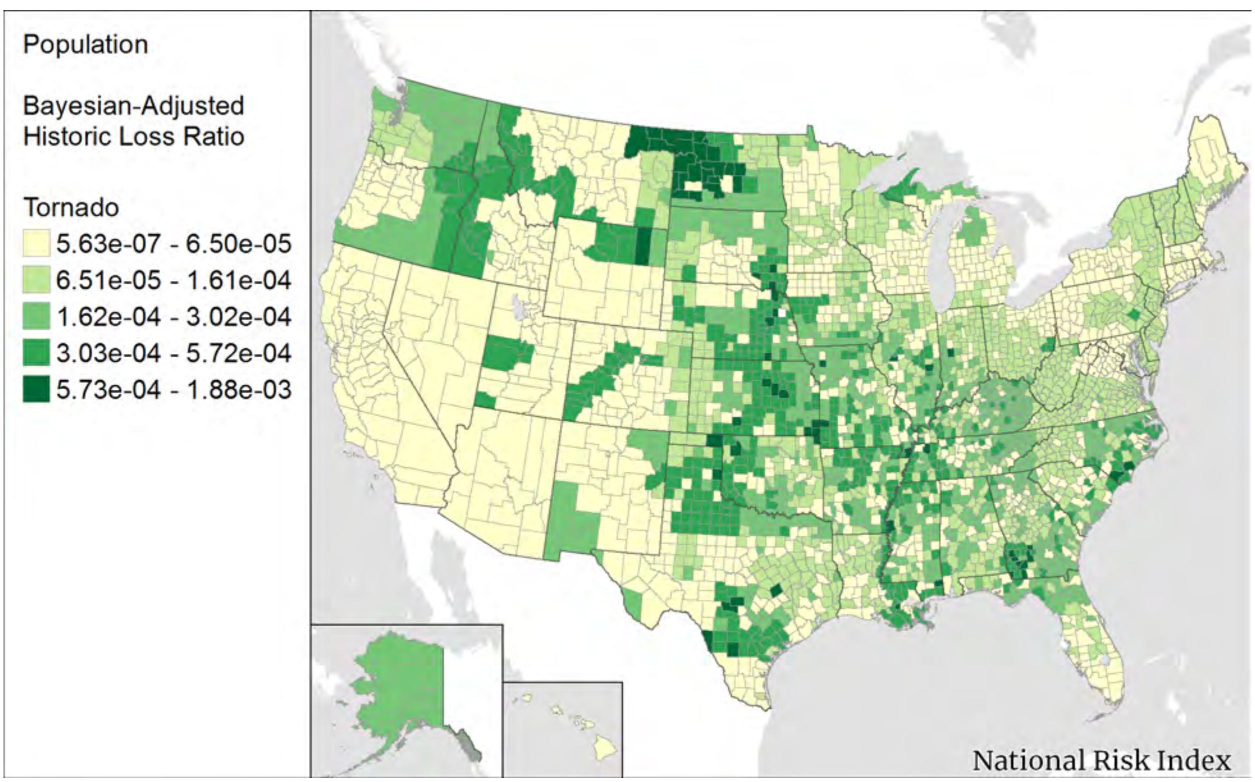

Figure 127: Tornado HLR – Population

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census tracts within the county.

19.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census tract level as in *Equation 106*.

Equation 106: Census Tract Expected Annual Loss to Tornado

$$EAL_{TRND\,CT_{Bldg}} = Exposure_{TRND\,CT_{Bldg}} \times Freq_{TRND\,CT} \times HLR_{TRND\,CT_{Bldg}}$$

$$EAL_{TRND\,CT_{Pop}} = Exposure_{TRND\,CT_{Pop}} \times Freq_{TRND\,CT} \times HLR_{TRND\,CT_{Pop}}$$

where:

$EAL_{TRND\,CT_{Bldg}}$	is the Expected Annual Loss to building value due to Tornado events for a specific Census tract (in dollars).
$Exposure_{TRND\,CT_{Bldg}}$	is the building value exposed to Tornado events in the Census tract (in dollars).
$Freq_{TRND\,CT}$	is the annualized Tornado frequency calculated for the Census tract (events per year).
$HLR_{TRND\,CT_{Bldg}}$	is the Bayesian-adjusted building Historic Loss Ratio for Tornado for the Census tract.
$EAL_{TRND\,CT_{Pop}}$	is the Expected Annual Loss to population value due to Tornado events for a specific Census tract (in dollars).
$Exposure_{TRND\,CT_{Pop}}$	is the population value exposed to Tornado events in the Census tract (in dollars).
$HLR_{TRND\,CT_{Pop}}$	is the Bayesian-adjusted population Historic Loss Ratio for Tornado for the Census tract.

The total EAL value at the county level is the sum of the aggregated value of the building and population loss at the Census tract level as in *Equation 107*.

Equation 107: County Expected Annual Loss to Tornado

$$EAL_{TRND\,Co} = \sum_{CT}^{Co} EAL_{TRND\,CT_{Bldg}} + \sum_{CT}^{Co} EAL_{TRND\,CT_{Pop}}$$

where:

$EAL_{TRND_{Co}}$	is the total Expected Annual Loss due to Tornado events for a specific county (in dollars).
$\sum_{CT}^{Co} EAL_{TRND_{CT_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Tornado events for all Census tracts in the county (in dollars).
$\sum_{CT}^{Co} EAL_{TRND_{CT_{Pop}}}$	is the summed Expected Annual Loss to population value due to Tornado events for all Census tracts in the county (in dollars).

Figure 128 shows the total EAL (building value and population combined) to Tornado events.

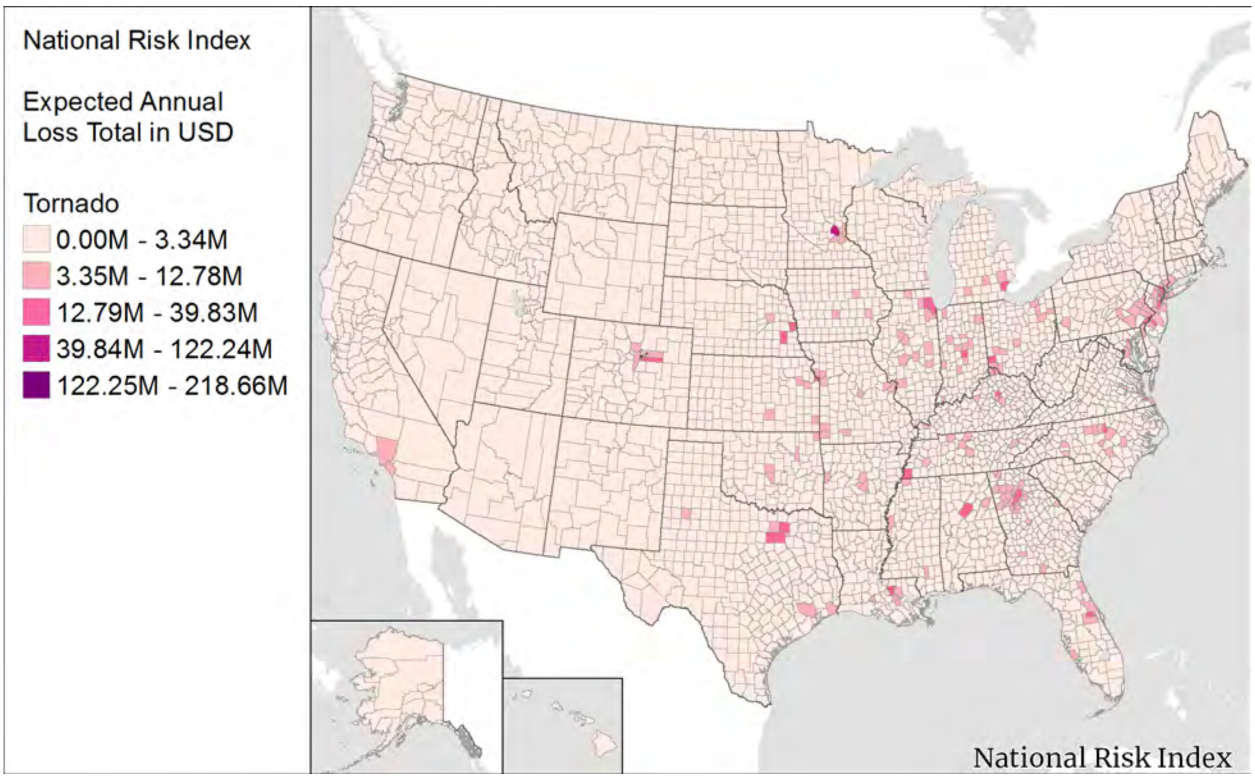

Figure 128: Total Expected Annual Loss by County to Tornado

With the Tornado total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Tornado Risk Index score.

20 Tsunami

A Tsunami is a wave or series of waves generated by an earthquake, landslide, volcanic eruption, or even a large meteor hitting the ocean and causing a rise or mounding of water at the ocean surface. A Tsunami can travel across open ocean at about 500 mph and slow down to about 30 mph as it approaches land, causing it to grow significantly in height.

20.1 Spatial Source Data

Susceptible Area Source: *State of California, Department of Conservation, California Official Tsunami Inundation Maps*[67]

California's Tsunami inundation zones are available for download as a KMZ map file. The dataset consists of polygons representing populated areas at risk of Tsunami inundation. It was "produced collectively by tsunami modelers, geologic hazard mapping specialists, and emergency planning scientists" from the California Geological Survey, California's Office of Emergency Services, and the Tsunami Research Center at the University of Southern California.

Susceptible Area Source: *Hawaii Statewide GIS Program, Tsunami Evacuation Zones*[68]

Hawaii's Tsunami inundation zones are available for download as a set of KML files or shapefiles. The dataset consists of polygons representing all areas at risk of Tsunami inundation and were produced by state and local public safety officials.

Susceptible Area Source: *Hawaii Statewide GIS Program, Extreme Evacuation Zones*[69]

Hawaii's Extreme Evacuation Zones were also produced by state and local public safety officials in Hawaii. They represent the possible extent of inundation for modelled worst-case scenario Tsunami events for the counties of Kauai, Maui, and Oahu.

Susceptible Area Source: *Oregon Department of Geology and Mineral Industries, Tsunami Inundation Zones*[70]

The Oregon dataset is available in shapefile format and contains several layers of polygons representing inundation zones under varying scenarios generated by the hydrodynamic computer model SELFE (Semi-implicit Eulerian-Lagrangian Finite Element). The Oregon XXL tsunami scenario is

[67] State of California. (2009). Tsunami Inundation Map for Emergency Planning; produced by California Emergency Management Agency, California Geological Survey, and University of Southern California – Tsunami Research Center [online dataset]. Retrieved from http://www.conservation.ca.gov/cgs/geohazards/tsunami/maps#DownloadData.
[68] Hawaii Statewide GIS Program, Office of Planning, State of Hawaii. (2014). *Tsunami Evacuation Zones* [online dataset]. Retrieved from http://geoportal.hawaii.gov/datasets/tsunami-evacuation-zones/data.
[69] Hawaii Statewide GIS Program, Office of Planning, State of Hawaii. (2016). *Extreme Tsunami Evacuation Zones* [online dataset]. Retrieved from http://geoportal.hawaii.gov/datasets/extreme-tsunami-evacuation-zones.
[70] Department of Geology and Mineral Industries, State of Oregon. (2018). *Tsunami inundation scenarios for Oregon* [online dataset]. Retrieved from https://www.oregongeology.org/pubs/ofr/p-O-13-19.htm.

the current recommended evacuation zone for a local tsunami and covers the largest area out of any of the possible inundation scenarios, so this is the layer used for exposure determination in the NRI.

Susceptible Area Source: *Washington State Department of Natural Resources, Tsunami Inundation Data*[71]

Washington's Tsunami Inundation dataset is available for download on the Washington Geologic Information Portal as a layer in a file geodatabase and contains polygons representing inundation areas under varying scenarios with local earthquake sources.

Susceptible Area Source: *Alaska Department of Natural Resources, Tsunami Inundation Maps*[72]

Alaska's inundation maps are made using numerical modeling of Tsunami wave dynamics and are generated for communities deemed vulnerable to Tsunami hazards. The maps are available in raster format (GeoTIFF) and cell values provide the modeled depth (in meters) of maximum inundation.

Historical Event Source: *NOAA, National Centers for Environmental Information (formerly NGDC), Global Historical Tsunami Runup Data*[73]

NOAA maintains a database of historical Tsunami runup points with records of Tsunami events dating back to 1800. These records supply spatiotemporal information, including geographic coordinates and observation date, and occasionally some information on magnitude (like water height) or damage, such as deaths, injuries, and destruction to property. Each runup point has a unique identifier and each Tsunami originating event also has a unique identifier. Each Tsunami event typically causes multiple runup events. Runup points are available for download in CSV format (see *Table 54*).

Table 54: Sample Data from the Global Historical Tsunami Database

Tsunami Runup ID	Tsunami Event ID	Year	Month	Day	Country	State	Location Name	Latitude	Longitude
6291	2249	1995	7	30	USA	AK	KODIAK, AK	57.730313	-152.513871
6632	2373	2001	6	23	USA	CA	LOS ANGELES, CA	33.719	-118.272
6636	2373	2001	6	23	USA	CA	SAN DIEGO, CA	32.715	-117.174

[71] Washington Geological Survey. (2017). Tsunami inundation--GIS data, September 2017: Washington Geological Survey Digital Data Series DS-21, version 3.0, previously released June 2010 [online dataset]. Retrieved from https://www.dnr.wa.gov/programs-and-services/geology/publications-and-data/gis-data-and-databases
[72] Division of Geological & Geophysical Surveys, Alaska Department of Natural Resources. (2017). Tsunami inundations maps [online dataset]. Retrieved from http://dggs.alaska.gov/pubs/tsunami
[73] National Geophysical Data Center, National Oceanic and Atmospheric Administration. (2018). Global Historical Tsunami Database [online database]. Retrieved from https://doi.org/10.7289/v5pn93h7

20.1.1 PERIOD OF RECORD

Tsunami runup point data ranges from 1/1/1800 to 10/25/2018, so the period of record for which Tsunami data are utilized is 218.96 years.

20.2 Spatial Processing

Each of the inundation zones are converted into polygon layers. The raster files from Alaska are filtered on cell value using a raster calculation that sets all cells above 0 to 1 and all cells below 0 to 0. All pixels with a value of one are then converted to polygons and merged into a single layer. Then the polygon layers for each state (Alaska, California, Hawaii, Oregon, and Washington) are merged into a single Tsunami-inundation polygon layer (see *Figure 129*) that will be used to calculate exposure at the Census block level.

Figure 129: Tsunami Inundation Zone Map

Tsunami runup points are buffered by 500 meters (see *Figure 130*). These buffers will be used to estimate frequency at the Census tract level. The goal of buffering the runup points is to correct for possible geopositional inaccuracies in the source data.

Figure 130: Tsunami Runup Buffer Map

20.3 Determination of Possibility of Hazard Occurrence

To distinguish between areas where no Tsunami runup events have occurred and those where such events are not deemed possible, a control table was generated to designate which counties have some probability of being impacted by a Tsunami runup event. Any county that intersected a Tsunami inundation polygon or a buffered runup point, or had experienced economic loss due to Tsunami events (as recorded in SHELDUS) is included as one in which Tsunami runup events are possible (see *Figure 131*).

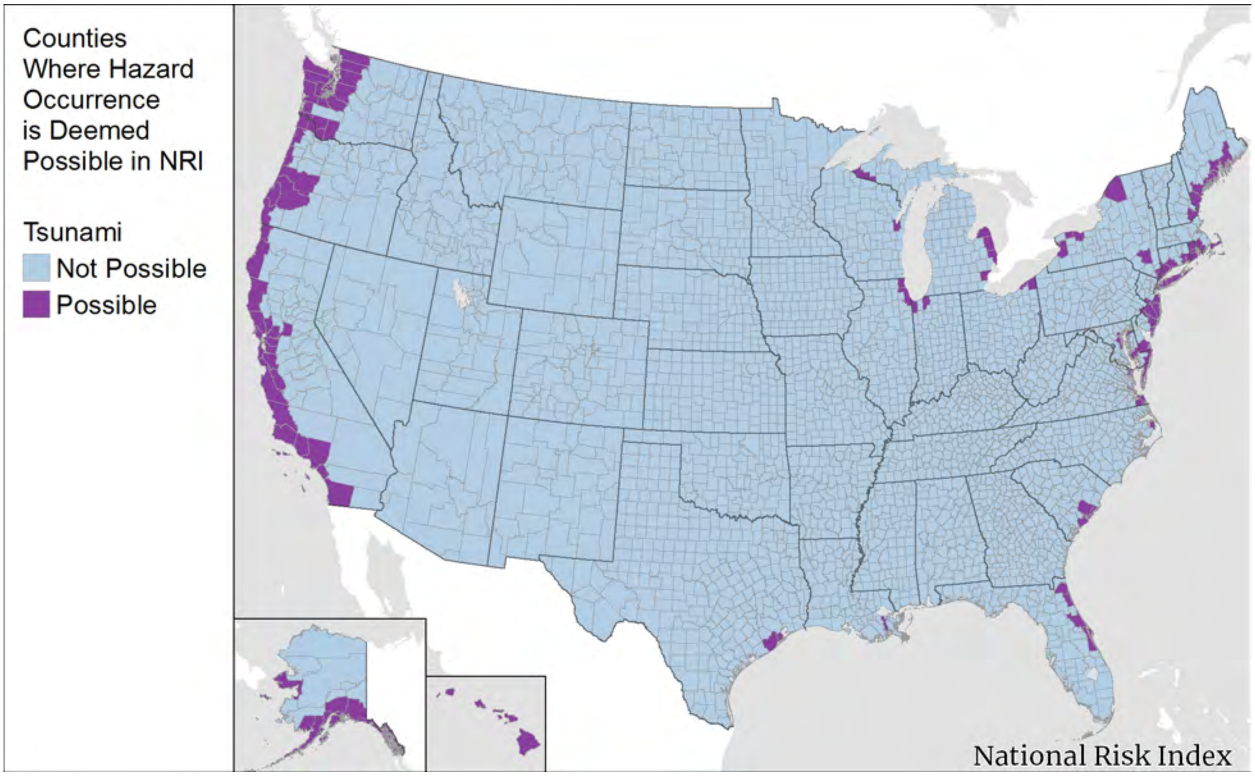

Figure 131: Map of Counties Deemed Possible for Tsunami Occurrence

20.4 Exposure

To identify areas of exposure, the Tsunami inundation polygons are intersected with the Census block polygons within the NRI processing database. Tabulation against CropScape and NLCD raster layers is then performed on the areas of intersection to find the developed area of the intersection (see *Section 4.3.2*). The resulting table contains the inundation polygon's unique identifier, Census block number, the intersected area, and the developed area of intersection (see *Table 55*). All area values are in square kilometers.

Table 55: Sample Data from the Tsunami Area Census Block Intersection Table

TsunamiAreaID	CensusBlock	IntersectedAreaKm2	AreaDevelopedKm2
893	021500002002000	0.0012102734375	0.0001557373046875
939	021500003001011	0.003233	0.0029837041015625
939	021500003001020	0.0022572783203125	0.0022572783203125

To determine exposure value, the sum of the developed areas of the Tsunami inundation polygons intersected with each Census block is multiplied by the developed area building value density and the developed area population value density of the Census block to model the conservative-case concentration of exposure within the Census block. These developed area Census block building and population value densities have been calculated by dividing the total values (as recorded in Hazus

4.2 SP1) by the developed land area (in square kilometers; see *Equation 108*). VSL was used to express population exposure in terms of dollars.

Equation 108: Census Block Tsunami Exposure

$$Exposure_{TSUN_{CB_{Bldg}}} = \sum_{TSUN}^{CB} IntsctDevArea_{TSUN_{CB}} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{TSUN_{CB_{Pop}}} = \left(\sum_{TSUN}^{CB} IntsctDevArea_{TSUN_{CB}} \times DevAreaDen_{CB_{Pop}}\right) \times VSL$$

where:

$Exposure_{TSUN_{CB_{Bldg}}}$	is the building value exposed to Tsunami inundation in a specific Census block (in dollars).
$\sum_{TSUN}^{CB} IntsctDevArea_{TSUN_{CB}}$	is the sum of the developed areas of Tsunami inundation polygons intersected with the Census block (in square kilometers).
$DevAreaDen_{CB_{Bldg}}$	is the developed area building value density of the Census block (in dollars per square kilometer).
$Exposure_{TSUN_{CB_{Pop}}}$	is the population value exposed to Tsunami inundation in a specific Census block (in dollars).
$DevAreaDen_{CB_{Pop}}$	is the total population density of the Census block (in dollars per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).

Because the exposure model uses a conservative-case concentration of exposure and a developed area density value, it is possible to mathematically generate an exposure value that is greater than the total value of the Census block. The Hazus-recorded population and building value are considered ceilings on exposure. For example, if the calculated exposed population exceeds the Hazus-recorded population, then the Hazus-recorded population is used as the population exposure value for the Census block.

20.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 109*).

Equation 109: Census Tract and County Tsunami Exposure Aggregation

$$Exposure_{TSUN_{CT_{Bldg}}} = \sum_{CB}^{CT} Exposure_{TSUN_{CB_{Bldg}}}$$

$$Exposure_{TSUN_{Co_{Bldg}}} = \sum_{CB}^{Co} Exposure_{TSUN_{CB_{Bldg}}}$$

$$Exposure_{TSUN_{CT_{Pop}}} = \sum_{CB}^{CT} Exposure_{TSUN_{CB_{Pop}}}$$

$$Exposure_{TSUN_{Co_{Pop}}} = \sum_{CB}^{Co} Exposure_{TSUN_{CB_{Pop}}}$$

where:

$Exposure_{TSUN_{CT_{Bldg}}}$	is the building value exposed to Tsunami inundation in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{TSUN_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Tsunami inundation for each Census block within the Census tract (in dollars).
$Exposure_{TSUN_{Co_{Bldg}}}$	is the building value exposed to Tsunami inundation in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{TSUN_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Tsunami inundation for each Census block within the county (in dollars).
$Exposure_{TSUN_{CT_{Pop}}}$	is the population value exposed to Tsunami inundation event-days in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{TSUN_{CB_{Pop}}}$	is the summed value of all population exposed to Tsunami inundation for each Census block within the Census tract (in dollars).
$Exposure_{TSUN_{Co_{Pop}}}$	is the population value exposed to Tsunami inundation in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{TSUN_{CB_{Pop}}}$	is the summed value of all population exposed to Tsunami inundation for each Census block within the county (in dollars).

20.5 Historic Event Count

The count of historic Tsunami events is computed as the number of distinct Tsunami events that have caused runup events (from the Global Historical Tsunami Runup Data, see *Section 20.1*) for which the buffered points intersect a Census tract. A Historic Event Count is also supplied at the county level as the number of distinct Tsunami events that have caused runup events for which the buffered points intersect the county.

20.6 Frequency

The frequency value represents the estimated number of recorded Tsunami events that impact a specific area each year. Because Tsunami events are rare and have the capacity to impact larger areas than a Census block-level frequency would imply, the annualized frequency is calculated at the Census tract level (see *Equation 110*) and inherited by the Census blocks it contains. This inherited Census block frequency is used in the EAL calculations.

Frequency calculations use the buffered Tsunami runup-event polygons generated in *Section 20.2* intersected with the Census tract polygons. Rather than counting the distinct Tsunami runup-event polygons intersecting each Census tract, the historic event count represents the number of distinct Tsunami event identifiers for those buffered runup points because a single Tsunami originating event can cause multiple runup events in an area. The Census block inherits this count from the Census tract that encompasses it.

Equation 110: Census Tract Annualized Tsunami Frequency

$$Freq_{TSUN_{CT}} = \frac{EventCount_{TSUN_{CT}}}{PeriodRecord_{TSUN}}$$

where:

$Freq_{TSUN_{CT}}$	is the annualized frequency of Tsunami runup events determined for a specific Census tract (events per year).
$EventCount_{TSUN_{CT}}$	is the number of Tsunami runup-event polygons (with distinct dates) that intersect the Census tract.
$PeriodRecord_{TSUN}$	is the period of record for Tsunami (218.96 years).

20.6.1 MINIMUM ANNUAL FREQUENCY

If a Census tract's historical Tsunami runup event count is 0, the Census tract is assigned the minimum annual Tsunami frequency. This minimum frequency is set at 0.004587, or once in the period of record (1 in 218 years).

20.6.2 FREQUENCY INHERITANCE AND AGGREGATION

The Census block inherits its frequency value from the Census tract that contains it as in *Equation 111*.

Equation 111: Census Block Tsunami Frequency Inheritance

$$Freq_{TSUN_{CB}} = Freq_{TSUN_{CT}}$$

where:

$Freq_{TSUN_{CB}}$	is the annualized Tsunami frequency determined for a specific Census block (events per year).
$Freq_{TSUN_{CT}}$	is the annualized Tsunami frequency determined for a specific Census tract (events per year).

The NRI application provides area-weighted average frequency values at the county level. These values may not exactly match that of dividing the number of recorded Tsunami events at the county level by the period of record. The frequency values at the Census block level are rolled up to the county level using area-weighted aggregations as in *Equation 112*. Only Census blocks with a non-zero frequency were included in the aggregation so that landlocked areas did not overly influence the frequency values of the county.

Equation 112: County Area-Weighted Tsunami Frequency Aggregation

$$Freq_{TSUN_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{TSUN_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{TSUN_{Co}}$	is the annualized area-weighted Tsunami frequency calculated for a specific county.
$Freq_{TSUN_{CB}}$	is the non-zero annualized Tsunami frequency calculated for a specific Census block.
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 132 displays annualized Tsunami frequency at the county level.

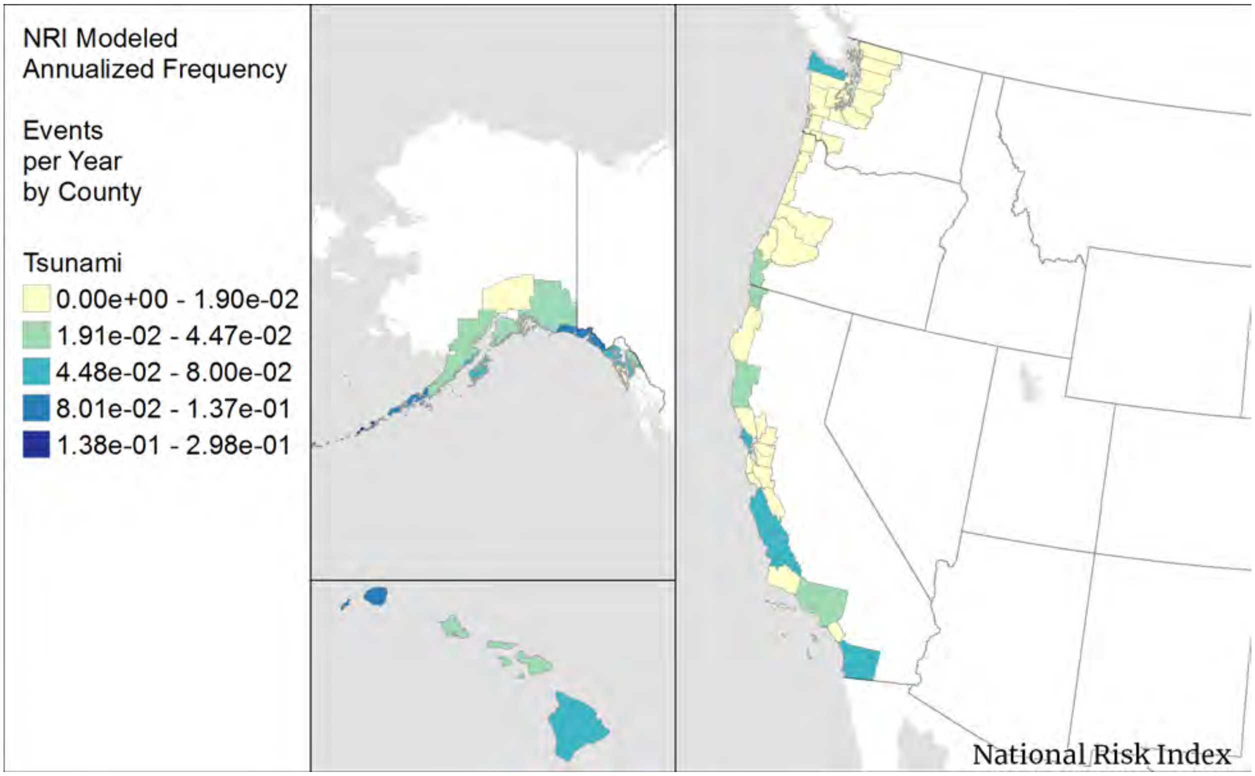

Figure 132: Annualized Tsunami Frequency by County

20.7 Historic Loss Ratio

The Tsunami HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Tsunami event, or the average rate of loss associated with the occurrence of a Tsunami event. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Tsunami hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Two peril types are mapped to the hazard Tsunami (see *Table 56*). These are expanded on an event basis based on the number of records from SHELDUS[74] (see *Section 5.4.1*).

Table 56: Tsunami Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Tsunami	0	0
TsunamiSeiche	23	26

[74] For Tsunami loss information, SHELDUS compiles data from the Global Historical Tsunami Database maintained by NOAA's National Centers for Environmental Information.

The HLR exposure value used in the LRB calculation is the value of the county's area that is susceptible to Tsunamis. This value is determined by summing the developed area density exposure values of the Census blocks that intersect the Tsunami inundation zone footprint (see *Section 20.4*). The LRB for each SHELDUS-documented event and each consequence type (building and population) is calculated using *Equation 113*.

Equation 113: Loss Ratio per Basis Calculation for a Single Tsunami Event

$$LRB_{TSUN_{Co_{CnsqType}}} = \frac{Loss_{TSUN_{Co_{CnsqType}}}}{HLRExposure_{TSUN_{Co_{CnsqType}}}}$$

where:

$LRB_{TSUN_{Co_{CnsqType}}}$	is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Tsunami event. Calculation is performed for each consequence type (building and population).
$Loss_{TSUN_{Co_{CnsqType}}}$	is the loss (by consequence type) experienced from the Tsunami event documented to have occurred in the county (in dollars).
$HLRExposure_{TSUN_{Co_{CnsqType}}}$	is the value (by consequence type) of the susceptible area estimated to have been exposed to the Tsunami event (in dollars).

Tsunami events may result in no recorded loss to buildings or population. SHELDUS does not record events in which no loss occurred, so a number of zero-loss event records are inserted into the loss data to align the event count in the HLR calculation to the historic event count experienced within the SHELDUS period of record (1995 to 2016). For Tsunami, the historic year-month event count is extracted by creating an intersection between the buffered Tsunami runup points (see *Section 20.2*) and the Census block polygons. The observation date of each Tsunami runup event (see *Table 54*) is used to sync the event to its year-month. A list of distinct Tsunami observation dates is compiled for the Tsunami event polygon-Census block intersections within the county, and the historic year-month event count is the number of distinct Tsunami observation dates in this list.

If the number of loss-causing Tsunami event records from SHELDUS is less than the summed historic year-month event counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, regional, and national. The regional definition for Tsunami is derived from the FEMA regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 133 and *Figure 135* display the largest weighting factor contributor in the Bayesian credibility calculation for the Tsunami HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Tsunami events within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local, regional, or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from regional- or national-level loss data. *Figure 134* and *Figure 136* represent the final county-level HLR values for Tsunami.

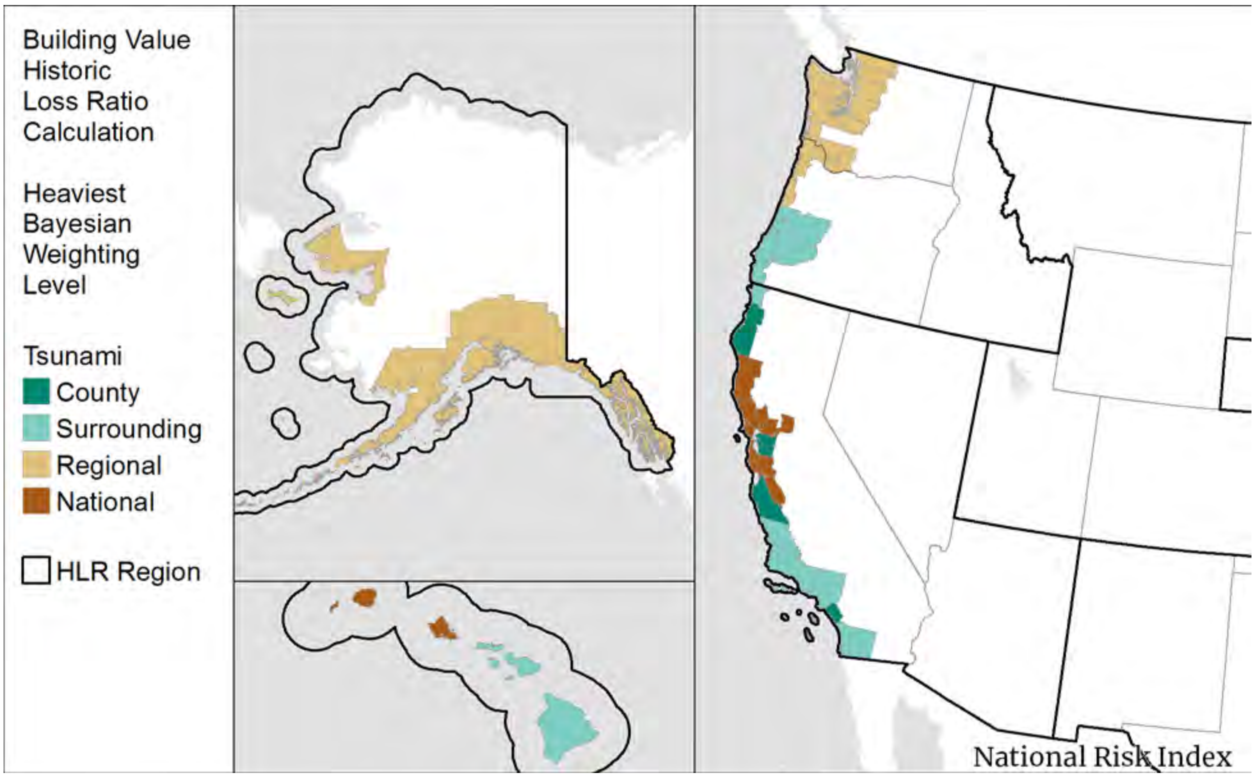

Figure 133: Tsunami Heaviest Bayesian Influence Level – Building Value

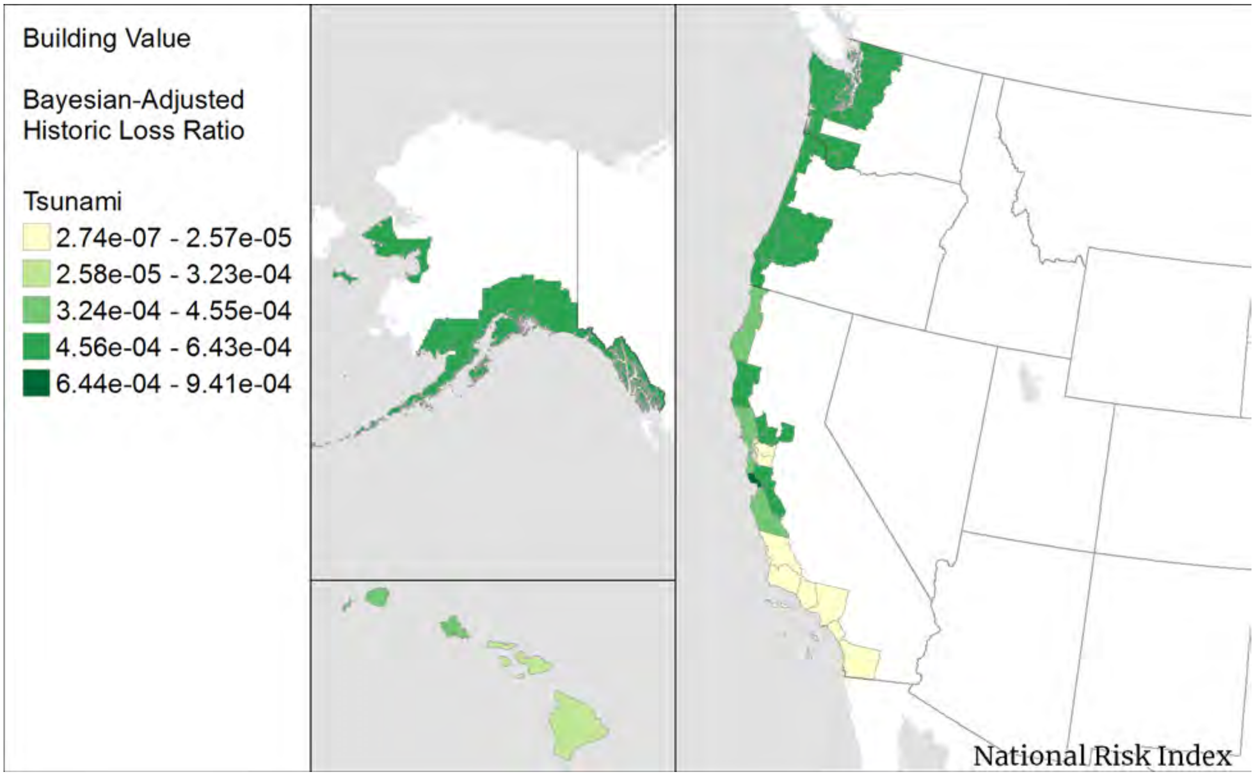

Figure 134: Tsunami HLR – Building Value

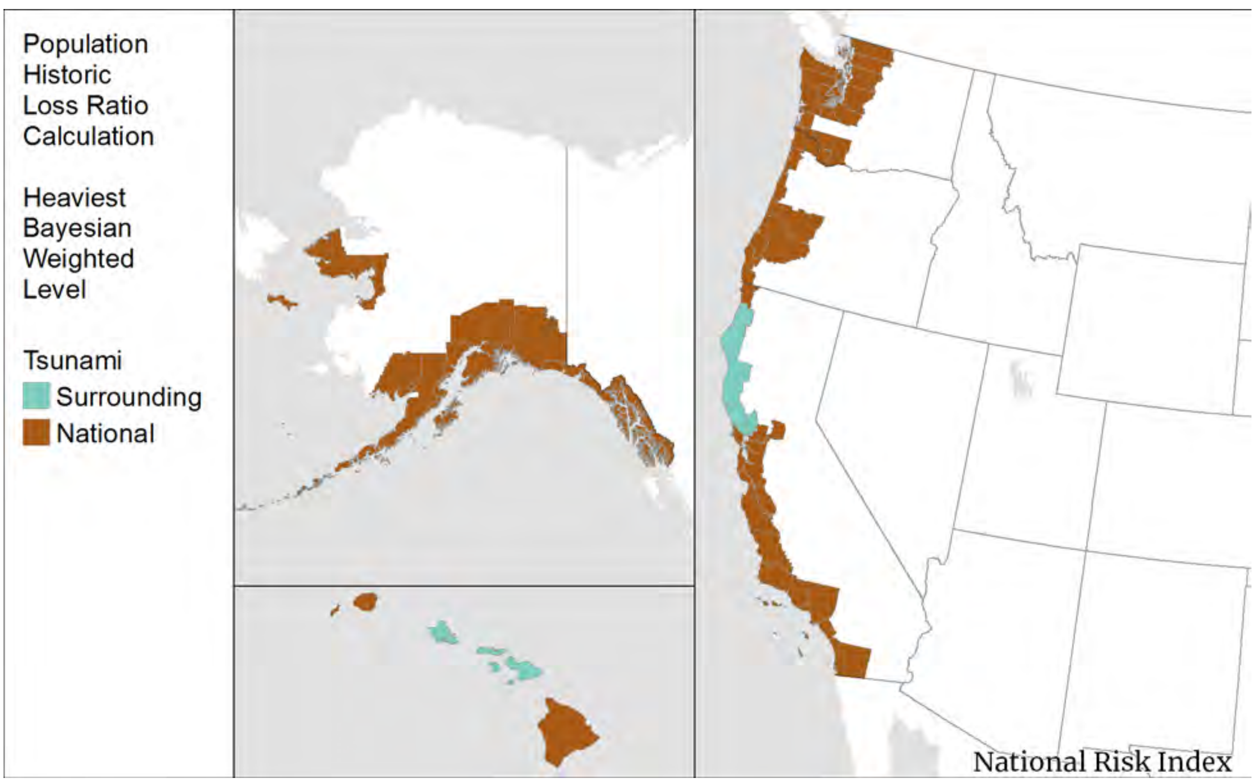

Figure 135: Tsunami Heaviest Bayesian Influence Level – Population

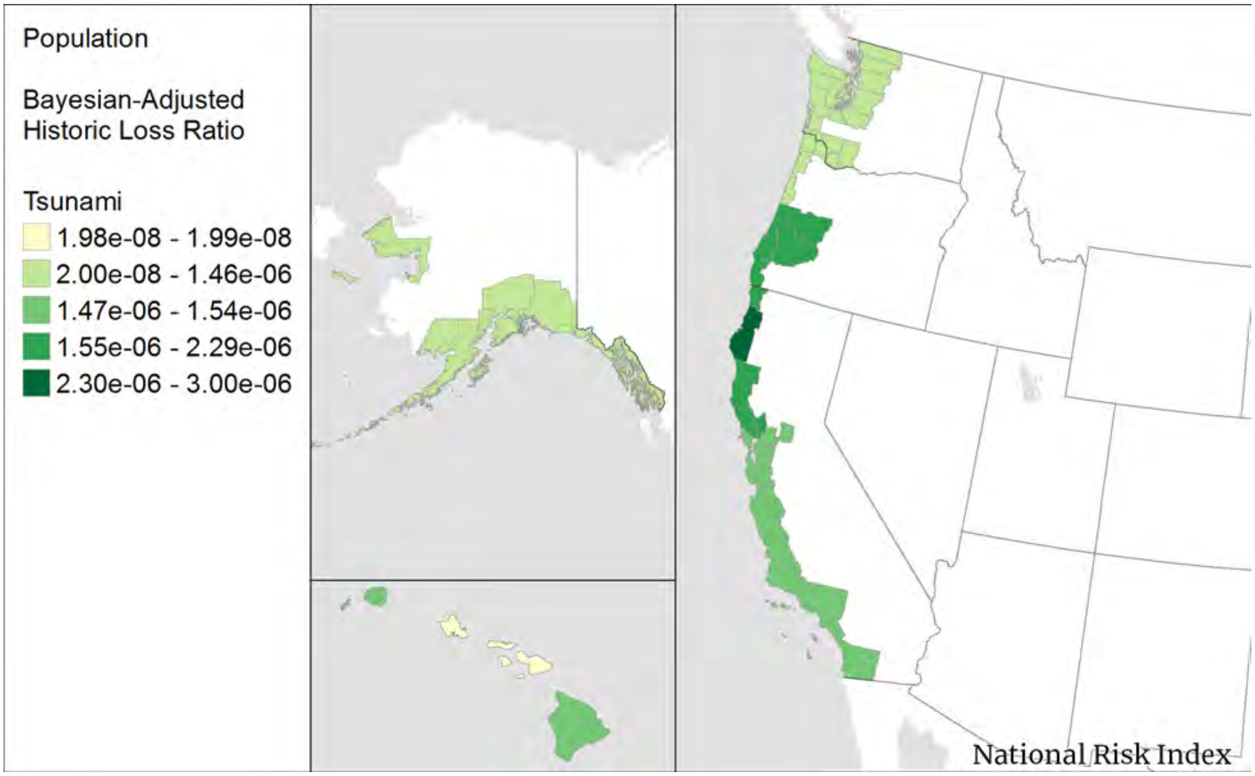

Figure 136: Tsunami HLR – Population

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

20.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 114*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 114: Census Block Expected Annual Loss to Tsunami

$$EAL_{TSUN_{CB_{Bldg}}} = Exposure_{TSUN_{CB_{Bldg}}} \times Freq_{TSUN_{CB}} \times HLR_{TSUN_{CB_{Bldg}}}$$

$$EAL_{TSUN_{CB_{Pop}}} = Exposure_{TSUN_{CB_{Pop}}} \times Freq_{TSUN_{CB}} \times HLR_{TSUN_{CB_{Pop}}}$$

where:

$EAL_{TSUN_{CB_{Bldg}}}$	is the Expected Annual Loss to building value due to Tsunami events for a specific Census block (in dollars).
$Exposure_{TSUN_{CB_{Bldg}}}$	is the building value exposed to Tsunami events in the Census block (in dollars).

$Freq_{TSUN_{CB}}$	is the annualized Tsunami frequency for the Census block (events per year).
$HLR_{TSUN_{CB_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Tsunami for the Census block.
$EAL_{TSUN_{CB_{Pop}}}$	is the Expected Annual Loss to population value due to Tsunami events for a specific Census block (in dollars).
$Exposure_{TSUN_{CB_{Pop}}}$	is the population value exposed to Tsunami events in the Census block (in dollars).
$HLR_{TSUN_{CB_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Tsunami for the Census block.

The total EAL values at the Census tract and county levels are the sums of the aggregated values of the building and population values of their Census block values as in *Equation 115*.

Equation 115: Census Tract and County Expected Annual Loss to Tsunami

$$EAL_{TSUN_{CT}} = \sum_{CB}^{CT} EAL_{TSUN_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{TSUN_{CB_{Pop}}}$$

$$EAL_{TSUN_{Co}} = \sum_{CB}^{Co} EAL_{TSUN_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{TSUN_{CB_{Pop}}}$$

where:

$EAL_{TSUN_{CT}}$	is the total Expected Annual Loss due to Tsunami events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{TSUN_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Tsunami events for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{TSUN_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Tsunami events for all Census blocks in the Census tract (in dollars).
$EAL_{TSUN_{Co}}$	is the total Expected Annual Loss due to Tsunami events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{TSUN_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Tsunami events for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{TSUN_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Tsunami events for all Census blocks in the county (in dollars).

Figure 137 shows the total EAL (building value and population combined) to Tsunami events.

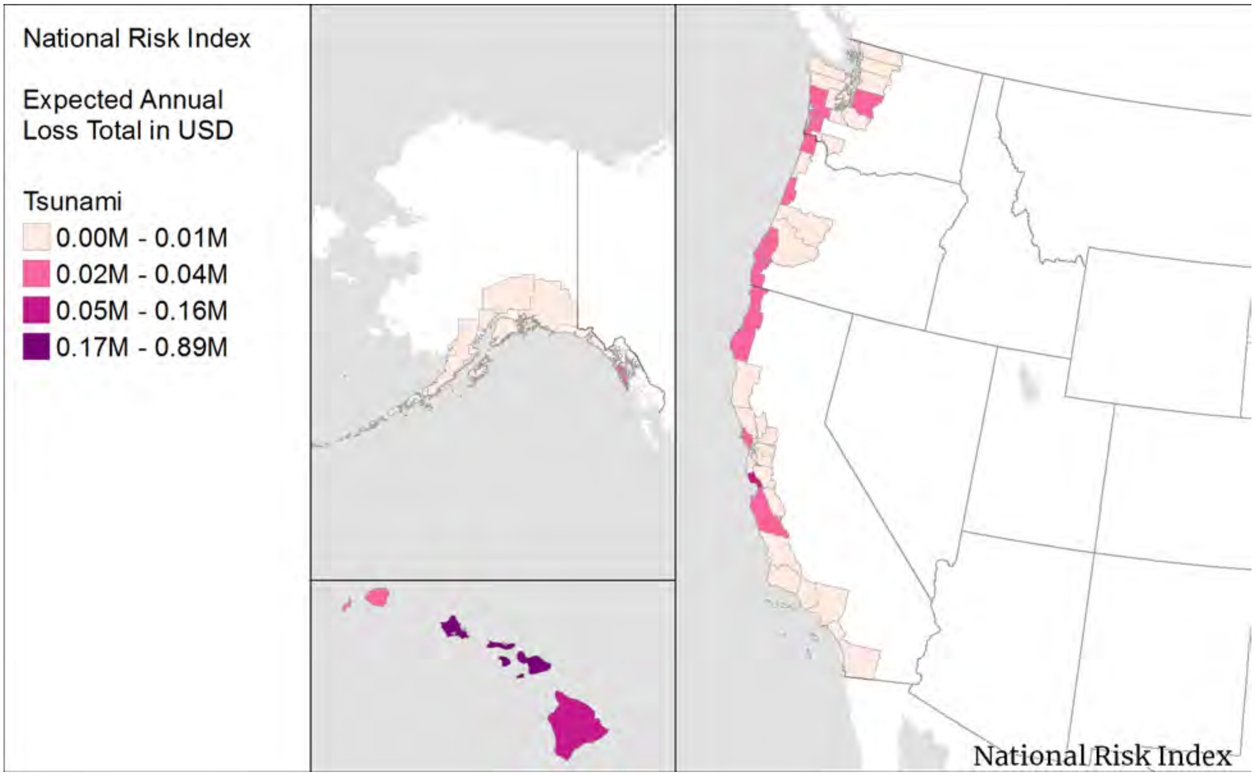

Figure 137: Total Expected Annual Loss by County to Tsunami

With the Tsunami total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Tsunami Risk Index score.

21 Volcanic Activity

Volcanic Activity occurs via vents that act as a conduit between the Earth's surface and inner layers, and erupt gas, molten rock, and volcanic ash when gas pressure and buoyancy drive molten rock upward and through zones of weakness in the Earth's crust.

21.1 Spatial Source Data

Susceptible Area Source: *United Nations Office for Disaster Risk Reduction, Volcano-Population Exposure Index*[75]

Historical Event Source: *Smithsonian Institution, Volcanoes of the World*[76]

Compiled by the Global Volcano Model (GVM), the Volcano-Population Exposure Index database of global volcano locations includes attributes for Population Exposure Index, Volcano Hazard Index, country, and eruption history information. The data are available for download in both shapefile and CSV format from the Humanitarian Data Exchange website (see *Table 57* and *Figure 138*). The Volcanoes of the World Eruptions database provided by the Smithsonian Institution's Global Volcanism Program contains details on each recorded Holocene eruption and is available in spreadsheet format (see *Table 58*).

Table 57: Sample of Volcano-Population Exposure Index Data

VolcanoID	V_Name	Country	Region	Subregion	Latitude	Longitude	PEI	H_active	VEI_Holoce
311300	Bogoslof	United States	Alaska	Aleutian Islands	53.93	-168.03	2	1	3
332060	Haleakala	United States	Hawaii and Pacific Ocean	Hawaiian Islands	20.708	-156.25	4	1	Unknown VEI
323120	Mono Craters	United States	Canada and Western USA	USA (California)	37.88	-119	2	0	4

[75] United Nations Office for Disaster Reduction. (2018). *Volcano-Population Exposure Index, Global Volcano Model (GVM)* [online database]. Retrieved from https://data.humdata.org/dataset/volcano-population-exposure-index-gvm.
[76] Global Volcanism Program, Smithsonian Institution. (2013). *Volcanoes of the World, v. 4.8.3. Venzke, E (ed.).* [online dataset]. Retrieved from https://doi.org/10.5479/si.GVP.VOTW4-2013.

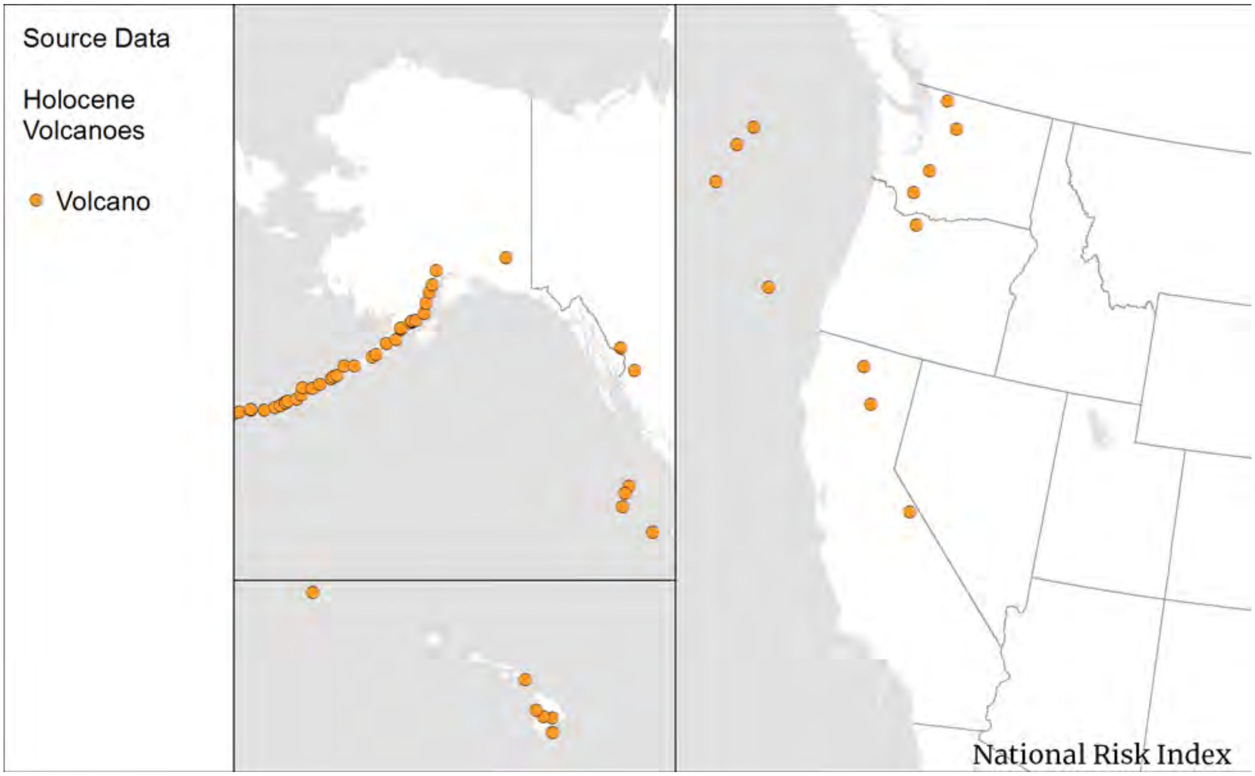

Figure 138: Map of Volcanoes

Table 58: Sample of Volcanoes of the World-Eruption Data

Volcano Number	Volcano Name	Eruption Number	Eruption Category	Evidence Method	Start Year	Start Month	Start Day	End Year	End Month	End Day
311300	Bogoslof	22182	Confirmed Eruption	Historical Observations	2016	12	20	2017	8	30
332060	Haleakala	10296	Confirmed Eruption	Anthropology	1750	0	0	NULL	NULL	NULL
323120	Mono-Inyo Craters	20670	Confirmed Eruption	Radiocarbon (corrected)	620	0	0	NULL	NULL	NULL

The Volcano Number is a unique identifier provided by the Smithsonian's Global Volcanism Program to prevent ambiguity regarding the name and location of volcanoes that may not have unique names or are known by multiple names. It is an agreed-upon standard among international agencies that study Volcanic Activity, including the GVM.

21.1.1 PERIOD OF RECORD

The datasets include every known volcanic eruption since 9310 BCE to December 18, 2018, so the period of record for which volcano data are utilized is 11,328 years.

21.2 Spatial Processing

A 100-km buffer is created from the Holocene active volcano points contained in the GVM source data (see *Figure 139*). The 100-km buffer size was chosen as a worst-case scenario area of impact in case of eruption. The resulting volcano polygons (also called volcano risk areas) are then used in calculating frequency and exposure at the Census block level.

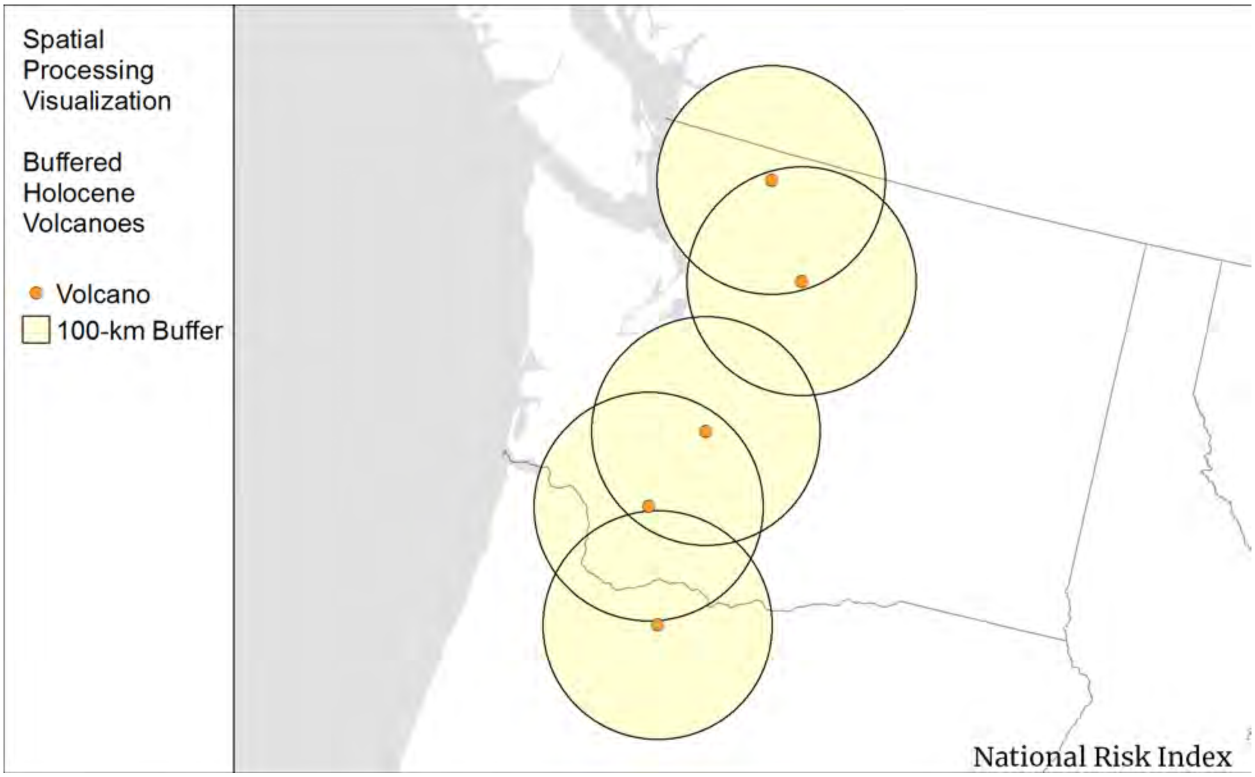

Figure 139: Buffered Volcanoes

21.3 Determination of Possibility of Hazard Occurrence

To distinguish between areas where no Volcanic Activity has occurred and those where such events are not deemed possible, a control table was generated to designate which counties have some probability of Volcanic Activity. Any county that intersected one or more buffered Holocene active volcano polygons or had experienced economic loss due to Volcanic Activity (as recorded in SHELDUS) is included as one in which Volcanic Activity is possible (see *Figure 140*).

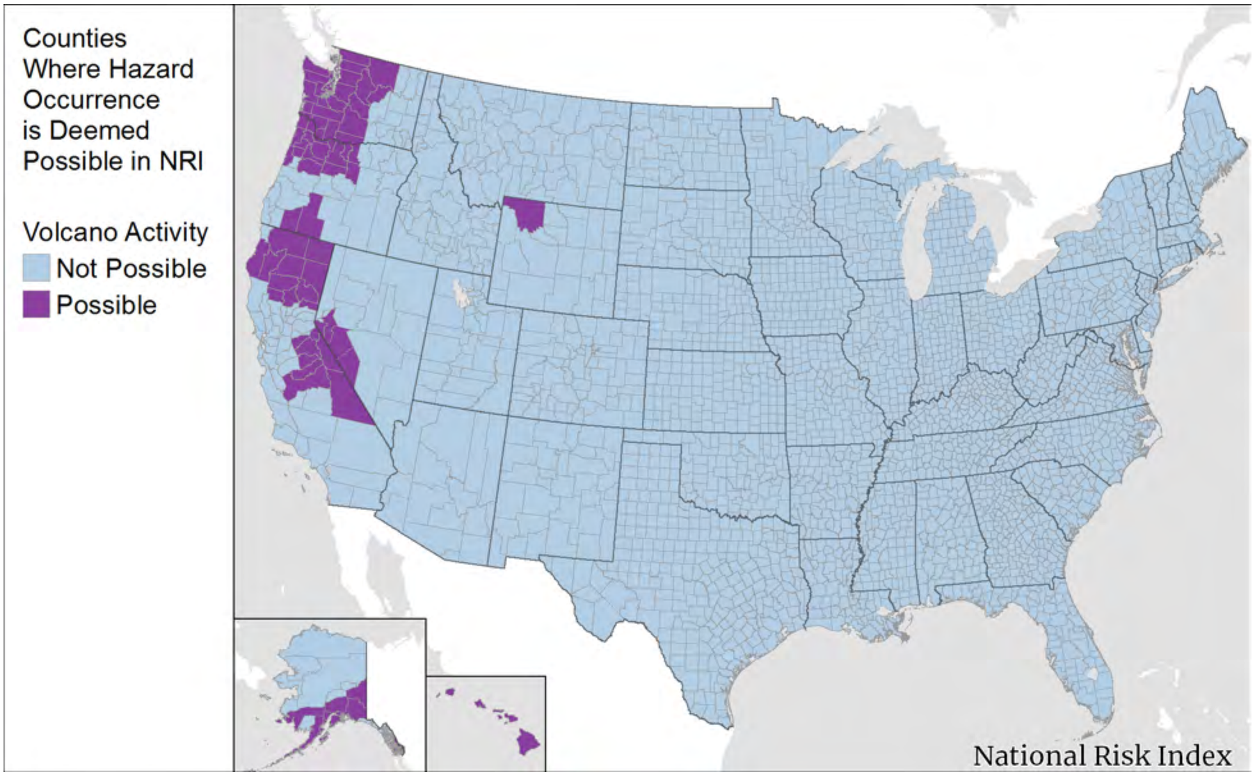

Figure 140: Map of Counties Deemed Possible for Volcanic Activity Occurrence

21.4 Exposure

To identify areas of exposure, the volcano polygons are intersected with the Census block polygons within the NRI processing database. The resulting table contains the volcano's unique identifier, Census block number, and the intersected area in square kilometers (see *Table 59*).

Table 59: Sample Data from the Volcano Census Block Intersection Table

VolcanoID	CensusBlock	IntersectedAreaKm2
321030	530079605005035	2.94928345910645
321030	530079605005160	1.71343073498535
321030	530150018001001	2.76947270727539

To determine exposure value, the average coverage of a volcano risk area is found by summing the intersected areas for volcano polygons that intersected the Census block and dividing this sum by the number of intersecting volcano polygons. This is multiplied by the developed area building value density and the developed area population value density of the Census block to model the conservative-case concentration of exposure within the Census block. These developed area Census block building and population value densities have been calculated by dividing the total values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers; see *Equation 116*).

The VSL was used to express population exposure in terms of dollars. Exposure is only computed for volcanoes designated as Holocene active in the GVM source data (H_active = 1).

Equation 116: Census Block Volcano Exposure

$$Exposure_{VLCN\,CB_{Bldg}} = \frac{\sum IntsctArea_{VLCN\,CB}}{VolcanoCount_{CB}} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{VLCN\,CB_{Pop}} = \left(\frac{\sum IntsctArea_{VLCN\,CB}}{VolcanoCount_{CB}} \times DevAreaDen_{CB_{Pop}}\right) \times VSL$$

where:

$Exposure_{VLCN\,CB_{Bldg}}$	is the building value exposed to Volcanic Activity for a specific Census block (in dollars).
$\sum IntsctArea_{VLCN\,CB}$	is the sum of the intersected areas of volcano polygons with the Census block (in square kilometers).
$VolcanoCount_{CB}$	is the total number of volcano polygons (each associated with a specific volcano) that intersect the Census block.
$DevAreaDen_{CB_{Bldg}}$	is the developed area building value density of the Census block (in dollars per square kilometer).
$Exposure_{VLCN\,CB_{Pop}}$	is the population value exposed to Volcanic Activity at the Census block level (in dollars).
$DevAreaDen_{CB_{Pop}}$	is the developed area population density of the Census block (in people).
VSL	is the Value of Statistical Life ($7.4M per person).

Because the exposure model uses a conservative-case concentration of exposure and a developed area density value, it is possible to mathematically generate an exposure value that is greater than the total value of the Census block. The Hazus-recorded population and building value are considered ceilings on exposure. For example, if the calculated exposed population exceeds the Hazus-recorded population, then the Hazus-recorded population is used as the population exposure value for the Census block.

21.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 117*).

Equation 117: Census Tract and County Volcano Exposure Aggregation

$$Exposure_{VLCN_{CT_{Bldg}}} = \sum_{CB}^{CT} Exposure_{VLCN_{CB_{Bldg}}}$$

$$Exposure_{VLCN_{Co_{Bldg}}} = \sum_{CB}^{Co} Exposure_{VLCN_{CB_{Bldg}}}$$

$$Exposure_{VLCN_{CT_{Pop}}} = \sum_{CB}^{CT} Exposure_{VLCN_{CB_{Pop}}}$$

$$Exposure_{VLCN_{Co_{Pop}}} = \sum_{CB}^{Co} Exposure_{VLCN_{CB_{Pop}}}$$

where:

$Exposure_{VLCN_{CT_{Bldg}}}$	is the building value exposed to Volcanic Activity in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{VLCN_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Volcanic Activity for each Census block within the Census tract (in dollars).
$Exposure_{VLCN_{Co_{Bldg}}}$	is the building value exposed to Volcanic Activity in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{VLCN_{CB_{Bldg}}}$	is the summed value of all buildings exposed to Volcanic Activity for each Census block within the county (in dollars).
$Exposure_{VLCN_{CT_{Pop}}}$	is the population value exposed to Volcanic Activity in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{VLCN_{CB_{Pop}}}$	is the summed value of all population exposed to Volcanic Activity for each Census block within the Census tract (in dollars).
$Exposure_{VLCN_{Co_{Pop}}}$	is the population value exposed to Volcanic Activity in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{VLCN_{CB_{Pop}}}$	is the summed value of all population exposed to Volcanic Activity for each Census block within the county (in dollars).

21.5 Volcano Count

The NRI application supplies a count of Holocene active volcanoes that may impact an area as the number of distinct volcano polygons that intersect a specific Census tract or county.

21.6 Frequency

The frequency of eruption or activity for volcanoes is exceptionally low. A frequency value is assigned to each buffered volcano polygon or area of exposure based on the total number of its eruptions in the Volcanoes of the World Eruption database over the period of record as in *Equation 118*. Annualized frequency is only computed for volcanoes that are designated as Holocene active in the GVM source data (H_active = 1).

Equation 118: Annualized Volcano Frequency

$$Freq_{VLCN} = \frac{Eruptions_{VLCN}}{PeriodRecord_{VLCN}}$$

where:

$Freq_{VLCN}$	is the annualized frequency of Volcanic Activity for the volcano (events per year).
$Eruptions_{VLCN}$	is the total number of the volcano's recorded eruptions or active events.
$PeriodRecord_{VLCN}$	is the period of record for Volcanic Activity (11,328 years).

The frequency value at the Census block level represents the estimated number of Volcanic eruptions each year for a specific area, or the probability that a volcano in the area will erupt in a given year. The annualized frequency is calculated at the Census block level using *Equation 119*, and the Census block-level value is used in the EAL calculations.

Frequency calculations use the same intersection between volcano polygons and Census block polygons that was used to calculate exposure.

Equation 119: Census Block Area-Weighted Volcanic Activity Frequency

$$Freq_{VLCN_{CB}} = \frac{\sum_{VLCN}^{CB}\left(IntsctArea_{VLCN_{CB}} \times Freq_{VLCN}\right)}{Area_{CB}}$$

where:

$Freq_{VLCN_{CB}}$	is the annualized area-weighted frequency of Volcanic Activity determined for a specific Census block (events per year).
$IntsctArea_{VLCN_{CB}}$	is the intersected area of the volcano polygon with the Census block (in square kilometers).
$Freq_{VLCN}$	is the annualized frequency of eruption for the volcano (events per year).

$\sum_{VLCN}^{CB}$	is the sum for all volcano polygons that intersect the Census block.
$Area_{CB}$	is the total area of the Census block (in square kilometers).

21.6.1 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level. The frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 120.

Equation 120: Census Tract and County Area-Weighted Volcanic Activity Frequency Aggregation

$$Freq_{VLCN_{CT}} = \frac{\sum_{CB}^{CT}(Freq_{VLCN_{CB}} \times Area_{CB})}{Area_{CT}}$$

$$Freq_{VLCN_{Co}} = \frac{\sum_{CB}^{Co}(Freq_{VLCN_{CB}} \times Area_{CB})}{Area_{Co}}$$

where:

$Freq_{VLCN_{CT}}$	is the annualized area-weighted frequency of Volcanic Activity calculated for a specific Census tract (events per year).
$Freq_{VLCN_{CB}}$	is the annualized frequency of Volcanic Activity associated with a specific Census block (events per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{VLCN_{Co}}$	is the annualized area-weighted frequency of Volcanic Activity calculated for a specific county (events per year).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 141 displays annualized Volcanic Activity frequency at the county level.

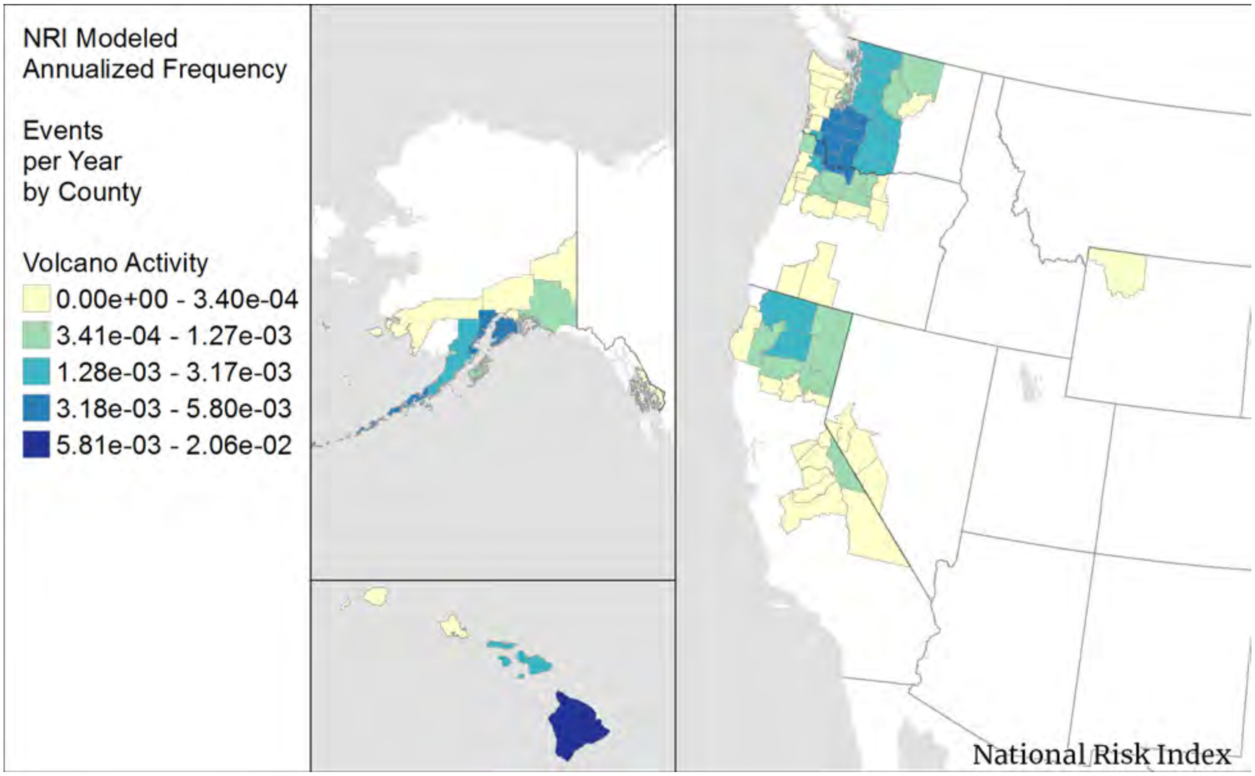

Figure 141: Annualized Volcanic Activity Frequency by County

21.7 Historic Loss Ratio

The Volcanic Activity HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a volcanic event, or the average rate of loss associated with the occurrence of a volcanic event. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Volcano Activity hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1960 to 2016 are included in the HLR calculation. Six peril types are mapped to the hazard Volcanic Activity (see *Table 60*). These are expanded on an event basis based on the number of records from SHELDUS[77] (see *Section 5.4.1*).

[77] For Volcanic Activity loss information, SHELDUS compiles data from the Significant Volcanic Eruptions Database maintained by NOAA's National Centers for Environmental Information and RJ Blong's *Volcanic Hazards: A Source Book on the Effects of Eruptions* (Academic Press, 1984).

Table 60: Volcanic Activity Peril Types and Recorded Events from 1960-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Ashfall	17	17
Lahar	2	2
LavaFlow	1	1
PyroclasticFlow	0	0
Vog	2	2
Volcano	6	6

The HLR exposure value used in the LRB calculation is the value of the county's area that is susceptible to Volcanic Activity. This value is determined by summing the developed area density exposure values of the Census blocks that intersect a volcano polygon (see *Section 21.4.1*). The LRB for each SHELDUS-documented event and each consequence type (building and population) is calculated using *Equation 121*.

Equation 121: Loss Ratio per Basis Calculation for a Single Volcanic Event

$$LRB_{VLCN_{Co_{CnsqType}}} = \frac{Loss_{VLCN_{Co_{CnsqType}}}}{HLRExposure_{VLCN_{Co_{CnsqType}}}}$$

where:

$LRB_{VLCN_{Co_{CnsqType}}}$	is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific volcanic event. Calculation is performed for each consequence type (building and population).
$Loss_{VLCN_{Co_{CnsqType}}}$	is the loss (by consequence type) experienced from the volcanic event documented to have occurred in the county (in dollars).
$HLRExposure_{VLCN_{Co_{CnsqType}}}$	Is the value (by consequence type) of the susceptible area estimated to have been exposed to the volcanic event (in dollars).

A Historic Event Count is not computed for Volcanic Activity, so no zero-loss events are inserted into the Loss Ratio table. After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and national.

Figure 142 and *Figure 144* display the largest weighting factor contributor in the Bayesian credibility calculation for the Volcanic Activity HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Volcanic Activity within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from national-level loss data. *Figure 143* and *Figure 145* represent the final county-level HLR values for Volcanic Activity.

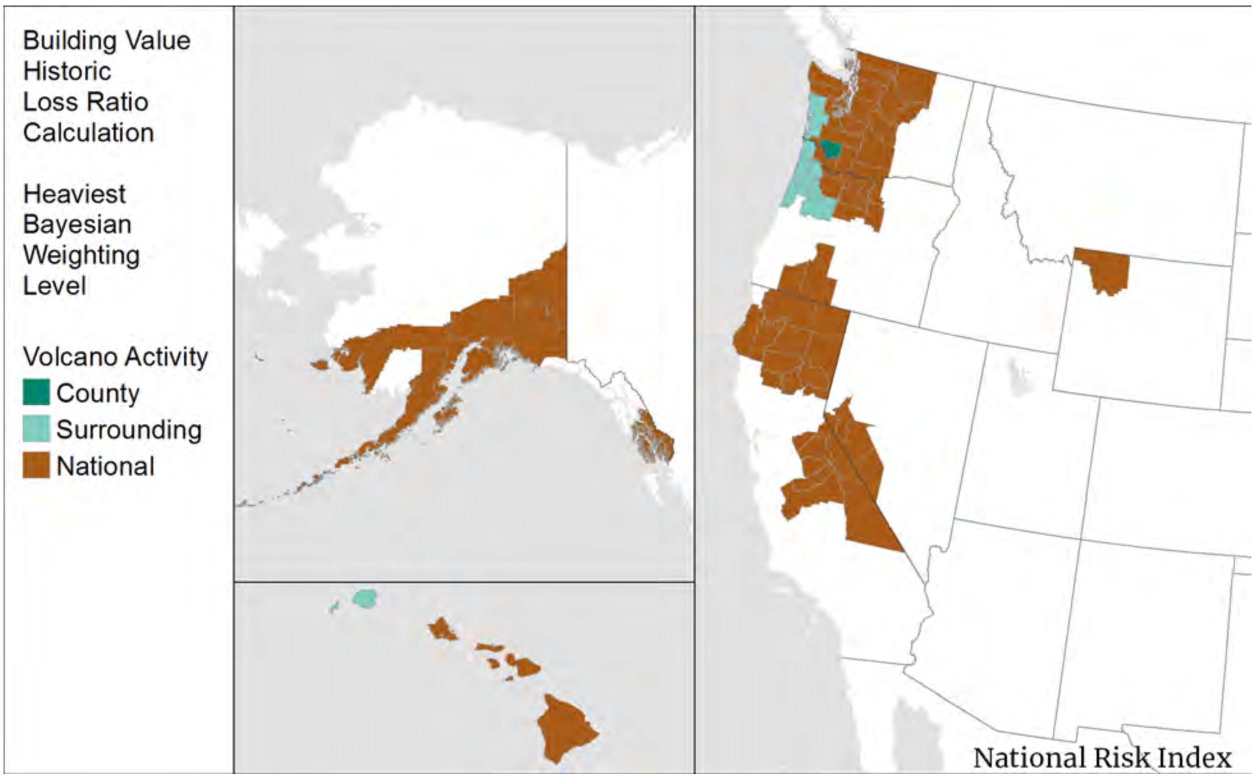

Figure 142: Volcanic Activity Heaviest Bayesian Influence Level – Building Value

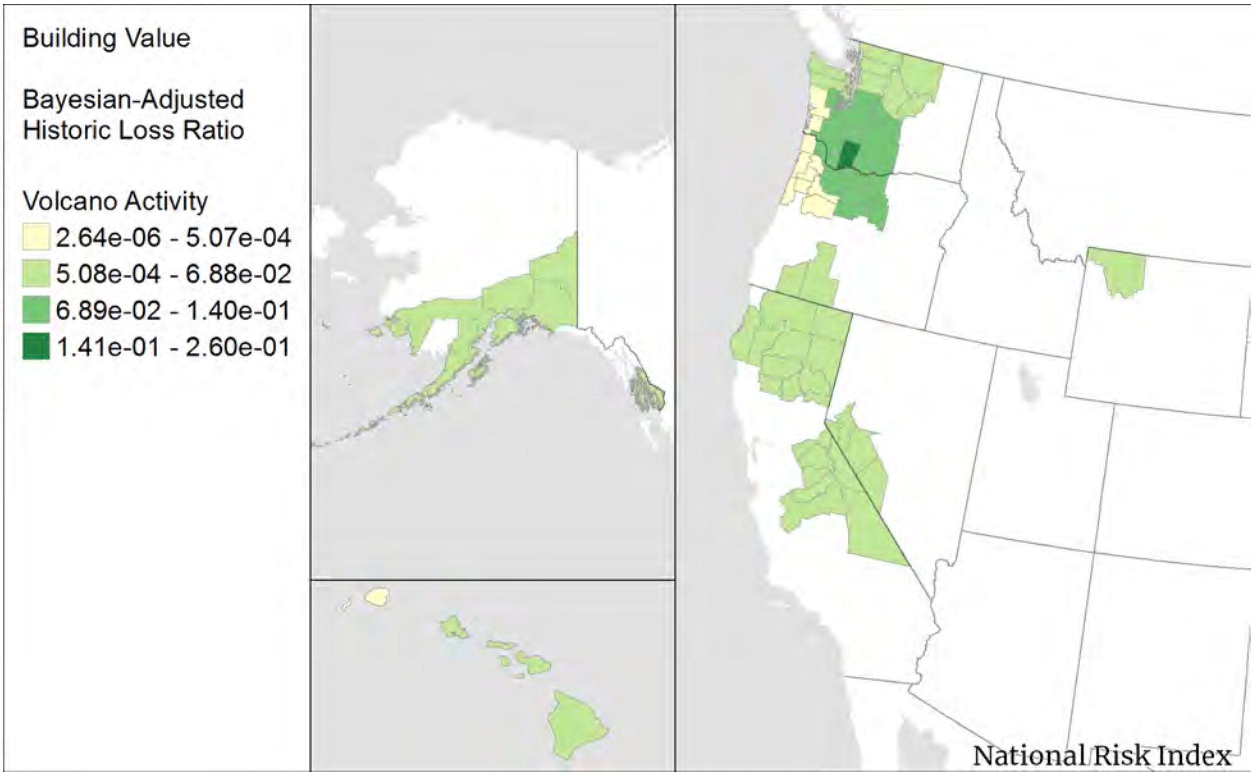

Figure 143: Volcanic Activity HLR – Building Value

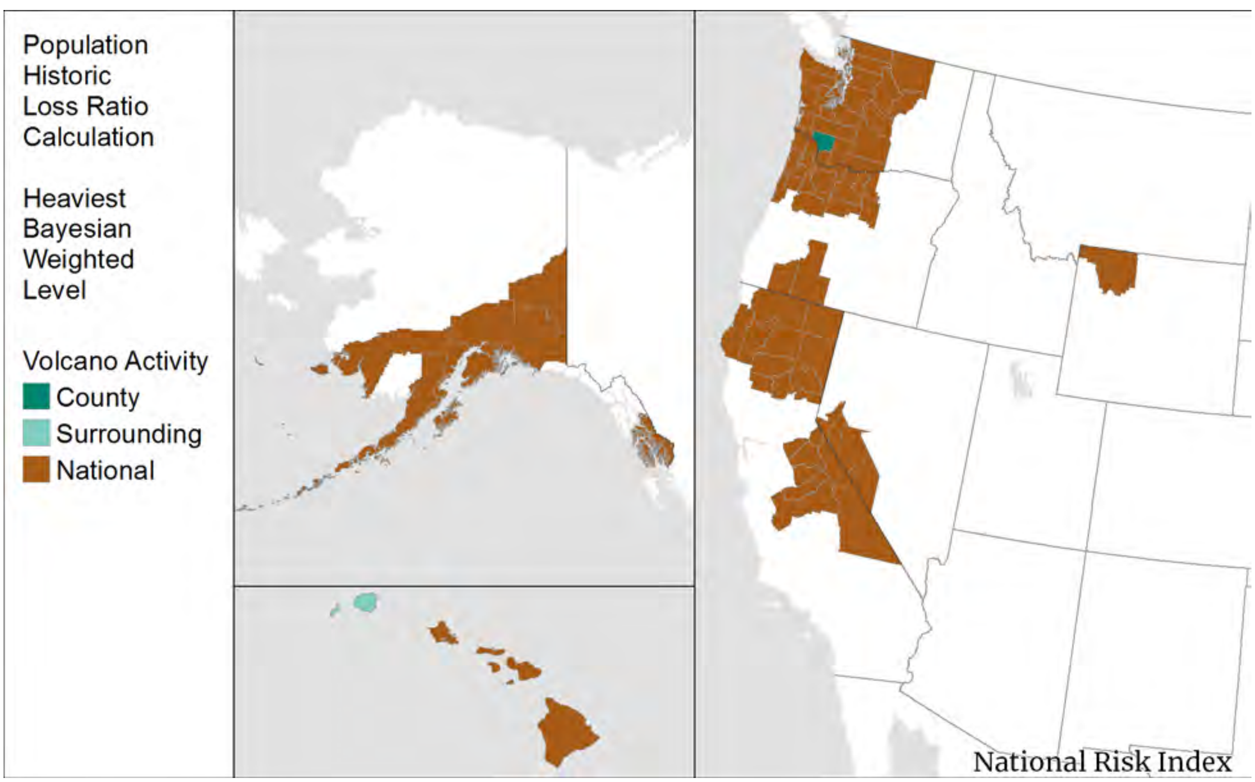

Figure 144: Volcanic Activity Heaviest Bayesian Influence Level – Population

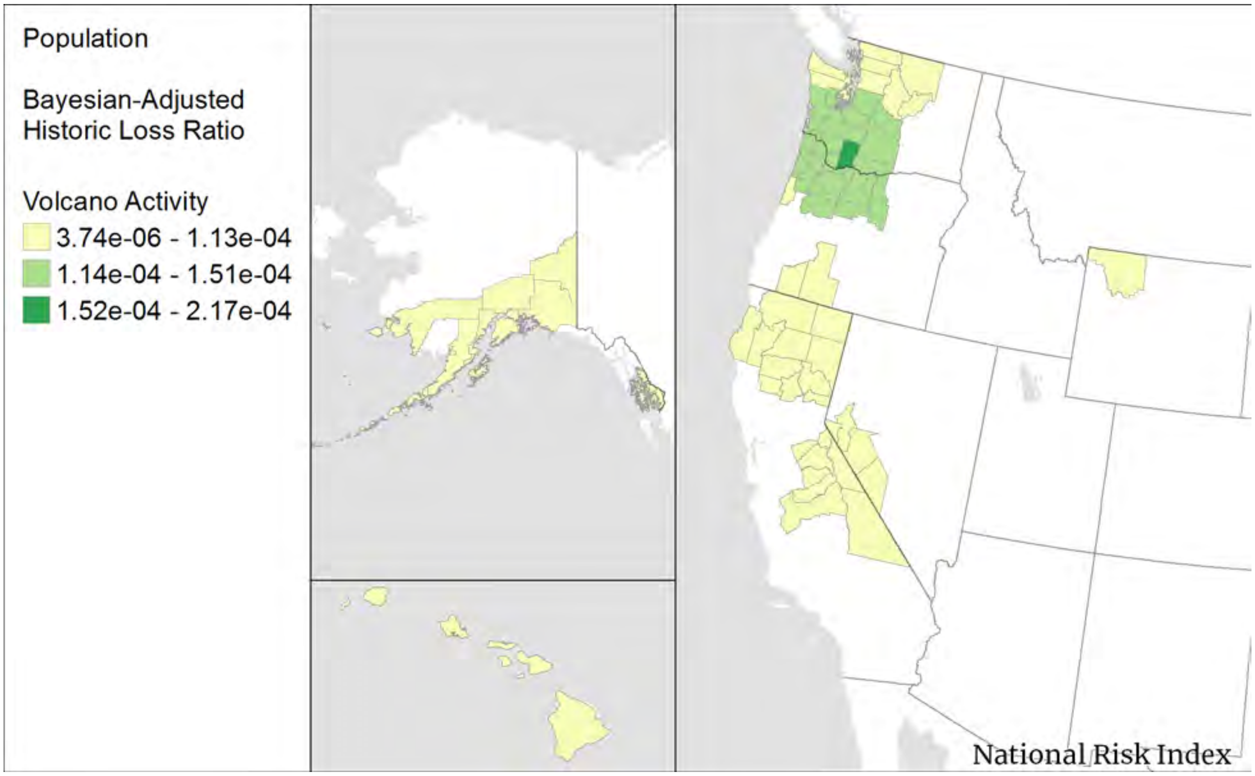

Figure 145: Volcanic Activity HLR – Population

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

21.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 122*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 122: Census Block Expected Annual Loss to Volcanic Activity

$$EAL_{VLCN_{CB_{Bldg}}} = Exposure_{VLCN_{CB_{Bldg}}} \times Freq_{VLCN_{CB}} \times HLR_{VLCN_{CB_{Bldg}}}$$

$$EAL_{VLCN_{CB_{Pop}}} = Exposure_{VLCN_{CB_{Pop}}} \times Freq_{VLCN_{CB}} \times HLR_{VLCN_{CB_{Pop}}}$$

where:

$EAL_{VLCN_{CB_{Bldg}}}$	is the Expected Annual Loss to building value due to Volcanic Activity for a specific Census block (in dollars).

$Exposure_{VLCN_{CB_{Bldg}}}$ is the building value exposed to Volcanic Activity in the Census block (in dollars).

$Freq_{VLCN_{CB}}$ is the annualized Volcanic Activity frequency for the Census block (events per year).

$HLR_{VLCN_{CB_{Bldg}}}$ is the Bayesian-adjusted building Historic Loss Ratio for Volcanic Activity for the Census block.

$EAL_{VLCN_{CB_{Pop}}}$ is the Expected Annual Loss to population value due to Volcanic Activity for a specific Census block (in dollars).

$Exposure_{VLCN_{CB_{Pop}}}$ is the Population value exposed to Volcanic Activity in the Census block (in dollars).

$HLR_{VLCN_{CB_{Pop}}}$ is the Bayesian-adjusted population Historic Loss Ratio for Volcanic Activity for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building and population loss at the Census block level as in *Equation 123*.

Equation 123: Census Tract and County Expected Annual Loss to Volcanic Activity

$$EAL_{VLCN_{CT}} = \sum_{CB}^{CT} EAL_{VLCN_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{VLCN_{CB_{Pop}}}$$

$$EAL_{VLCN_{Co}} = \sum_{CB}^{Co} EAL_{VLCN_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{VLCN_{CB_{Pop}}}$$

where:

$EAL_{VLCN_{CT}}$ is the total Expected Annual Loss due to Volcanic Activity for a specific Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{VLCN_{CB_{Bldg}}}$ is the summed Expected Annual Loss to building value due to Volcanic Activity for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{VLCN_{CB_{Pop}}}$ is the summed Expected Annual Loss to population value due to Volcanic Activity for all Census blocks in the Census tract (in dollars).

$EAL_{VLCN_{Co}}$ is the total Expected Annual Loss due to Volcanic Activity for a specific county (in dollars).

$\sum_{CB}^{Co} EAL_{VLCN_{CB_{Bldg}}}$ is the summed Expected Annual Loss to building value due to Volcanic Activity for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{VLCN\,CB_{Pop}}$ is the summed Expected Annual Loss to population value due to Volcanic Activity for all Census blocks in the county (in dollars).

Figure 146 shows the total EAL (population and building value combined) to Volcanic Activity.

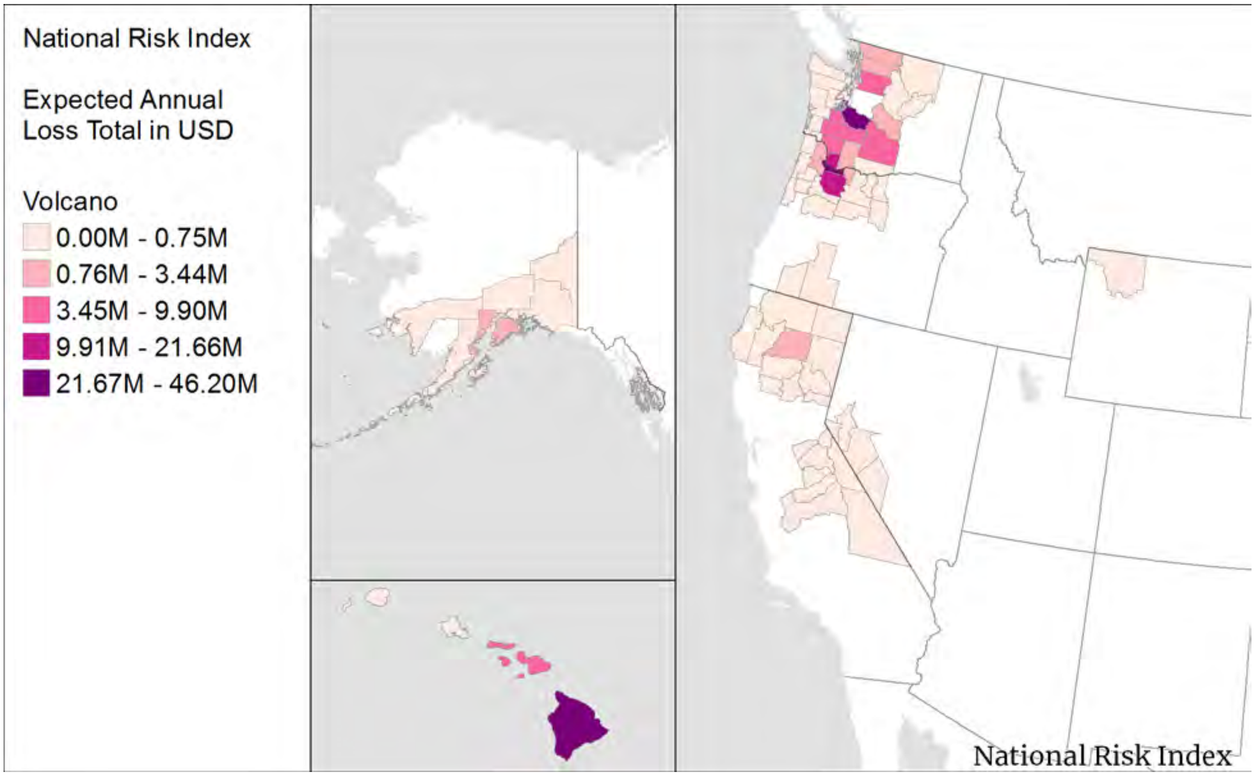

Figure 146: Total Expected Annual Loss by County to Volcano Activity

With the Volcanic Activity total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Volcanic Activity Risk Index score.

22 Wildfire

A Wildfire is an unplanned fire burning in natural or wildland areas, such as forest, shrub lands, grasslands, or prairies.

22.1 Spatial Source Data

Probabilistic Modelling and Susceptible Area Source: *U.S. Department of Agriculture, Forest Service, FSim Burn Probability and Fire Intensity Level Data*[78]

The U.S. Forest Service Missoula Fire Sciences Laboratory generated a series of raster datasets representing burn probability (BP) and conditional fire intensity level (FIL, also referred to as flame length) for the conterminous United States through its geospatial Fire Simulation (FSim) system. FSim estimated the probabilistic components of wildfire risk for 128 distinct regions of contemporary wildfire activity, simulating the occurrence and growth of large and fast-moving wildfires under tens for thousands of hypothetical contemporary fire seasons.

The burn probability raster dataset models the probability of an area being burned by a large fire (i.e., a fire that escapes initial fire suppression and spreads) at a 270-meter grid spatial resolution. The cell value in the raster file contains the mean annual burn probability as a value between 0 and 1 and represents the tendency for the cell area to burn due to a large fire on an annual basis given its landscape, contemporary weather conditions, and probability of containment (see *Figure 147*).

The fire intensity level dataset consists of six raster files, each representing the portion of all simulated fires that burned in the cell area at the specified flame length: FIL1 = < 2 feet (ft); FIL2 = 2 < 4 ft.; FIL3 = 4 < 6 ft.; FIL4 = 6 < 8 ft.; FIL5 = 8 < 12 ft.; and FIL6 = 12+ ft. These files are also at a 270-meter grid spatial resolution.

Note: Because burn probability and fire intensity level data are not available for Alaska and Hawaii, exposure, frequency, and, therefore, EAL cannot be computed for these states.

[78] Short, K.C., Finney, M.A., Scott, J.H., Gilbertson-Day, J.W. & Grenfell, I.C. (2016). Spatial dataset of probabilistic wildfire risk components for the conterminous United States. Fort Collins, CO: Forest Service Research Data Archive. Retrieved from https://doi.org/10.2737/RDS-2016-0034.

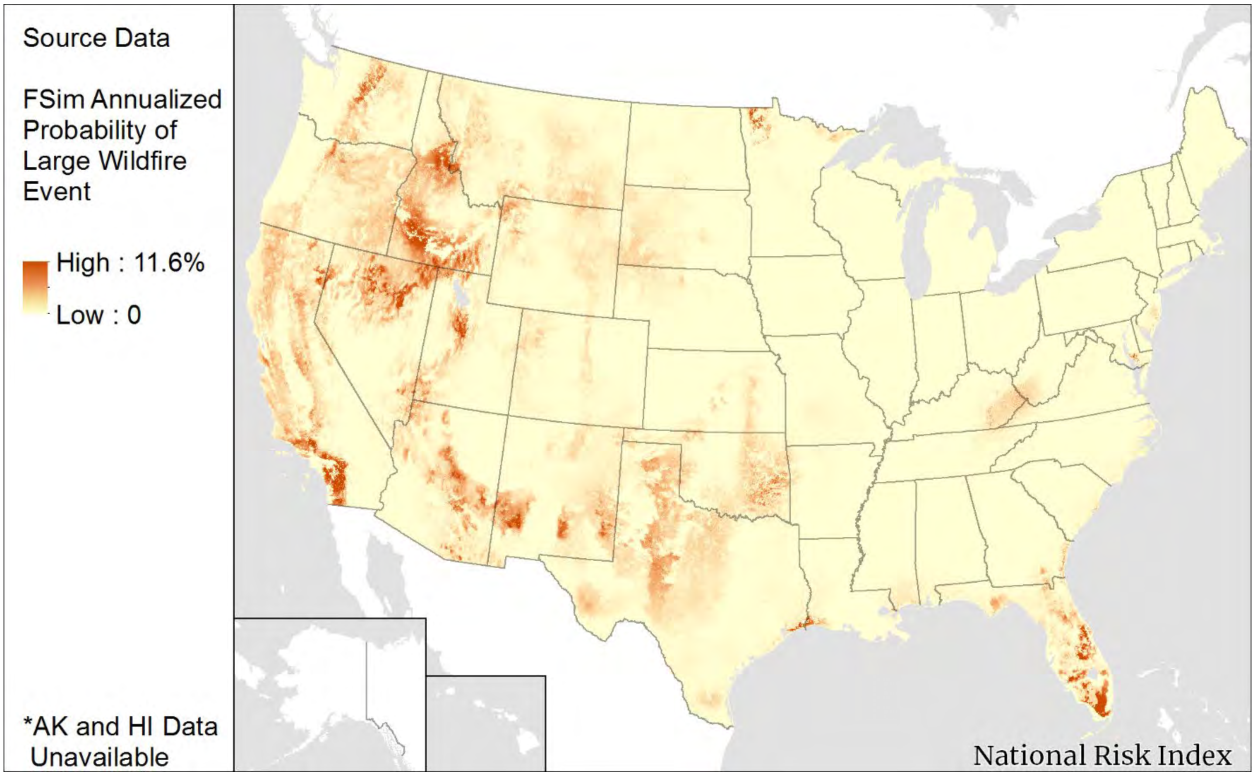

Figure 147: Burn Probability Raster

22.2 Spatial Processing

To determine the intersections of the raster cells with Census blocks, the raster formatted data must be converted to a vector format (polygons). Converting the raster dataset to vector format greatly improves the processing speed and repeatability of resource-intensive intersection functions performed within the NRI processing database. A polygon fishnet for which the dimensions (270-by-270-m) and coverage match the raster datasets was created to make the conversion. Because these polygons matched the cells of the raster datasets, the coordinates of each polygon's centroid could be used to query each raster and return its associated value for the corresponding raster cell. The result is that burn probability and flame intensity level percentage for each flame-length class are now tabularly related to a single cell Wildfire-probability fishnet polygon that can then be intersected with the Census blocks to determine Wildfire exposure and frequency (see *Table 61*).

Table 61: Sample Data from the Wildfire Fishnet Attribute Table

WildfireFishnetID	BurnProbabilityValue	Fil1Value	Fil2Value	Fil3Value	Fil4Value	Fil5Value	Fil6Value
6833438	0.0174	0.023	0.4483	0.454	0.0575	0.0172	0
6850554	0.0209	0	0	0	0.0048	0.2632	0.7321
853511	0	0	0	0	0	0	0

22.3 Determination of Possibility of Hazard Occurrence

Every county covered by the Wildfire probability raster had at least some possibility of Wildfire occurrence, so all counties were deemed possible for Wildfire occurrence. While the current data source does not supply information for Alaska and Hawaii, these states are still included as possible for Wildfire occurrence. In the NRI application, no risk scoring will be available for Alaska and Hawaii as the data are insufficient.

22.4 Exposure

Areas deemed susceptible to Wildfire are defined as areas where the burn probability is greater than 0 and the modeled possibility of large fires reaching a fire intensity level of 5 or 6 is greater than 0. To identify areas of exposure, the Wildfire-susceptible fishnet polygons are intersected with the Census block polygons within the NRI processing database. The resulting table contains the fishnet polygon's unique identifier, Census block number, and the intersected area in square kilometers (see *Table 62*).

Table 62: Sample Data from the Wildfire Fishnet Census Block Intersection Table

WildfireFishnetID	CensusBlock	IntersectedAreaKm2
102645159	060510001012069	0.00328397478103638
102645160	060510001012069	0.0191040656890869
102645161	060510001012069	0.0361694129104614

To find exposure value, the sum of the intersection areas of the Wildfire-susceptible fishnet polygons with each Census block is multiplied by the average building value density and the average population density of the Census block to model the conservative-case concentration of exposure within the Census block. These average Census block building value and population densities have been calculated by dividing the total Census block values (as recorded in Hazus 4.2 SP1) by the total Census block area (in square kilometers; see *Equation 124*). The VSL was used to express population exposure in terms of dollars.

Equation 124: Census Block Wildfire Exposure

$$Exposure_{WFIR_{CB_{Bldg}}} = \sum_{Fish}^{CB} IntsctArea_{WFIR_{Fish_{CB}}} \times AvgDen_{CB_{Bldg}}$$

$$Exposure_{WFIR_{CB_{Pop}}} = \left(\sum_{Fish}^{CB} IntsctArea_{WFIR_{Fish_{CB}}} \times AvgDen_{CB_{Pop}}\right) \times VSL$$

where:

$Exposure_{WFIR_{CB_{Bldg}}}$	is the building value exposed to Wildfire in a specific Census block (in dollars).

$\sum_{Fish}^{CB} IntsctArea_{WFIR_{Fish_{CB}}}$	is the sum of the intersected areas of Wildfire fishnet polygons within the Census block (in square kilometers) where the burn probability was greater than 0 and the value for the fire intensity level of 5 or 6 is greater than 0.
$AvgDen_{CB_{Bldg}}$	is the average building value density of the Census block (in dollars per square kilometer).
$Exposure_{WFIR_{CB_{Pop}}}$	is the population value exposed to Wildfire in a specific Census block (in dollars).
$AvgDen_{CB_{Pop}}$	is the average population value density of the Census block (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).

22.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 125*).

Equation 125: Census Tract and County Wildfire Exposure Aggregation

$$Exposure_{WFIR_{CT_{Bldg}}} = \sum_{CB}^{CT} Exposure_{WFIR_{CB_{Bldg}}}$$

$$Exposure_{WFIR_{Co_{Bldg}}} = \sum_{CB}^{Co} Exposure_{WFIR_{CB_{Bldg}}}$$

$$Exposure_{WFIR_{CT_{Pop}}} = \sum_{CB}^{CT} Exposure_{WFIR_{CB_{Pop}}}$$

$$Exposure_{WFIR_{Co_{Pop}}} = \sum_{CB}^{Co} Exposure_{WFIR_{CB_{Pop}}}$$

where:

$Exposure_{WFIR_{CT_{Bldg}}}$	is the building value where the fire intensity level of 5 or 6 is greater than 0 in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{WFIR_{CB_{Bldg}}}$	is the summed value of all buildings where the fire intensity level of 5 or 6 is greater than 0 for each Census block within the Census tract (in dollars).
$Exposure_{WFIR_{Co_{Bldg}}}$	is the building value where the fire intensity level of 5 or 6 is greater than 0 in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{WFIR_{CB_{Bldg}}}$	is the summed value of all buildings where the fire intensity level of 5 or 6 is greater than 0 for each Census block within the county (in dollars).
$Exposure_{WFIR_{CT_{Pop}}}$	is the population value where the fire intensity level of 5 or 6 is greater than 0 in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{WFIR_{CB_{Pop}}}$	is the summed value of all population where the fire intensity level of 5 or 6 is greater than 0 for each Census block within the Census tract (in dollars).
$Exposure_{WFIR_{Co_{Pop}}}$	is the population value where the fire intensity level of 5 or 6 is greater than 0 in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{WFIR_{CB_{Pop}}}$	is the summed value of all population where the fire intensity level of 5 or 6 is greater than 0 for each Census block within the county (in dollars).

22.5 Frequency

The frequency value represents the area-weighted burn probability (due to a large fire) of a location in a given year. The annualized frequency is calculated at the Census block level (see *Equation 126*), and the Census block-level value is used in the EAL calculations.

Frequency calculations use the same intersection between Wildfire-probability fishnet polygons and Census block polygons that were used to calculate exposure.

Equation 126: Census Block Area-Weighted Wildfire Frequency

$$Freq_{WFIR_{CB}} = \frac{\sum_{Fish}^{CB}\left(IntsctArea_{WFIR_{Fish_{CB}}} \times BProb_{WFIR_{Fish_{CB}}}\right)}{Area_{CB}}$$

where:

$Freq_{WFIR_{CB}}$	is the annualized area-weighted frequency of Wildfire probability determined for a specific Census block (probability per year).

$IntsctArea_{WFIR\,Fish_{CB}}$	is the intersected area of a specific Wildfire fishnet grid cell (where the burn probability was greater than 0) with the Census block (in square kilometers).
$BProb_{WFIR\,Fish_{CB}}$	is the probability of Wildfire occurrence for the Wildfire fishnet grid cell.
$Area_{CB}$	is the total area of the Census block (in square kilometers).

22.5.1 FREQUENCY AGGREGATION

The frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 127*.

Equation 127: Census Tract and County Area-Weighted Wildfire Frequency Aggregation

$$Freq_{WFIR_{CT}} = \frac{\sum_{CB}^{CT}\left(Freq_{WFIR_{CB}} \times Area_{CB}\right)}{Area_{CT}}$$

$$Freq_{WFIR_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{WFIR_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{WFIR_{CT}}$	is the annualized area-weighted Wildfire frequency for a specific Census tract.
$Freq_{WFIR_{CB}}$	is the annualized Wildfire frequency associated with a specific Census block.
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{WFIR_{Co}}$	is the annualized area-weighted Wildfire frequency for a specific county.
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 148 displays annualized Wildfire frequency at the county level.

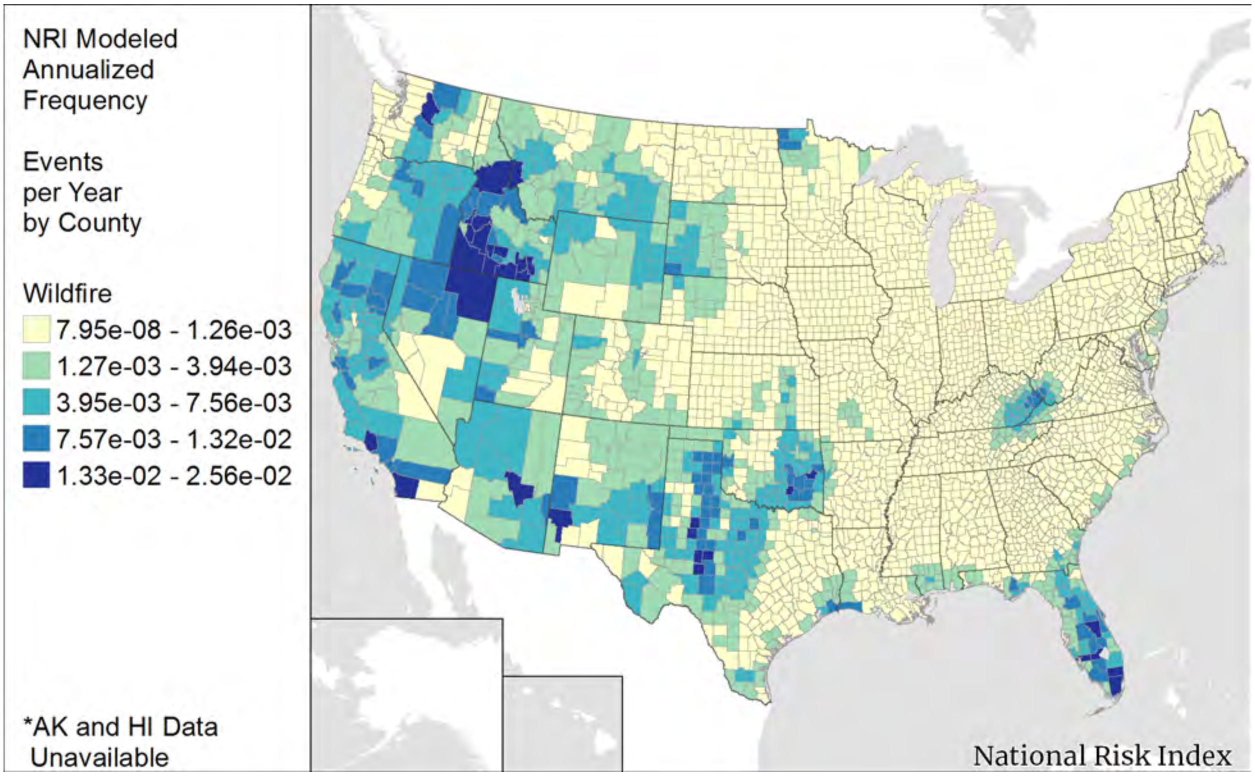

Figure 148: Annualized Wildfire Frequency by County

22.6 Historic Loss Ratio

The Wildfire HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Wildfire event, or the average rate of loss associated with the occurrence of a Wildfire event. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Wildfire hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Five peril types are mapped to the hazard Wildfire (see *Table 63*). These are expanded on an event basis based on the number of records from SHELDUS[79] (see *Section 5.4.1*).

Table 63: Wildfire Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
FireBrush	1	1
FireBush	0	0
FireForest	231	252

[79] For Wildfire loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
FireGrass	13	13
Wildfire	1,985	2,486

For building value HLR, Wildfire counties that intersect Wildfire fishnet cells for which the fire intensity level reaches 6 receive a default HLR value of 0.2. (Bayesian credibility is not utilized for building value HLR). Using this default value resulted in a nationwide property EAL to Wildfire that best approximated the average annual property loss reported in SHELDUS.

For population, the HLR exposure value used in the LRB calculation is the population of the county's area that is most susceptible to Wildfire. This value is determined by summing the average population density exposure values of the Census blocks that intersect Wildfire fishnet cells for which the fire intensity level reaches 6 (average flame length of 12 feet or more). The LRB for each SHELDUS-documented event is calculated using *Equation 128*.

Equation 128: Population Loss Ratio per Basis Calculation for a Single Wildfire Event

$$LRB_{WFIR_{Co_{Pop}}} = \frac{Loss_{WFIR_{Co_{Pop}}}}{HLRExposure_{Co_{Pop}}}$$

where:

$LRB_{WFIR_{Co_{Pop}}}$	is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Wildfire event for population.
$Loss_{WFIR_{Co_{Pop}}}$	is the fatalities and injuries experienced from the Wildfire event documented to have occurred in the county.
$HLRExposure_{Co_{Pop}}$	is the population of the county estimated to have been exposed to the Wildfire event.

A Historic Event Count is not computed for Wildfire, so no zero-loss events are inserted into the Loss Ratio table. After the population LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and national.

Figure 149 displays the largest weighting factor contributor in the Bayesian credibility calculation for the Wildfire population HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Wildfire events within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or national events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing events or have widely varying loss ratios get the most influence from national-level loss data. *Figure 150* represents the final county-level population HLR values for Wildfire.

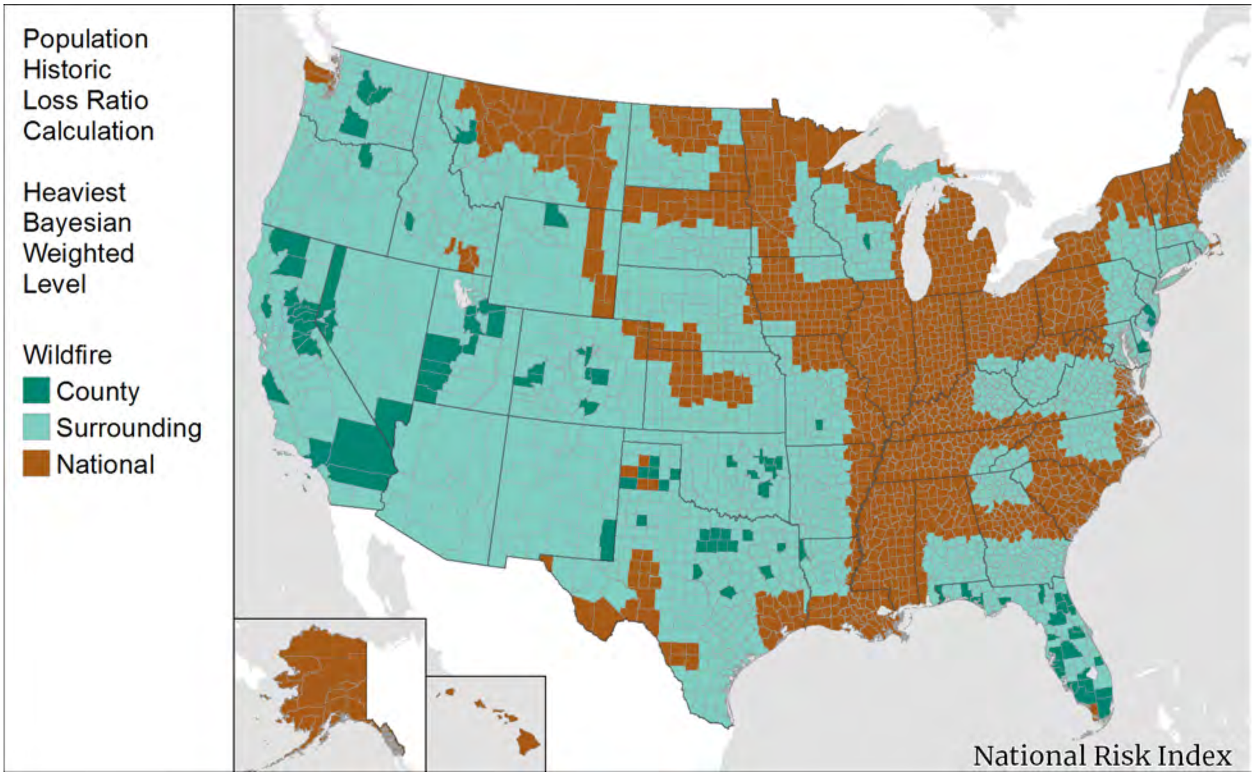

Figure 149: Wildfire Heaviest Bayesian Influence Level – Population

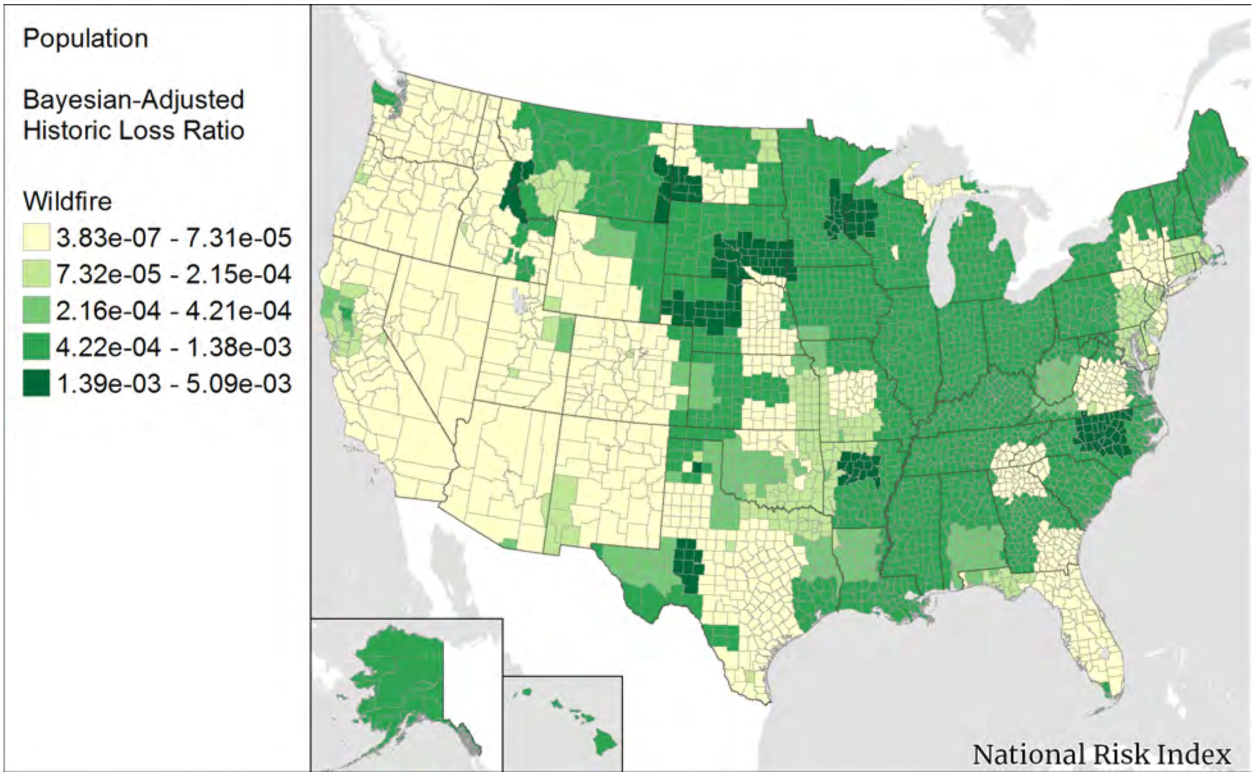

Figure 150: Wildfire HLR – Population

The resulting population HLR is then inherited by the Census blocks and Census tracts within the county.

22.7 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 129*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 129: Census Block Expected Annual Loss to Wildfire

$$EAL_{WFIR_{CB_{Bldg}}} = Exposure_{WFIR_{CB_{Bldg}}} \times Freq_{WFIR_{CB}} \times HLR_{WFIR_{CB_{Bldg}}}$$

$$EAL_{WFIR_{CB_{Pop}}} = Exposure_{WFIR_{CB_{Pop}}} \times Freq_{WFIR_{CB}} \times HLR_{WFIR_{CB_{Pop}}}$$

where:

$EAL_{WFIR_{CB_{Bldg}}}$	is the Expected Annual Loss to building value due to Wildfire events for a specific Census block (in dollars).

$Exposure_{WFIR_{CB_{Bldg}}}$	is the building value where the flame intensity level of 5 or 6 is greater than 0 in the Census block (in dollars).
$Freq_{WFIR_{CB}}$	is the annualized Wildfire frequency for the Census block (probability per year).
$HLR_{WFIR_{CB_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Wildfire for the Census block.
$EAL_{WFIR_{CB_{Pop}}}$	is the Expected Annual Loss to population value due to Wildfire events for a specific Census block (in dollars).
$Exposure_{WFIR_{CB_{Pop}}}$	is the population value where the flame intensity level of 5 or 6 is greater than 0 in the Census block (in dollars).
$HLR_{WFIR_{CB_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Wildfire for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building and population loss at the Census block level as in *Equation 130*.

Equation 130: Census Tract and County Expected Annual Loss to Wildfire

$$EAL_{WFIR_{CT}} = \sum_{CB}^{CT} EAL_{WFIR_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{WFIR_{CB_{Pop}}}$$

$$EAL_{WFIR_{Co}} = \sum_{CB}^{Co} EAL_{WFIR_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{WFIR_{CB_{Pop}}}$$

where:

$EAL_{WFIR_{CT}}$	is the total Expected Annual Loss due to Wildfire events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{WFIR_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Wildfire events for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{WFIR_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Wildfire events for all Census blocks in the Census tract (in dollars).
$EAL_{WFIR_{Co}}$	is the total Expected Annual Loss due to Wildfire events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{WFIR_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Wildfire events for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{WFIR_{CB_{Pop}}}$ is the summed Expected Annual Loss to population value due to Wildfire events for all Census blocks in the county (in dollars).

Figure 151 shows the total EAL (population and building value combined) to Wildfire events.

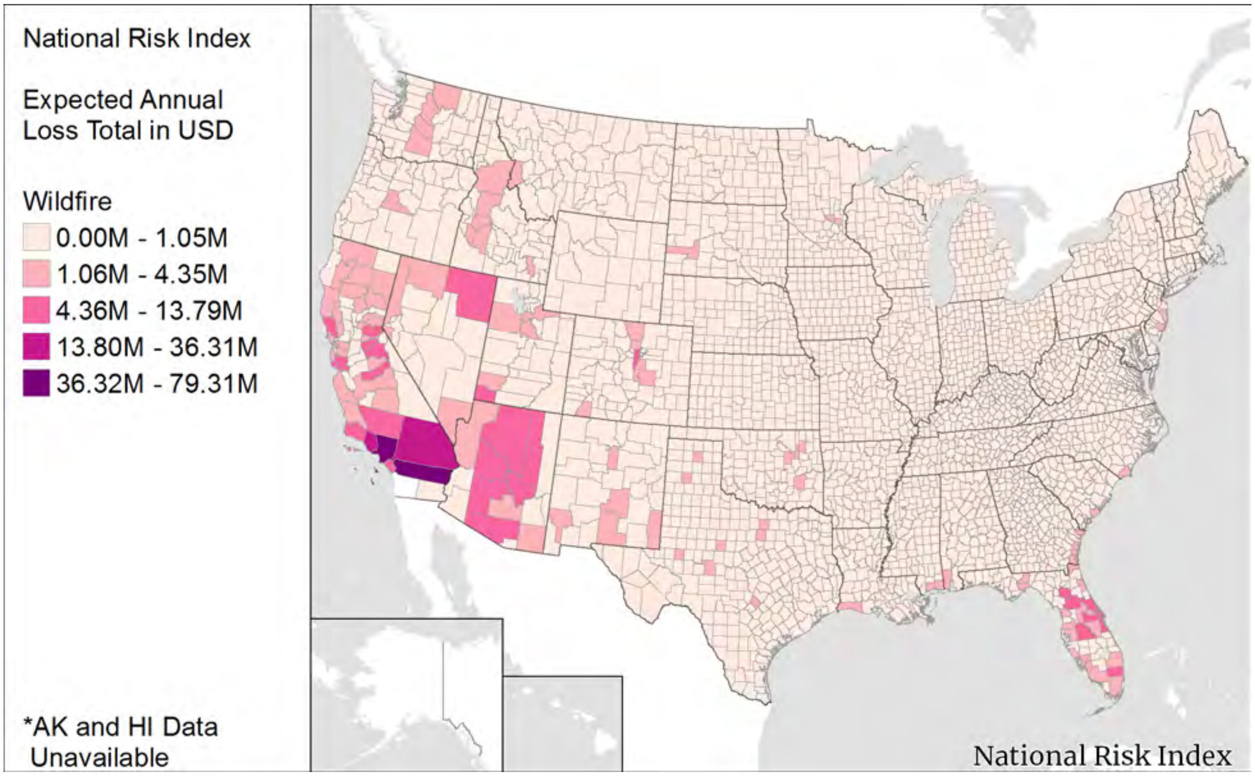

Figure 151: Total Expected Annual Loss by County to Wildfire

With the Wildfire total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Wildfire Risk Index score.

23 Winter Weather

Winter Weather consists of winter storm events in which the main types of precipitation are snow, sleet, or freezing rain.

23.1 Spatial Source Data

Historical Event Generating Source: *National Weather Service, Winter Weather Alerts*[80]

Historical Event Compiling Source: *Iowa State University, Iowa Environmental Mesonet*[81]

The NWS is continuously issuing weather alerts based on current weather conditions. Each alert is coded by type and significance, and conceptually can serve as documentation of the potential for weather event activities in a specific area. Archived NWS alerts are aggregated, continuously updated, and made available for download in shapefile format by Iowa State University's Iowa Environmental Mesonet. Data include geometry for each alert's issued area and attributes related to each alert's severity and phenomena type. Weather alerts are also timestamped with the time of issuance and the time of expiration. A table describing this dataset's attributes can be found in *Appendix C – Mesonet-NWS Weather Event Attribute Description*.

Because the spatial representations of the alert areas will be intersected with Census blocks for the determination of exposure and frequency, it is important to use the best possible resolution of the Winter Weather alert.

The geometry shape for each alert record represents the geographic area for which the NWS alert applied. However, the Mesonet shapes are simplified versions of the more detailed NWS Public Forecast Zone shape originally associated with the alert record. Because the Mesonet tabular data still retain the reference ID for the NWS Public Forecast Zone, the ID can be used to relate to the zone associated with each alert record.

The NWS Public Forecast Zones can be downloaded in shapefile format[82] and represent the codified areas for which weather alerts are issued by NWS. The Public Forecast Zones shape definitions are predominantly derived from county boundaries. While the Public Forecast Zone boundaries are more refined than those substituted into the Mesonet data, they are not at the same resolution as the current county boundaries derived from Census blocks.

[80] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *Active Alerts* [online dataset]. Retrieved from https://www.weather.gov/.
[81] Department of Agronomy, Iowa State University. (2018). *Iowa Environmental Mesonet* [online database]. Retrieved from https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml.
[82] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *NWS Public Forecast Zones* [online dataset]. Retrieved from https://www.weather.gov/gis/PublicZones.

Utilizing the Public Forecast Zone shapefile in conjunction with the Public Forecast Zone – County Correlation file,[83] a determination was made as to which Public Forecast Zones have single-county coverage and which are either sub-county zones or made of portions of multiple counties. For perspective, the following approximate distribution of forecast zone composition were found:

- 70% of the zones are single-county coverage.
- 20% are cases where a single county is subdivided into multiple zones.
- 10% are zones that breach parts of multiple contiguous counties.

For the Forecast Zones covering a single county, the U.S. Census 2017 county boundaries are substituted. For all other zone shapes, the native NWS Public Forecast Zone shape found in the Mesonet data or correlation file is used. See *Figure 152* for an example of the differences in the spatial resolution of weather alert boundaries.

Another aspect of the NWS Public Forecast Zones is that they can and have changed over time. In the Mesonet data (2005 through 2017), there are 4,364 distinct Forecast Zones referenced that do not exist in the current NWS Public Forecast Zone shapefile. This occurs when an NWS Public Forecast Zone has been modified in shape, renamed, and/or "retired" from use.

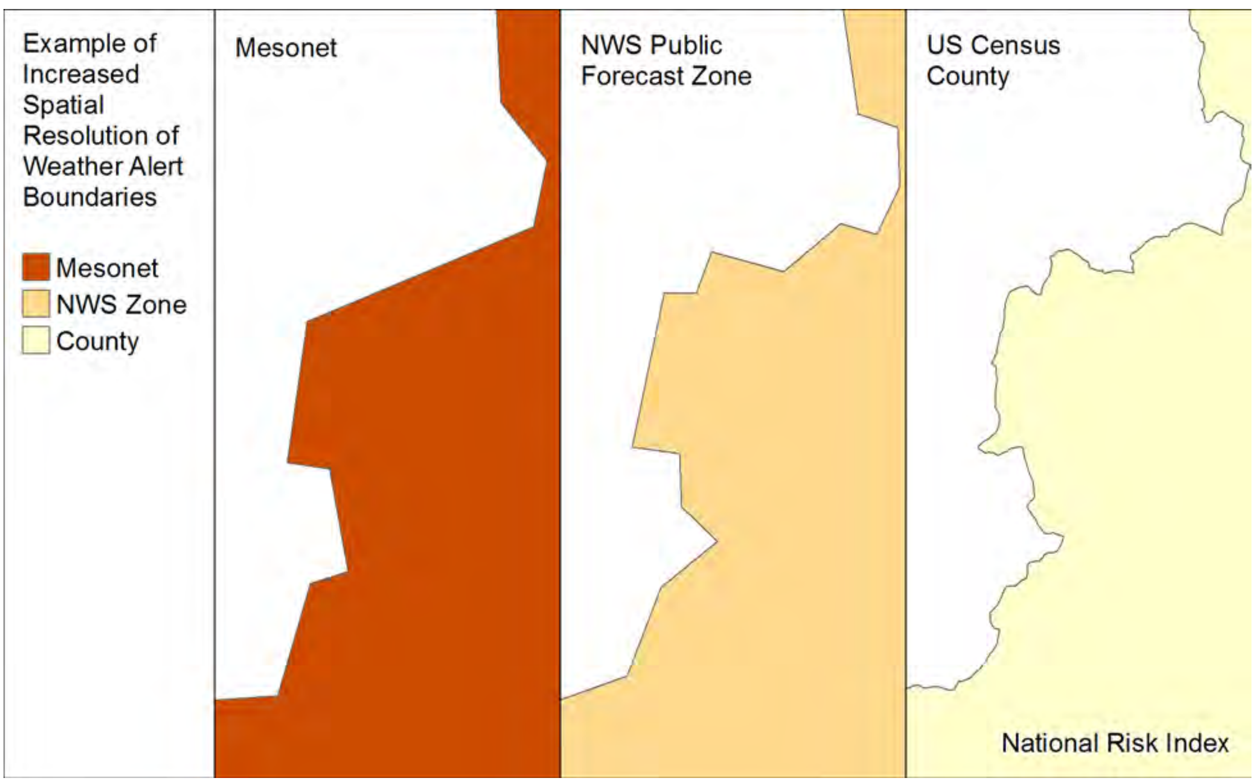

Figure 152: Three Boundary Definitions – Mesonet, Forecast Zone, U.S. Census County

[83] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *Zone-County Correlation File* [online dataset]. Retrieved from https://www.weather.gov/gis/ZoneCounty

Further research found that the NWS maintains a downloadable Change History log of the various changes in Forecast Zone areas since 1997. This text file does not contain the pre- nor post-shape of the altered forecast zone. Archived versions of these changes are likely available via contact with NWS, but the effort to match the NWS issued alert record to the version-controlled shape representation of the forecast zone at the time of alert issue seems to be beyond the scope of the NRI processing effort, though a Mesonet representative was contacted to see if Forecast Zone shapes associated with each year of alert data had been archived. Unfortunately, no such archival information was available. For cases where the more refined NWS Forecast Zone shape is unavailable, the simplified Mesonet boundary version shape is used.

23.1.1 PERIOD OF RECORD

In the 1990s and early 2000s, the NWS's system of recording watch, warnings, and advisories (WWA) made automated processing too difficult. So, in 2005, the Valid Time Extent Code (VTEC) system was implemented, which allowed for the easy automated parsing of alert data. Therefore, NWS weather events data were downloaded for 2005 through 2017. The date range utilized for the NRI is 11/12/2005 to 12/31/2017, so the period of record for which Winter Weather data are utilized is 12.14 years.

23.2 Spatial Processing

With the intended spatial processing goal of intersecting NWS event shapes to determine the Census block area impacted by each event, there are three main preparatory efforts required prior to the intersection of Winter Weather event polygons with Census block polygons for the purposes of calculating Winter Weather exposure and frequency.

Winter Weather event alerts are extracted from the dataset based on the VTEC significance code (SIG field) and the phenomena code (PHENOM field) values. Only Warning alerts (SIG = 'W') of one of the Phenomena types in *Table 64* are considered NRI Winter Weather events (see *Table 65*).

Table 64: Winter Weather Phenomena Types

PHENOM Code	Phenomena Code Description
BZ	Blizzard
HS	Heavy Snow
LB	Lake Effect Snow and Blowing Snow
LE	Lake Effect Snow
SN	Snow
SB	Snow and Blowing Snow
WS	Winter Storm
WW	Winter Weather

Table 65: Original Mesonet Winter Weather Records

WFO	ISSUED	EXPIRED	PHENOM	SIG	NWS_UGC	AREA_KM2
GJT	201702271300	201703010339	WS	W	COZ019	9720.85253906
PHI	201703140000	201703141849	BZ	W	NJZ001	1386.35180664
AFG	200803292000	200803301217	HS	W	AKZ214	25092.76593474

To remove unintended error in spatial results due to the use of the simplified event area shapes contained in the Mesonet data, event areas with a higher resolution version are substituted. This substitution uses the NWS Public Forecast Zone shape associated with the alert record or, in cases where the forecast zone is for a single county, a better resolution version of the county boundary area.

Winter Weather occurrences are measured in event-days as this more accurately represents the variability of Winter Weather event duration. To capture this, each native alert record with a duration greater than a single day is replaced with multiple records, one for each day of the original record's duration.

If a Winter Weather event's duration on any given day is less than 6 hours, then the event is assigned to the day having the greatest duration of the event. This handles cases where the event occurs in the late evening and actually endures for a greater length of time on the next calendar day than on the day the alert was issued.

For cases where the event duration is longer, the following logic is used: If a weather event's duration is greater than 6 hours, assign the event to all days on which 6 or more hours occur. For example, if a 14-hour weather event was issued for 2 AM until 6 PM on January 1, then the event would be assigned to January 1. If the alert was issued from 11 PM on January 1 to 1 PM on January 2, then the event would be assigned to only January 2. If the alert was issued from 7 PM on January 1 to 9 AM on January 2, then the event would be assigned to both January 1 and January 2.

Additionally, there are some data quality issues with the Mesonet data. For example, some warnings have an expiration date that is prior to the issue date. In these cases, a single record is used and assigned the issue date. To illustrate this concept, the Winter Weather events in *Table 66* are expanded to create the Winter Weather event-day records in *Table 67.*

Table 66: Sample Winter Weather Data after Zone Shape Re-Sourcing

Winter StormID	WFO	Issued	Expired	PHENOM	SIG	NWS_UGC	AreaKm2	NewShape Source
45437	GJT	2/27/2017 1:00:00 PM	3/1/2017 3:39:00 AM	WS	W	COZ019	9707.610	Census County
45253	AJK	3/12/2017 11:50:00 PM	3/14/2017 2:00:00 AM	WS	W	AKZ022	4153.062	NWS Forecast Zone
45416	CYS	2/27/2017 9:00:00 PM	2/28/2017 10:02:00 AM	WS	W	WYZ112	2354.592	NWS Forecast Zone

Table 67: Sample Data from the Winter Weather Date Expansion Table

WinterStormDate ExpansionID	WinterStormID	Issued	Expired	DateType	WinterStormHours
35072	45437	2/27/2017 1:00:00 PM	2/28/2017 12:00:00 AM	Expanded Dates - Issued	11
35073	45437	2/28/2017 12:00:00 AM	3/1/2017 12:00:00 AM	Expanded Dates - New Dates	24
35058	45253	3/13/2017 12:00:00 AM	3/14/2017 12:00:00 AM	Expanded Dates - New Dates	24
35067	45416	2/28/2017 12:00:00 AM	2/28/2017 10:02:00 AM	Expanded Dates - Expired	10.033333

To avoid overestimating the area of influence a “single” distinct weather event has due to multiple NWS alerts being issued for that same weather event, a process to combine all Winter Weather event areas occurring on the same day (Year, Month, and Day specific) into one representative event shape is performed. This process results in an impact area shape for a single event for each day on which a Winter Weather event occurred. These event-day polygons can then be intersected with the Census block polygons to determine Winter Weather exposure and frequency.

23.3 Determination of Possibility of Hazard Occurrence

Winter Weather can occur almost anywhere in the United States as the definition of a Winter Weather event is locally defined by the area’s weather forecast office. For example, a forecast office in Texas may define a Winter Weather event differently than a forecast office in New York. Therefore, all counties were deemed possible for Winter Weather occurrence.

23.4 Exposure

To identify areas of exposure, the Winter Weather event-day polygons (also referred to as Winter Storm Date Expansions to acknowledge the spatiotemporal processing described in Section 23.2) are intersected with the Census block polygons within the NRI processing database. The resulting table contains the Winter Weather event-day's unique identifier, Census block number, and the intersected area in square kilometers (see Table 68).

Table 68: Sample Data from the Winter Weather Census Block Intersection Table

WinterStormDateExpansionID	CensusBlock	IntersectedAreaKm2
44082	517750105012023	0.00380071655273438
44082	517700023004045	0.00177242324829102
44082	517750102005022	0.090136718170166

To determine exposure value, the average coverage of a Winter Weather event-day is found by summing the intersected areas for all Winter Weather event-days that intersected the Census block and dividing this sum by the number of intersecting event-days. This is multiplied by the developed area building value density and the developed area population density of the Census block to model the conservative-case concentration of exposure within the Census block. These developed area building and population densities of the Census block have been calculated by dividing the total values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers; see Equation 131). The VSL was used to express population exposure in terms of dollars.

Equation 131: Census Block Winter Weather Exposure

$$Exposure_{WNTW_{CB_{Bldg}}} = \frac{\sum IntsctArea_{WNTW_{CB}}}{EventCount_{WNTW_{CB}}} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{WNTW_{CB_{Pop}}} = \left(\frac{\sum IntsctArea_{WNTW_{CB}}}{EventCount_{WNTW_{CB}}} \times DevAreaDen_{CB_{Pop}}\right) \times VSL$$

where:

$Exposure_{WNTW_{CB_{Bldg}}}$	is the building value exposed to Winter Weather event-days in a specific Census block (in dollars).
$\sum IntsctArea_{WNTW_{CB}}$	is the sum of the intersected areas of past Winter Weather event-days with the Census block (in square kilometers).
$EventCount_{WNTW_{CB}}$	is the total number of Winter Weather event-days that intersect the Census block.

$DevAreaDen_{CB_{Bldg}}$	is the developed area building value density of the Census block (in dollars per square kilometer).
$Exposure_{WNTW_{CB_{Pop}}}$	is the population value exposed to Winter Weather event-days in a specific Census block (in dollars).
$DevAreaDen_{CB_{Pop}}$	is the developed area population density of the Census block (in people per square kilometer).
VSL	is the Value of Statistical Life ($7.4M per person).

It should be noted that, for a Winter Weather event-day polygon's intersection with a Census block to be included, the area of the intersection must cover more than 5% of the Census block. This is a spatial modeling technique to correct for the small intersect "slivers" generated by differing versions of county boundary geometry being used.

Because the exposure model uses a conservative-case concentration of exposure and a developed area density value, it is possible to mathematically generate an exposure value that is greater than the total value of the Census block. The Hazus-recorded population and building value are considered ceilings on exposure. For example, if the calculated exposed population exceeds the Hazus-recorded population, then the Hazus-recorded population is used as the population exposure value for the Census block.

23.4.1 EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see *Equation 132*).

Equation 132: Census Tract and County Winter Weather Exposure Aggregation

$$Exposure_{WNTW_{CT_{Bldg}}} = \sum_{CB}^{CT} Exposure_{WNTW_{CB_{Bldg}}}$$

$$Exposure_{WNTW_{Co_{Bldg}}} = \sum_{CB}^{Co} Exposure_{WNTW_{CB_{Bldg}}}$$

$$Exposure_{WNTW_{CT_{Pop}}} = \sum_{CB}^{CT} Exposure_{WNTW_{CB_{Pop}}}$$

$$Exposure_{WNTW_{Co_{Pop}}} = \sum_{CB}^{Co} Exposure_{WNTW_{CB_{Pop}}}$$

where:

$Exposure_{WNTW_{CT_{Bldg}}}$ is the building value exposed to Winter Weather event-days in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{WNTW_{CB_{Bldg}}}$ is the summed value of all buildings exposed to Winter Weather for each Census block within the Census tract (in dollars).

$Exposure_{WNTW_{Co_{Bldg}}}$ is the building value exposed to Winter Weather event-days in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{WNTW_{CB_{Bldg}}}$ is the summed value of all buildings exposed to Winter Weather for each Census block within the county (in dollars).

$Exposure_{WNTW_{CT_{Pop}}}$ is the population value exposed to Winter Weather event-days in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{WNTW_{CB_{Pop}}}$ is the summed value of all population exposed to Winter Weather for each Census block within the Census tract (in dollars).

$Exposure_{WNTW_{Co_{Pop}}}$ is the population value exposed to Winter Weather event-days in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{WNTW_{CB_{Pop}}}$ is the summed value of all population exposed to Winter Weather for each Census block within the county (in dollars).

23.5 Historic Event-Day Count

The count of historic Winter Weather event-days is computed as the number of distinct Winter Weather event-day polygons that intersect a Census block and have an area of intersection that is at least 5% of the block's total area. This count uses the same Winter Weather expansion Census block intersection table used to find exposure at the Census block level and will be used to compute frequency at the Census block level.

Historic Event-Day Counts are also supplied at the Census tract and county levels as the number of distinct Winter Weather event-day polygons that intersect the Census tract and county, respectively.

23.6 Frequency

The number of recorded Winter Weather event-days each year over the period of record (12.14 years) is used to estimate the frequency of Winter Weather events in an area. Because a Winter Weather event can occur over several days or a single day, an event-day basis was used to estimate frequency as this method better captures the variability in duration between events. The annualized frequency is calculated at the Census block level using *Equation 133*, and the Census block-level value is used in the EAL calculations.

Frequency calculations use the same intersection between Winter Weather event-days (or Winter Storm Date Expansion) polygons and Census block polygons that were used to calculate exposure. The count of distinct Winter Weather event-day polygons intersecting each Census block is recorded and used to calculate the annualized frequency of Winter Weather event-days.

Equation 133: Census Block Winter Weather Frequency

$$Freq_{WNTW_{CB}} = \frac{EventCount_{WNTW_{CB}}}{PeriodRecord_{WNTW}}$$

where:

$Freq_{WNTW_{CB}}$	is the annualized frequency of Winter Weather event-days determined for a specific Census block (event-days per year).
$EventCount_{WNTW_{CB}}$	is the number of Winter Weather event-days that intersect the Census block.
$PeriodRecord_{WNTW}$	is the period of record for Winter Weather (12.14 years).

23.6.1 FREQUENCY AGGREGATION

The NRI application provides area-weighted average frequency values at both the Census tract and county level. These values may not exactly match that of dividing the number of recorded Winter Weather events at the Census tract and county level by the period of record. The frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in *Equation 134*.

Equation 134: Census Tract and County Area-Weighted Winter Weather Frequency Aggregation

$$Freq_{WNTW_{CT}} = \frac{\sum_{CB}^{CT}\left(Freq_{WNTW_{CB}} \times Area_{CB}\right)}{Area_{CT}}$$

$$Freq_{WNTW_{Co}} = \frac{\sum_{CB}^{Co}\left(Freq_{WNTW_{CB}} \times Area_{CB}\right)}{Area_{Co}}$$

where:

$Freq_{WNTW_{CT}}$	is the Annualized area-weighted Winter Weather frequency for a specific Census tract.
$Freq_{WNTW_{CB}}$	is the annualized Winter Weather frequency associated with a specific Census block.
$Area_{CB}$	is the total area of the Census block (in square kilometers).

$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{WNTW_{Co}}$	is the annualized area-weighted Winter Weather frequency for a specific county.
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

Figure 153 displays annualized Winter Weather frequency at the county level.

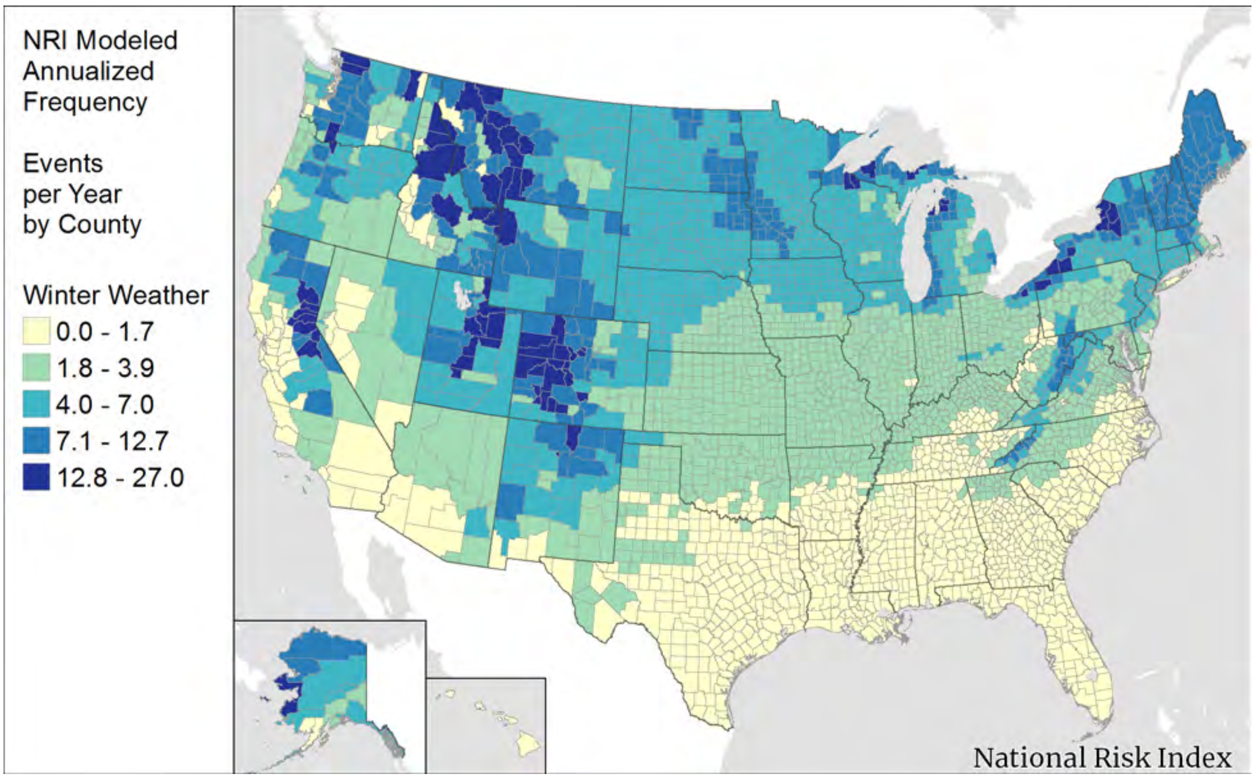

Figure 153: Annualized Winter Weather Frequency by County

23.7 Historic Loss Ratio

The Winter Weather HLR is the representative percentage of a location's hazard exposure area that experiences loss due to a Winter Weather event-day, or the average rate of loss associated with the occurrence of a Winter Weather event-day. For a detailed description of the HLR calculation process, see *Section 5.4*. The HLR parameters described below are specific to the Winter Weather hazard.

Historic Loss data are aggregated from SHELDUS at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1995 to 2016 are included in the HLR calculation. Three peril types are mapped to the hazard Winter Weather (see *Table 69*). These are expanded on an event-day basis based on the number of event duration days from SHELDUS[84] (see *Section 5.4.1*).

Table 69: Winter Weather Peril Types and Recorded Events from 1995-2016

Peril Type in SHELDUS	Total SHELDUS Loss Records	Total Records per Event Basis
Blizzard	1,913	3,733
StormWinter	7,813	16,300
WinterWeather	3,771	6,769

The HLR exposure value used in the LRB calculation is a county-level value that represents the dollar value of the total building value or the entire population of a county as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event-day and each consequence type (building and population) is calculated using *Equation 135*.

Equation 135: Loss Ratio per Basis Calculation for a Single Winter Weather Event-Day

$$LRB_{WNTW\,Co_{CnsqType}} = \frac{Loss_{WNTW\,Co_{CnsqType}}}{HLRExposure_{Co_{CnsqType}}}$$

where:

$LRB_{WNTW\,Co_{CnsqType}}$ is the Loss Ratio per Basis representing the ratio of loss to exposure experienced by a specific county due to the occurrence of a specific Winter Weather event-day. Calculation is performed for each consequence type (building and population).

$Loss_{WNTW\,Co_{CnsqType}}$ is the loss (by consequence type) experienced from the Winter Weather event-day documented to have occurred in the county (in dollars).

$HLRExposure_{Co_{CnsqType}}$ is the total value (by consequence type) of the county estimated to have been exposed to the Winter Weather event-day (in dollars).

Winter Weather event-days can occur with a high frequency in areas, but often result in no recorded loss to buildings or population. SHELDUS does not record events in which no loss occurred, so a number of zero-loss event-day records are inserted into the loss data to align the event-day count in the HLR calculation to the historic event-day count within the SHELDUS period of record (1995 to 2016). For Winter Weather, the historic year-month event-day count is extracted using the intersection between the Winter Weather event-day polygons and the Census block polygons used to

[84] For Winter Weather loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

calculate exposure and frequency (see *Table 67*). The date when the Winter Weather alert was issued for each Winter Weather event-day polygon is used to sync the event to its year-month. A list of distinct Winter Weather alert issue dates is compiled for the event-day polygon-Census block intersections within the county, and the historic year-month event count is the number of distinct Winter Weather alert issue dates in this list.

If the number of loss-causing Winter Weather event-day records from SHELDUS is less than the summed historic year-month event-day counts for the county, then a number of zero-loss records equal to the difference is inserted into the LRB table with zero values for the consequence ratios.

After the LRBs are calculated for each county, Bayesian credibility weighting factors are computed and applied at several levels: county, surrounding 196-by-196-km fishnet grid cell, and regional. The regional definition for Winter Weather is derived from the FEMA regions with Regions I, II, and III merged (see *Section 5.4.4*).

Figure 154 and *Figure 156* display the largest weighting factor contributor in the Bayesian calculation for the Winter Weather HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Winter Weather event-days within the county that its loss data are the dominant driver for its HLR value, though its HLR may be influenced by other local or regional events. The surrounding area's loss ratios have the greatest influence on the HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing event-days or have widely varying loss ratios get the most influence from regional-level loss data. *Figure 155* and *Figure 157* represent the final county-level HLR values for Winter Weather.

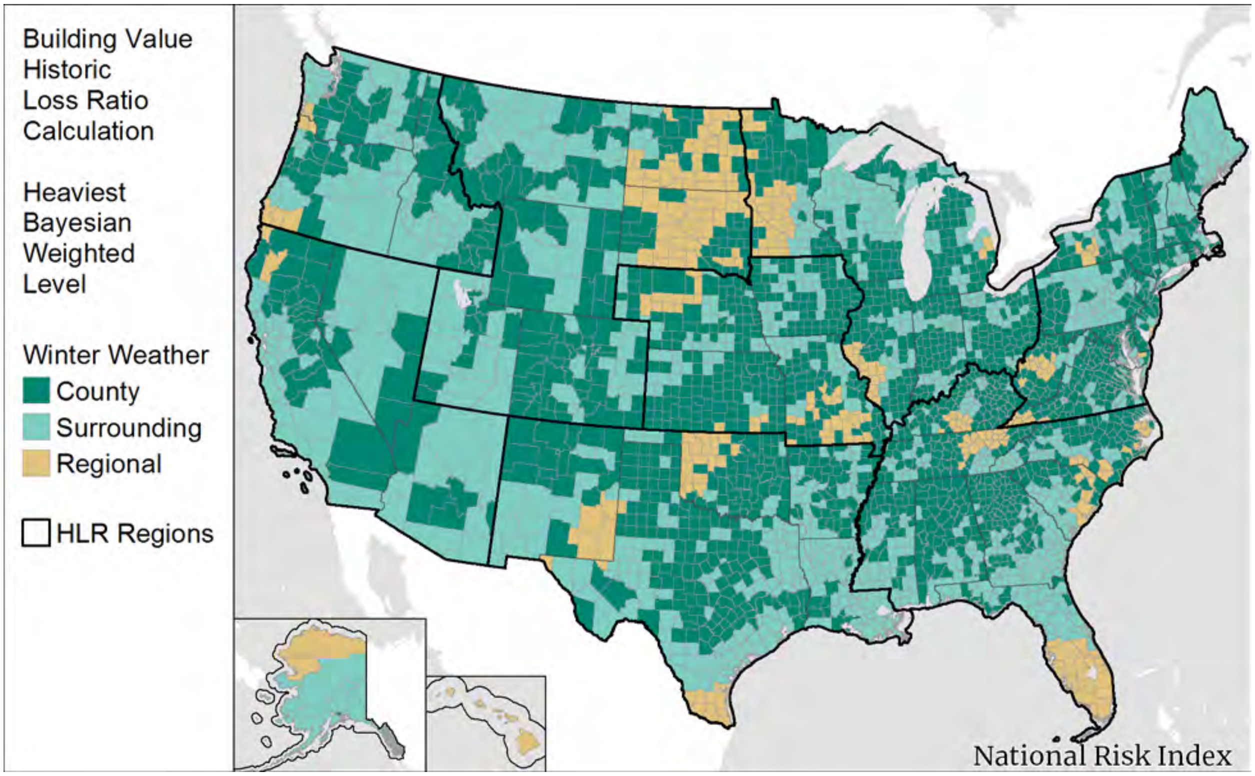

Figure 154: Winter Weather Heaviest Bayesian Influence Level – Building Value

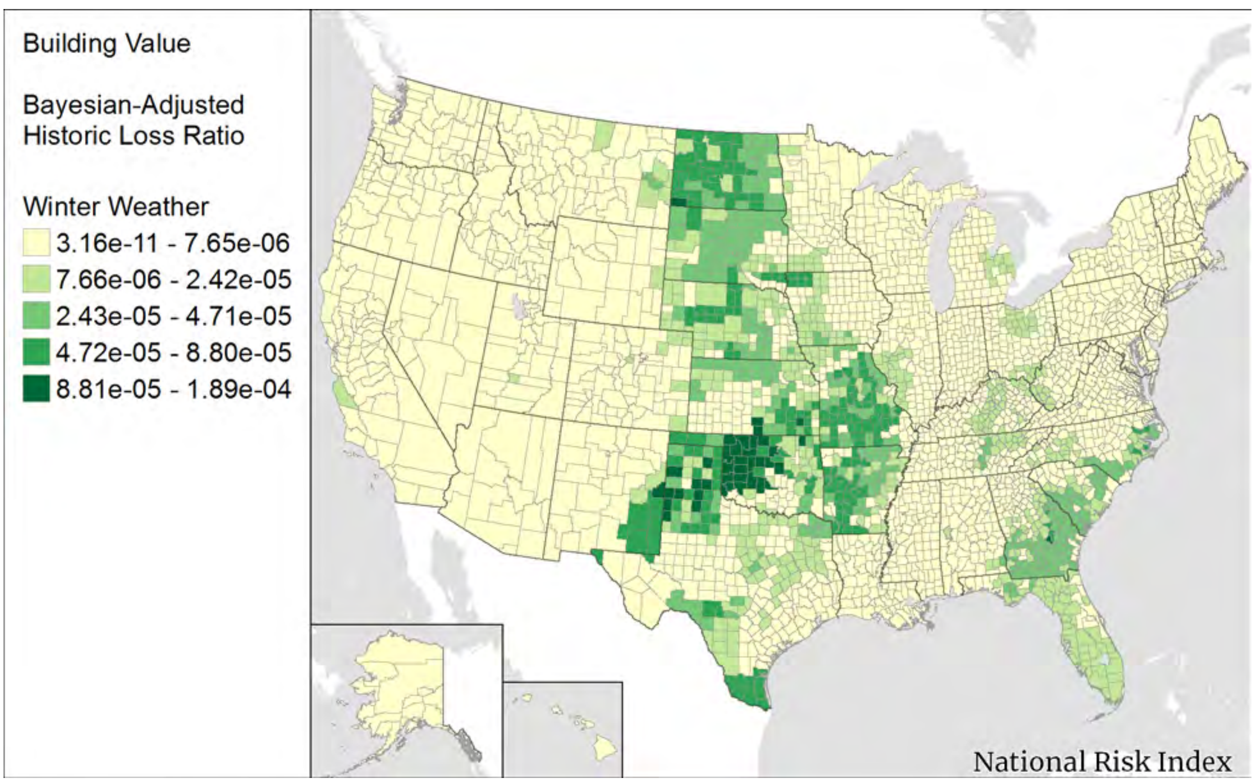

Figure 155: Winter Weather HLR – Building Value

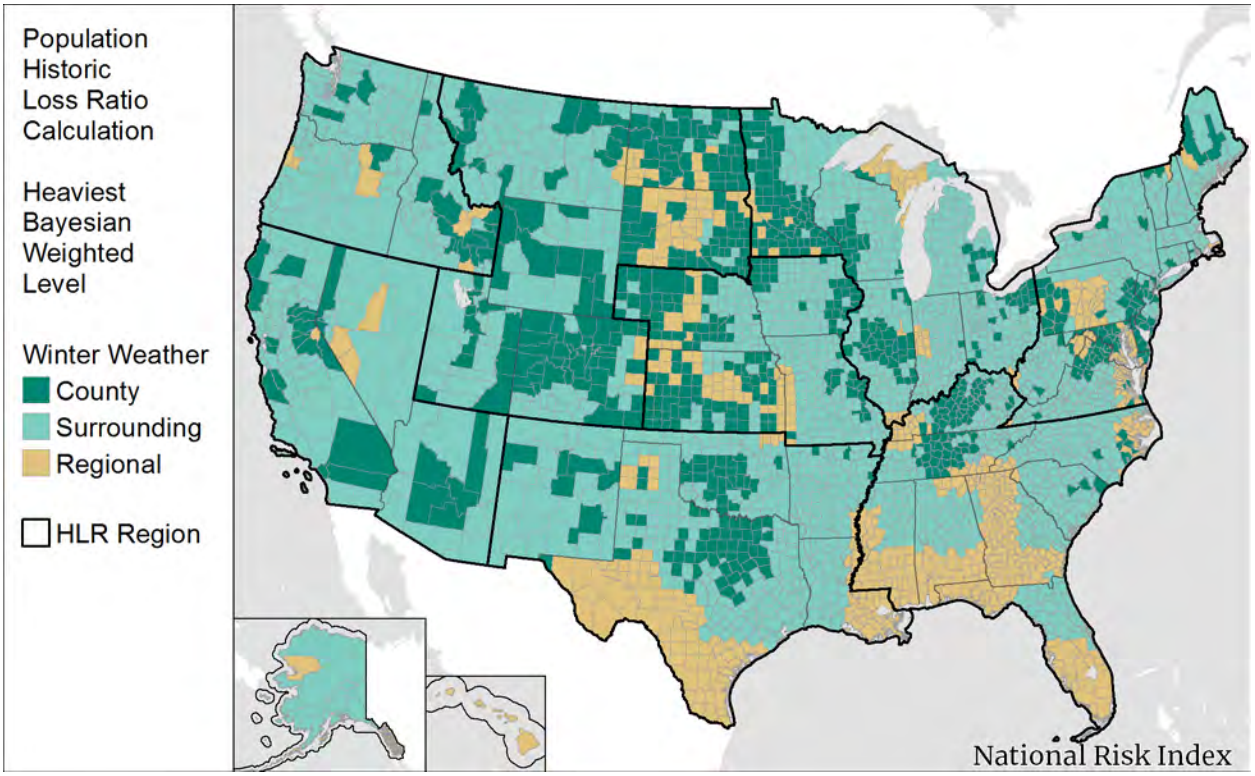

Figure 156: Winter Weather Heaviest Bayesian Influence Level – Population

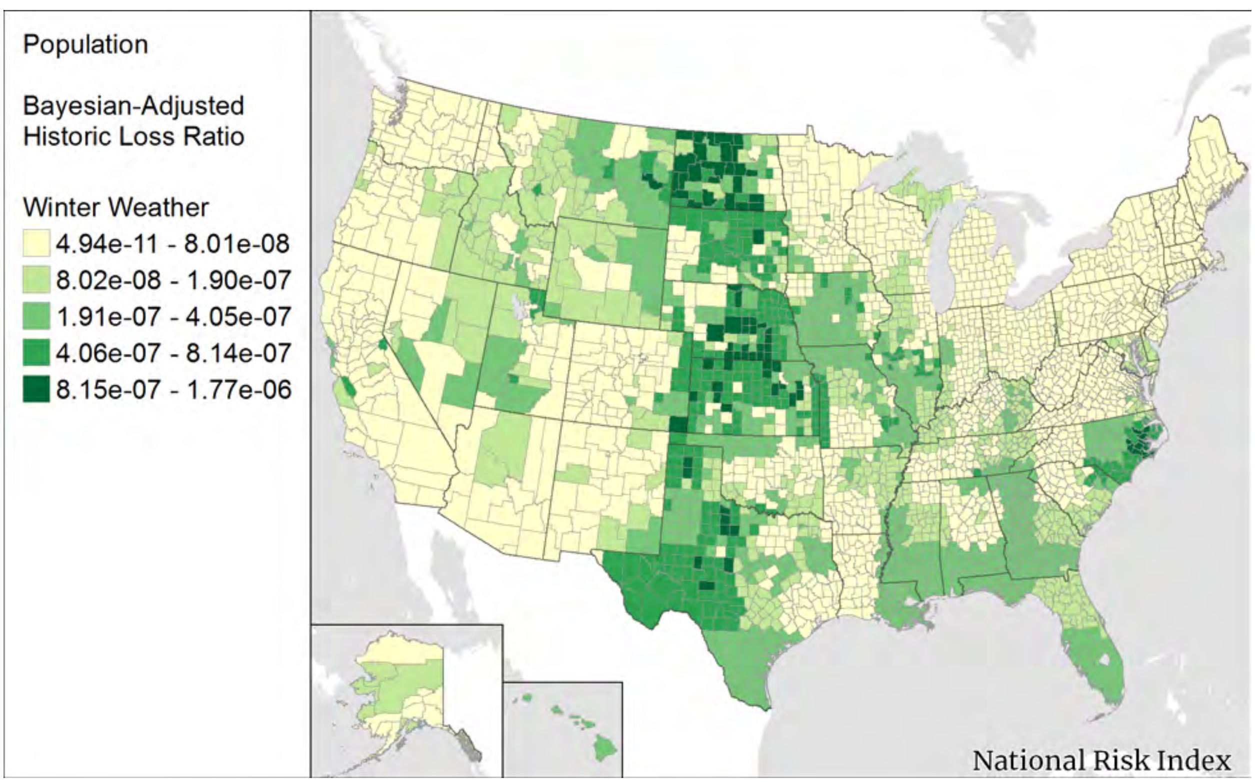

Figure 157: Winter Weather HLR – Population

The resulting county specific Bayesian-adjusted HLR by consequence type is then inherited by the Census blocks and Census tracts within the county.

23.8 Expected Annual Loss

Once exposure, frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in *Equation 136*. Performing the base calculations once at the Census block level and aggregating up allows for the most detailed and accurate estimation of EAL at higher levels.

Equation 136: Census Block Expected Annual Loss to Winter Weather

$$EAL_{WNTW_{CB_{Bldg}}} = Exposure_{WNTW_{CB_{Bldg}}} \times Freq_{WNTW_{CB}} \times HLR_{WNTW_{CB_{Bldg}}}$$

$$EAL_{WNTW_{CB_{Pop}}} = Exposure_{WNTW_{CB_{Pop}}} \times Freq_{WNTW_{CB}} \times HLR_{WNTW_{CB_{Pop}}}$$

where:

$EAL_{WNTW_{CB_{Bldg}}}$ is the Expected Annual Loss to building value due to Winter Weather events for a specific Census block (in dollars).

$Exposure_{WNTW_{CB_{Bldg}}}$ is the building value exposed to Winter Weather events in the Census block (in dollars).

$Freq_{WNTW_{CB}}$ is the annualized Winter Weather frequency for the Census block (event-days per year).

$HLR_{WNTW_{CB_{Bldg}}}$ is the Bayesian-adjusted building Historic Loss Ratio for Winter Weather for the Census block.

$EAL_{WNTW_{CB_{Pop}}}$ is the Expected Annual Loss to population value due to Winter Weather events for a specific Census block (in dollars).

$Exposure_{WNTW_{CB_{Pop}}}$ is the population value exposed to Winter Weather events in the Census block (in dollars).

$HLR_{WNTW_{CB_{Pop}}}$ is the Bayesian-adjusted population Historic Loss Ratio for Winter Weather or the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated values of the building and population loss at the Census block level as in *Equation 137*.

Equation 137: Census Tract and County Expected Annual Loss to Winter Weather

$$EAL_{WNTW_{CT}} = \sum_{CB}^{CT} EAL_{WNTW_{CB_{Bldg}}} + \sum_{CB}^{CT} EAL_{WNTW_{CB_{Pop}}}$$

$$EAL_{WNTW_{Co}} = \sum_{CB}^{Co} EAL_{WNTW_{CB_{Bldg}}} + \sum_{CB}^{Co} EAL_{WNTW_{CB_{Pop}}}$$

where:

$EAL_{WNTW_{CT}}$	is the total Expected Annual Loss due to Winter Weather events for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{WNTW_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Winter Weather events for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{WNTW_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Winter Weather events for all Census blocks in the Census tract (in dollars).
$EAL_{WNTW_{Co}}$	is the total Expected Annual Loss due to Winter Weather events for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{WNTW_{CB_{Bldg}}}$	is the summed Expected Annual Loss to building value due to Winter Weather events for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{WNTW_{CB_{Pop}}}$	is the summed Expected Annual Loss to population value due to Winter Weather events for all Census blocks in the county (in dollars).

Figure 158 shows the total EAL (population and building value combined) to Winter Weather events.

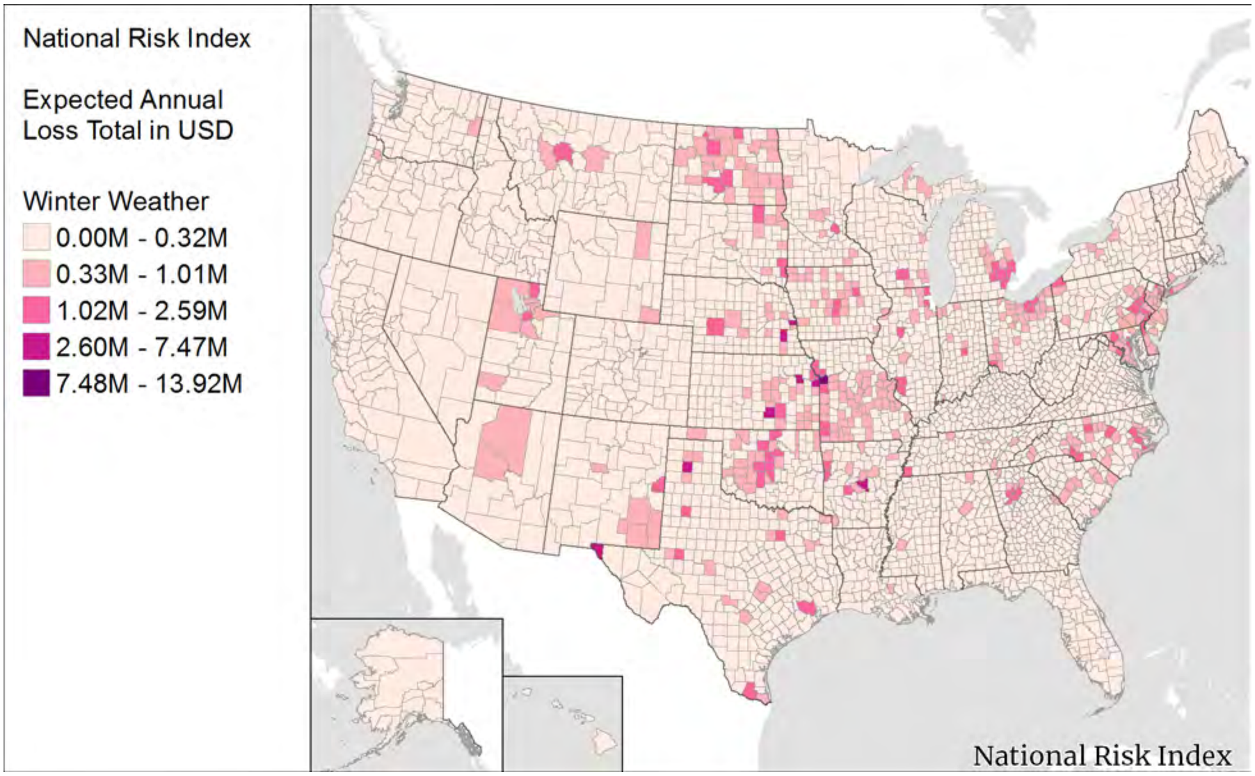

Figure 158: Total Expected Annual Loss by County to Winter Weather

With the Winter Weather total EAL value computed for each Census tract and county, the companion EAL score is computed (see *Section 3.2*). The EAL score is a normalized value that describes the relative position of a specific Census tract or county among its national counterparts. For each Census tract and county, the EAL score is multiplied by its Social Vulnerability score and divided by its Community Resilience score to produce the Winter Weather Risk Index score.

Appendix A – Contributors

Multiple entities contributed to the development of the NRI by providing domain expertise and/or data.

Contributor	Description	Expertise / Source Data
Argonne National Laboratory	Argonne National Laboratory is a multidisciplinary science and engineering research center that seeks to answer the biggest questions facing humanity, from how to obtain affordable clean energy to protecting ourselves and our environment.	Natural Hazards Expertise
ASU Arizona State University	Arizona State University's Center for Emergency Management and Homeland Security (CEMHS) is a university-wide interdisciplinary hub for the research and practice of emergency management and homeland security.	Hazard Loss Source Data
California Department of Conservation	The California Department of Conservation administers a variety of programs vital to California's public safety, environment, and economy.	Tsunami Source Data
The Great Seal of the State of California	The California Geological Survey's mission is to provide scientific products and services about the state's geology, seismology, and mineral resources.	Tsunami Source Data
Cal OES Governor's Office of Emergency Services	The California Office of Emergency Services takes a proactive approach to addressing the risks, threats, and vulnerabilities of California's people, property, economy, and environment.	Tsunami Source Data
Augusta Georgia	City of Augusta, Georgia	Natural Hazards Expertise
Colorado Avalanche Information Center	The Colorado Avalanche Information Center is a part of the Colorado Geological Survey and provides Avalanche-safety classes and issues forecasts of Avalanche and mountain weather conditions.	Avalanche Source Data

Contributor	Description	Expertise / Source Data
Community & Regional Resilience Institute	The Community and Regional Resilience Institute (CARRI) is an organization that assists communities across the nation with understanding their strengths and vulnerabilities, taking positive collection actions to limit the impact of disruptive crisis, and providing guidance to communities recovering from disasters.	Community Resilience and Social Vulnerability Expertise
Compass Identify, Interpret, Integrate	Compass PTS is a joint venture that provides architectural and engineering technical services. It includes ABS Consulting, AECOM, CDM Smith, Inc., and FACTOR, Inc., as well as other companies who were not directly involved with the NRI.	Natural Hazards; Risk; User Experience Design; Software Development; Data Processing
CoreLogic	CoreLogic provides information intelligence to identify and manage growth opportunities, improve business performance, and manage risk. Its flood services include flood determinations, flood portfolio servicing, natural hazard reports, and flood insurance coverage analyses.	Riverine Flooding Source Data
Coulbourne Consulting	Coulbourne Consulting is a structural engineering consulting firm specializing in solutions to natural hazard-caused problems from high wind and flood events, including Hurricanes, storm surges, Riverine Floods, and Tornadoes.	Natural Hazards Expertise
FACTOR	FACTOR delivers essential expertise to clients enabling them to better manage the risks inherent in their operations. They apply advanced methodologies, technology, and data analysis to support risk-based decision making and create competitive advantage for their clients.	Data and Methods
FEMA	The Federal Emergency Management Agency is a federal agency responsible for helping people before, during, and after disasters.	Natural Hazards Expertise; Built Environment Source Data; Riverine Flooding Source Data

Contributor	Description	Expertise / Source Data
FLASH FEDERAL ALLIANCE FOR SAFE HOMES	The Federal Alliance for Safe Homes (FLASH) is a consumer advocate that promotes safety, property protection, and resiliency by empowering the community with knowledge and resources for strengthening homes and safeguarding families from natural and manmade disasters.	Natural Hazards Expertise
HINMAN	Hinman Consulting is a consulting group of engineers and technical experts who offer a full range of services, from risk management to engineering design.	Natural Hazards Expertise
HDX	The Humanitarian Data Exchange (HDX), managed by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA)'s Centre for Humanitarian Data, is an open platform for sharing data across crises and organizations.	Volcanic Activity Source Data
INL Idaho National Laboratory 70 YEARS OF SCIENCE & INNOVATION	Idaho National Laboratory (INL) is one of the national laboratories of the United States Department of Energy.	Community Resilience and Social Vulnerability Expertise
Insurance Institute for Business & Home Safety	The Insurance Institute for Business and Home Safety (IBHS) is an independent, nonprofit, scientific research and communications organization of property insurers and reinsurers that conducts objective research to identify and promote the most effective ways to strengthen homes, businesses, and communities against natural hazard disasters and other causes of loss.	Natural Hazards Expertise
IOWA STATE UNIVERSITY	The Iowa Environmental Mesonet of Iowa State University collects environmental data from cooperating members with observing networks, and stores and makes the data publicly available.	Cold Wave, Heat Wave, Winter Weather Source Data
LSU LOUISIANA STATE UNIVERSITY	Louisiana State University is a public research university located in Baton Rouge, Louisiana.	Natural Hazards Expertise

Contributor	Description	Expertise / Source Data
NASA	The Open Data Portal of the National Aeronautics and Space Administration (NASA) is supported by NASA's Innovation Team, which is part of NASA's Office of the Chief Information Officer in the Technology, Data & Innovation Division. The Open Data Portal supports NASA's pursuit to make its data and information resources accessible, discoverable, and usable by the public to fuel entrepreneurship, innovation, and scientific discovery.	Landslide Source Data
National Drought Mitigation Center · University of Nebraska · NDMC	The National Drought Mitigation Center (NMDC) at the University of Nebraska-Lincoln helps people and institutions develop and implement measures to reduce societal vulnerability to Drought, stressing preparedness and risk management rather than crisis management.	Drought Source Data
nehrp	The National Earthquake Hazards Reduction Program (NEHRP) was established by the U.S. Congress to reduce the risks of life and property from future Earthquakes in the United States through the establishment and maintenance of an effective Earthquake hazards reduction program. Four primary agencies contribute to the program's mitigation efforts: FEMA, National Institute of Standards and Technology (NIST), National Science Foundation (NSF), and USGS.	Earthquake Source Data
NIST National Institute of Standards and Technology U.S. Department of Commerce	The National Institute of Standards and Technology (NIST) is a physical science and measurement standards laboratory with programs in Nanoscale Science and Technology, Engineering, Information Technology, Neutron Research, Material Measurement, and Physical Measurement, and a mission to promote innovation and industrial competitiveness.	Natural Hazards Expertise
NHMA Natural Hazard Mitigation Association	The Natural Hazard Mitigation Association (NHMA) is a professional association that promotes reducing the risk and consequences of natural hazard events with a special emphasis on protecting the most vulnerable populations in our communities.	Natural Hazards Expertise

Contributor	Description	Expertise / Source Data
	The National Oceanic and Atmospheric Administration (NOAA) is a federal agency that provides scientific products and services to understand the earth's changing environment, share its knowledge, and conserve and manage coastal and marine ecosystems and resources. It includes the NWS, National Climatic Data Center (NCDC), Office for Coastal Management (OCM), SPC, NHC, and NCEI.	Natural Hazards Expertise; Coastal Flooding, Cold Wave, Hail, Heat Wave, Hurricane, Lightning, Strong Wind, Tornado, Winter Weather Source Data
	Old Dominion University is a public research university in Norfolk, Virginia.	Data and Methods, Natural Hazards Expertise
	The Oregon Department of Geology and Mineral Resources seeks to increase understanding of Oregon's geologic resources and hazards through science and stewardship.	Tsunami Source Data
	Pacific Disaster Center is an applied science, information, and technology center working to reduce disaster risks and impacts on life, property, and economies worldwide.	Natural Hazard Expertise
	Poland Consultants is a consulting practice that specializes in Earthquake engineering, disaster resilience, and related research and development.	Natural Hazards Expertise
	The Polis Center at Indiana University-Purdue University Indianapolis (IUPUI) is a collaborative, applied research center that specializes in community-based research and analysis and advanced information technologies to build understanding of community issues from a variety of perspectives.	Community Resilience Expertise; Social Vulnerability Expertise

Contributor	Description	Expertise / Source Data
resilienceaction partners A JOINT VENTURE OF OGILVY PUBLIC RELATIONS & MICHAEL BAKER INTERNATIONAL	Resilience Action Partners is a joint venture between Ogilvy and Michael Baker International that offers holistic approaches to achieving community resilience through the combination of expertise in risk communications, stakeholder engagement, behavior change, mitigation, risk reduction, and community planning.	Data and Methods, Natural Hazards Expertise
Smithsonian Institution *National Museum of Natural History* Global Volcanism Program	The mission of the Smithsonian Institution's Global Volcanism Program is to document, understand, and disseminate information about global volcanic activity.	Volcanic Activity Source Data
SSEC	The Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison develops and utilizes space-, aircraft-, and ground-based instrumentation to collect and analyze observations of the Earth's atmosphere, oceans, land surface, and other planetary atmospheres to improve our understanding of weather, climate, and atmospheric processes.	Natural Hazards Expertise
State of Hawaii 1959	The State of Hawaii Office of Planning GIS Program leads a multi-agency effort to establish, promote, and coordinate the use of geographic information systems (GIS) technology among Hawaii state government agencies.	Tsunami Source Data
STARR II Strategic Alliance for Risk Reduction	STARR II (Strategic Alliance for Risk Reduction) is a joint venture comprised of three leaders in DFIRM mapping, risk assessment, risk communication, and mitigation planning. It includes Atkins Global, Dewberry, and Stantec.	Natural Hazards Expertise
Swiss Re	Swiss Re is a wholesale provider of reinsurance, insurance, and other insurance-based forms of risk transfer.	Natural Hazards Expertise
Tsunami Research Center	The Tsunami Research Center of the University of Southern California (USC) is actively involved with all aspects of tsunami research, including field surveys, numerical and analytical modeling, and hazard assessment, mitigation, and planning.	Tsunami Source Data

Contributor	Description	Expertise / Source Data
URBAN INSTITUTE ELEVATE THE DEBATE	Urban Institute is a nonprofit research organization that provides unbiased, authoritative insight to inform consequential choices about the well-being of people and places in the US. Their experts diagnose current challenges and look ahead to identify opportunities for change, and help stakeholders develop solutions and strategies to address concerns and remove roadblocks.	Community Resilience and Social Vulnerability Expertise
	The U.S. Army Corps of Engineers is a federal agency made up of approximately 37,000 civilian and military personnel who deliver engineering services to customers in more than 130 countries worldwide. With environmental sustainability as a guiding principle, USACE works to strengthen our Nation's security by building and maintaining America's infrastructure and provide military facilities for service members at home and abroad.	Ice Storm Source Data
FOREST SERVICE U S DEPARTMENT AGRICULTURE	The U.S. Forest Service is a multi-faceted federal agency that cares for the nation's forests and grasslands, and serves communities through research, technical support, and financial assistance to sustain the healthy, diversity, and productivity of the nation's lands.	Wildfire Source Data, Avalanche Source Data
USGS science for a changing world	The U.S. Geological Survey (USGS) is a federal agency that provides new scientific methods and tools to enable timely, relevant, and useful information about the Earth and its processes.	Natural Hazards Expertise; Landslide and Earthquake Source Data
UNISDR United Nations Office for Disaster Risk Reduction	The United Nations Office for Disaster Risk Reduction (UNISDR) is an organizational unit of the UN Secretariat that serves as the focal point in the UN system for the coordination of disaster reduction and to ensure synergies among disaster reduction activities.	Volcanic Activity Source Data
UAF UNIVERSITY OF ALASKA FAIRBANKS ALASKA EARTHQUAKE CENTER	The Alaska Earthquake Center of the University of Alaska – Fairbanks is dedicated to reducing the impacts of earthquakes, tsunamis, and volcanic eruptions in Alaska.	Tsunami Source Data

Contributor	Description	Expertise / Source Data
University of Colorado Boulder	The University of Colorado – Boulder is a public research university located in Boulder, Colorado.	Community Resilience and Social Vulnerability Expertise
University of Colorado Denver	The University of Colorado – Denver is a public research university located in Denver, Colorado.	Natural Hazards Source Data
University of Idaho	The University of Idaho is a public research university located in Moscow, Idaho.	Natural Hazards Expertise
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN	The Wind Engineering Laboratory at the University of Illinois at Urbana-Champaign is a research laboratory that focuses on developing technologies and physical resources necessary to extend current understanding of windstorm hazards and their impacts on structures.	Natural Hazards Expertise
M UNIVERSITY OF MICHIGAN	The University of Michigan is a public research university located in Ann Arbor, Michigan.	Natural Hazards Expertise
M	The University of Missouri is a public research university located in Columbia, Missouri.	Community Resilience Expertise; Social Vulnerability Expertise
W	Waggonner and Ball Architects is an architectural and planning firm that provides a variety of architectural services, including facility assessment, programming site planning, schematic design, design development, and more.	Natural Hazards Expertise
WASHINGTON DEPARTMENT OF NATURAL RESOURCES	The mission of the Washington State Department of Natural Resources is to manage, sustain, and protect the health and productivity of Washington's lands and waters to meet the needs of present and future generations.	Tsunami Source Data

Contributor	Description	Expertise / Source Data
WATER WORKS	Water Works is a low-profit LLC dedicated to building resilience and reducing risk from flooding, pollution, and natural hazards by contributing to community-driven solutions through a mix of consulting, research, and pro bono projects.	Natural Hazards Expertise
Wildfire Planning International	Wildfire Planning International works with communities across the United States and Canada to make informed decisions in Wildfire planning and help reduce risk in the wildland-urban interface through consulting services for a wide-ranging customer base.	Natural Hazards Expertise

Appendix B – Hazard Data Characteristics Comparison

Table 70: Avalanche Hazard Characteristics

Hazard	Avalanche
Consequence Types	Population, Property
Frequency Data Source	SHELDUS
Frequency Period of Record	1960-2016
Exposure Extent Data Source	Default exposure values
Exposure Type	Default exposure values
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, National

Table 71: Coastal Flooding Hazard Characteristics

Hazard	Coastal Flooding
Consequence Types	Population, Property
Frequency Data Source	FEMA, NFIP National Flood Hazard Layer (SFHA 100- & 500-Year); NOAA, OCM Flood Frequency and Sea Level Rise Data; NOAA, NHC SLOSH Model Data
Frequency Period of Record	Not applicable; frequency modeled on each layer's frequency and exposure area
Exposure Extent Data Source	FEMA, NFIP National Flood Hazard Layer (SFHA 100- & 500-Year); NOAA, OCM Flood Frequency and Sea Level Rise Data; NOAA, NHC SLOSH Model Data
Exposure Type	Total building value/population of developed areas
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, Surrounding, Regional

Table 72: Cold Wave Hazard Characteristics

Hazard	Cold Wave
Consequence Types	Population, Property, Agriculture
Frequency Data Source	Iowa Environmental Mesonet
Frequency Period of Record	2005-2017
Exposure Extent Data Source	Iowa Environmental Mesonet
Exposure Type	Developed area density applied to area of the average hazard event
Historic Loss Data Source	NWS Storm Events Database
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 73: Drought Hazard Characteristics

Hazard	Drought
Consequence Types	Agriculture
Frequency Data Source	U.S. Drought Monitor
Frequency Period of Record	2000-2017
Exposure Extent Data Source	U.S. Drought Monitor
Exposure Type	Agriculture value density applied to area of the average hazard event
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional

Table 74: Earthquake Hazard Characteristics

Hazard	Earthquake
Consequence Types	Population, Property
Frequency Data Source	USGS 100-Year Probability of Minor-Damage Earthquake Shaking
Frequency Period of Record	100-year probability
Exposure Extent Data Source	P-366 Hazus Study
Exposure Type	Building value and population exposure from P-366 Hazus
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1960-2016
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, Surrounding, National

Table 75: Hail Hazard Characteristics

Hazard	Hail
Consequence Types	Population, Property, Agriculture
Frequency Data Source	NOAA, SPC Severe Weather Database
Frequency Period of Record	1986-2017
Exposure Extent Data Source	Total county value
Exposure Type	Total building value, population, and agriculture value
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 76: Heat Wave Hazard Characteristics

Hazard	Heat Wave
Consequence Types	Population, Property
Frequency Data Source	Iowa Environmental Mesonet
Frequency Period of Record	2005-2017
Exposure Extent Data Source	Iowa Environmental Mesonet
Exposure Type	Developed area density applied to area of the average hazard event
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional

Table 77: Hurricane Hazard Characteristics

Hazard	Hurricane
Consequence Types	Population, Property
Frequency Data Source	NOAA, NHC HURDAT2 Best Track Data
Frequency Period of Record	Atlantic: 1851-2017; Pacific: 1949-2017
Exposure Extent Data Source	NOAA HURDAT2 Best Track Data
Exposure Type	Developed area density applied to area of the average hazard event
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional

Table 78: Ice Storm Hazard Characteristics

Hazard	Ice Storm
Consequence Types	Population, Property
Frequency Data Source	USACE, CRREL Damaging Ice Storm GIS
Frequency Period of Record	1946-2014
Exposure Extent Data Source	USACE CRREL Damaging Ice Storm GIS
Exposure Type	Developed area density applied to area of the average hazard event
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 79: Landslide Hazard Characteristics

Hazard	Landslide
Consequence Types	Population, Property
Frequency Data Source	NASA Global Landslide Catalog
Frequency Period of Record	2010-2018
Exposure Extent Data Source	USGS Landslide Hazard Map
Exposure Type	Developed area density applied to Landslide susceptible areas
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	No, but default loss values are inserted for susceptible counties with no past hazard events
Bayesian Weighting Levels	None, HLR is a county average

Table 80: Lightning Hazard Characteristics

Hazard	Lightning
Consequence Types	Population, Property
Frequency Data Source	NOAA, NCEI Cloud-to-Ground Lightning Strikes
Frequency Period of Record	1991-2012
Exposure Extent Data Source	Total county value
Exposure Type	Total building value and population
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2012
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, National

Table 81: Riverine Flooding Hazard Characteristics

Hazard	Riverine Flooding
Consequence Types	Population, Property, Agriculture
Frequency Data Source	NWS Storm Events Database
Frequency Period of Record	1995-2016
Exposure Extent Data Source	FEMA, NFIP National Flood Hazard Layer (SFHA 100-Year Floodplain)
Exposure Type	Developed area density applied to the floodplain area
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, National

Table 82: Strong Wind Hazard Characteristics

Hazard	Strong Wind
Consequence Types	Population, Property, Agriculture
Frequency Data Source	NOAA, SPC Severe Weather Database
Frequency Period of Record	1986-2017
Exposure Extent Data Source	Total county value
Exposure Type	Total building value, population, and agriculture value
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 83: Tornado Hazard Characteristics

Hazard	Tornado
Consequence Types	Population, Property
Frequency Data Source	NOAA, SPC Severe Weather Database
Frequency Period of Record	1986-2017
Exposure Extent Data Source	Average impact area (2 sq. km)
Exposure Type	Average density applied to the average area of hazard impact
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 84: Tsunami Hazard Characteristics

Hazard	Tsunami
Consequence Types	Population, Property
Frequency Data Source	NOAA, NCEI Global Historical Tsunami Runup Data
Frequency Period of Record	1800-2018
Exposure Extent Data Source	Tsunami Inundation or Evacuation Zones from Alaska, California, Hawaii, Oregon, and Washington
Exposure Type	Developed area density applied to developed areas within the inundation zones
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 85: Volcanic Activity Hazard Characteristics

Hazard	Volcanic Activity
Consequence Types	Population, Property
Frequency Data Source	Smithsonian Institution Volcanoes of the World
Frequency Period of Record	9310 BCE-2018
Exposure Extent Data Source	UN Office for Disaster Reduction Volcano-Population Exposure Index
Exposure Type	Developed area density applied to areas exposed to possible Volcanic eruption
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1960-2016
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, Surrounding, National

Table 86: Wildfire Hazard Characteristics

Hazard	Wildfire
Consequence Types	Population, Property
Frequency Data Source	USDA, Forest Service Fsim Burn Probability and Fire Intensity Level Data
Frequency Period of Record	Annualized probability
Exposure Extent Data Source	USDA, Forest Service Fsim Burn Probability and Fire Intensity Level Data
Exposure Type	Average density applied to Wildfire susceptible areas
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, Surrounding, National

Table 87: Winter Weather Hazard Characteristics

Hazard	Winter Weather
Consequence Types	Population, Property
Frequency Data Source	Iowa Environmental Mesonet
Frequency Period of Record	2005-2017
Exposure Extent Data Source	Iowa Environmental Mesonet
Exposure Type	Developed area density applied to area of the average hazard event
Historic Loss Data Source	SHELDUS
Historic Loss Period of Record	1995-2016
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional

Appendix C – Mesonet-NWS Weather Event Attribute Description

Table 88: Mesonet-NWS Weather Event Attribute Descriptions

Attribute	Description
WFO	Three letter ID for issuing Weather Forecast Office
ISSUED	String representing product initial valid UTC timestamp YYYYMMDDHHMM
EXPIRED	String representing product expiration, this is not the original product expiration, but the actual time the product was no longer valid. For example, the product could have been extended in time or cancelled.
INIT_ISS	String representing the issuance time of the product UTC timestamp YYYYMMDDHHMM
INIT_EXP	String representing the initial time of the product expiration UTC timestamp YYYYMMDDHHMM
PHENOM	VTEC phenomena code. Ex) SV == Severe Thunderstorm, TO == Tornado
GTYPE	Geographical type of polygon. C == County, P == Polygon
SIG	VTEC significance. Ex) A == Watch, W == Warning
ETN	VTEC Event Tracking Number
STATUS	The three-character code for the VTEC status field. (i.e., EXP, CAN, NEW. For the case of polygons of GTYPE='P'(Storm Based Warnings), the STATUS code is always NEW. For all other cases, this STATUS is the last status parsed for the associated WWA product.
NWS_UGC	NWS code used for a zone of a county
AREA_KM2	Area of the geometry in sq. kilometers (Projection: EPSG 2163)

Appendix D – Fishnet Event Count

Table 89: Sample Historic Fishnet Hazard Event/Event-Day Count Data

Fishnet49kmID	NumberHailDays	NumberHurricane Events	NumberIceStormDays	NumberTornado Events	NumberWindDays
170	1	39	0	14	5
171	1	41	0	17	8
172	1	36	0	24	8

For widespread hazards that can occur anywhere within a county, a historic event or event-day count is performed at the level of a 49-by-49-km fishnet grid cell (see *Table 89*), which is then intersected with the Census block, tract, or county to estimate frequency. If a Census block, tract, or county intersects multiple fishnet grid cells (see *Figure 159*), an area-weighted average count is calculated. For example, the reference Census block below is intersected by four fishnet cells, each of which intersects a different count of hazard event (or event-day) polygons. The hazard event count for this Census block would be calculated according to *Equation 138* and aggregated to the Census tract and county levels according to *Equation 139*.

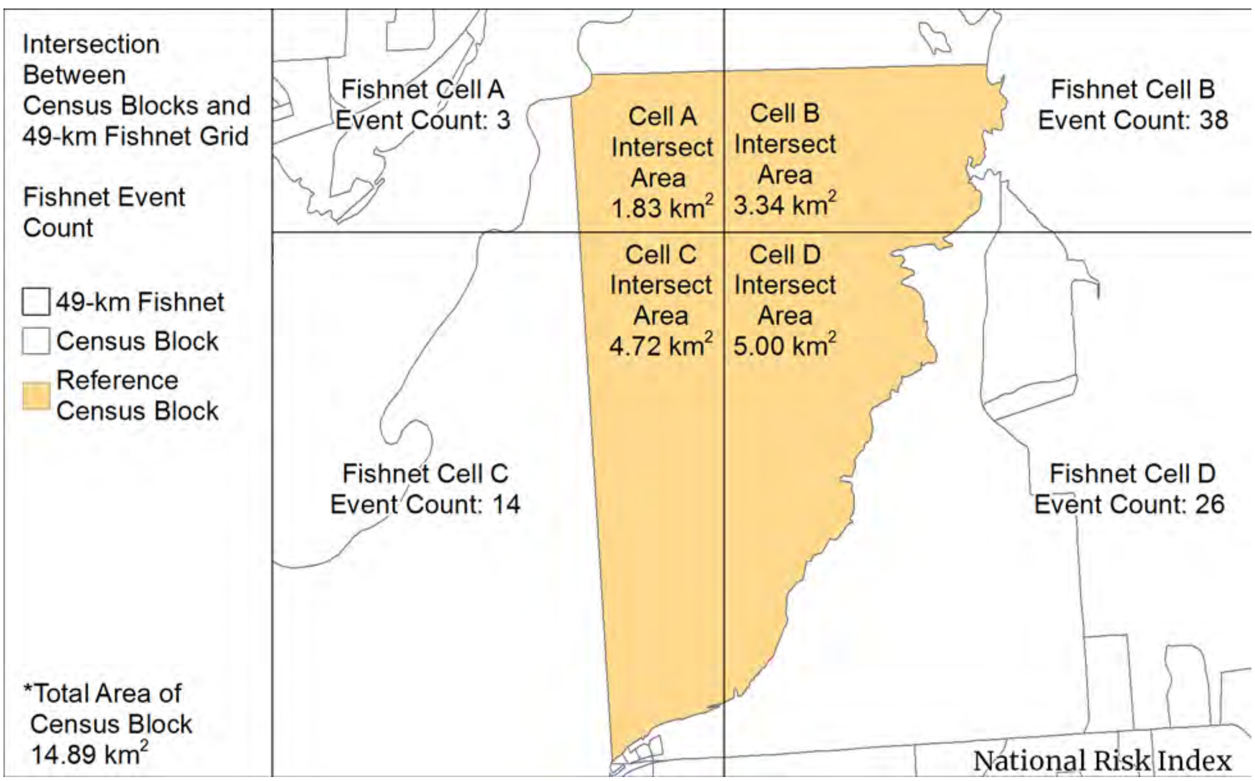

Figure 159: Intersection Between Census Blocks and 49-by-49 km Fishnet Grid

Equation 138: Census Block Area-Weighted Fishnet Event Count

$$EventCount_{Hazard_{CB}} = \frac{\sum_{Fish}^{CB}\left(EventCount_{Hazard_{Fish}} \times IntsctArea_{CB_{Fish}}\right)}{Area_{CB}}$$

where:

$EventCount_{Hazard_{CB}}$	is the number of hazard events (or event-days) calculated for a specific Census block.
$EventCount_{Hazard_{Fish}}$	is the number of hazard events (or event-days) calculated for the fishnet grid cell.
$IntsctArea_{CB_{Fish}}$	is the intersected area of the Census block with a specific fishnet grid cell (in square kilometers).
$\sum_{Fish}^{CB}$	is the sum for all fishnet grid cells that intersect the Census block.
$Area_{CB}$	is the total area of the Census block (in square kilometers).

Equation 139: Census Tract and County Area-Weighted Fishnet Event Count

$$EventCount_{Hazard_{CT}} = \frac{\sum_{CB}^{CT}\left(IntsctArea_{CB_{Fish}} \times EventCount_{Hazard_{Fish}}\right)}{Area_{CT}}$$

$$EventCount_{Hazard_{Co}} = \frac{\sum_{CB}^{Co}\left(IntsctArea_{CB_{Fish}} \times EventCount_{Hazard_{Fish}}\right)}{Area_{Co}}$$

where:

$EventCount_{Hazard_{CT}}$	is the count of hazard events (or event-days) calculated for a specific Census tract.
$IntsctArea_{CB_{Fish}}$	is the intersected area of a specific fishnet grid cell with a specific Census block (in square kilometers).
$EventCount_{Hazard_{Fish}}$	is the count of hazard events (or event-days) calculated for the fishnet grid cell.
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$Area_{CT}$	is the total area of the Census tract (in square kilometers).

$EventCount_{Hazard_{Co}}$	is the count of hazard events (or event-days) calculated for a specific county.
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).