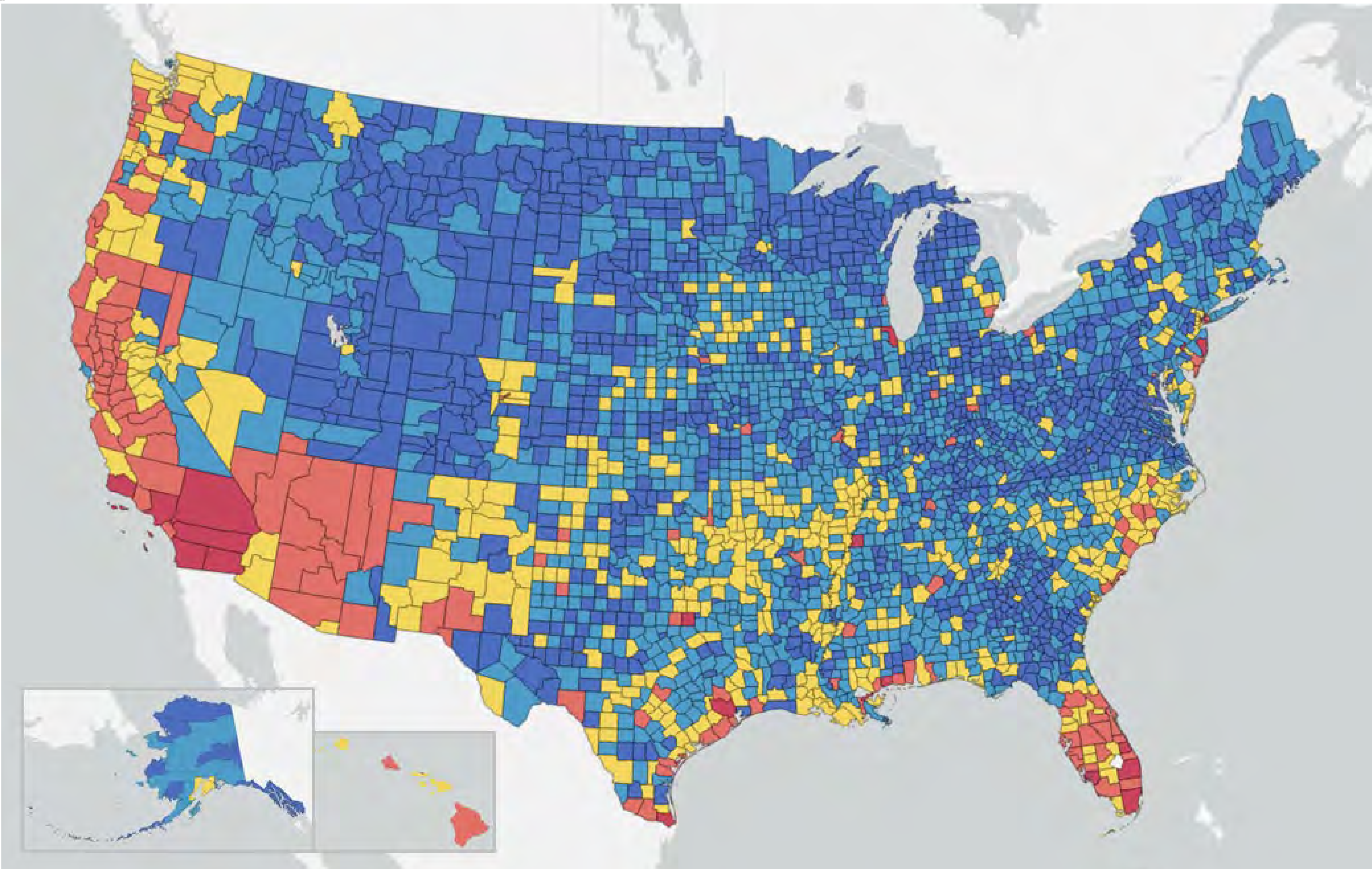

National Risk Index

Technical Documentation

July 2021

FEMA

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Acronym List

AEL	Annualized Earthquake Loss
AIANNH	American Indian/Alaska Native/Native Hawaiian
ASCE	American Society of Civil Engineers
BIA	Bureau of Indian Affairs
BP	Burn Probability
BRIC	Baseline Resilience Indicators for Communities
CARRI	Community and Regional Resilience Institute
CEMHS	Arizona State University's Center for Emergency Management and Homeland Security
COOLR	Cooperative Open Online Landslide Repository
CRREL	U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory
EAL	Expected Annual Loss NEPA National Environmental Policy Act
EC	Extreme Cold
EF-	Enhanced Fujita Scale
EH	Excessive Heat
F-	Fujita Scale
FEMA	Federal Emergency Management Agency
FIL	Fire Intensity Level
FIRM	Flood Insurance Rate Map
FLASH	Federal Alliance for Safe Homes
FSim	Fire Simulation
GIS	Geographic Information Systems
GVM	Global Volcano Model

HDX	Humanitarian Data Exchange
HHL	Hawaiian home lands
HIFLD	Homeland Infrastructure Foundation-Level Data
HLR	Historic Loss Ratio
HTF	High Tide Flooding
HVRI	University of South Carolina's Hazards and Vulnerability Research Institute
IBHS	Insurance Institute for Business and Home Safety
INL	Idaho National Laboratory
IUPUI	Indiana University-Purdue University Indianapolis
LAR	Land Area Representation
LRB	Loss Ratio per Basis
MAF	Minimum Annual Frequency
MHHW	Mean Higher High Water
MOM	Maximum of the Maximum
NAC	National Avalanche Center
NASA	National Aeronautics and Space Administration
NCEI	National Centers for Environmental Information
NDMC	University of Nebraska-Lincoln National Drought Mitigation Center
NEHRP	National Earthquake Hazards Reduction Program
NFHL	National Flood Hazard Layer
NHC	National Hurricane Center
NHMA	Natural Hazard Mitigation Association
NHRAP	Natural Hazards Risk Assessment Program
NIST	National Institute of Standards and Technology

NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRI	National Risk Index
NWS	National Weather Service
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
OCM	Office for Coastal Management
SFHA	Special Flood Hazard Areas
SHELDUS	Spatial Hazard Events & Losses Database for the United States
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SLR	Sea Level Rise
SLRHT	Sea Level Rise and High Tide
SoVI	Social Vulnerability Index
SPC	Storm Prediction Center
SSEC	Space Science and Engineering Center
STARR II	Strategic Alliance for Risk Reduction
TSA	Tribal Statistical Area
UNISDR	United Nations Office for Disaster Risk Reduction
USACE	U.S. Army Corps of Engineers
USC	University of South Carolina
USD	U.S. dollars
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VSL	Value of Statistical Life
VTEC	Valid Time Extent Code

WC	Wind Chill
WCM	Warning Coordination Meteorologist
WWA	Watch, Warnings, and Advisories

1. Introduction

The National Risk Index is a dataset and online tool to help illustrate the U.S. communities most at risk for 18 natural hazards. It was designed and built by FEMA in close collaboration with various stakeholders and partners in academia; local, state and federal government; and private industry. The Risk Index leverages available source data for natural hazard and community risk factors to develop a baseline relative risk measurement for each U.S. county and Census tract. The National Risk Index is intended to help users better understand the natural hazard risk of their communities. 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 documentation provides a detailed overview of the National Risk Index, including its background, data sources, and processing methodologies. It describes the concepts used to develop the National Risk Index and calculate its components. The methodologies for computing each hazard type's Expected Annual Loss (EAL) are also explained in depth in the sections for each hazard type (Sections 6 through 23).

Note: This document is specific to the July 2021 release (version 1.18.0).

2. Background

All communities in the U.S. 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 National Risk Index 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 dataset, and then researched, designed, and built the website and application.

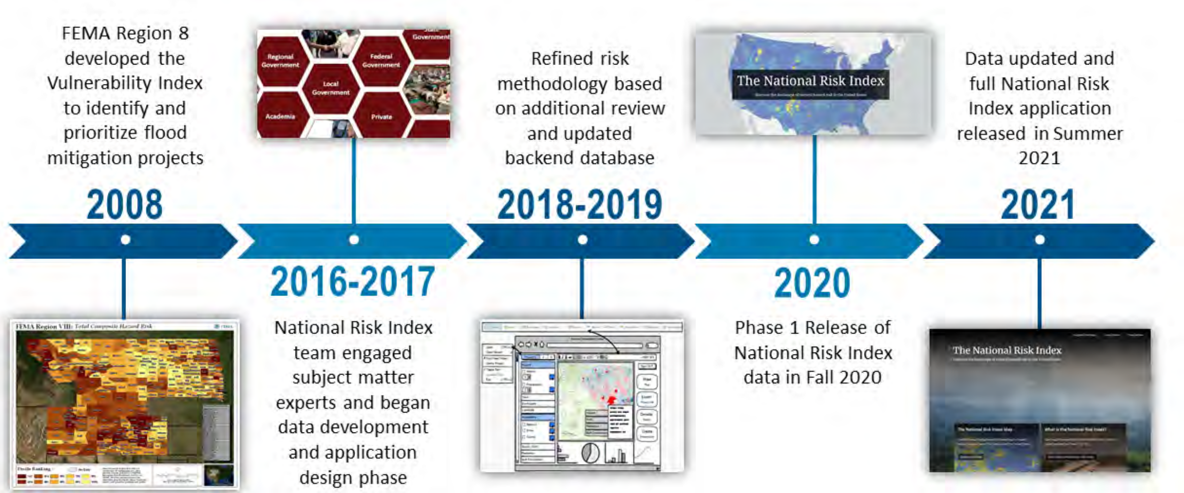

Figure 1: Timeline of the Development of the National Risk Index

The National Risk Index 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 National Risk Index. 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 hazard types.

2.1. Natural Hazard Selection

A community's susceptibility to natural hazards varies from location to location. The 18 hazard types evaluated by the National Risk Index were chosen after reviewing FEMA-approved State Hazard Mitigation Plans for all 50 states in early 2016. 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 hazard types 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 (see Figure 2). A regionally significant hazard is defined as having the capacity to cause widespread, catastrophic damage, such as Hurricane, 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 as there was no reliable, nationwide dataset cataloging this type of hazard occurrence.

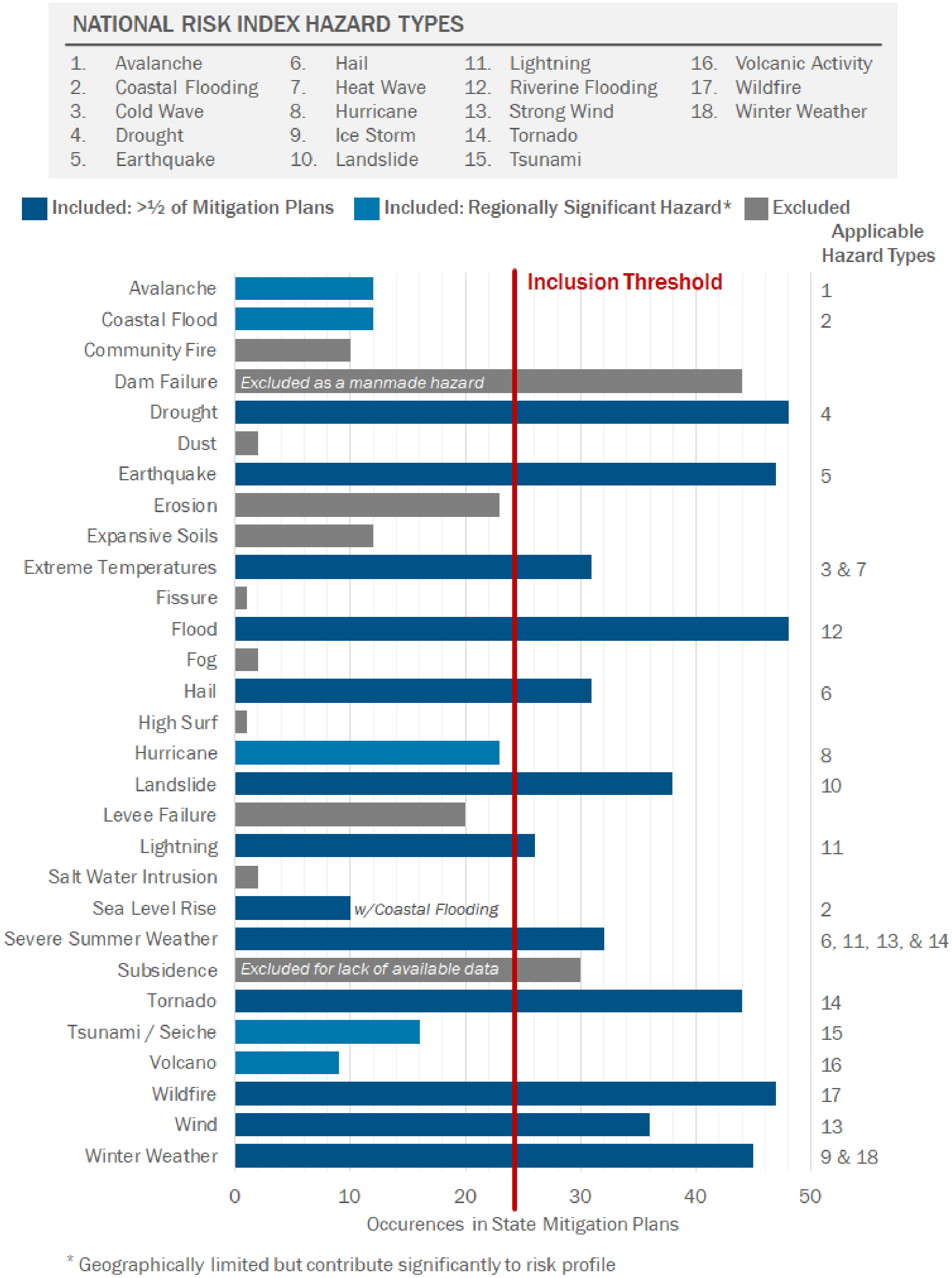

Figure 2: Determination of Hazard Inclusion Based on State Hazard Mitigation Plans from January 2016

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 are not nationally or publicly available. A levee analysis may be incorporated into the riverine or coastal flooding 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.

2.2. Working Groups

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

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

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, resilience, or both) and which indices should be used. As a result, both Social Vulnerability and Community Resilience are components of the National Risk Index.

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 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 assessments 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	*Individual Risk Indicators*	
▪ Social	▪ Income	▪ Road Systems
▪ Economic	▪ Age	▪ Economic Productivity
▪ Environmental	▪ Illnesses	▪ Housing
▪ Infrastructure	▪ Hospitals	▪ Community Revenue

After review, the team concluded the National Risk Index 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 National Risk Index began in 2017 and proceeded through the end of 2019. Over this period, the National Risk Index Team continually iterated on their data processing and risk calculation methodologies, and engaged with subject matter experts throughout. See Appendix A – Contributors for the full list of organizations whose members contributed to the subject matter expert reviews and the development of the National Risk Index.

At major milestones, the team paused development to engage in broader, more comprehensive review periods by subject matter experts. The first major milestone arrived in January 2019, where teams of experts 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 experts provided feedback to the National Risk Index 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 National Risk Index Team continued iterating through improvements to data sourcing and processing. From July through September 2019, they conducted a final comprehensive subject matter expert review period to focus on the new Methodology's results. More than 40 experts participated in over 20 review sessions and helped the Team reach concurrence on the validity and value of the dataset. From these sessions, the National Risk Index 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 working groups concluded their work by reviewing and providing feedback on an iterative version of the National Risk Index dataset. The Phase 1 release made the National Risk Index data publicly available via FEMA's Hazards GeoPlatform in the fall of 2020. After this release, data and methodology enhancements were made for select risk factors and hazard types.

Briefly stated, the National Risk Index 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 Methodology is unique and carefully constructed to meet 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. Risk Calculation.

The National Risk Index's most important and central component, EAL, is a robust measurement that quantifies in dollars the anticipated economic damage resulting from natural hazards each year. Details of its equation and analytical techniques are available in Section 4.3. Expected Annual Loss. EAL consists of the best available datasets for 18 hazard types of national and regional significance, with source data being processed to match the unique nature of each hazard type. Full processing details for each hazard type 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. Social Vulnerability and Section 4.2. Community Resilience, respectively.

3. Risk Analysis Overview

Natural hazard 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 National Risk Index includes three components: a natural hazards risk 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 agriculture value each year due to natural hazards. Social Vulnerability is the consequence enhancing component and analyzes demographic characteristics to measure the susceptibility of 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 components are combined into one risk value using Equation 2.

Equation 2: Generalized National Risk Index Risk Equation

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

3.2. Scores and Ratings

In the risk equation, each component is represented by a unitless index score that depicts a community's score relative to all other communities at the same level. From the three scores in Equation 2, the composite Risk Index score is calculated to measure a community's risk to all 18 hazard types. The Risk Index score is also a unitless index and represents a community's relative risk in comparison to all other communities at the same level. The Risk Index score and EAL score are provided as both composite scores from the summation of all 18 hazard types, as well as scores where each specific hazard type is considered separately.

All calculations are performed separately at two levels—County and Census tract—so scores are relative only within their level. It must be stressed that scores are relative, representing a community's relative position among all other communities for a given component and level. 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 building 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 National Risk Index 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 communities 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 at the same level, 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 for a single hazard 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 at the same level.

To determine ratings, an unsupervised machine learning technique known as k-means clustering or natural breaks is applied to each score. This approach divides all communities into groups or clusters such that the communities within each cluster are as similar as possible (minimized variance or inertia) while the clusters are as different as possible (maximized variance).

K-means clustering for rating designation is performed in the National Risk Index processing database using the k-means clustering algorithm in the Python library scikit-learn.[1] The algorithm is initialized with the following parameters:

- Number of clusters (n_clusters): 5
- Maximum iterations (max_iter): 500
- Number of times the algorithm is run with different centroid seeds to arrive at the output with the least inertia (n_init): 20
- Relative tolerance in the cluster centers of consecutive iterations to declare convergence (tol): 1×10^{-15}
- Random number generation seed for centroid initialization (random_state): 42

All other parameters are defaults. The algorithm works by selecting five random initial scores, one for each cluster centroid, and then the rest of the scores are iteratively assigned to a cluster based on proximity to the centroid. Cluster centroids are updated in each iteration as the mean value of the scores within each cluster. The algorithm stops when it completes the maximum number of iterations or the centroid calculations converge within the established tolerance, whichever occurs

[1] See scikit-learn clustering documentation retrieved from https://scikit-learn.org/stable/modules/clustering.html#k-means.

first. The finalized cluster of the lowest scores is assigned the rating “Very Low,” the next lowest cluster receives a rating of “Relatively Low,” and so on.

In the 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). 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 standard color schemes are shown in Figure 3 with several illustrative examples of EAL, Social Vulnerability, Community Resilience, and risk scores and rating categories.

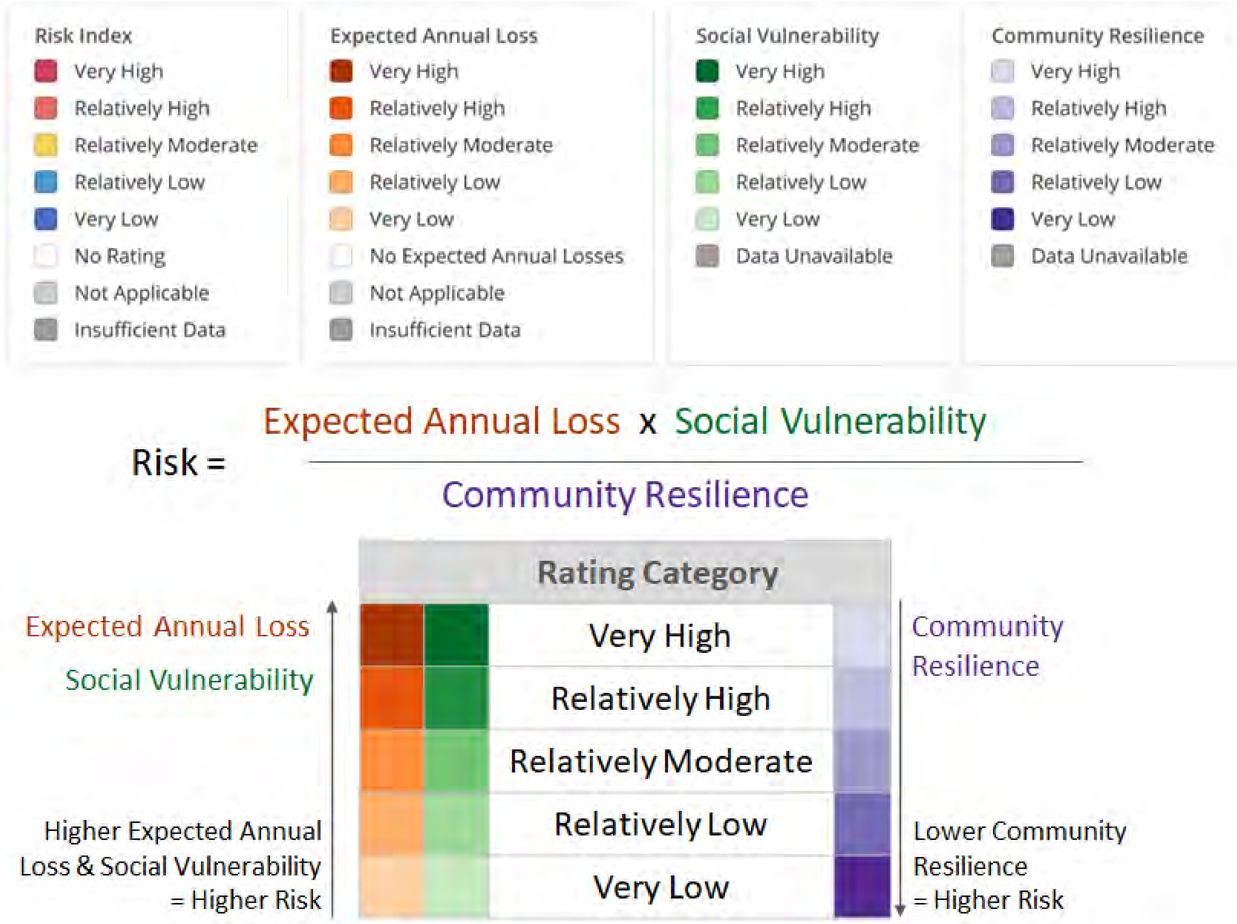

Illustration of Risk Component Scores

County	Expected Annual Loss	Social Vulnerability	Community Resilience	Risk
County 1	100	45	52	100
County 2	26	94	58	55
County 3	54	48	35	51
County 4	16	92	56	37
County 5	32	36	44	24
County 6	22	45	43	22
County 7	9	69	59	15
County 8	25	21	57	13
County 9	10	44	45	9
County 10	16	4	39	1

Figure 3: National Risk Index Qualitative Rating Legend and Illustration of Risk Component Scores

Scores of 0 (zero) or missing values ("nulls") in the EAL factors receive ratings that reflect the logic behind the score. A community where the EAL is zero either has no building value, population, or agriculture value exposed to the hazard type, or has a calculated annualized frequency of zero for the hazard type. These areas are displayed in the application as having "No Expected Annual Loss" for the designated hazard type.

In collaboration with subject matter experts most familiar with a hazard type and the source data, a priori definitions of hazard type applicability have also been applied to help distinguish between where no risk exists for the hazard type and where the hazard type is deemed not able to occur. For example, Avalanche EAL is not computed for areas with no mountainous terrain. These areas are displayed in the NRI application as "Not Applicable" for EAL computation for the designated hazard type.

Finally, if a factor used to calculate the EAL of a Census tract or county for a hazard type has a null value, the community is rated as "Insufficient Data." For example, certain hazard types, such as Wildfire, Lightning, and Landslide, only have source data used to determine annualized frequency or exposure available for the conterminous U.S., meaning that both Alaska and Hawaii are rated as "Insufficient Data" to compute the EAL for those hazard types. Census tracts and counties without Social Vulnerability or Community Resilience data are also given a Risk Index rating of "Insufficient Data." When a hazard type is not applicable or there are insufficient data for a community, EAL for that hazard type is simply not included in the community's final summation and scoring. A summary of non-numerical ratings is provided in Table 2.

Table 2: Definitions of Ratings without Numerical Scores

Rating	*Expected Annual Loss*	*Social Vulnerability*	*Community Resilience*	*Risk Index*
Not Applicable	Community is not considered at risk for hazard type.	n/a	n/a	Community is not considered at risk for hazard type.
Data Unavailable	n/a	Social Vulnerability data are not available.	Community Resilience data are not available.	n/a
Insufficient Data	Hazard source data are not available.	n/a	n/a	Social Vulnerability, Community Resilience, or hazard source data are not available.
No Expected Annual Loss	Hazard type exposure or annualized frequency is zero.	n/a	n/a	n/a
No Rating	n/a	n/a	n/a	EAL is zero.

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 are in many cases not as accurate as locally available data. Users with access to local data for each risk component should consider substituting those data to calculate a more accurate EAL value at the local level.

The National Risk Index 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 most recent source datasets only include a period of record up to 2019. 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 type severity and annualized frequency, as well as fluctuations in local economic value and/or population density.

Most of the hazard types use an annualized frequency model to determine EAL. This makes it difficult to accurately estimate EAL for high consequence, low frequency events. Certain rare hazard types (such as Earthquake, Hurricane, Tsunami, and Volcanic Activity) benefit from using a probabilistic model that estimates the likelihood of a hazard occurrence 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.[2]

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, annualized frequency, and historic loss ratio measurements.

The Methodology makes various efforts to control for possible discrepancies in source data but cannot correct for all accuracy problems present in that data. The processing database is a complex system, and localized inaccuracies in source data have the potential to propagate. Therefore, the National Risk Index and its components should be considered a baseline measurement and a guideline for determining natural hazard risk but should not be used as an absolute measurement of risk.

[2] 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.

4. Risk Components Overview

The Risk Index score is based on three components: Social Vulnerability, Community Resilience, and EAL, with EAL based on Exposure, Annualized Frequency, and Historic Loss Ratio (HLR) factors, 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: Risk Components and Factors

Risk Component	*Risk Factors*	*Risk Factor Description*	*Risk Contribution*	*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 Ratio	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 in comparison to all other communities at the same level. The higher a county's or census tract's Social Vulnerability is, the higher the risk. 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 (USC) 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.[3]

- 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

The SoVI dataset was incorporated using min-max normalization (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 are absent for 292 Census tracts. Risk scores cannot be calculated for Census tracts

[3] 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.

without Social Vulnerability scores, so those Census tracts are rated “Insufficient Data.” (See Section 3.2 Scores and Ratings.)

4.2. Community Resilience

Community Resilience is defined by National Institute of Standards and Technology (NIST) as the ability of a community to prepare for anticipated natural hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions.[4]

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 National Risk Index 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 and represents the relative level of community resilience in comparison to all other communities at the same level. A higher Community Resilience score results in a lower Risk Index 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 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

The HVRI BRIC dataset was incorporated using min-max normalization (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 41.1 to 64.7. HVRI BRIC is only available at

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

the county level, so Community Resilience scores were inferred from counties to Census tracts by assigning each Census tract the score of its parent county. Community Resilience scores were classified into five qualitative categories, from “Very Low” to “Very High,” using k-means clustering. (See Section 3.2 Scores and Ratings.)

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).[5,6]

4.3. Expected Annual Loss (EAL)

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, population, or agriculture). For example, many hazard types 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 agriculture (crops and livestock) in its computation. Agriculture is considered a relevant consequence type for hazard types where it has historically contributed greater than 1% of the total reported losses.

All loss is quantified as a dollar amount. While building and agriculture losses 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 into a population equivalence value using a Value of Statistical Life (VSL) approach in which each fatality or ten injuries is treated as $7.6 million of economic loss, an inflation-adjusted VSL used by FEMA.[7] To adjust for inflation, all historic losses are converted to 2020 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, HLR, and the likelihood risk factor of natural hazard annualized frequency for 18 hazard types. The EAL value for each consequence type is calculated by multiplying the exposure value of an area by the estimated annualized frequency and the HLR (see Equation 3). See Section 5 Natural Hazards Expected Annual Loss Factors for further explanation of these EAL factors and how they are computed. EAL values are computed at the Census block level (or for some hazard types, the Census tract level) for each relevant consequence type and summed to produce a total EAL for each hazard type. A composite EAL is also summed from all hazard type EAL values for the community (see Equation 3).

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[5] 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.

[6] 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.

[7] 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.

Equation 3: Expected Annual Loss Values

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

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

$$Expected\ Annual\ Loss_{Composite} = \sum_{i=1}^{18} Expected\ Annual\ Loss_{Hazard\ Type_{Total_i}}$$

Equation 4: Expected Annual Loss Scores

$$EAL\ Cube\ Root_{Hazard\ Type_{Total}} = \left(\sqrt[3]{Expected\ Annual\ Loss_{Hazard\ Type_{Total}}}\right)$$

$$Expected\ Annual\ Loss\ Score_{Hazard\ Type_{Total}} = \frac{EAL\ Cube\ Root_{Hazard\ Type_{Total}} - Min(EAL\ Cube\ Root_{Hazard\ Type_{Total}})}{Max(EAL\ Cube\ Root_{Hazard\ Type_{Total}}) - Min(EAL\ Cube\ Root_{Hazard\ Type_{Total}})}$$

A cube root transformation is applied to the hazard type EAL value for each community 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 type (see Equation 4). The composite EAL score is calculated using the same cube root transformation and min-max normalization process shown in Equation 4. County and Census tract EAL scores were classified into five qualitative categories, from “Very Low” to “Very High,” using k-means clustering (see Section 3.2 Scores and Ratings).

While each hazard type uses the same factors to calculate EAL, these computations require different approaches due to the varying nature of the hazard types and the differences in source data format. A set of common analytical techniques (see Section 4.3.2 Analytical Techniques) are leveraged to achieve the best possible consistency between all hazard types for accurate calculation. The process for computing the EAL and its factors for each hazard type will be described in the specific sections for each hazard type (Sections 6 through 23).

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

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

EAL Factor	*Building Value*	*Population & Population Equivalence*	*Agriculture Value*
Exposure	$28.21 B	310,235 people or $2.36 T	$77.03 M
Annualized Frequency	3.9 events/year	3.9 events/year	3.9 events/year
Historic Loss Ratio	3.1e-5	1.3e-8	3.2e-6
Expected Annual Loss	$3.47 M	0.016 people or $121,600	$968

4.3.2. ANALYTICAL TECHNIQUES

Arriving at a dollar value representing the EAL due to each of the 18 hazard types for every county and Census tract in the U.S. requires multiple analytical techniques utilized across all hazard types to ensure the most accurate and consistent representation of EAL.

Processing Database

To support the processing of the National Risk Index, a dedicated SQL Server database environment was established. Using a relational database with spatial capabilities to store and analyze each dataset used to compute the National Risk Index's values and scores provides a variety of benefits. The database allows for computational efficiencies when calculating the factors of the EAL for more than 11 million Census blocks in the U.S. Grouping and aggregation functions can be used to easily roll these values into the Census tract- and county-level values displayed in the application. Implementation of Methodologies in stored procedures allows for the application and adaptation of complex business logic and spatial analysis. The 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 type only requires the replacement of source data tables for that hazard type and for the reprocessing of a single hazard type. The 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 processing database. However, some processes, such as land use tabulation, necessitate the additional use of ArcGIS tools and functions. The outputs of these external processes are transferred and stored within the processing database, where they are used to compute the components of the EAL.

Geographic/Administrative Layers

EAL factors may be calculated at three different administrative layers: Census block, Census tract, and county. The most granular level is the Census block. 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.[8] The shapefiles include U.S. territories and some large bodies of water, which are either manually removed or clipped based on a county boundary shapefile provided by Esri.[9] All spatial layers use the North America Albers Equal Area Conic projection. Figure 4 provides examples of Census block, Census tract, and county boundaries.

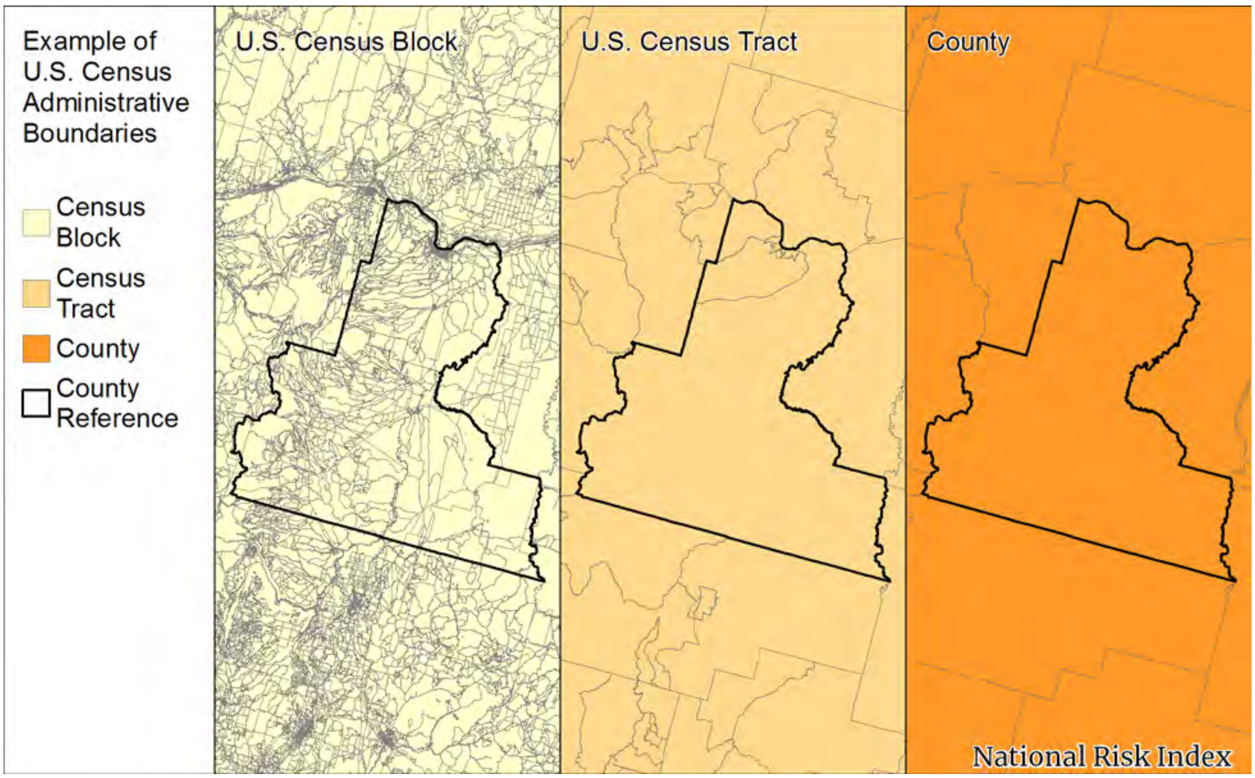

Figure 4: Example of Census Block, Census Tract, and County Shapes

The National Risk Index also supplies a relational dataset mapping Census tract and county data to American Indian Areas. FEMA utilizes two authoritative sources for the locations of tribal lands, including reservations, statistical areas, and trust lands. The first is the Homeland Infrastructure Foundation-Level Data (HIFLD) American Indian/Alaska Native/Native Hawaiian (AIANNH) Areas[10] shapefile that is adapted from the U.S. Census Bureau's TIGER/Line American Indian Area

[8] 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.

[9] 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.

[10] Department of Homeland Security (DHS). (2020). *American Indian/Alaska Native/Native Hawaiian (AIANNH) Areas.* [cartographic dataset] Supplied by Federal Emergency Management Agency.

Geography shapefile.[11] The shapefile includes federally recognized American Indian reservations and off-reservation trust land areas, state-recognized American Indian reservations, and Hawaiian home lands (HHLs). The second shapefile used internally by FEMA, referred to as the FEMA Mitigation Planning Jurisdiction Layer,[12] is adapted from the Bureau of Indian Affairs (BIA) geographic information system (GIS) data.[13] This data includes Land Area Representations (LARs) and Tribal Statistical Areas (TSAs), among other types of tribal areas. While the HIFLD and FEMA datasets have most areas in common, they are not identical.

To build the relational dataset, each shapefile was intersected against the Census block layer. If a tribal area covered at least 5% of at least one Census block within a Census tract, a relationship was established between the area and the Census tract. Census tracts that intersect a tribal area, but with less than 5% coverage in a Census block, were visually inspected to ensure that areas of intersection arose out of natural imprecision in the boundaries rather than valid cases of small tribal areas within the Census tract. Following this process, 18 relationship records at the Census tract level and 8 records at the county level had to be manually included in the final dataset.

The work of the National Risk Index to evaluate risk at the county and Census tract level has not been duplicated to give tribal entity risk. Instead, descriptive tribal data is associated with the Census tracts and counties that contain tribal areas.

Determining County-Level Possibility of Hazard Occurrence

Not all hazard types are able to occur in all areas. For example, Coastal Flooding is not able to occur in Kansas, and Avalanches are not able to occur on flat terrain. The National Risk Index logically differentiates areas where a given hazard type is unlikely or has never occurred from areas where that hazard type is not able to occur using a control table in the database that designates where each hazard type is able to occur. This table is based on counties that intersect past hazard occurrence 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. Hazard type EAL is only calculated for communities where it is possible for the hazard type to occur.

Base Calculation and Aggregation

One of the National Risk Index'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 community's annualized frequency and associated consequence if it were to occur (for example, how often Riverine Flooding occurs in the area and

[11] U.S. Census Bureau. (2020). *American Indian Area Geography.* [cartographic dataset] Retrieved from https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html.
[12] Federal Emergency Management Agency (FEMA). (2020). *FEMA Mitigation Planning Jurisdiction Layer.* [cartographic dataset] Supplied by FEMA.
[13] Bureau of Indian Affairs (BIA) Branch of Geospatial Support, US Department of the Interior. (2018). *American Indian and Alaskan Native Land Area Representations (LAR).* [cartographic dataset] Retrieved from https://biamaps.doi.gov/bogs/datadownload.html.

what buildings, population, and agriculture are potentially affected). For many hazard types, annualized frequency and exposure can be highly localized. Modeling the annualized frequency in coordination with its exposure provides the best assessment.

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 National Risk Index is more accurately assessing EAL by looking at specific annualized frequency and exposure combinations at the lowest possible resolution. The National Risk Index provides the most relevant aggregations to its users, namely EAL values at the Census tract and county levels. For most hazard types, Census tract- and county-level exposure and annualized frequency are calculated by “rolling up” or aggregating values from the Census block level. The processing database ensures that the EAL values do not exceed exposure values.

Data are also aggregated at the state level. Exposure and EAL values of all Census blocks within each state are summed to give that state’s values for each hazard type by consequence types. State-level exposure and EAL aggregation for all hazard types except Avalanche, Coastal Flooding, Earthquake, and Tornado is performed in this way. Avalanche, Coastal Flooding, and Tornado exposure and EAL values are summed from the county level. Earthquake exposure and EAL values are extracted from the Hazus P-366 study, which provides state level estimations of these values, so a simple table lookup is performed.

EAL values for each hazard type are provided by consequence type as the EAL due to all hazard types for each state and each consequence type. Total state building values, population, and agriculture values are set as ceilings on values by consequence type. The sum of the EALs for each hazard type for each relevant consequence type is used to calculate the state’s national EAL percentile using a cumulative distribution function to determine the state’s relative EAL. Predictably, this statistic places more populated states with higher building values in the highest percentiles while small and sparsely populated states are in the lower percentiles.

Risk scores and ratings are not currently supplied at the state level in the application. SoVI and BRIC, the sources for social vulnerability and community resilience components respectively, are only provided at the county level and it was determined that deriving meaningful state level representations of these values was out of the current scope of the National Risk Index, so state-level risk scores are not calculated. Hazard type annualized frequency and HLR are also not calculated at the state level.

Representation of Hazard Types as Spatial Polygons

EAL factors for each hazard type are derived from one or more sources of spatial hazard information. This can include identified hazard-susceptible zones, spatiotemporal records of past hazard occurrences, and countywide records of economic loss due to a hazard occurrence. The format of spatial source data varies by hazard type. Annualized frequency and exposure calculations typically require spatiotemporal records of past hazard occurrences or probabilistic modeling. To achieve a uniform level of accuracy, any spatial hazard source data were converted to a vector polygon format and intersected with the Census blocks or Census 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 calculations are the buffering of points and lines to form polygons and raster-to-polygon conversion.

Point and line representations of hazard occurrences or hazard-susceptible zones are buffered by different distances depending on the hazard type. Point buffers allow for better representation of hazard occurrence 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 severity of the Tornado (Enhanced-Fujita scale) or Hurricane (Saffir-Simpson scale) hazard occurrence. See the spatial processing discussion in the sections for each hazard type (Sections 6 through 23) for more detail on the buffering techniques used.

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 methodology calculations for a specific hazard type.

Intersection

Determining areas of spatial intersection between hazard occurrences or hazard-susceptible zones and the various levels of reference layers is an essential function used in calculating EAL. The results of these intersections are stored in the processing database and used for multiple purposes. For many hazard types, the quantification of a hazard type'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 occurrence shape intersecting a Census block.

Annualized frequency computations also typically involve counting the number of hazard occurrence polygons that intersect the Census block. Widespread hazards, like Hurricanes, often require a larger aggregation layer to more accurately represent the annualized frequency of hazard occurrences. For these hazard types, 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 Occurrence and Census Block

The 49-by-49 km grid cell size was used because of analysis 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 Census 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 annualized frequency for widespread hazard types.

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,[14] which describes the land use of the conterminous U.S. 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 (i.e., 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 areas (Developed, Developed Open Space,

[14] 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/.

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 109 crop classes can be summed to give a total agriculture area. This same tabulation is performed at the Census tract and Census block level to support the computation of developed area and agriculture value densities at these levels. The EAL calculations for most hazard types utilize the developed area andTable agriculture value densities at the Census block level (see Approach 1. Developed Area/Agriculture Area Density Concentrated Exposure).

The CropScape layer only contains information for the conterminous U.S. For Alaska and Hawaii, a similar tabulation process is carried out by substituting the 2016 National Land Cover Database (NLCD) raster files[15] for both states. NLCD uses the same classification types for developed land as CropScape. It has two classifications for agriculture 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 to whether they completely contain the Census block, Census 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 shapes are not tabulated using the primary method, secondary methods specific to the hazard type are pursued. 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.

[15] Multi-Resolution Land Characteristics Consortium. (2016). *National Land Cover Database (NLCD)* [online dataset]. Retrieved from https://www.mrlc.gov/data.

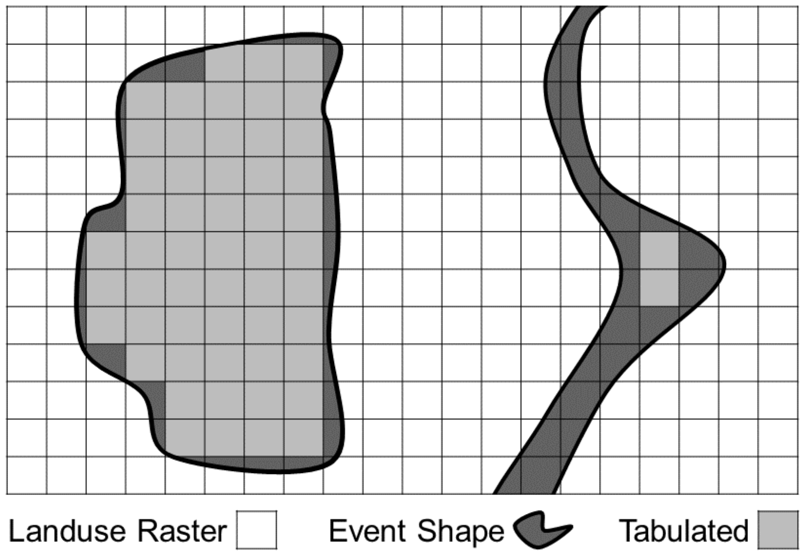

Figure 6: Land Use Raster Tabulation

5. Natural Hazards Expected Annual Loss Factors

The National Risk Index represents natural hazards in terms of EAL, which incorporates data for natural hazard exposure, annualized frequency, and HLR. A single "mental model" was leveraged throughout all methodological processes in calculating these EAL factors to ensure consistency across the 18 hazard types.

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 considered a manmade hazard.

Natural hazard occurrences can induce secondary natural hazard occurrences. 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 a negative impact following an actual occurrence of a natural hazard in the event that it significantly harms a community. Only primary natural hazard occurrences are considered and not their results or after-effects.

The National Risk Index considers 18 hazard types. These hazard types are listed below and described in more detail in the hazard type-specific 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 natural hazard annualized frequency is defined as the expected frequency or probability of a hazard occurrence per year. Annualized frequency is derived either from the number of recorded hazard occurrences each year over a given period or the modeled probability of a hazard occurrence each year. The National Risk Index 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 National Risk Index has built-in minimum representative annualized frequency values for certain geographical areas and hazard types, such as Hurricane, Ice Storm, Landslide, Tornado, and Tsunami.

5.2.1. SELECTING SOURCE DATA

Annualized frequency data were derived from multiple sources and depend on the hazard types. Data sources were identified through public knowledge, guidance by subject matter experts, 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 type-specific sections (Sections 6 through 23) for more information on spatial data sources.

5.2.2. ANNUALIZED FREQUENCY METHODOLOGY

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

Equation 5: Annualized Frequency Equation

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

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 annualized frequency value represents the probability of a hazard occurrence in a given year.

For hazard types that track actual hazard occurrences, the historical hazard occurrence 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 Heat Wave event was reported). The determination of whether hazard occurrence was defined by distinct event or event-days was based on subject matter expert review of the source data. This determination depended on how hazard occurrence was recorded as well as how losses were reported. Table 5 gives the hazard occurrence basis (event or event-day) for each hazard type.

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

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

While the 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 factors are assessed at the Census block level, so the number of hazard occurrences (events or event-days) is determined for each Census block.

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

For large geographic areas and areas with a statistically significant number of hazard occurrences recorded, the logic supporting Equation 5 is sound and is used as one approach for calculating annualized frequency for some hazard types. However, for hazard types with few hazard occurrences historically recorded, due to urban bias and varying demographics across the U.S., 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 type and/or recorded hazard occurrences are being calculated as having no risk from that hazard type. (Remember, the EAL and risk equation are multiplicative, and, therefore, any individual factor of zero results in a risk 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 the 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 Census tracts that easily could have impacted a given community.

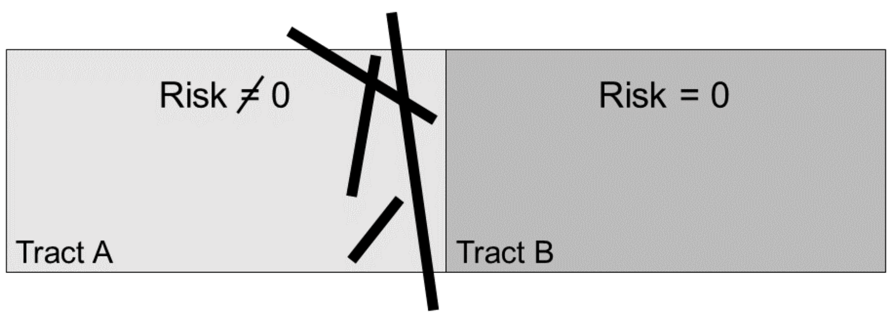

Figure 7: Example of the Issues with a Simplistic Annualized Frequency Methodology

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

1. **Hazard Occurrence Counting Using a 49-by-49 km Fishnet Grid**: This approach involves creating a fishnet grid covering the U.S. and counting the number of hazard occurrences (event or event-days) within each cell. Communities within the cell inherit the hazard occurrence count (or receive an area-weighted hazard occurrence count when intersecting multiple cells; see Section 5.2.3 Data Aggregation) and annualized frequency is then calculated according to Equation 5. Hazard types using this approach include Hail, Hurricane, Ice Storm, Strong Wind, and Tornado.

2. **Minimum Annual Frequency**: A minimum annual frequency (MAF) is assigned to communities 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 for most hazards were identified by hazard type subject matter experts. The estimated values are low given the fact that historic occurrences had never been recorded over the period of record, which sometimes dated back multiple centuries. MAF values were typically defined in the format of “once in the period of record,” or similar. Hazard types using this approach include Avalanche, Hurricane, Ice Storm, Landslide, Riverine Flooding, Tornado, and Tsunami.

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

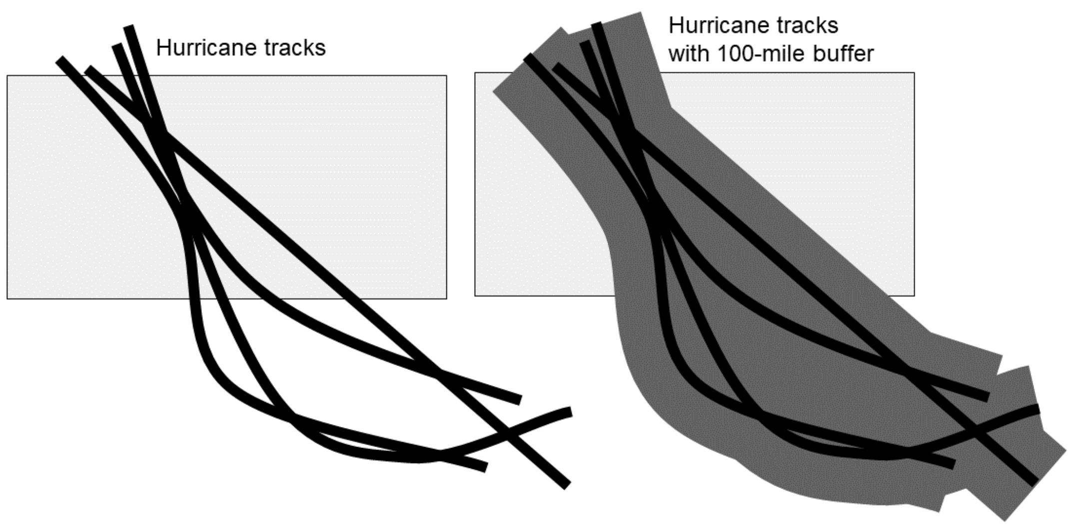

Figure 8: Example of Buffering Hazard Occurrences to Determine Areas Applicable to Minimum Annual Frequency Values

Some hazard types do not require any of these solutions due to the nature of the source data or the widespread prevalence of the hazard type. For example, the spatial data for Cold Wave, Heat Wave, and Winter Weather occurrences cover areas the size and shape of NWS Forecast Zones and counties. These hazard occurrences happen across the entire U.S., so it is not necessary to spread the hazard types’ 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 hazard occurrence count is evaluated at the fishnet level (see Table 5), the Census block inherits the hazard occurrence 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 hazard occurrence count of about 22. This fishnet-aggregated count is used to calculate the Census block annualized frequency.

Equation 6: Census Block Area-Weighted Fishnet Hazard Occurrence Count Calculation

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

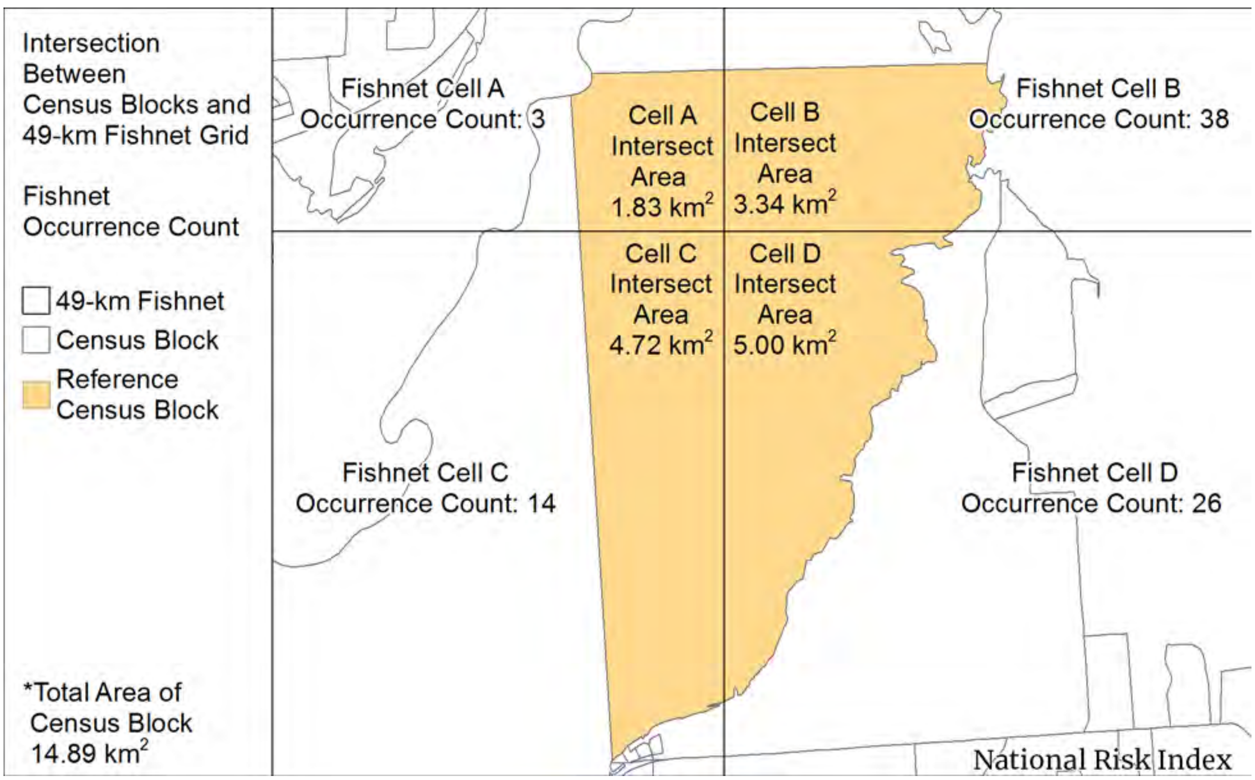

Figure 9: Aggregation from Fishnet Cell to Census Block Example

The National Risk Index 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 annualized frequency values may not exactly match that of dividing the number of historical hazard occurrences at the Census tract and county level by the period of record, as they are based on an area-weighted aggregation of Census block hazard occurrence values.

Equation 7: Census Tract and County Annualized Frequency Aggregations

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

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

For a few hazard types, annualized frequency is calculated at the Census tract level, after which the Census block simply inherits the value of its parent Census tract (see Table 5). Avalanche and Riverine Flooding are the only hazard types for which annualized frequency is calculated at the county level directly, and the Census tracts and Census blocks then inherit the value of their parent county.

5.3. Exposure

Exposure is defined as the representative value of buildings, population, or agriculture potentially exposed to a natural hazard occurrence. Data sources with the best available national-level data for each hazard type 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 type is used to identify areas of exposure. Data sources were selected for their accuracy, long period of record, and spatial component, based on the best available, national-level data per hazard type. Sources were identified through public knowledge, subject matter expert recommendations, and research. Providers of 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 consequence is defined in the National Risk Index as economic loss or bodily harm to individuals that is directly caused by a hazard occurrence. Consequences of hazard occurrences are categorized into three different types: buildings, population, and agriculture.

Buildings

Building exposure value is defined as the dollar value of the buildings determined to be exposed to a hazard according to a hazard type-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),[16] which provides 2018 valuations of the 2010 Census.[17]

Population

Population exposure is defined as the estimated number of people determined to be exposed to a hazard according to a hazard type-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. Population loss is monetized into a population equivalence value using a VSL approach in which each fatality or ten injuries is treated as $7.6 million of economic loss (2020 dollars).

Agriculture

Agriculture exposure value is defined as the estimated dollar value of the crops and livestock determined to be exposed to a hazard according to a hazard type-specific methodology. This is derived from the USDA 2017 Census of Agriculture[18] county-level value of crop and pastureland.

5.3.3. EXPOSURE METHODOLOGY

Exposure is typically calculated at the Census block level and then aggregated to the Census tract and county level by summing the Census block exposure values within the parent Census tract or parent county. See the hazard type-specific exposure sections (Sections 6 through 23) for more information.

Some hazard type exposure areas are represented as polygons in the source data, while others are represented as points, lines, or raster cells. Exposure is based on either historic hazard occurrence 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 type-specific methodology. This polygon represents an area of exposure to the hazard type.

To calculate the hazard type's representative size for a given area, the National Risk Index leverages a few techniques, such as using subject matter experts to define a single representative hazard type

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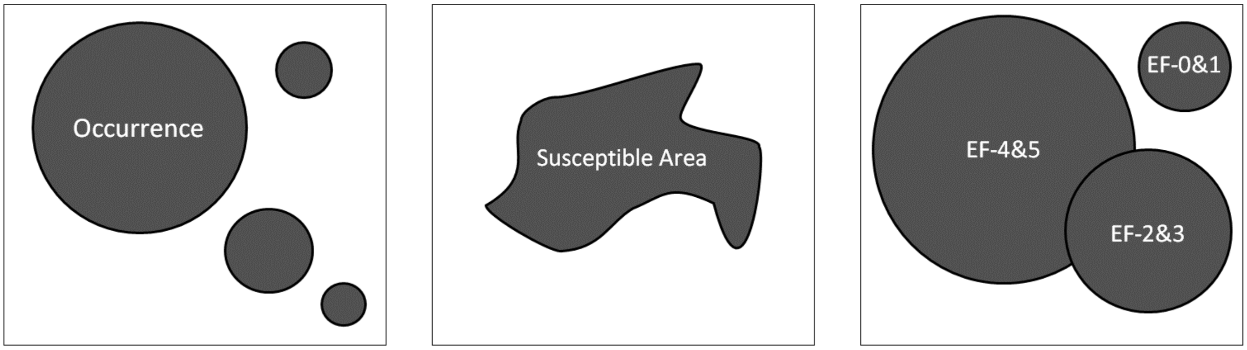
16 Federal Emergency Management Agency (FEMA). (2018). *Hazus 4.2, Service Pack 01 Release*. Retrieved from https://msc.fema.gov/portal/resources/hazus.
17 U.S. Census Bureau. (2010). *2010 Census*. Retrieved from http://www.Census.gov/2010Census/data/.
18 U.S. Department of Agriculture. (2017). *2017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

size, calculating historical average hazard occurrence sizes, or defining the size of probabilistic/susceptible zones for hazard types within the area of interest using existing source data (Figure 10).



Historical Average Size
Cold Wave
Heat Wave
Hurricane
Ice Storm
Volcanic Activity
Winter Weather

Susceptible Area
Coastal Flooding
Earthquake
Landslide
Riverine Flooding
Tsunami
Wildfire

Pre-Defined Representative Area by Subtype
Tornado

Figure 10: Examples of Representative Hazard Type Size

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

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

1. **Widespread Hazard Occurrence Exposure.** The entire administrative area is considered to be exposed. This approach is leveraged for hazard types where the extent likely spans the entire administrative area and the boundaries are indefinable.
2. **Developed Area/Agriculture Area Density Concentrated Exposure.** The determined area of exposure intersected with the administrative area is multiplied by the density of either the population or building value within the developed land of the administrative area to calculate the worst-case concentration of consequence for the hazard type. To estimate agriculture exposure, this method uses the density of crop and livestock value within the agriculture land of the administrative area.
3. **Pre-Defined Representative Exposure.** Subject matter experts define a default, representative exposure value or area.

Approach 1. Widespread Hazard Occurrence Exposure

For certain hazard types where extent is widespread with indefinable boundaries, the entire community is considered exposed. For these hazard types, exposure values are defined to be the entire community's building value, agriculture value, or population as recorded by Hazus 4.2 SP1 or the 2017 Census of Agriculture.

Approach 2. Developed Area/Agriculture Area Density Concentrated Exposure

Exposure is calculated for most of the hazard types using the developed area density approach. This approach uses the area of the hazard occurrence exposure shape (intersection of hazard occurrence shape with the census block) multiplied by the developed area density of the administrative area to generate the worst-case representative building value or population that could be exposed to a future hazard occurrence within the area. This can result in exposure values exceeding the total values of the Census block. In these cases, exposure is capped at the total Census block value.

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 hazard types, a density estimate was needed for the hazard type'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), an 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 agriculture (crop and pasture) areas as well (see the Tabulation section).

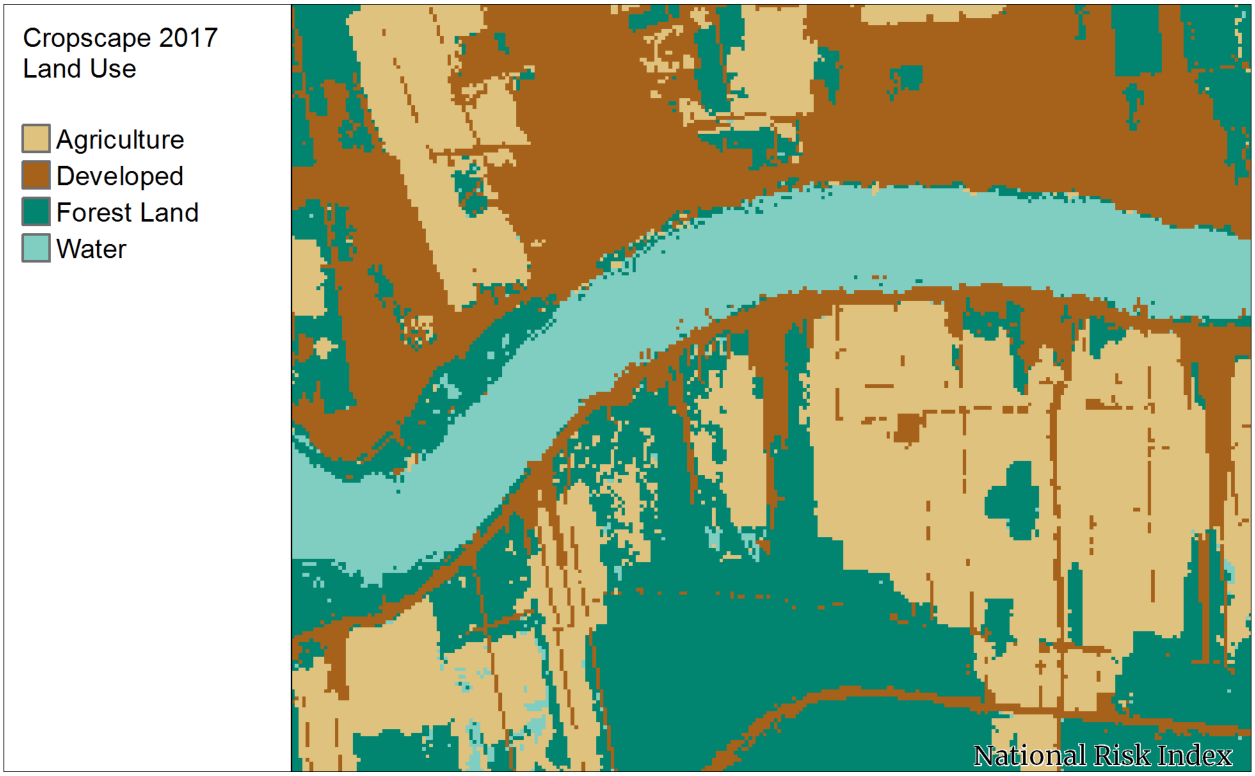


Figure 11: CropScape Developed Land Layer

With an estimate of the developed area and agriculture 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 developed area building density and developed area population density. 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 a developed area, but the Hazus data did not report any population or building values, the densities were 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 the developed area within the administrative area when Hazus data do not consider it populated or developed.

To compute the developed area building and population 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 Developed Area Building and Population Density

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

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

where:

$BldgValueDen_{CB}$ is the developed area 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 developed area 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 agriculture area of the county to find its agriculture value density (see Equation 9). The county-level agriculture value density is inherited by any Census tracts or Census blocks that contain crop or pastureland.

Equation 9: County Agriculture Value Density

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

where:

$AgValueDen_{Co}$ is the agriculture value density calculated at the county level (in dollars per square kilometer).

$AgValue_{Co}$ is the total agriculture (crop and livestock) value of the county as reported in the 2017 Census of Agriculture (in dollars).

$AgArea_{Co}$ is the total agriculture area of the county (in square kilometers).

Approach 3. Pre-defined Representative Exposure

Avalanche and Tornado each have unique methods of calculating exposure. For Avalanche, a single exposure value, defined by subject matter experts, is pre-determined and assigned to all areas deemed at risk of Avalanche occurrences. For Tornado, an average historical damage area is calculated for each EF-scale grouping subtype. For each sub-type, the representative footprint area is multiplied by the average building and population densities of the Census tract to find exposure.

5.3.4. DATA AGGREGATION

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

5.4. Natural Hazard Historic Loss Ratio

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

The 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 occurrences and is used to estimate the potential impact of a future hazard occurrence. 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 as the value of the loss divided by the exposed value for each relevant consequence type.

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 HLR 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 resulting Bayesian-adjusted HLR value—computed for each county-hazard type-consequence type combination—serves as a prediction of the ratio of loss to exposed consequence type value that can be expected from a single hazard occurrence.

Computation of the HLR also considers zero-loss hazard occurrences for some hazard types prior to performing the Bayesian credibility spatial modeling analysis. This ensures that HLR can be multiplied by annualized frequency within the EAL equation without overinflating the EAL value.

5.4.1. SOURCE DATA: SHELDUS

Historic Losses source data provider: Arizona State University, Spatial Hazard Events and Losses Database of the United States (SHELDUS)[19]

Arizona State University's (ASU) Spatial Hazard Events and Losses Database of the U.S. (SHELDUS) loss data are used to calculate HLR for most hazard types. SHELDUS provides county-level data that correspond to nearly all of the hazard types. It also offers a further degree of description by identifying hazard occurrences by peril type as well as hazard. SHELDUS represents the best available national dataset on building, population, and agriculture losses.

Through its website, ASU provides summary SHELDUS data that aggregates property damage, crop losses, injuries, and fatalities due to a peril or hazard by month, year, and county since 1960. However, ASU allowed unaggregated data collected at the hazard occurrence level to be shared with FEMA for the development of the National Risk Index. Much of this data was originally collected by NOAA and published in the monthly Storm Data and Unusual Weather Phenomena report, though information may have also been extracted from additional resources. The records have been processed by ASU to enable appropriate spatial aggregation by distributing losses among multiple counties for events with losses reported at the forecast zone or even the state level. For example, in Table 6, a Winter Weather injury is recorded in SHELDUS records as 0.5 for two neighboring counties. Both occurred in the same date range and have the same level of property damage. This implies that the specific county where the injury occurred could not be determined because the reporting covered two counties, so ASU split the injury evenly between them.

Table 6: Sample SHELDUS Peril Occurrence Data

SHELDUS ID	*Hazard Begin Date*	*Hazard End Date*	*County FIPS*	*Fatalities*	*Injuries*	*Property Damage*	*Crop Damage*	*Peril*
25773	1/22/1999	1/22/1999	01033	0	0	5000	0	Hail
26427	9/14/1999	9/14/1999	04013	0	2	7,000,000	0	Severe Storm/ Thunderstorm, Wind
9884227	12/17/2010	12/20/2010	06003	0	0.5	100,000	0	Winter Weather
9884228	12/17/2010	12/20/2010	06017	0	0.5	100,000	0	Winter Weather
27491	9/18/1999	9/18/1999	12099	0	0	1,000	0	Hail, Wind

Peril-level data are mapped via a control table in the processing database to the appropriate hazard types (see Table 7). The National Risk Index's hazard definitions are very similar to those of SHELDUS; however, they are not identical. For example, SHELDUS classifies all flooding perils under

[19] Center for Emergency Management and Homeland Security, Arizona State University. (2020). Spatial Hazard Events and Losses Database for the United States, Version 19.0. [online database]. Retrieved from https://cemhs.asu.edu/sheldus.

the hazard Flood, while the National Risk Index explores two flooding hazard types (Coastal and Riverine) and classifies the different flooding perils accordingly.

Table 7: National Risk Index Hazard to SHELDUS Peril Mapping

National Risk Index Hazard Type	*Perils in SHELDUS*
Avalanche	Avalanche, Avalanche-Debris, Avalanche-Snow, Snow-Slide
Coastal Flooding	Coastal, Coastal Storm, Flood-Coastal, Flood-Tidal
Drought	Drought
Earthquake	Earthquake, Fire-following Earthquake, Landslide following EQ, Liquefaction
Hail	Hail
Heat Wave	Heat, Heat Wave
Hurricane	Cyclone-Extratropical, Cyclone-Subtropical, Cyclone-Unspecified, Hurricane/Tropical Storm, Nor'easter, Storm Surge, Tropical Depression, Tropical Storm
Ice	Ice Storm
Landslide	Landslide, Landslide-Slump, Mud Flow, Mudslide, Rock Slide
Lightning	Fire-St Elmo's, Lightning
Riverine Flooding	Flood-Flash, Flood-Ice Jam, Flooding, Flood-Lakeshore, Flood-Lowland, Flood-Riverine, Flood-Small Stream, Flood-Snowmelt
Strong Wind	Derecho, Wind, Wind-Straight Line
Tornado	Fire-Tornado, Tornado, Waterspout, Wind-Tornadic, Wind-Vortex
Tsunami	Tsunami, Tsunami/Seiche
Volcanic Activity	Ashfall, Lahar, Lava Flow, Pyroclastic Flow, Vog, Volcano
Wildfire	Fire-Brush, Fire-Bush, Fire-Forest, Fire-Grass, Wildfire
Winter Weather	Blizzard, Storm-Winter, Winter Weather

SHELDUS loss records were acquired for all perils and all counties in the U.S. Loss types include property damage, injuries, fatalities, and crop damage. Property damage and crop damage are quantified in nominal dollars as they were reported at the time the loss occurred. The loss records utilized for the HLR computation of most hazard types range from January 1996 through December 2019 as loss data captured during and after 1996 were deemed to be the most accurately and uniformly collected due to the standardization of collection practices that began in 1995. However, data from January 1960 to December 2019 are used to compute HLR for the two most rarely occurring hazard types: Earthquake and Volcanic Activity (see Sections 10.6 and 21.7). Older data are also used to identify which counties had ever experienced losses for a specific hazard type, ensuring that these were set in the processing database as counties where there was some possibility of the hazard type occurring (see Determining County-Level Possibility of Hazard Occurrence section).

Not all perils to which loss is attributed in SHELDUS are included as National Risk Index hazard types. However, all SHELDUS records that attribute loss to at least one National Risk Index hazard type are extracted. Loss records in SHELDUS can attribute losses for a single loss-causing event to multiple perils. For example, losses from a single storm can be attributed to Wind, Hail, Tornado, and Severe Storm/Thunder Storm. In the processing database, these multi-peril occurrence records are expanded to multiple records, each attributing a portion of the total loss to a single hazard type. The loss reallocation in these cases does not estimate what degree of loss may be due to perils not included in the hazard types, like Severe Storm/Thunder Storm. Instead, a conservative approach is taken that assumes that all economic loss is due to National Risk Index hazard types.

Loss reallocation for each relevant consequence type is based on comparisons between the typical loss caused by each hazard type (see Table 8). To arrive at these percentages, loss attributed to a single hazard type was aggregated across the 1996-2019 period of record for each consequence type, and this loss was compared to the aggregated loss of the other hazard types within the combination as a portion of the combined loss of all hazards in the combination.

Table 8: Loss Allocation by Hazard Type Combination

Hazard Type Combination	*Building*	*Population*	*Agriculture*
Hail, Strong Wind	90%/10%	50%/50%	50%/50%
Hail, Strong Wind, Tornado	35%/5%/60%	20%/20%/60%	40%/40%/20%
Hail, Tornado	35%/65%	25%/75%	70%/30%
Lightning, Strong Wind	45%/55%	50%/50%	10%[20]/90%
Strong Wind, Tornado	5%/95%	20%/80%	60%/40%

Past losses occurring in counties that have been dissolved are included in SHELDUS data as well. These counties are flagged in the SHELDUS data as all records are assigned the name of the county at the time the loss was reported. SHELDUS provided a county table that includes the date range when each county definition was applicable. Most changes are due to renaming, a change in the county FIPS code, or the absorption of one county by another. More complex boundary changes necessitate additional processing. The HLR methodology attempts to reapportion loss from these dissolved counties to their present-day equivalents if the loss occurred during the period of record for a particular hazard type.

[20] Agriculture is not used as a consequence type for Lightning.

The U.S. Census Bureau maintains a list of Substantial Changes to Counties and County Equivalent Entities[21] that was used to map the dissolved counties to their present-day equivalents. Most of these counties were completely absorbed by new or existing counties, and the economic loss of the dissolved county could be 100% reallocated to its present-day equivalent (see Table 9). If a county was dissolved into two or more new or existing counties, the population of the county at the time it was dissolved was compared to the population of the present-day counties to estimate the proportion of loss that should be attributed to each present-day county. The exception to this rule is the reapportionment of the Yellowstone National Park county-equivalent. Loss allocation was divided roughly according to land area reapportionment because the permanent population of the national park is so low.

Table 9: Dissolved County Allocation of SHELDUS Loss

Dissolved County	*Year Dissolved*	*Present-day Counties*	*Loss Allocation*
Skagway-Yakutat, AK	1980	Skagway, Yakutat	67%/33%
Aleutians Islands, AK	1987	Aleutians East, Aleutians West	20%/80%
Skagway-Yakutat-Angoon, AK	1992	Yakutat, Skagway, Hoonah-Angoon	20%/20%/60%
Yellowstone National Park, MT	1997	Gallatin, Park	60%/40%
Skagway-Hoonah-Angoon, AK	2007	Skagway, Hoonah-Angoon	25%/75%
Prince of Wales – Outer Ketchikan, AK	2008	Ketchikan Gateway, Prince of Wales-Hyder, Wrangell	10%/80%/10%
Wrangell-Petersburg, AK	2008	Petersburg, Wrangell	64%/36%

5.4.2. SOURCE DATA: NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION (NCEI) STORM EVENTS DATABASE

Historic Losses source data provider: National Centers for Environmental Information, Storm Events Database[22]

Unlike the other hazard types, the loss information for Cold Wave is derived from the NCEI Storm Events Database. Loss data for building damage and agriculture 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 peril occurrences regardless of whether there was any reported loss. LRB calculation is initially based only on those records with reported loss.

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

[21] U.S. Census Bureau. (2020). *Substantial Changes to Counties and County Equivalent Entities: 1970-Present*. Retrieved from https://www.census.gov/programs-surveys/geography/technical-documentation/county-changes.2020.html
[22] National Centers for Environmental Information. (2020). *Storm Events Database, Version 3.1.* [online database]. Retrieved from https://www.ncdc.noaa.gov/stormevents/.

provided by the NWS (see Section 8.2). Cold Wave occurrences also have start and end dates recorded so the number of event-days can be computed. Cold Wave occurrences extracted from the Storm Events Database use the same date range as most of the data utilized from SHELDUS, 1/1/1996 to 12/31/2019. The resulting extracted records are similar in structure to the SHELDUS data.

5.4.3. CONSEQUENCE TYPES

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

Building

Building loss is defined as the SHELDUS or NCEI reported damage to property caused by the hazard occurrence in dollars (inflation-adjusted to 2020 dollars). In the calculation of HLR, property loss is treated as analogous to the 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 the data. SHELDUS and Hazus data remain the best available estimates of loss and value that could be utilized.

Population

Population loss is defined as the SHELDUS or NCEI reported number of fatalities and injuries caused by the hazard occurrence. 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 NCEI Storm Events Database classifies injuries and fatalities as direct or indirect. Both direct and indirect injuries and fatalities are counted as population loss.

Agriculture

Agriculture loss is defined as the SHELDUS or NCEI reported damage to crops and livestock caused by the hazard occurrence in dollars (inflation-adjusted to 2020 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

An HLR could be computed as the average of the individual hazard occurrence loss rates (referred to here as LRBs). However, HLR cannot be calculated in these simple terms and be considered accurate. Many counties that have not experienced a loss-causing hazard occurrence 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 type. 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 occurrence during the 24-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 the HLR is represented in a rational way without allowing anomalous hazard occurrences to distort the data.

To implement Bayesian credibility weighting, loss ratio averages and variances need to be computed for spatial groupings of national, surrounding area, county, and, for some hazard types, regional levels. The nature of the source data requires some pre-processing within the database to ensure that all historical hazard occurrences are structured appropriately for inclusion in the HLR calculations, including (1) per-basis record expansion; (2) single-day, timeframe, or consecutive-day aggregation of the SHELDUS and NCEI loss records; and (3) the insertion of records representing zero-loss hazard occurrences.

See Section 5.4.5 Limitations and Assumptions in Historic Loss Ratio Methodology for more information.

Loss Record Expansion to per Basis Records

A series of manipulations of the SHELDUS and NCEI hazard occurrence records are performed to adapt the data for use. For hazards in which the occurrence basis is event-day, records of hazard events that span multiple days have their loss split evenly into a single record per day. For example, the January 2009 Ice Storm event (peril Ice) in Table 10 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 11).

Table 10: SHELDUS Loss Records

SHELDUS ID	*Hazard Begin Date*	*Hazard End Date*	*County FIPS*	*Fatalities*	*Injuries*	*Property Damage*	*Crop Damage*	*Peril*
10043726	7/2/2002	7/17/2002	08067	0	0	8,000,000	0	Wildfire
10044246	7/2/2002	7/17/2002	08067	0	0	2,500,000	0	Wildfire
10053354	5/2/2003	5/2/2003	01047	0	0	5,000	0	Hail
10053765	5/2/2003	5/2/2003	01047	0	0	45,000	0	Hail
10090870	6/12/2006	6/14/2006	12129	0	0	20,000	0	Tropical Storm
10090997	6/12/2006	6/13/2006	12129	0	0	5,000	0	Storm Surge
10139562	1/26/2009	1/28/2009	05007	0	0	30,000,000	0	Ice

Table 11: SHELDUS Loss Allocation Date Expansion Records

County FIPS	*Utilize Start Date*	*Utilize End Date*	*Hazard Type*	*Basis*	*Property Damage*	*Injuries*	*Fatalities*	*Crop Damage*
05007	1/26/2009	1/26/2009	Ice Storm	Event-Day	10,000,000	0	0	0
05007	1/27/2009	1/27/2009	Ice Storm	Event-Day	10,000,000	0	0	0
05007	1/28/2009	1/28/2009	Ice Storm	Event-Day	10,000,000	0	0	0

This record count expansion process is performed because HLRs 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. For some hazard types, a cap on the number of days to which a single occurrence could be expanded was set (see Table 13) to prevent certain errors in the date fields from propagating. If the date range for a loss record extends beyond this cap, dates from the begin date to the cap are included in the date expansion and have losses allocated to them. The rest of the days over the cap are discarded.

Loss Record Aggregation of per Basis Records

The HLR Methodology assumes that multiple reports of loss that occur in the same county during the same date range and are due to the same hazard type can be classified as part of the same hazard occurrence. For event-day based hazards, following the date expansions process described above, multiple loss-causing records occurring on the same day are replaced by a single record with the summed losses for each consequence type. For example, the two Hail event records from Table 10 (peril Hail) that both occurred on 5/2/2003 are aggregated into a single record in Table 12. This single-day timeframe aggregation ensures that a single-day recorded loss occurring within the date range of a multiple-day recorded loss is treated as the same event-day as one of the days within the multiple-day event. Some event-based hazard types use timeframe aggregation to replace multiple loss-causing records (occurring in the same county with the same Start and End Date combination) with a single loss record with the summed losses for each consequence type. For example, the two event records from Table 10 where the peril is wildfire have the same Start and End Date combination. These events are aggregated into a single record in Table 12. This addresses instances where SHELDUS reports damages impacting different areas of the country for the same multi-day event.

For a few event-based hazard types, a consecutive-day aggregation takes place in which loss records that occur in the same county on the same or consecutive days are combined into a single loss record with the summed loss. For example, the two multi-day Hurricane event records from Table 10 (peril Tropical Storm and Storm Surge) that occurred over consecutive days from 6/12/2006 to 6/14/2006 are aggregated into a single record in Table 12. This aggregation allows loss records that are due to the same loss-causing events to be logically combined so that each occurrence's loss ratio is accurately computed. Treating each loss record as a separate occurrence with a lower loss value could potentially dilute and underestimate the HLR of the county.

Table 12: SHELDUS Loss Aggregated Records

County FIPS	*Utilize Start Date*	*Utilize End Date*	*Hazard Type*	*Number of Records Aggregated*	*Property Damage*	*Injuries*	*Fatalities*	*Crop Damage*
08067	*7/2/2002*	*7/17/2002*	Wildfire	2	10,500,000	0	0	0
01047	5/2/2003	5/2/2003	Hail	2	50,000	0	0	0
12129	6/12/2006	6/14/2006	Hurricane	2	25,000	0	0	0

Hazard types are processed using one or more of the methods previously described. The nature of the hazard and its loss reporting inform which processes are utilized. Table 13 describes which processes are used for each hazard type.

Table 13: Loss Record Processing by Hazard Type

Hazard Type	*Day Expansion Performed?*	*Consecutive Day Aggregation Performed?*	*Timeframe Aggregation Performed?*	*Maximum Expansion Days*
Avalanche	No	No	Yes	N/A
Coastal Flooding	No	Yes	No	N/A
Cold Wave	Yes	No	Yes	31
Drought	Yes	No	Yes	365
Earthquake	No	No	Yes	N/A
Hail	No	No	Yes	1
Heat Wave	Yes	No	Yes	31
Hurricane	No	Yes	No	N/A
Ice Storm	Yes	No	Yes	31
Landslide	No	No	No	N/A
Lightning	No	No	Yes	1
Riverine Flooding	Yes	No	Yes	31
Strong Wind	No	No	Yes	1
Tornado	No	No	No	1
Tsunami	No	Yes	No	N/A

Hazard Type	Day Expansion Performed?	Consecutive Day Aggregation Performed?	Timeframe Aggregation Performed?	Maximum Expansion Days
Volcanic Activity	No	No	Yes	N/A
Wildfire	No	No	Yes	N/A
Winter Weather	Yes	No	Yes	31

Once this reallocation and aggregation of loss records has been completed, each building and agriculture loss value is inflation-adjusted to 2020 using the Bureau of Labor Statistics Consumer Price Index[23] as seen in Equation 10.

Equation 10: Conversion to 2020 Dollars

$$V_{Mo_{2020}} = V_{Orig} \times \frac{CPI_{Mo_{2020}}}{CPI_{Mo_{Year}}}$$

where:

$V_{Mo_{2020}}$	is the dollar value in 2020 dollars.
V_{Orig}	is the original dollar value (assumed dollar value at the time of the loss event).
$CPI_{Mo_{2020}}$	is the Consumer Price Index for the month of the loss event in 2020.
$CPI_{Mo_{Year}}$	is the Consumer Price Index for the month/year of the loss event.

Loss Ratio Per Basis Calculation

After all pre-processing is complete, the 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 for a specific hazard occurrence experienced by a specific

[23] Bureau of Labor Statistics. (2019). *Consumer Price Index for all urban consumers* [online dataset]. Retrieved from https://www.bls.gov/data/.

county. Calculation is 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 or impacted people).

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

The definition of the HLR exposure variable in the HLR formula does not always match the definition of the exposure factor utilized in the EAL formula. For hazard types that can occur almost anywhere or affect large geographic areas, the HLR exposure is the entire county's building value, population, or agriculture value. Hazard types that only occur in certain susceptible zones, such as floodplains and tsunami inundation zones, use the HLR exposure value associated with those susceptible zones. 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. Specific methods of determining HLR exposure in the LRB calculation can be found in the HLR section for each hazard type. Table 14 lists the exposure types used in each hazard type's LRB calculation.

Table 14: HLR Exposure Types Used in Loss Ratio per Basis Calculation

Hazard Type	*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	Total County Value
Lightning	Total County Value
Riverine Flooding	Value Defined by Hazard Intersect
Strong Wind	Total County Value
Tornado	Historical Footprint Matched to Specific SHELDUS Loss

Hazard Type	HLR Exposure Type
Tsunami	Value Defined by Hazard Intersect
Volcanic Activity	Total County Value
Wildfire	Value Defined by Hazard Intersect
Winter Weather	Total County Value

Zero-Loss Hazard Occurrences

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 occurrences. SHELDUS does not record events in which no loss was reported. In an effort to capture zero-loss hazard occurrences, a count of historic occurrences is estimated from hazard source data and compared to a count of loss-causing events from SHELDUS and the NCEI Storm Events Database. The period of record for most hazard source data only extends through 2017 while the period of record for SHELDUS data extends through 2019. To account for this gap, a county-level annual rate from the hazard source data is calculated as the count of total hazard occurrences divided by the hazard's period of record. This rate is then multiplied by the number of years in the SHELDUS period of record to estimate an expected hazard occurrence count.

When more occurrences are estimated by the hazard historic occurrence source than SHELDUS or the NCEI Storm Events Database, a number of zero-loss records are inserted into the set of LRBs to make up the difference between historic occurrences and loss-causing events from SHELDUS so that the 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 occurrences 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 occurrence.

The output of the LRB calculation (see Equation 11) and all corrective record insertion is stored in the LRB table within the processing database, and are then used to compute Bayesian metrics and calculate the weighting factors that are applied to find the hazard type Bayesian-adjusted HLR for each consequence type for the county. Table 15 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 occurrence source data) but resulted in no economic loss. These records can then be used to calculate loss ratio averages and variance.

Table 15: Sample Data from the Loss Ratio per Basis Table

Hazard Type	*Peril*	*Date*	*Conseq. Type*	*Conseq. Exposure*	*Conseq. Loss per Basis*	*Conseq. Ratio per Basis Unit*	*Record Type*
Ice Storm	Ice	1/26/2009	Population	221339	0.01666667	7.53E-08	Peril Basis Expansion
Ice Storm	Ice	1/27/2009	Population	221339	0.01666667	7.53E-08	Peril Basis Expansion
Ice Storm	Ice	1/26/2009	Building	2.3138E+10	5881140.47	0.00025	Peril Basis Expansion
Ice Storm	Ice	1/27/2009	Building	2.3138E+10	5881140.47	0.00025	Peril Basis Expansion
Ice Storm	Ice	11/2/1998	Population	221339	0	0	SHELDUS Native Record
Ice Storm	Ice	11/2/1998	Building	2.3138E+10	310468.525	0.0000134	SHELDUS Native Record
Ice Storm	Inserted Zero-Loss Record		Population	221339	0	0	Inserted Zero-Loss Record
Ice Storm	Inserted Zero-Loss Record		Building	2.3138E+10	0	0	Inserted Zero-Loss Record

Bayesian Credibility

To apply Bayesian credibility weighting factors and balance HLR accuracy with geographic precision in areas where small sample sizes result in volatile HLR estimates, LRB averages and variance may be calculated at several levels: county, surrounding 196-by-196-km fishnet grid cell,[24] 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, the regional grouping includes LRBs for all counties within the defined region, and national

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

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

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

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

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 type.
$LRB_{Haz_{Level_{CnsqType}}}$	is a single Loss Ratio per Basis (event or event-day) of the consequence type within the geographic level due to the hazard type occurrence basis.
$CountOccurrences_{Haz_{Level_{CnsqType}}}$	is the total number of records of hazard occurrences (events or event-days) in the geographic level by consequence type (includes any zero-loss occurrences).
$varLRB_{Haz_{Level_{CnsqType}}}$	is the Loss Ratio per Basis variance of the geographic level for the hazard and consequence type.

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 county's calculated HLR value. Figure 12 illustrates possible LRB variance in neighboring counties. Weighting factors in the Bayesian credibility calculation are what determines the contribution of each geographic level to the final, Bayesian-adjusted HLR value.

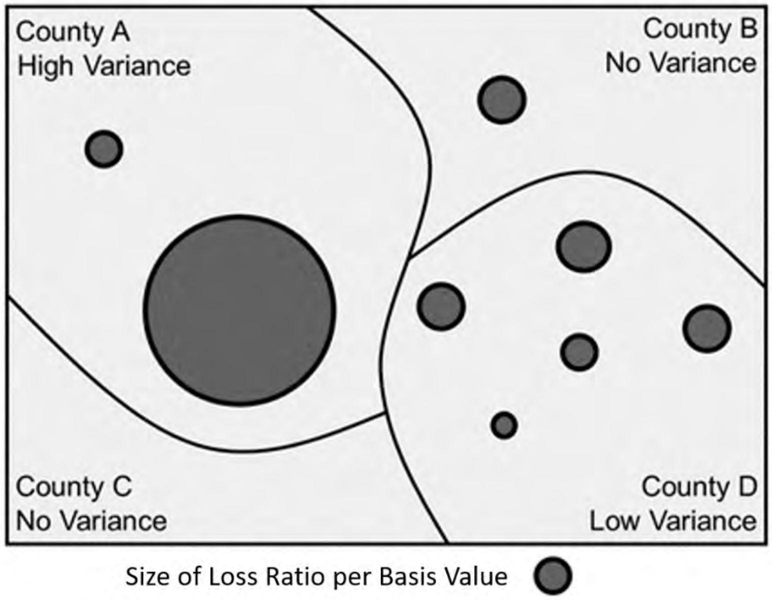


Figure 12: Example of Variance in County Loss Ratio per Basis Values

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. Levels not used for a specific hazard type are removed from the computation.

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 and is used as a denominator for the level weighting factors.
$Wt_{Haz_{X}_{CnsqType}}$	is the weighting factor to be applied to the average consequence type LRB for the hazard type at X level (national, regional, surrounding, county).
$varLRB_{Haz_{X}_{CnsqType}}$	is the consequence type LRB variance for the hazard type at X level (national, regional, surrounding, county).

For several hazard types, regional Bayesian HLR weighting supplies a more accurate estimation of HLR for areas that have not experienced losses due to hazard occurrences during the period of record. This is especially true for areas where hazard type annualized frequency and severity are dependent on their geographic location and climate. For example, Winter Weather 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 select hazard types.

To use this regional weighting, a regional definition for geographical groupings larger than states but smaller than the nationwide grouping 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.

Thus, most HLR region definitions for specific hazard types are derived from the FEMA administrative region definitions, with the only difference being that FEMA Regions 1, 2, and 3 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).[25]

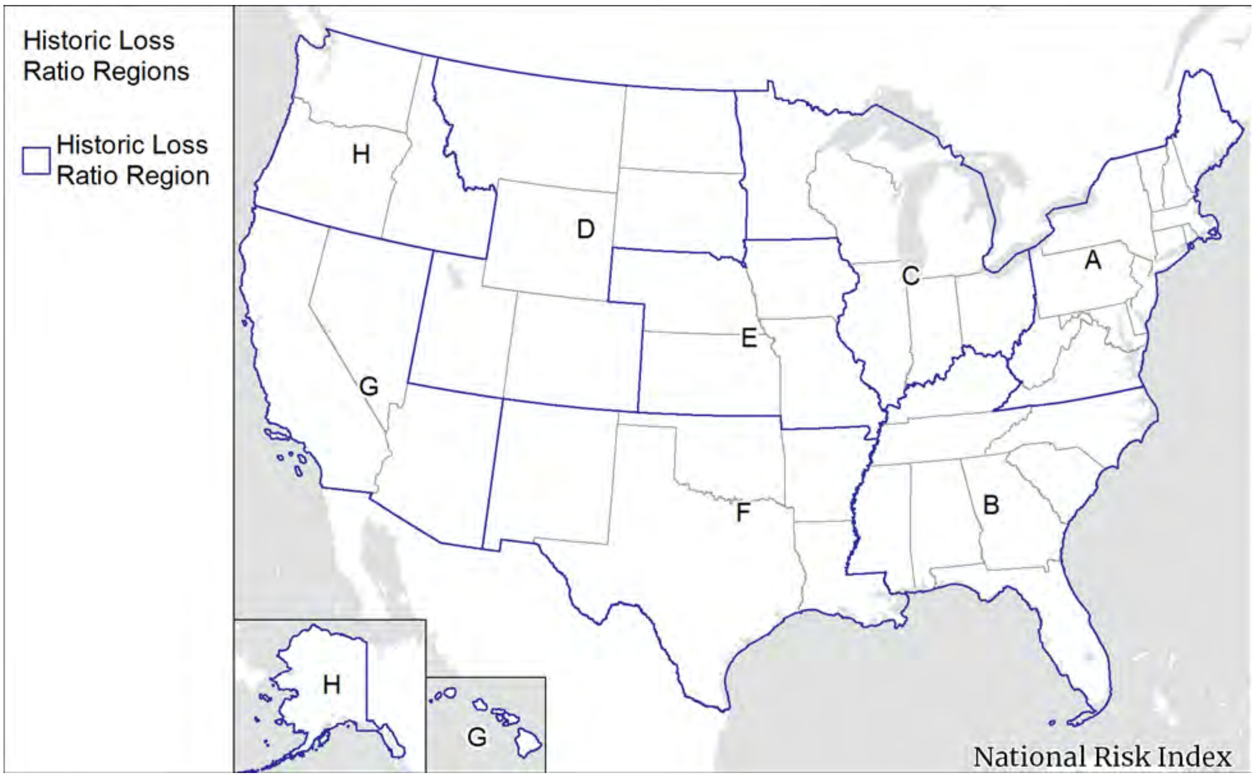


Figure 13: Historic Loss Ratio Region Definitions

[25] 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.

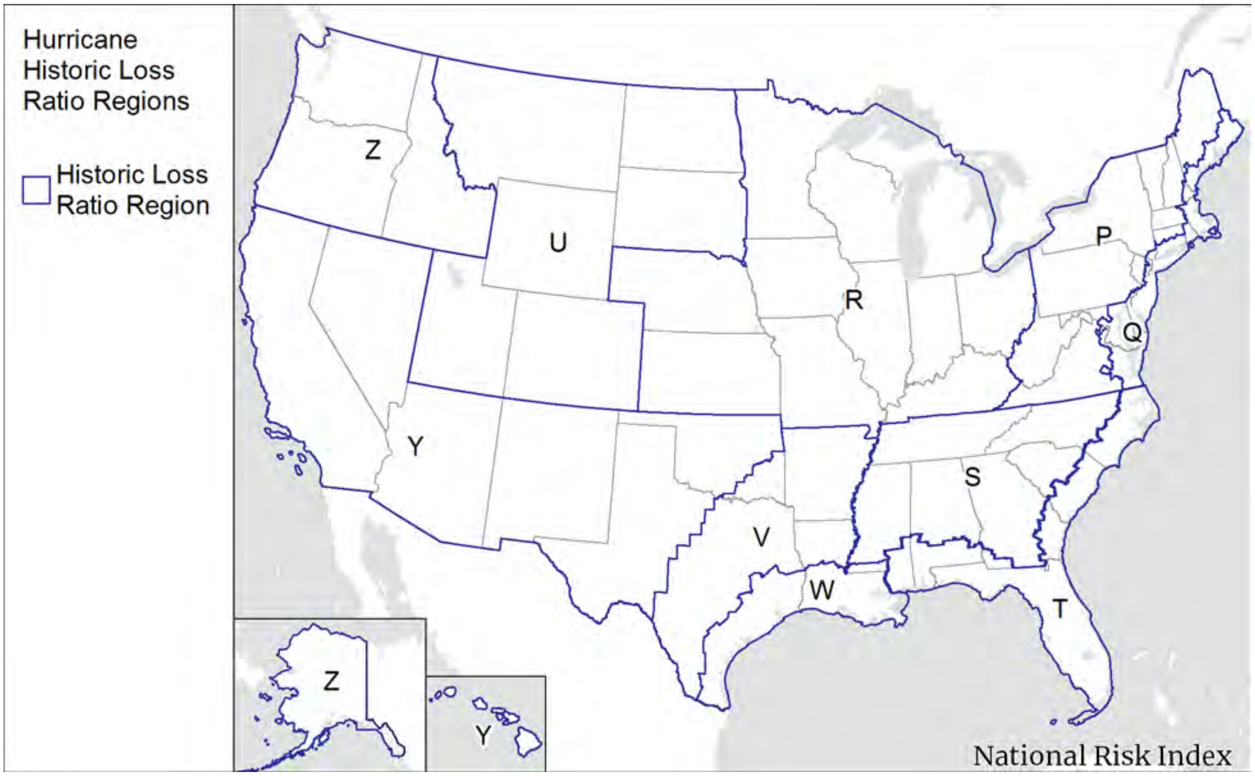


Figure 14: Hurricane Historic Loss Ratio Region Definitions

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

Equation 14: County Bayesian-Adjusted HLR Calculation

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

where:

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

$avgLRB_{Haz\,X_{CnsqType}}$ is the average Loss Ratio per Basis by consequence type for the hazard type at *X* level (national, regional, surrounding, county).

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

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

HLR Inheritance

The county Bayesian-adjusted HLR is inherited by the Census blocks and Census tracts within the parent county when used in the 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 type-county-consequence type specific value.

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

$HLR_{Haz_{CB_{CnsqType}}}$ is the inherited Historic Loss Ratio for the hazard type 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 occurrence 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 2020 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 occurrences, 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 occurrence may reduce the damage caused by subsequent flooding occurrences).

Characterizing agriculture losses from occurrences 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 hazard occurrence reports from NWS and other sources of SHELDUS data. The regional reporting data used to compile SHELDUS may mention multiple counties for a loss-causing occurrence. 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 hazard types and source data 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 type EAL rankings within a county
- County EAL rankings within a hazard type
- County EAL rankings across all hazard types
- Hazard type EAL rankings all counties

In an attempt to validate the EAL, historic losses from SHELDUS and the NCEI Storm Events Database for the period from 1996 to 2019 were aggregated for the U.S. for each hazard type and divided by the period of record (24 years) to give a rough nationwide annualized loss estimate.[26] This value was compared to the aggregated EAL estimate for its corresponding hazard type. All but two

[26] For Cold Wave, the historic loss data were aggregated from the NCEI Storm Events Database for 1996 to 2019 and divided by the 24-year period of record.

(Earthquake and Volcanic Activity) of the hazard type EALs are within the same order of magnitude as the experienced historic losses, and 15 of the 18 hazard types are within a factor of 2.

When evaluating the historical record, losses for some hazard types are driven by relatively few occurrences. For example, from 1996 to 2019, over 75% of all Hurricane consequences were caused by only 7 storms. 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 occurrences. For Wildfire and Earthquake, probabilistic statistics are used to compute an annualized frequency. Use of probabilistic data to calculate EALs for these hazard types accounts for the probability that the outlier event may occur. Reliance on historical data alone for the other hazard types will generally underestimate the EALs for hazard types where losses are driven by the rare catastrophic occurrences. For this reason, Hurricane EALs are significantly lower (~60%) 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 occurrences rather than the rare catastrophic occurrences.

Despite these outliers, a relatively high level of agreement between the calculated EAL and the historical loss records serves as an indication that the 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,[27] 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 where Avalanche are able to occur, but these areas are where population and buildings are most likely to be impacted by Avalanches. For the National Risk Index, 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.

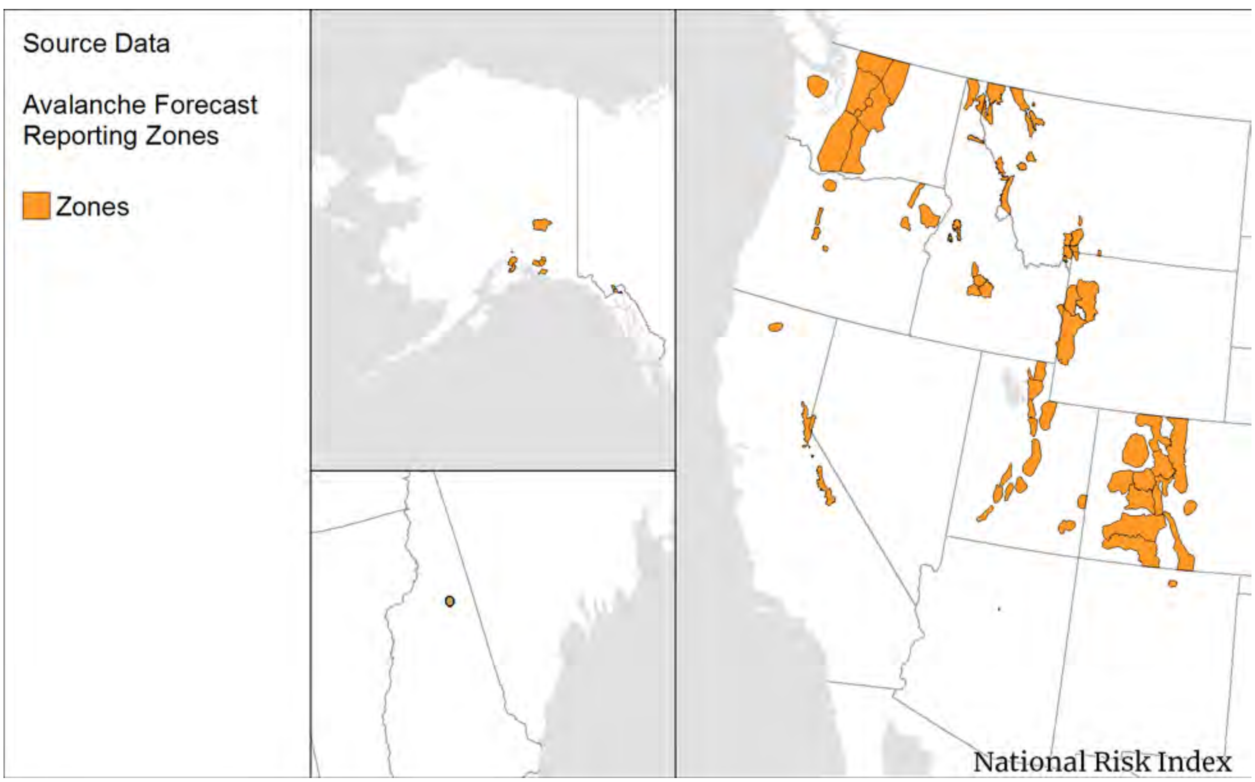


Figure 15: Avalanche Forecast Reporting Zones

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

Historical Occurrence Source: Arizona State University, Spatial Hazard Events and Losses Database of the United States[28]

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

6.1.1. PERIOD OF RECORD

To utilize the largest number of SHELDUS records, data from 1/1/1960 to 12/31/2019 are used to calculate annualized frequency, so the period of record for which Avalanche data are utilized is 60 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 occurrence. Any county that intersected an Avalanche forecast zone or had experienced losses due to credible Avalanche events (as recorded in SHELDUS) is included as one in which Avalanche occurrences are possible (see Figure 16).

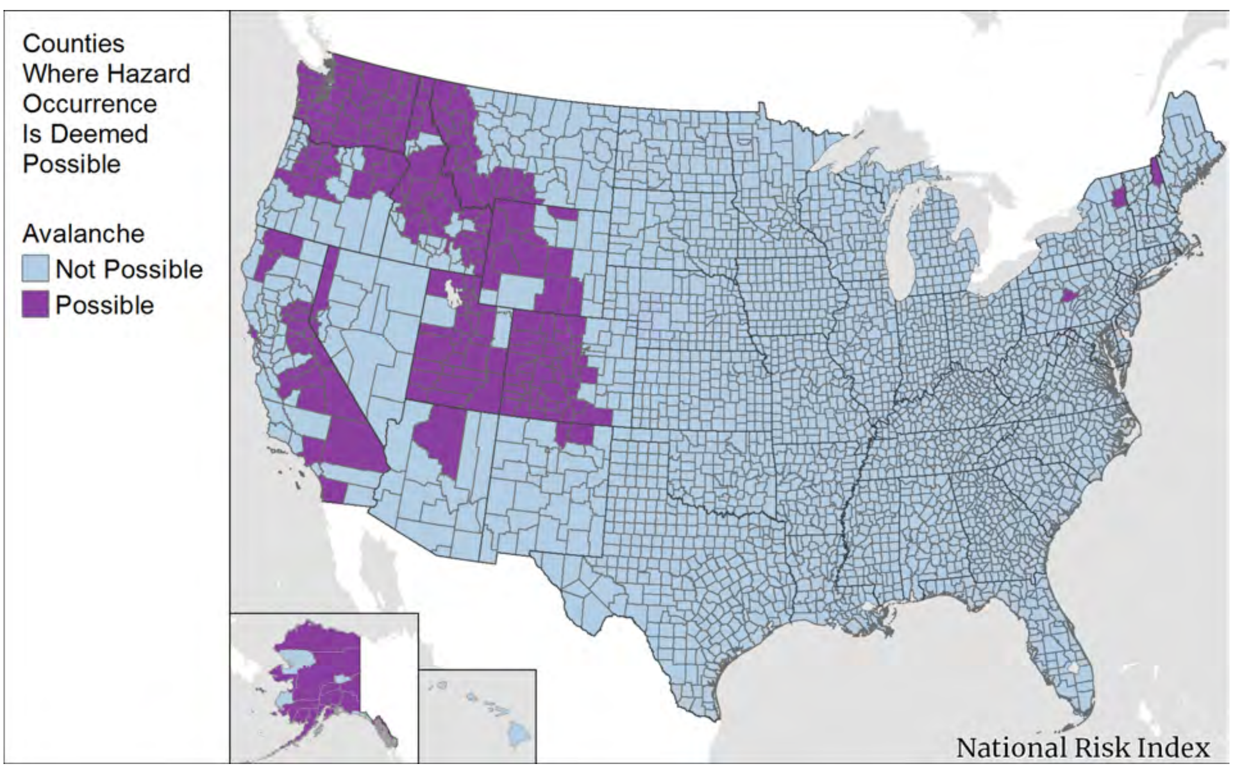


Figure 16: Map of Counties Deemed Possible for Avalanche Occurrence

[28] 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.

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 or $38M population equivalence (using VSL of $7.6M per person). 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 Occurrence Count

The historic occurrence count of Avalanche, in events, is computed as the number of SHELDUS-recorded Avalanche events that have occurred within the county from January 1960 to December 2019. 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. Annualized Frequency

The annualized frequency value represents the number of Avalanche loss-causing occurrences, in events, each year over the period of record (60 years). This annualized frequency is calculated at the county level. The Census tract inherits the parent county-level value, and the Census tract value is used in the EAL calculations.

Annualized frequency calculations use the SHELDUS Avalanche event count for the county and divide by the period of record using Equation 16.

Equation 16: County Avalanche Annualized 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 within the period of record.
$PeriodRecord_{AVLN}$	is the period of record for Avalanche (60 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 subject matter experts to be an acceptable assumption.

6.5.2. ANNUALIZED FREQUENCY INHERITANCE

The Census tract inherits its annualized frequency value from the parent county as in Equation 17.

Equation 17: Census Tract Avalanche Annualized 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 Avalanche annualized frequency at the county level.

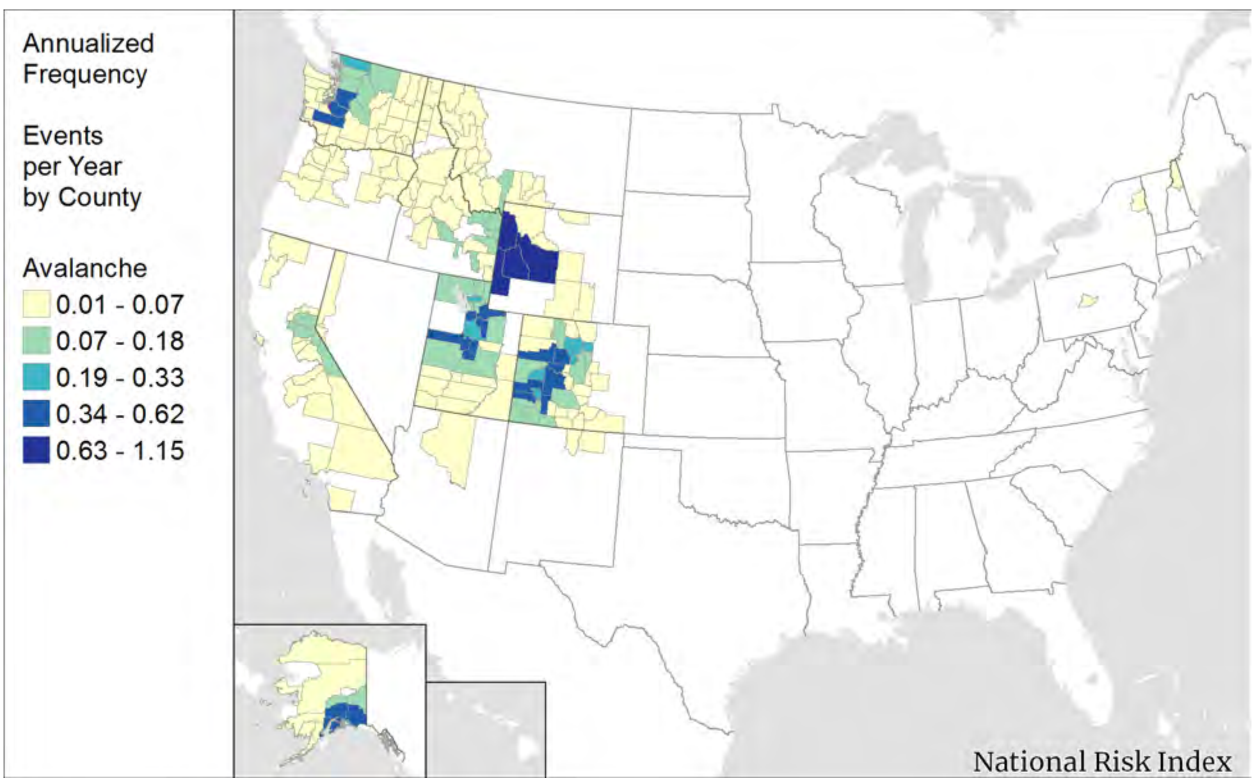


Figure 17: Avalanche Annualized Frequency by County

6.6. Historic Loss Ratio

The Avalanche HLR is the representative percentage of a location's hazard exposure that experiences loss due to an Avalanche occurrence, or the average rate of loss associated with an Avalanche occurrence. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Avalanche hazard type.

Loss data are provided by SHELDUS[29] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Four peril types are mapped to the hazard Avalanche (see Table 16). These native records are aggregated on a timeframe basis (see Section 5.4.4 Historic Loss Ratio Methodology).

Table 16: Avalanche Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Avalanche	1,344	1,174
Avalanche-Debris	0	0
Avalanche-Snow	0	0
Snow-Slide	0	0

The HLR exposure value used in the LRB calculation is the default consequence type value of the county (building value exposure of $1M and population exposure of 5 people; see Section 6.3 Exposure). 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

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

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).

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

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

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 Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Avalanche occurrences within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value, though its HLR may be influenced by national occurrences. Counties that have experienced few loss-causing Avalanche occurrences or have widely varying LRBs get the most influence from national-level loss data. Figure 19 and Figure 21 represent the final, Bayesian-adjusted county-level HLR values for Avalanche.

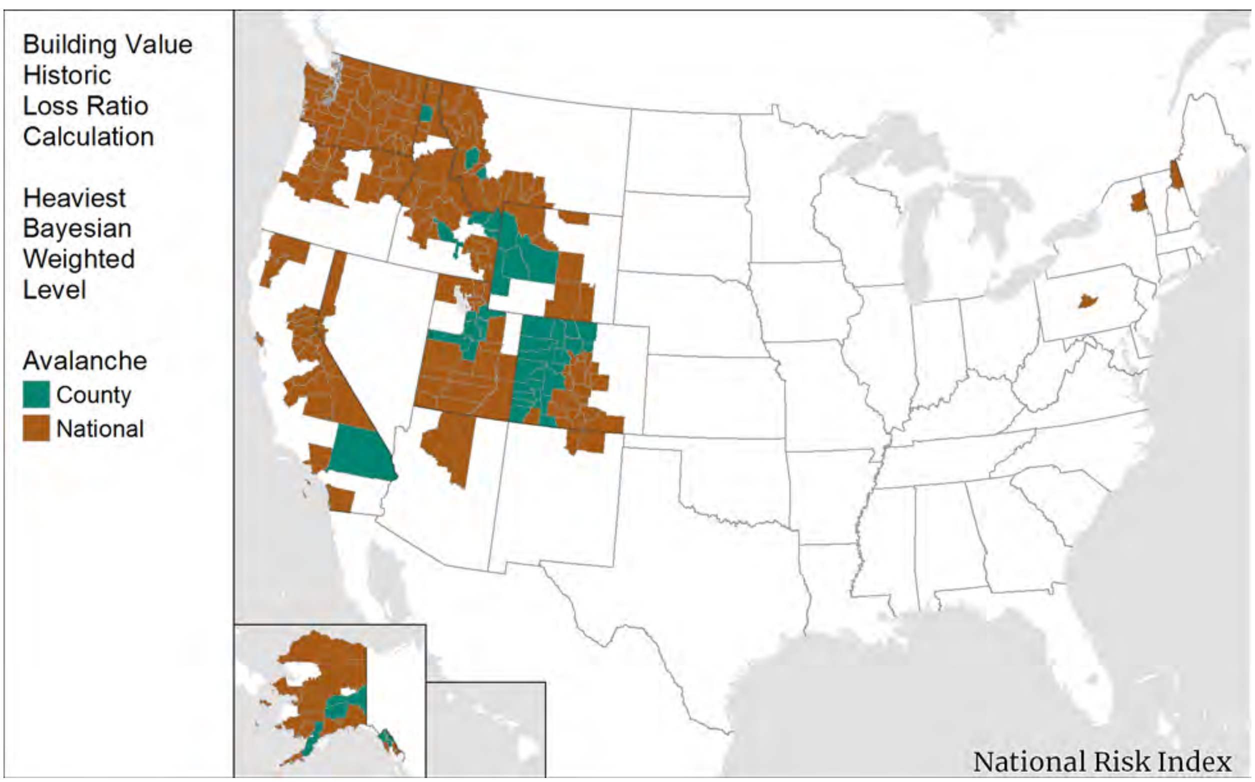


Figure 18: Avalanche Heaviest Bayesian Weighted Level – Building Value

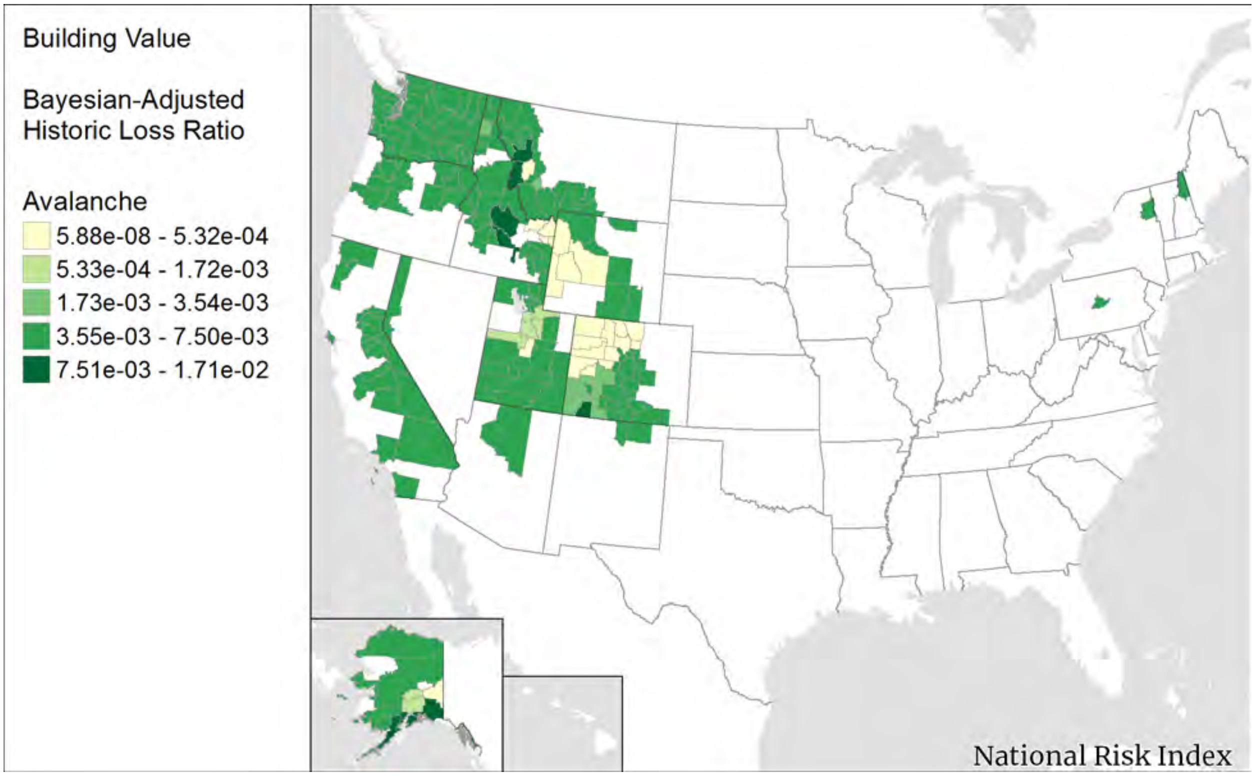


Figure 19: Avalanche Bayesian-Adjusted HLR – Building Value

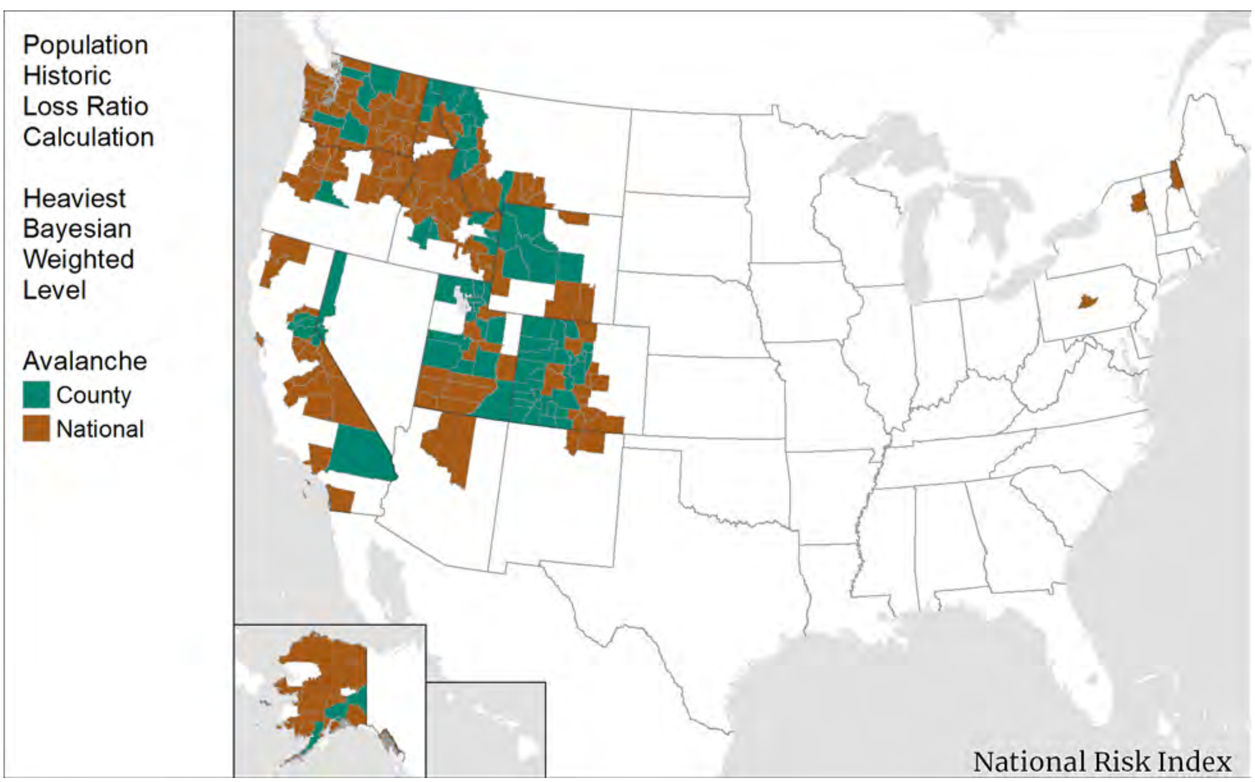


Figure 20: Avalanche Heaviest Bayesian Weighted Level – Population

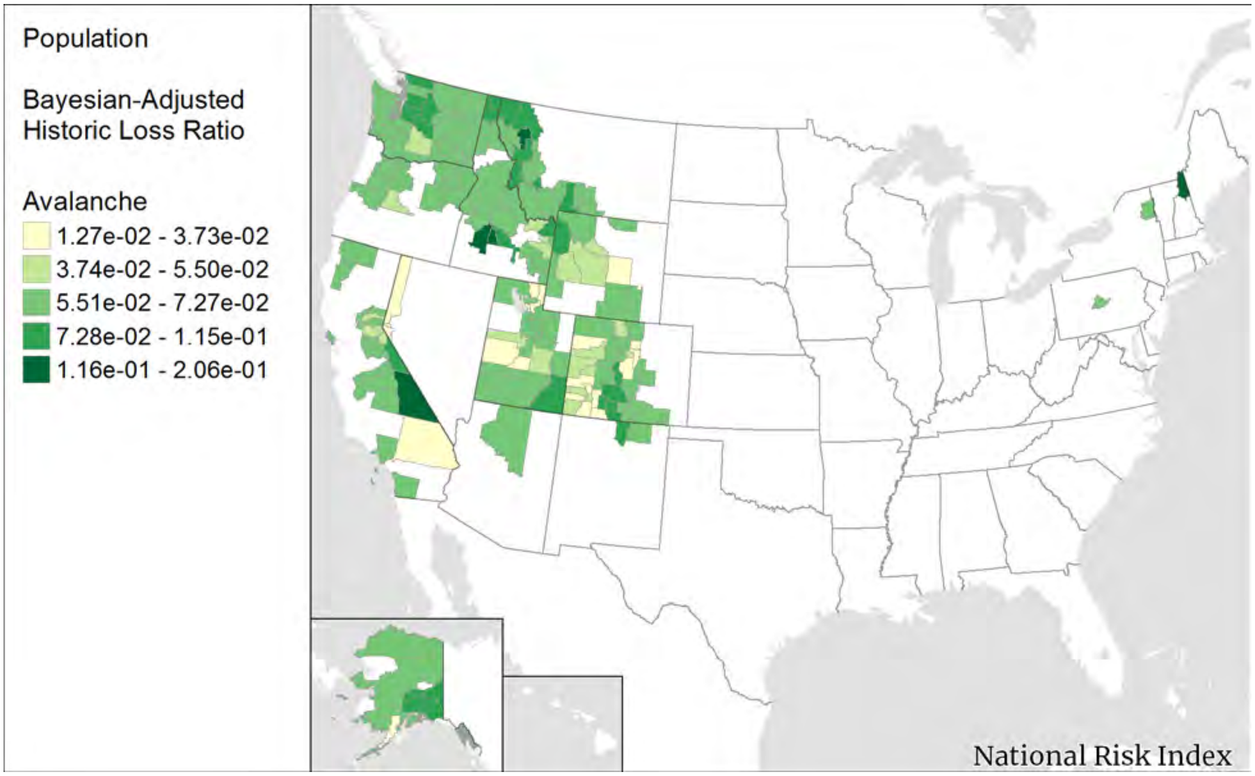


Figure 21: Avalanche Bayesian-Adjusted HLR – Population

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

6.7. Expected Annual Loss

Once exposure, annualized 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 building Expected Annual Loss due to Avalanche occurrences for a specific Census tract (in dollars).

$Exposure_{AVLN_{CT_{Bldg}}}$ is the building value exposed to Avalanche occurrences in the Census tract (in dollars).

$Freq_{AVLN_{CT}}$ is the Avalanche annualized 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 population equivalence Expected Annual Loss due to Avalanche occurrences for a specific Census tract (in dollars).

$Exposure_{AVLN_{CT_{Pop}}}$ is the population equivalence value exposed to Avalanche occurrences 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 building and population equivalence EAL values at the Census tract level as in Equation 20.

Equation 20: County Expected Annual Loss to Avalanche

$$EAL_{AVLN_{CO}} = \max\left(EAL_{AVLN_{CT_{Bldg}}}\right) + \max\left(EAL_{AVLN_{CT_{Pop}}}\right)$$

where:

$EAL_{AVLN_{Co}}$ is the total Expected Annual Loss due to Avalanche occurrences for a specific county (in dollars).

$\max\left(EAL_{AVLN_{CT_{Bldg}}}\right)$ is the maximum building Expected Annual Loss due to Avalanche occurrences of all Census tracts in the county (in dollars).

$\max\left(EAL_{AVLN_{CT_{Pop}}}\right)$ is the maxiumum population equivalence Expected Annual Loss due to Avalanche occurrences of all Census tracts in the county (in dollars).

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

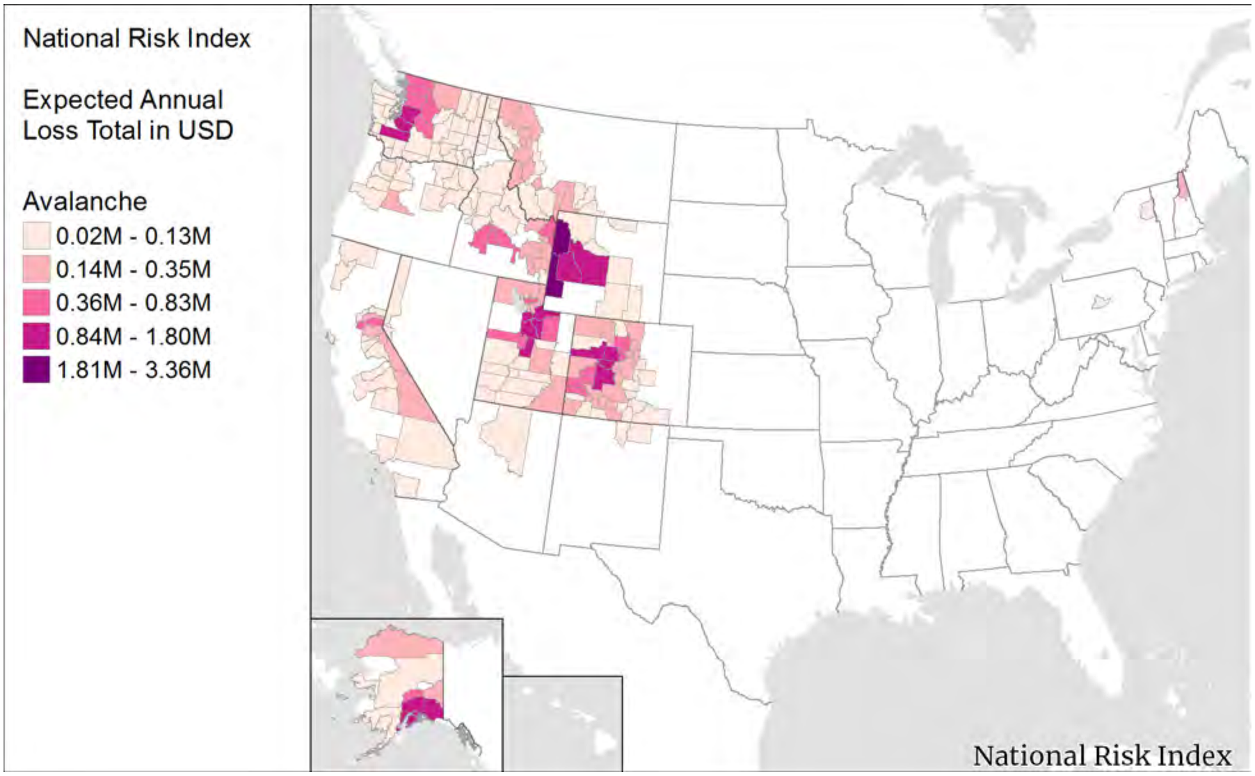


Figure 22: Total Expected Annual Loss by County to Avalanche

With the Avalanche total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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[30]

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 annualized frequency.

Susceptible Area Source: NOAA Office for Coastal Management, Flood Frequency and Sea Level Rise[31]

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 annualized frequency.

Susceptible Area Source: NOAA National Hurricane Center, Sea, Lake, and Overland Surges from Hurricane[32]

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 annualized frequency.

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[30] 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.

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

[32] 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[33]

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.[34]

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. The dataset is used in the calculation of Coastal Flooding annualized frequency.

7.1.1. PERIOD OF RECORD

The period of record for Coastal Flooding annualized frequency calculation varies across the flooding sub-types described in the following sections.

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 annualized frequencies for each flooding sub-type. The sub-types of flooding included in the Coastal Flooding hazard type are:

- Sea level rise and high tide (SLRHT) flooding
- 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 data are extracted for 1% annual chance coastal floodplains (100-year) and 0.2% annual chance floodplains (500-year) 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.

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

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 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 is used to compute surrogates for Coastal Flooding exposure and annualized frequency at the Census tract and county level.

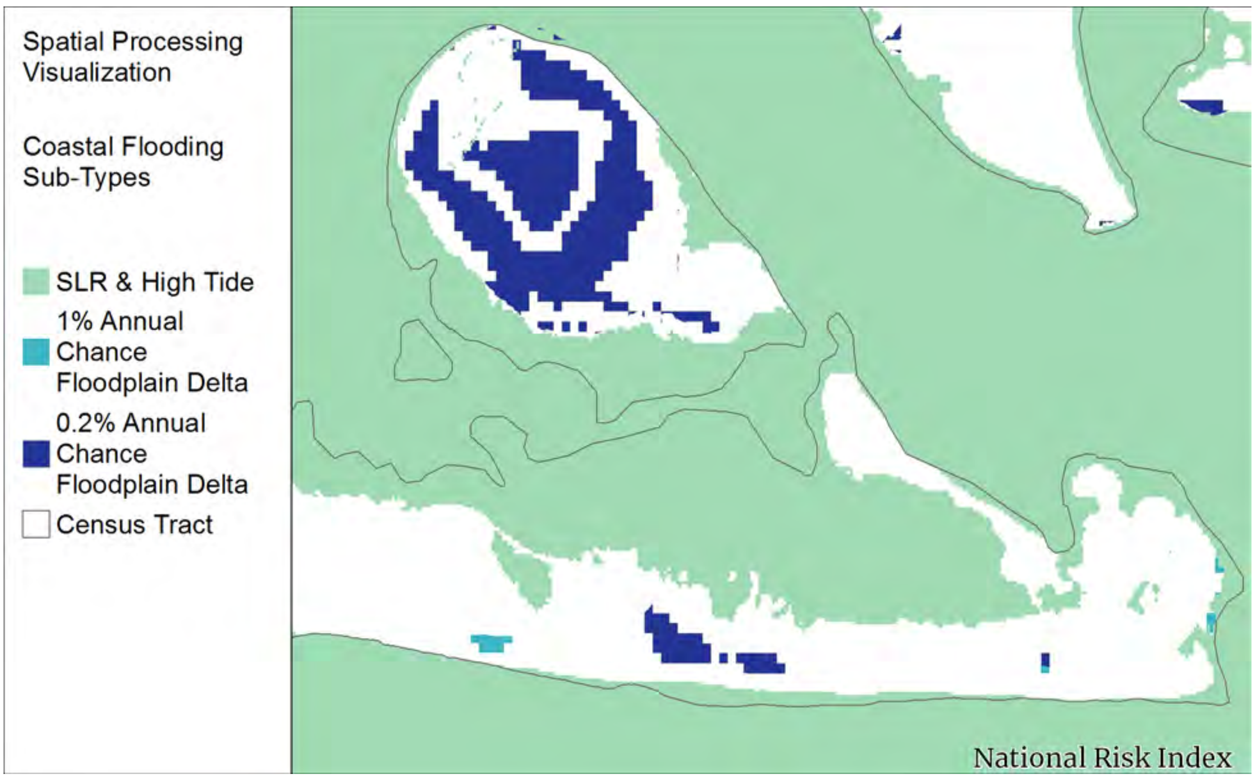

Figure 23: Coastal Flooding Sub-Types (1% Annual Chance and 0.2% Annual Chance Floodplain Delta, Unioned SLRHT)

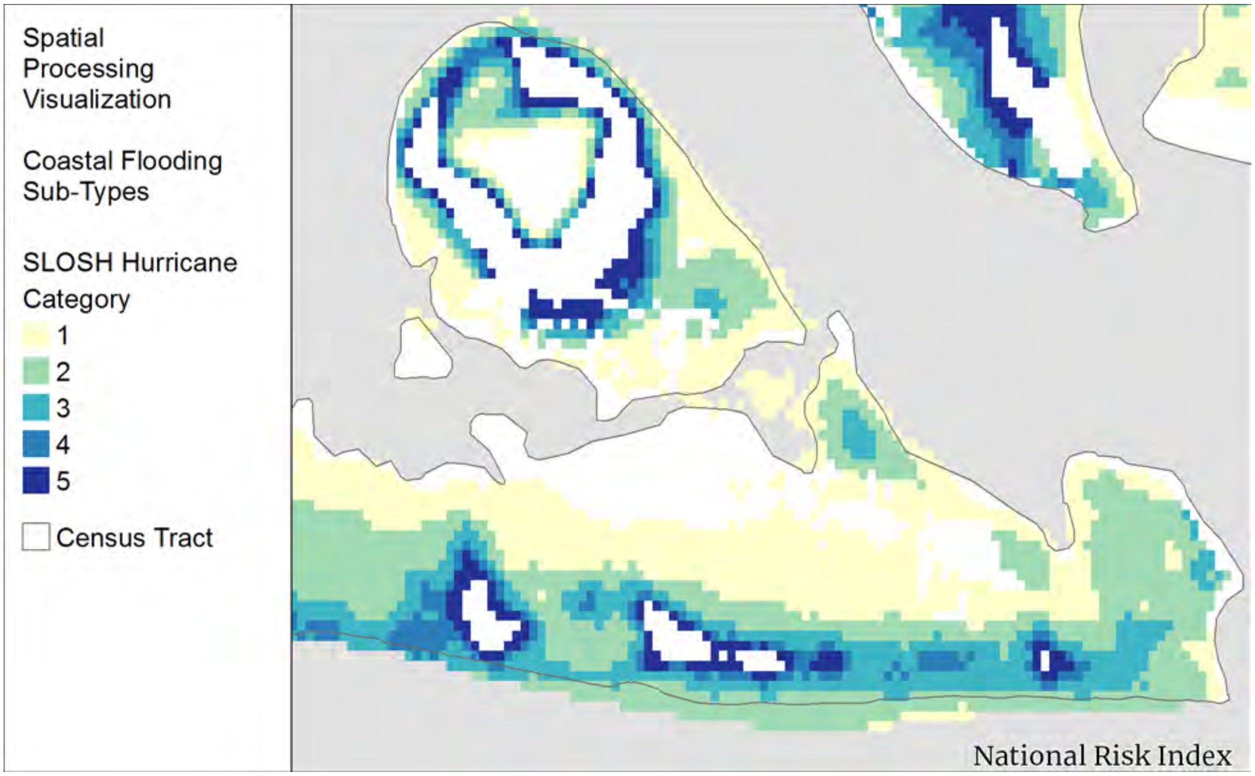

Figure 24: Coastal Flooding Sub-Types (SLOSH Layers, Categories 1-5)

An additional layer was created to divide the country into regions for the purpose of applying varying SLRHT frequencies. These are generally based on geographic groupings of NOAA tidal gauges across the United States.

The National Risk Index also models Coastal Flooding on coasts along large lakes that intersect the merged Coastal Flood Zone footprint or where historic loss has been recorded in SHELDUS due to Coastal Flooding, so regions were created for the Great Lakes and for two counties along the Great Salt Lake in Utah. Alaska was also defined as its own region (see Figure 25).

Figure 25: SLRHT Regions

7.3. Determination of Possibility of Hazard Occurrence

To distinguish between areas with no Coastal Flooding occurrences and those where such occurrences are not deemed possible, a control table was generated to designate which counties have some probability of being impacted by a Coastal Flooding occurrence. Any county that intersected the combined Coastal Flood Zone footprint (including counties along the Great Salt Lake in Utah), bordered coastal waterways (including the coastline of the Great Lakes), or had experienced losses due to Coastal Flooding events (as recorded in SHELDUS) is included as one in which Coastal Flooding occurrences are possible (see Figure 26).

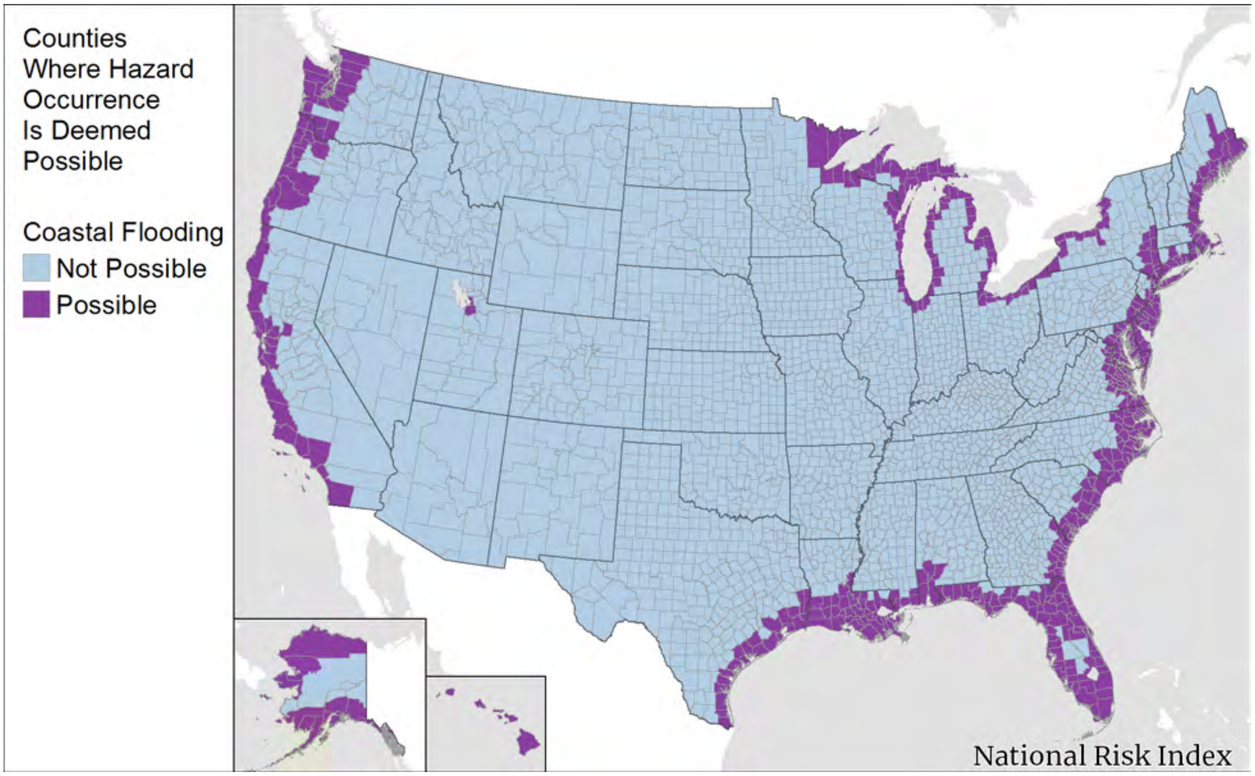

Figure 26: Map of Counties Deemed Possible for Coastal Flooding Occurrence

7.4. Exposure

To identify areas of exposure, each of the Coastal Flooding polygon layers (unioned SLRHT, 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 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 Analytical Techniques). The resulting tables contain the layer polygon's unique identifier, Census block number, the intersected area, and the developed area of intersection (see Table 17). All area values are in square kilometers.

Table 17: Sample Data from the Coastal Flood 1% Annual Chance-Census Block Intersection Table

CoastalFlood Zone100yrID	*CensusBlock*	*IntersectedAreaKm2*	*AreaDevelopedKm2*
391	150030099021008	0.007010063	0.001979101
445	150030098012011	0.111088226	0
2112	480079501002007	1.59E-06	1.59E-06

To determine exposure value for buildings and population, the developed area of the Coastal Flooding sub-type 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 (see Equation 21). These Census block developed area building and population value densities have been calculated by dividing the total exposure values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers; see Section 5.3.3 Exposure Methodology). The VSL was used to express population equivalence exposure in terms of dollars.

Equation 21: Census Block Coastal Flooding Sub-Type Building and Population Exposure

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

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

where:

$Exposure_{CFLDSub\,CB_{Bldg}}$	is the estimated building value exposed to the Coastal Flooding sub-type in a specific Census block (in dollars).
$IntsctDevArea_{CFLDSub\,CB}$	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).
$Exposure_{CFLDSub\,CB_{Pop}}$	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 ($7.6M per person).

These calculations are performed for each of the eight layers 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 annualized frequency. Exposure and annualized frequency for all Coastal Flooding sub-types are combined at the Census block level prior to being multiplied by the county-level Bayesian-adjusted HLR for EAL computation. For display in the application, a single consequence exposure value is needed. Individual Census block exposure values for each flooding sub-type cannot simply be summed to get total consequence 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 surrogate. The county-level exposure surrogate is the aggregation of its Census tracts' exposure values (see Equation 22). Neither of these exposure surrogates are 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 type 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. Annualized Frequency

The annualized frequency value represents the modeled frequency of a Coastal Flooding occurrence, in events, per year. Coastal Flooding annualized frequency is calculated at the Census block level by Coastal Flooding sub-type. The separate intersection of the Census block with the 1% annual chance floodplain delta layer, 0.2% annual chance floodplain delta layer, the unioned SLRHT layer, and SLOSH layers governs which sub-type frequencies are applicable to each Census block.

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

- SFHA 1% annual chance: 0.01
- SFHA 0.2% annual chance: 0.002
- Union of sea level rise and high tide flooding: varies by SLRHT region
- SLOSH polygon: varies by hurricane category

SLRHT annualized frequency is determined at the region level (see Section 7.2 Spatial Processing and Figure 25). An average frequency was calculated for each region from high tide flooding (HTF) recurrence intervals for 146 NOAA tidal gauges distributed throughout the continental U.S. and Hawaii. These regional frequencies are adapted from NOAA research on HTF patterns[35] that are now inclusive of the entire historic dataset through 2018 and based upon a Generalized Pareto Distribution fit. These regional frequencies are given in Table 18. Note that HTF data were not supplied for the Alaska, Great Salt Lake, or Great Lakes regions. For Alaska and the Great Lakes, the national average SLRHT frequency of 3.3 events per year is used.

Table 18: SLRHT Frequency by Region

Region	*Areas Included*	*Average SLRHT Frequency*
Alaska	Alaska	3.3
Pacific Northwest	Oregon and Washington	4.5
California	California	1.5
Hawaii	Hawaii	0.2
Great Lakes	Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Western Pennsylvania, Wisconsin	3.3
Great Salt Lake	Salt Lake and Davis counties in Utah	0
Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, Eastern Pennsylvania, Rhode Island, Virginia	4.4
Southeast	Atlantic Coast of Florida, Georgia, North Carolina, South Carolina	2.6
East Gulf Coast	Alabama, Gulf Coast of Florida, Mississippi	1.9
West Gulf Coast	Louisiana, Texas	3.8

To adjust SLRHT frequencies for areas protected by levees, any Census block that intersects an "X" Zone with sub-type "AREA WITH REDUCED FLOOD RISK DUE TO LEVEE" from the NFHL source data receives a SLRHT frequency of 1/500 years (0.002) rather than the average frequency for its region.

To calculate SLOSH annualized 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 19. (More information on the spatial processing of Hurricane source data can be found in Section 13.2 Spatial Processing.)

[35] Sweet, V.W., Dusek, G., Obeysekera, J., and Marra, J.J. (2018). *Patterns and projections of high tide flooding along the U.S. coastline using a common impact threshold*. NOAA Technical Report NOS CO-OPS 086. Retrieved from https://tidesandcurrents.noaa.gov/publications/techrpt86_PaP_of_HTFlooding.pdf.

Table 19: Hurricane Categorization with Average Radius of Storm Force Winds

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)*
Other	0	38.9	0	32.9	0
Tropical Storm	39	73.9	33	63.9	15
Category 1	74	95.9	64	82.9	26.45
Category 2	96	110.9	83	95.9	39.1
Category 3	111	129.9	96	112.9	43.7
Category 4	130	156.9	113	136.9	50.03
Category 5	157	9999	137	9999	54.04

For the SLOSH annualized 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) was 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-by-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 Hurricane Category Annualized Frequency Calculation

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

where:

$Freq_{SLOSH_{Co_{HRCNCat}}}$ is the SLOSH annualized 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 annualized frequency value of the parent county.

7.5.1. ANNUALIZED FREQUENCY AGGREGATION

In the application, a surrogate annualized frequency value calculated as the sum of the maximum Coastal Flooding sub-type frequencies within the community is provided at both the Census tract and county level (see Equation 24). Multiplying this summed annualized 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 Flooding sub-type exposure and associated annualized frequencies.

Equation 24: Census Tract Coastal Flooding Annualized Frequency Surrogate

$$Freq_{CFLD_{CT}} = \max\left(Freq_{100Yr_{CB}}\right) + \max\left(Freq_{500Yr_{CB}}\right) + \max\left(Freq_{SLRHT_{CB}}\right) + \max\left(Freq_{SLOSH1_{CB}}\right) + \max\left(Freq_{SLOSH2_{CB}}\right) + \max\left(Freq_{SLOSH3_{CB}}\right) + \max\left(Freq_{SLOSH4_{CB}}\right) + \max\left(Freq_{SLOSH5_{CB}}\right)$$

where:

$Freq_{CFLD_{CT}}$	is the surrogate annualized frequency of Coastal Flooding events in a specific Census tract (events per year).
$max\left(Freq_{100Yr_{CB}}\right)$	is the maximum annualized frequency of 1% annual chance Coastal Flooding of all Census blocks within a specific Census tract (1 event per 100 years or 0.01 events per year).
$max\left(Freq_{500Yr_{CB}}\right)$	is the maximum annualized frequency of 0.2% annual chance Coastal Flooding of all Census blocks within a specific Census tract (1 event per 500 years or 0.002 events per year).
$max\left(Freq_{SLRHT_{CB}}\right)$	is the maximum annualized frequency of Sea Level Rise and High Tide Coastal Flooding of all Census blocks within a specific Census tract (varies by SLRHT region).
$max\left(Freq_{SLOSH1-5_{CB}}\right)$	is the maximum annualized frequency of the SLOSH Hurricane category of all Census blocks within a specific Census tract (events per year).

The county-level annualized frequency surrogate uses the same formula as the Census tract surrogate by summing the maximum sub-type frequencies of all Census blocks within the county. If no Census block in the Census tract or county intersects a sub-type layer, the frequency value for that sub-type is 0.

Figure 27 displays the surrogate Coastal Flooding annualized frequency at the county level.

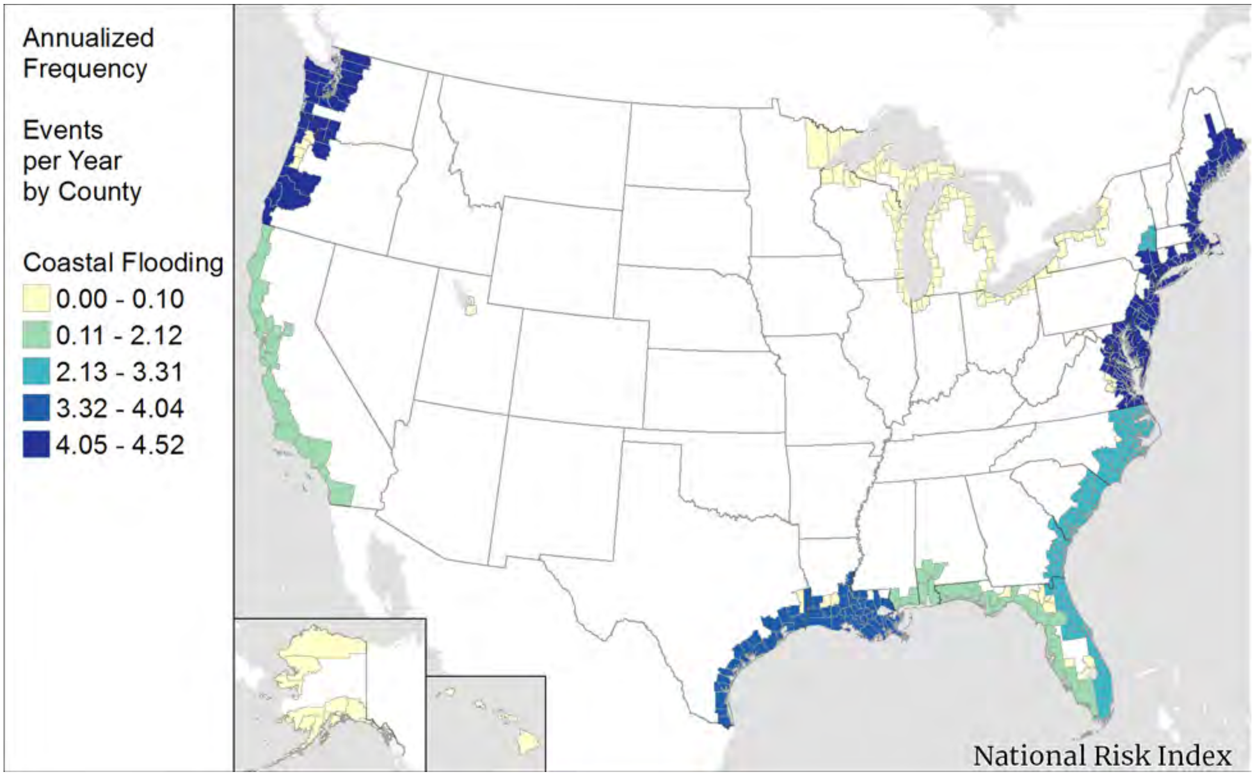

Figure 27: Coastal Flooding Annualized Frequency by County

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 occurrence, or the average rate of loss associated with a Coastal Flooding occurrence. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Coastal Flooding hazard type.

Loss data are provided by SHELDUS[36] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Four peril types are mapped to the hazard Coastal Flooding (see Table 20). These native records are aggregated on a consecutive day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

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

Table 20: Coastal Flooding Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Coastal	0	0
Coastal Storm	22	22
Flood-Coastal	795	620
Flood-Tidal	1	1

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 Exposure Aggregation). 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 or impacted people).

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

Since Coastal Flooding frequency is based on flooding probabilities, no zero-loss occurrences 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 derived from the FEMA regions with Regions 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

Figure 28 and Figure 30 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 Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Coastal Flooding occurrences within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value even though its HLR may be influenced by other local or regional occurrences. The surrounding area's HLRs have the greatest influence on the Bayesian-adjusted HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing occurrences 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 occurrence during the period of record, the coastal counties in that region receive the national average HLR for Coastal Flooding. Figure 29 and Figure 31 represent the final, Bayesian-adjusted county-level HLR values for Coastal Flooding.

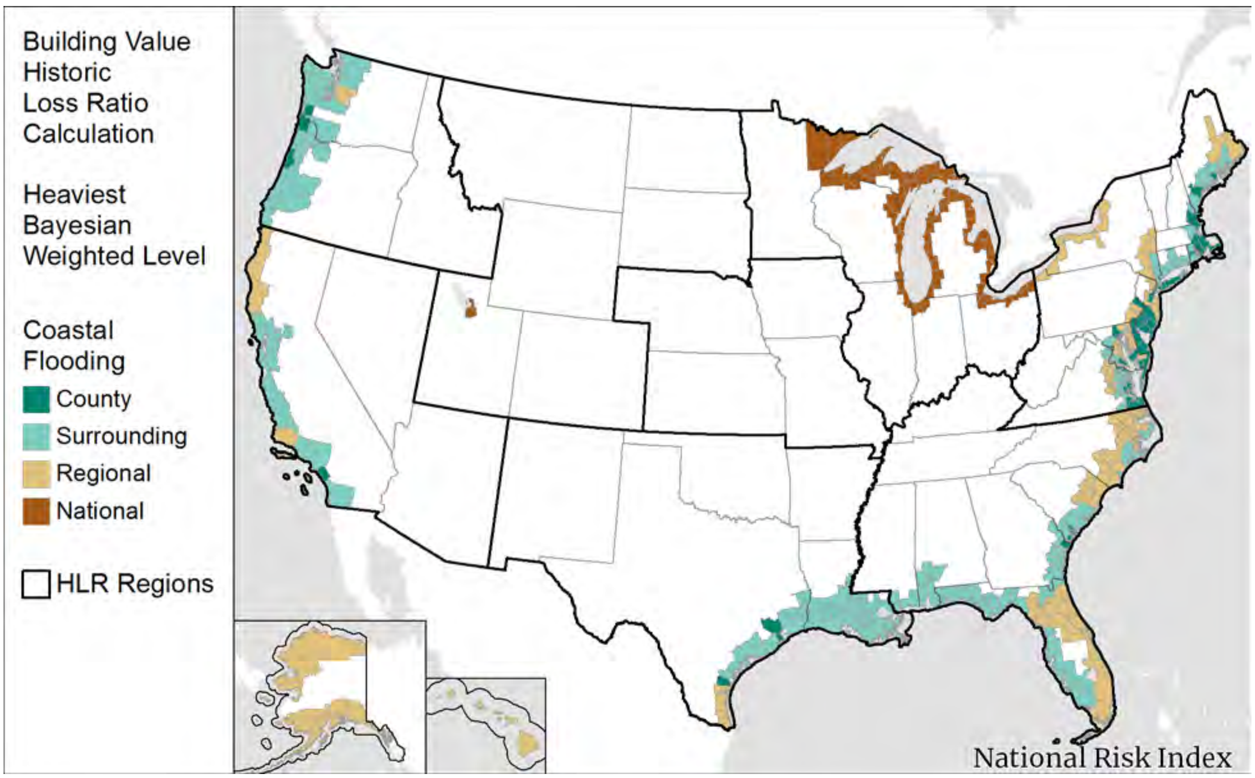

Figure 28: Coastal Flooding Heaviest Bayesian Weighted Level – Building Value

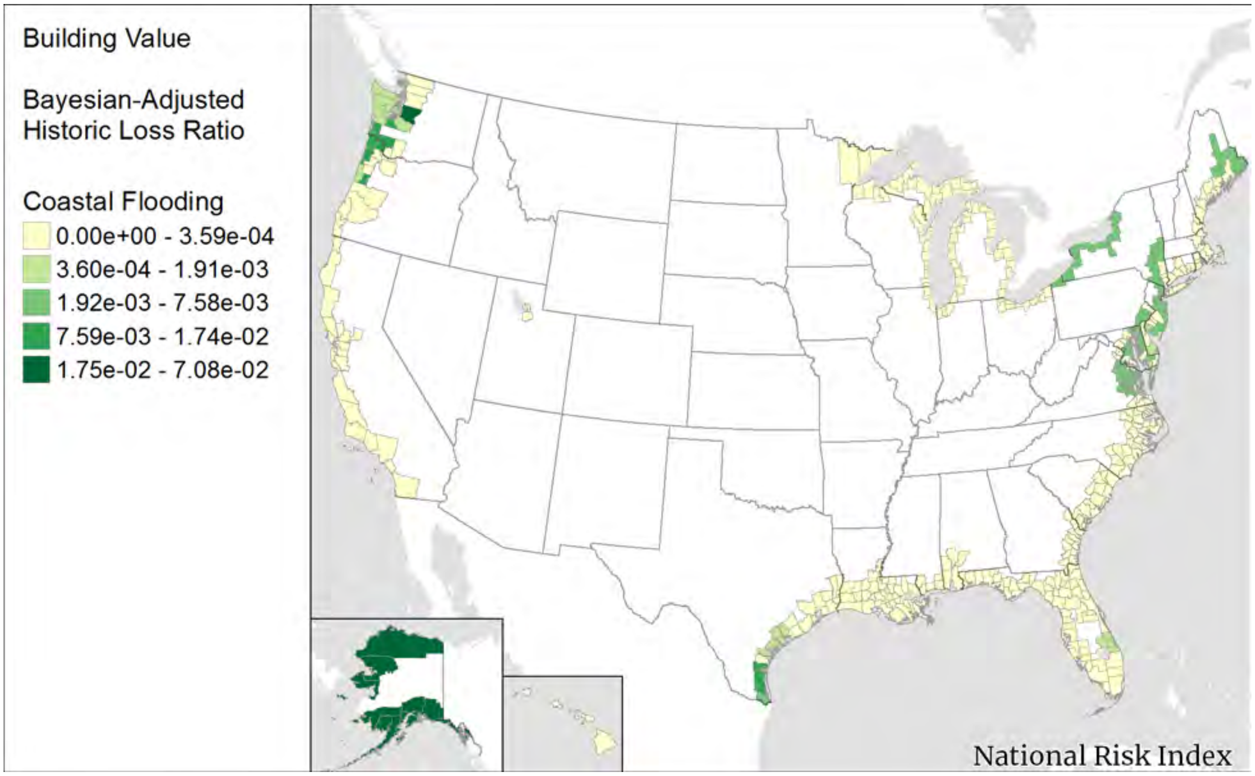

Figure 29: Coastal Flooding Bayesian-Adjusted HLR – Building Value

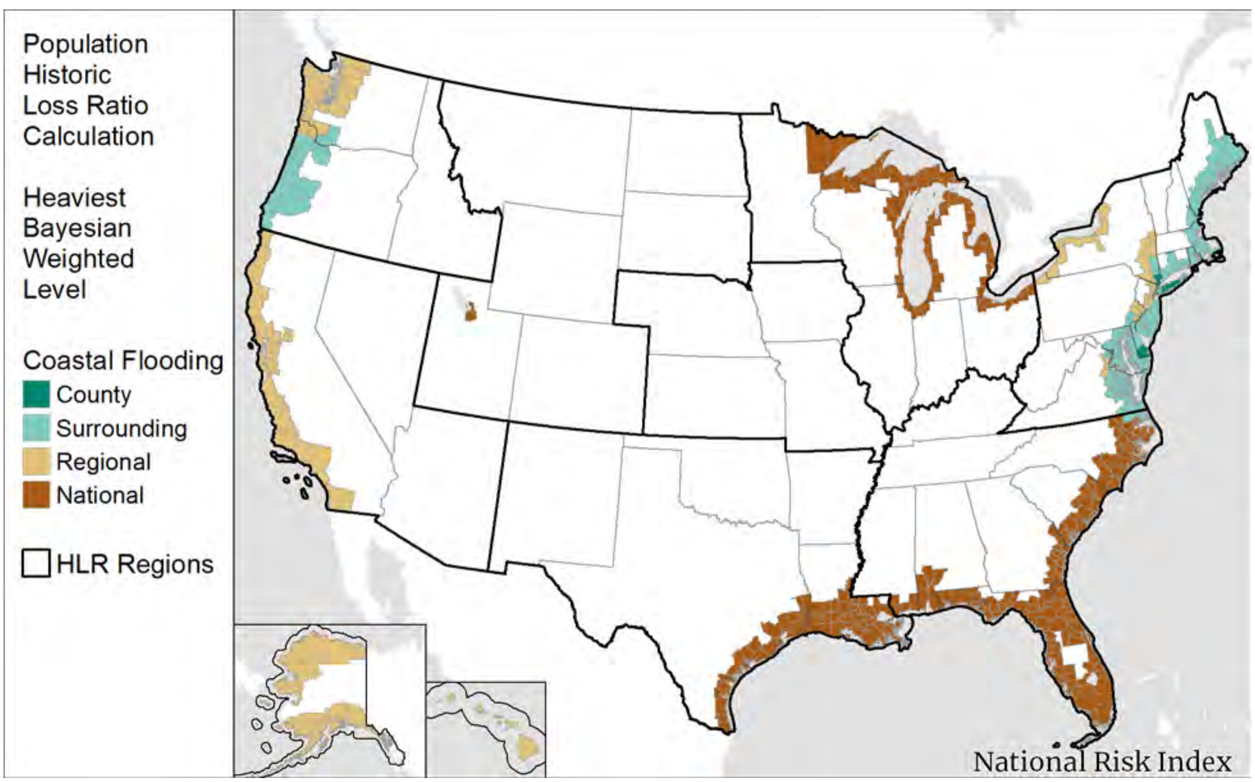

Figure 30: Coastal Flooding Heaviest Bayesian Weighted Level – Population

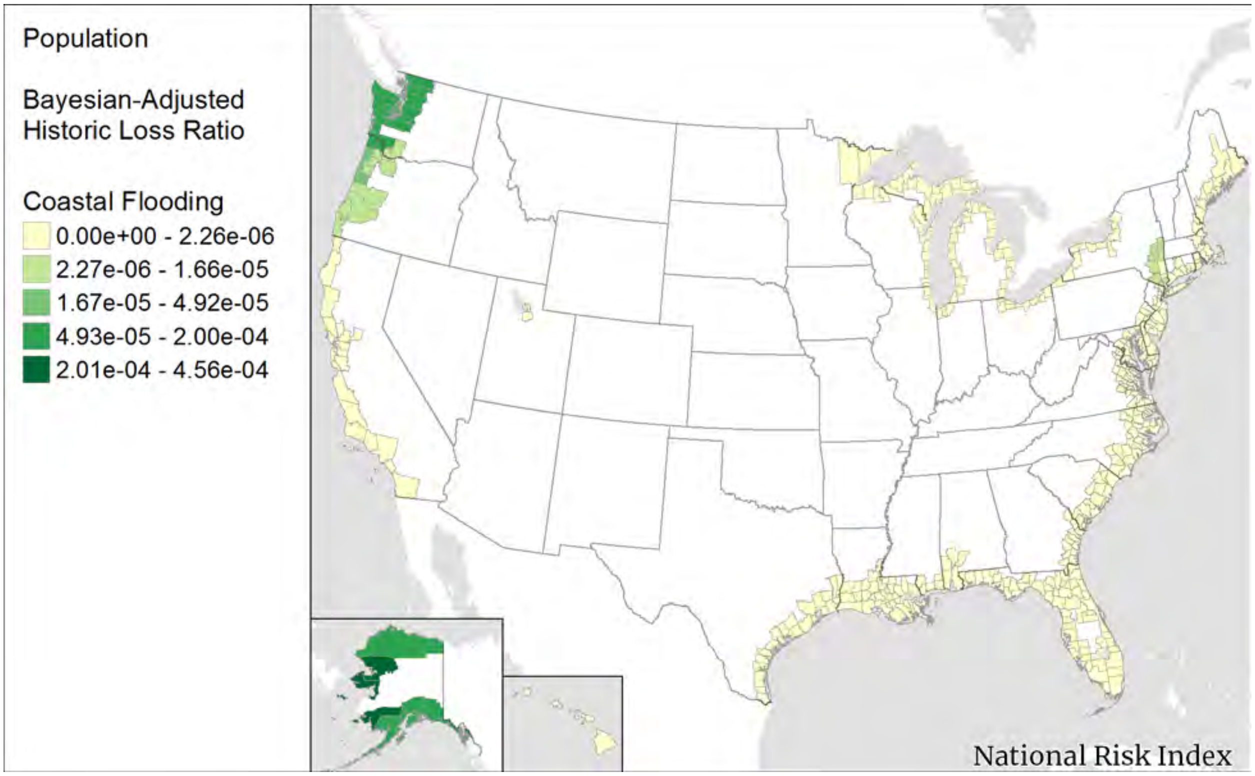

Figure 31: Coastal Flooding Bayesian-Adjusted HLR – Population

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

7.7. Expected Annual Loss

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

Equation 26: Census Block Coastal Flooding Annualized 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 summed product of Coastal Flooding annualized frequency and exposure by sub-type for the consequence type for a specific Census block.

$Exposure_{100Yr_{CB_{CnsqType}}}$ is the consequence type 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 type 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 type 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 (varies by SLRHT region in events per year).

$Exposure_{SLOSH1-5_{CB_{CnsqType}}}$ is the consequence type 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 annualized 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 building Expected Annual Loss due to Coastal Flooding occurrences for a specific Census block (in dollars).

$FreqExp_{CFLD_{CB}_{Bldg}}$ is the summed product of Coastal Flooding annualized 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 population equivalence Expected Annual Los due to Coastal Flooding occurrences for a specific Census block (in dollars).

$FreqExp_{CFLD_{CB}_{Pop}}$ is the summed product of Coastal Flooding annualized frequency and exposure for population equivalence 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 building and population equivalence EAL values 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 occurrences for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{CFLD_{CB_{Bldg}}}$	is the summed building Expected Annual Loss value due to Coastal Flooding occurrences for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{CFLD_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Coastal Flooding occurrences for all Census blocks in the Census tract (in dollars).
$EAL_{CFLD_{Co}}$	is the total Expected Annual Loss due to Coastal Flooding occurrences for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{CFLD_{CB_{Bldg}}}$	is the summed building Expected Annual Loss value due to Coastal Flooding occurrences for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{CFLD_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Coastal Flooding occurrences for all Census blocks in the county (in dollars).

Figure 32 shows the total EAL (building value and population equivalence combined) to Coastal Flooding occurrences.

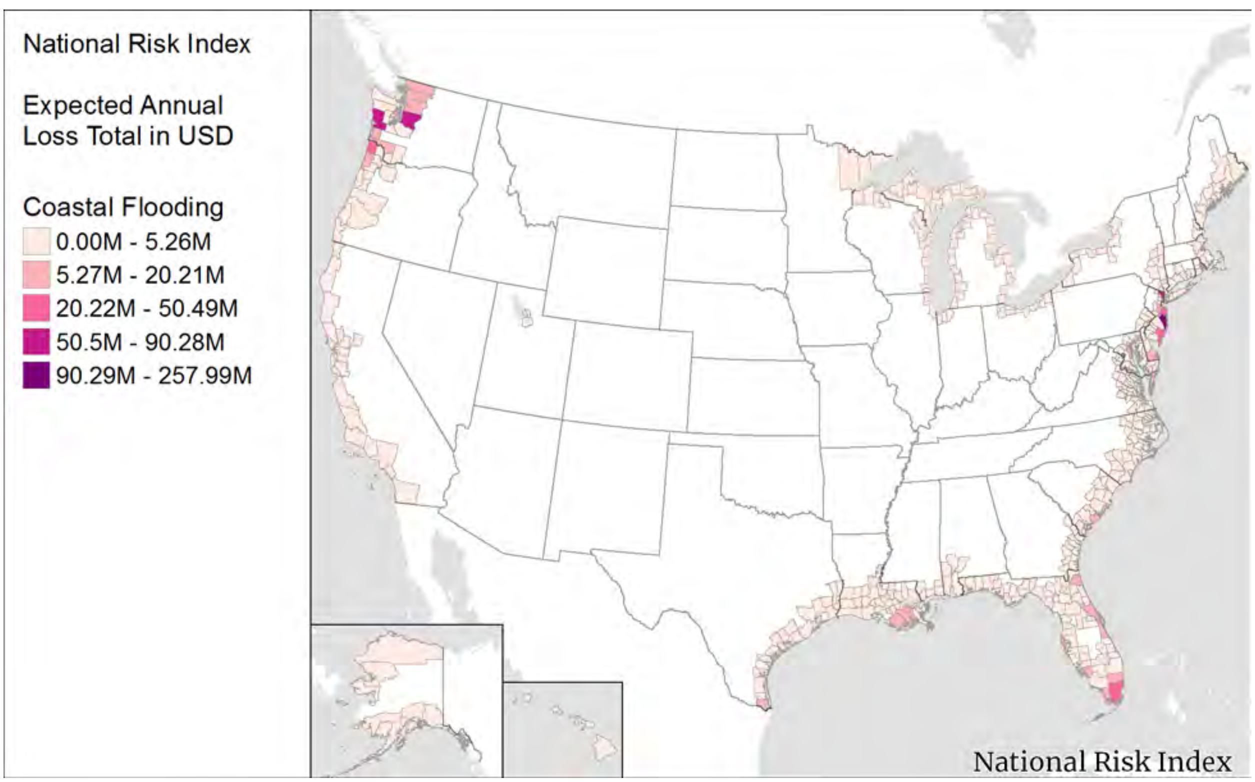

Figure 32: Total Expected Annual Loss by County to Coastal Flooding

With the Coastal Flooding total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 Occurrence Generating Source: National Weather Service, Weather Alerts[37]

Historical Occurrence Compiling Source: Iowa State University, Iowa Environmental Mesonet[38]

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 annualized 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[39] 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.

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

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

[39] 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,[40] 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 distributions 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.

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 many 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.

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 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. See Figure 33 for an example of the differences in the spatial resolution of weather alert boundaries.

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

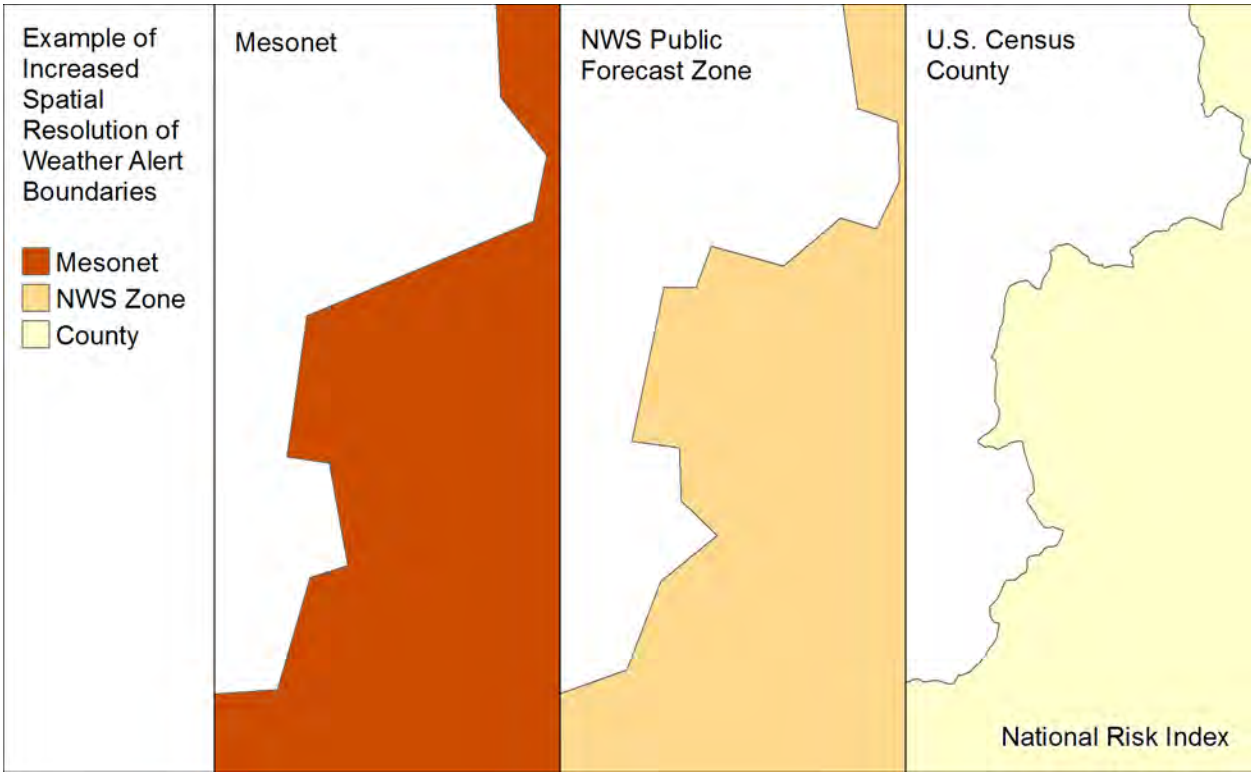

Figure 33: Three Boundary Definitions: Mesonet, Forecast Zone, and U.S. Census County

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 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 occurrence, 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 annualized 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 Cold Wave occurrences (see Table 21).

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 21: Original Mesonet Cold Wave Records

WFO	*ISSUED*	*EXPIRED*	*PHENOM*	*SIG*	*NWS_UGC*	*AREA_KM2*
DLH	12/25/2017 6:00 AM	12/26/2017 6:00 PM	WC	W	MNZ018	4648.70996
BIS	1/3/2017 9:06 PM	1/4/2017 6:07 PM	WC	W	NDZ020	1888.72131
MSO	2/6/2014 2:33 PM	2/6/2014 5:25 PM	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. To illustrate this concept, the Cold Wave events in Table 22 are expanded to create the Cold Wave event-day records in Table 23.

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.

Table 22: Sample Cold Wave Data after Zone Shape Re-Sourcing

ColdwaveID	*WFO*	*Issued*	*Expired*	*PHENOM*	*SIG*	*NWS_UGC*	*AreaKm2*	*NewShapeSource*
1189968	DLH	1/5/2014 12:00 AM	1/7/2014 5:07 PM	WC	W	WIZ002	3917.1735	Census County

Table 23: Sample Data from the Cold Wave Date Expansion Table

ExpansionID	*ColdwaveID*	*Issued*	*Expired*	*DateType*	*ColdwaveHours*
10771	1189968	1/5/2014 12:00 AM	1/6/2014 12:00 AM	Expanded Dates - Issued	24
10772	1189968	1/6/2014 12:00 AM	1/7/2014 12:00 AM	Expanded Dates - New Dates	24
10773	1189968	1/7/2014 12:00 AM	1/7/2014 5:07 PM	Expanded Dates - Expired	17.11666

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 annualized frequency.

8.3. Determination of Possibility of Hazard Occurrence

Cold Waves are able to occur almost anywhere in the U.S. 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 8.2 Spatial Processing) are intersected with the Census block polygons within the 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 24).

Table 24: 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-day polygons that intersected the Census block and dividing this sum by the number of intersecting event-day polygons. This is multiplied by the developed area building value density, the developed area population density, and the agriculture area value density of the Census block to model the conservative-case concentration of exposure within the Census block (see Equation 29). These Census block densities have been calculated by dividing the Census block total exposure values (as recorded in Hazus 4.2 SP1) by the developed or agriculture land area (in square kilometers). The VSL was used to express population equivalence exposure in terms of dollars.

Equation 29: Census Block Cold Wave Exposure

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

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

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

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).
$EventDayCount_{CWAV_{CB}}$	is the total number of Cold Wave event-day polygons 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 equivalence 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 ($7.6M per person).
$Exposure_{CWAV_{CB_{Ag}}}$	is the agriculture 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 building value exceeds the Hazus-recorded building value, then the Hazus-recorded building value is used as the building 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 Census 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 Tract 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 equivalence 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 equivalence exposed to Cold Wave for each Census block within the Census tract (in dollars).

$Exposure_{CWAV_{Co_{Pop}}}$ is the population equivalence 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 equivalence exposed to Cold Wave for each Census block within the county (in dollars).

$Exposure_{CWAV_{CT_{Ag}}}$ is the agriculture 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 agriculture value exposed to Cold Wave for each Census block within the Census tract (in dollars).

$Exposure_{CWAV_{Co_{Ag}}}$ is the agriculture 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 agriculture value exposed to Cold Wave for each Census block within the county (in dollars).

8.5. Historic Occurrence Count

The historic occurrence count of Cold Wave, in 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 Census 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 annualized 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. Annualized Frequency

The number of recorded Cold Wave occurrences, in event-days, each year over the period of record (12.14 years) is used to estimate the annualized 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 annualized frequency as this method better captures the variability in duration between occurrences. The annualized frequency is calculated at the Census block level, and this Census block-level value is used in the EAL calculations.

Annualized 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 Annualized Frequency

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

where:

$Freq_{CWAV_{CB}}$ is the annualized frequency of Cold Wave event-days determined for a specific Census block (event-days per year).

$EventDayCount_{CWAV_{CB}}$ 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. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized frequency values at both the Census tract and county level. To achieve this, the annualized 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 annualized frequency value reported by the 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 Annualized 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 area-weighted Cold Wave annualized frequency for a specific Census tract (event-days per year).
$Freq_{CWAV_{CB}}$	is the annualized frequency of Cold Wave event-days 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).
$Freq_{CWAV_{Co}}$	is the area-weighted Cold Wave annualized 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 34 displays Cold Wave annualized frequency at the county level.

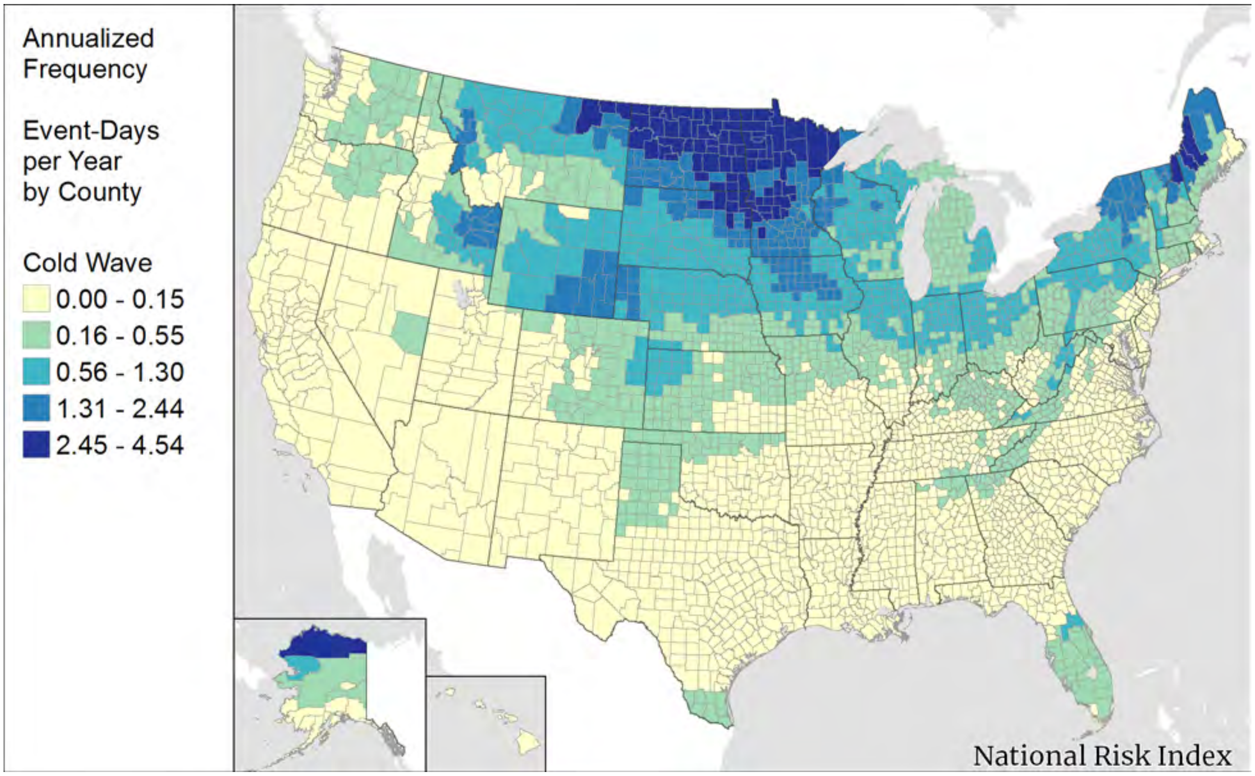

Figure 34: Cold Wave Annualized Frequency by County

8.7. Historic Loss Ratio

The Cold Wave HLR is the representative percentage of a location's hazard exposure 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 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Cold Wave hazard type.

Loss data are provided by the NCEI Storm Events Database[41] with either a forecast zone or county designation. Forecast zone references are related to a county via a county-zone correlation table (see Section 8.2 Spatial Processing). NCEI events from 1996 to 2019 are included in the HLR calculation. Three types of storm events in the Storm Events Database are categorized as Cold Wave (see Table 25). These native loss records are expanded based on the number of event duration days from the NCEI Storm Events Database (to a maximum of 31 event-days) and aggregated on a single-event-per-day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

[41] National Centers for Environmental Information. (2020). *Storm Events Database, Version 3.1.* [online database]. Retrieved from https://www.ncdc.noaa.gov/stormevents/.

Table 25: NCEI Event Types and Recorded Events from 1996-2019

Event Type	*Total NCEI Records with Loss*	*Total NCEI Loss Records per Event Basis*
Cold/Wind Chill	1,431	2,230
Extreme Cold/Wind Chill	427	315
Frost/Freeze	999	1,151

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 NCEI Storm Event Database-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 or impacted people).

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

Cold Waves can occur with a high frequency in areas, but often result in no recorded loss to buildings or population. Unlike SHELDUS, the NCEI Storm Events Database includes all hazard occurrences, regardless of whether they resulted in economic loss. To replicate the same process of padding the loss data with zero-loss occurrences, only NCEI event-days with recorded loss were included as the initial loss dataset. This count was then compared to the historic event-day count experienced within the Cold Wave source data period of record (2005 to 2017; see Section 8.1.1 Period of Record). For Cold Wave, the historic event-day count is extracted using the intersection between the Cold Wave event-day polygons and the Census block polygons used to calculate exposure and annualized frequency (see Table 24). An annual rate is calculated as the event-day count divided by the period of record of 12.14 years, and this rate is multiplied by the NCEI period of record of 24 years to estimate a historic event-day count for the appropriate time range.

If the number of loss-causing Cold Wave event-day records from the NCEI Storm Events Database is less than the scaled event-day count for the county, then a number of zero-loss records equal to the difference are 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 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

Figure 35, Figure 37, and Figure 39 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 Bayesian-adjusted 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 Bayesian-adjusted HLR value, though its HLR may be influenced by other local, regional, or national occurrences. The surrounding area's HLRs have the greatest influence on the Bayesian-adjusted 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 36, Figure 38, and Figure 40 represent the final, Bayesian-adjusted county-level HLR values for Cold Wave.

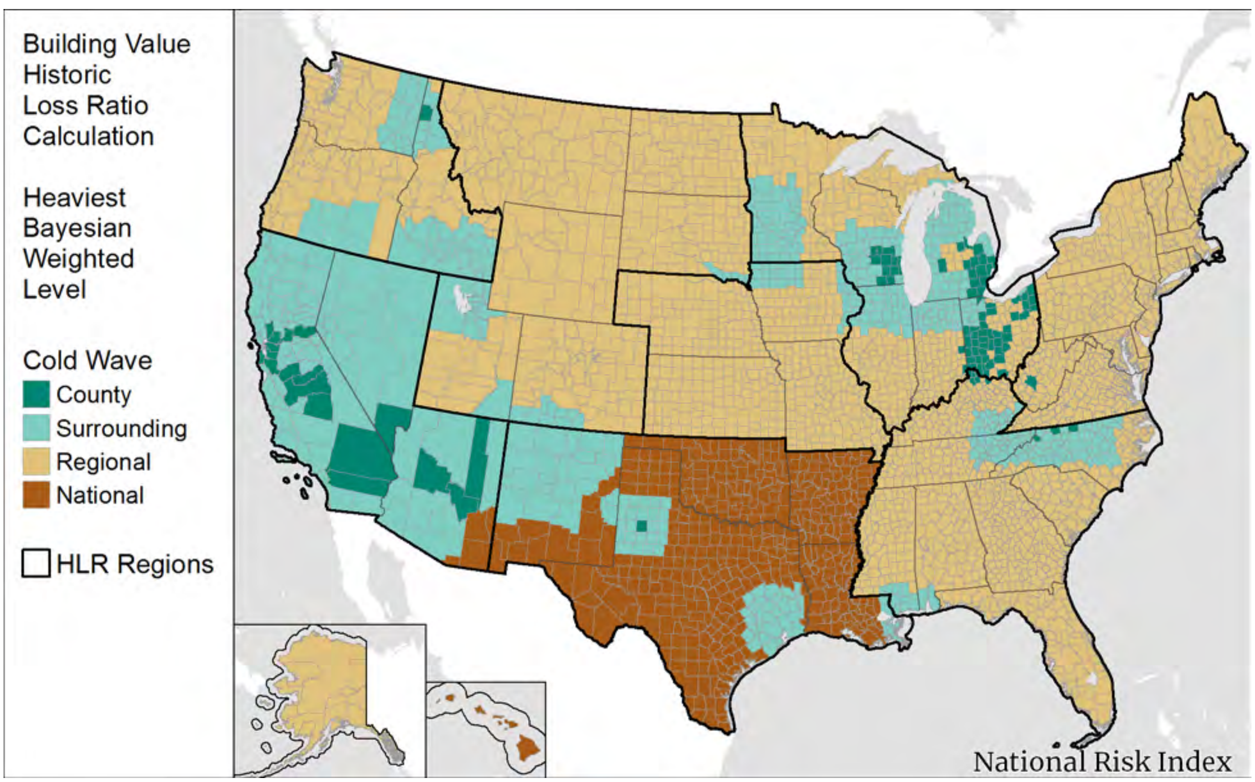

Figure 35: Cold Wave Heaviest Bayesian Weighted Level – Building Value

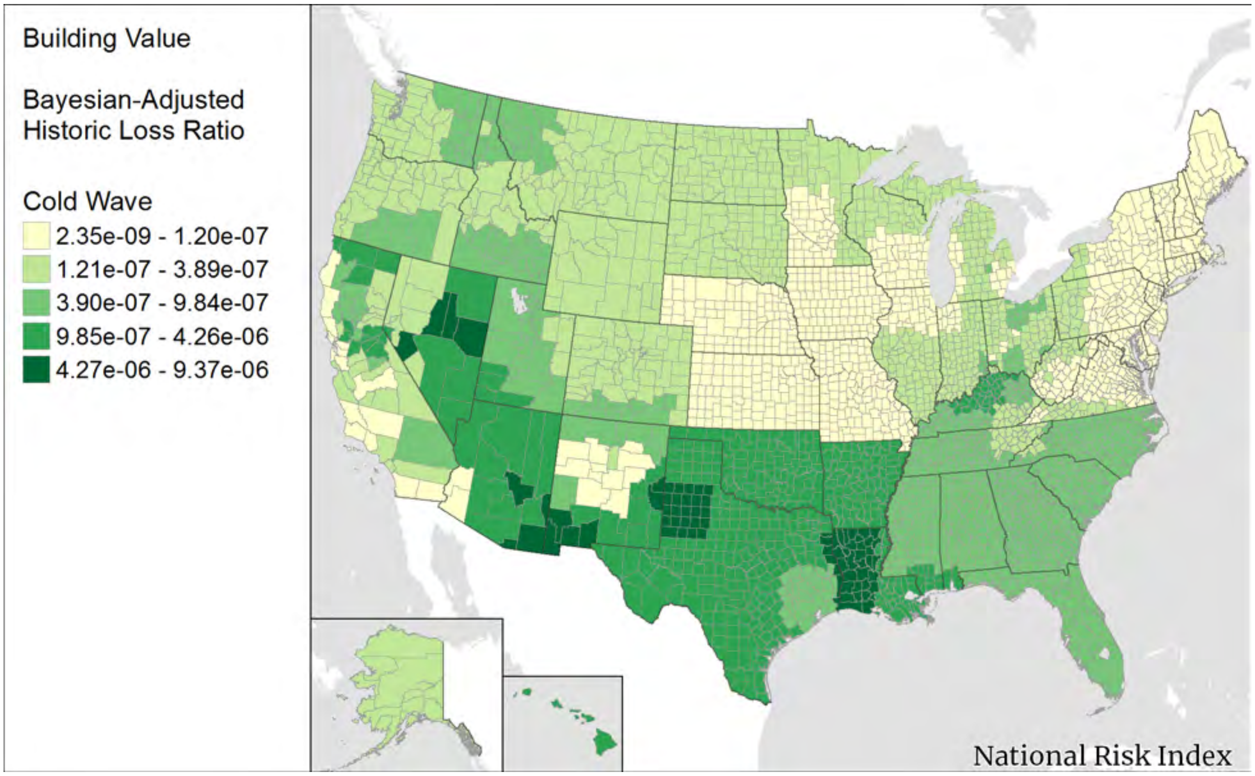

Figure 36: Cold Wave Bayesian-Adjusted HLR – Building Value

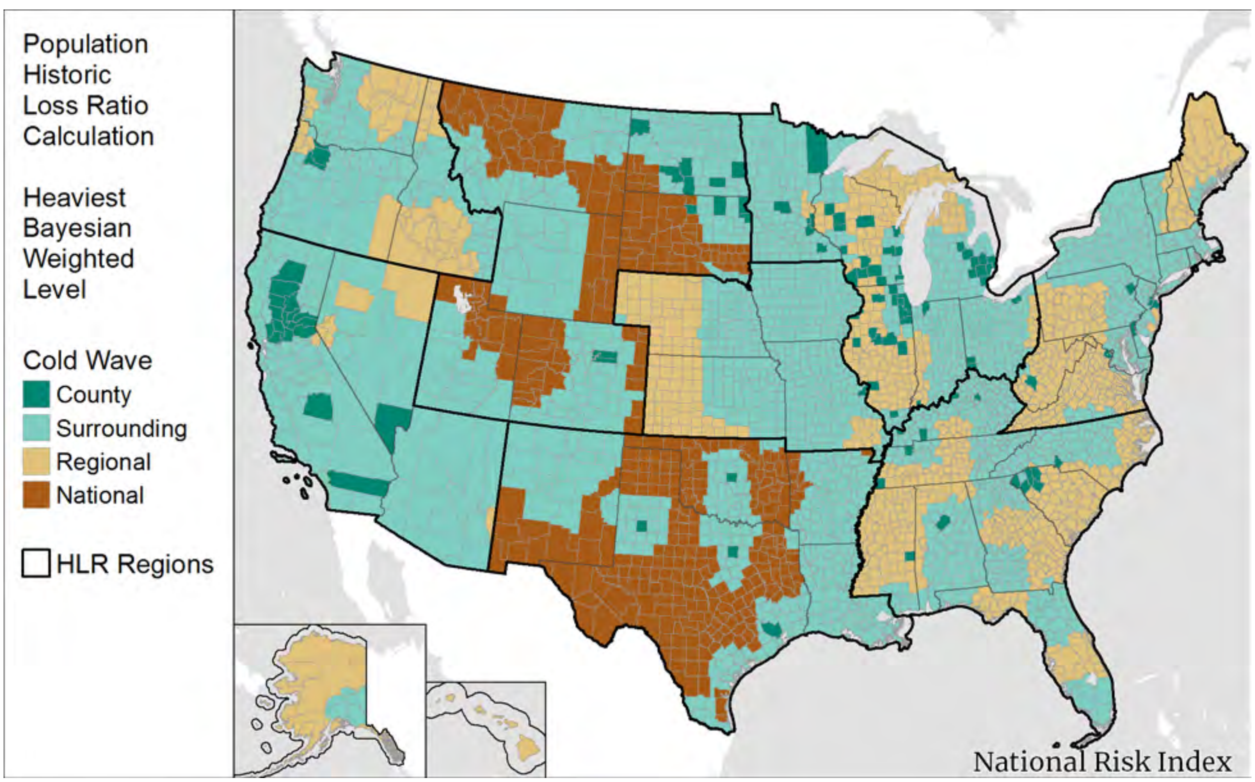

Figure 37: Cold Wave Heaviest Bayesian Weighted Level – Population

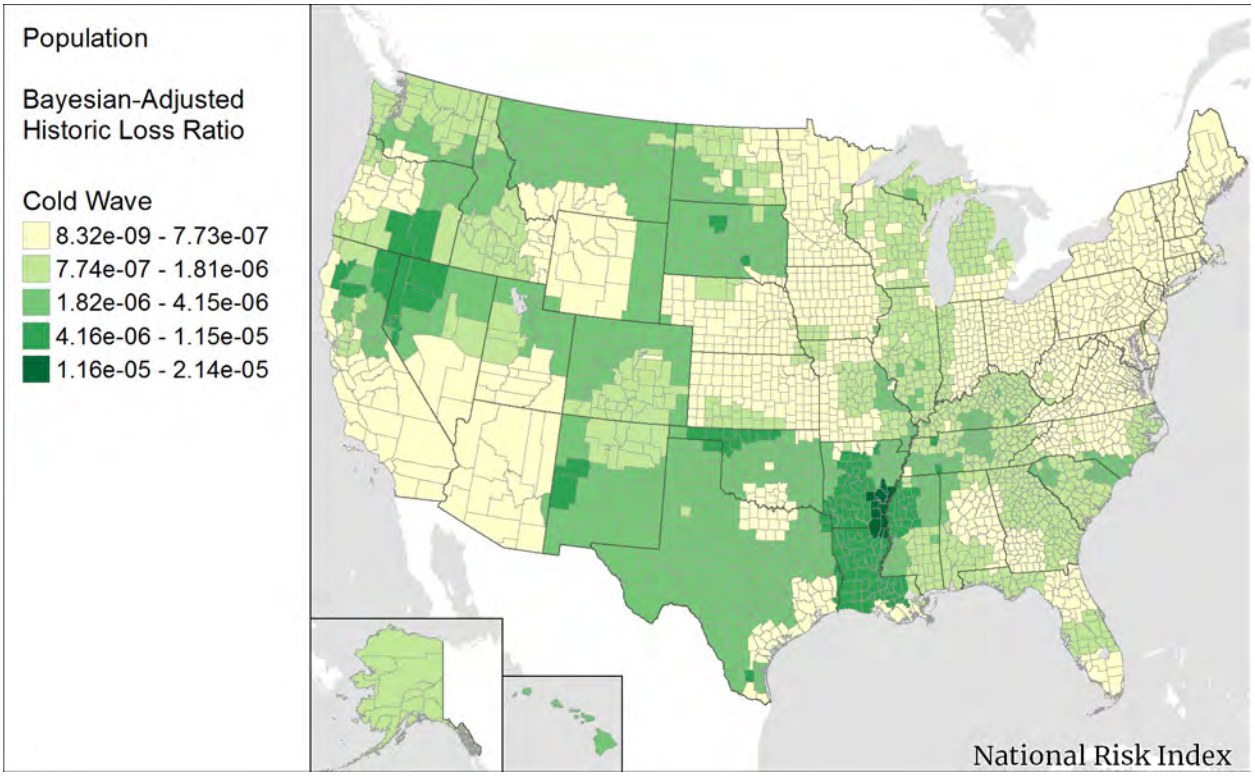

Figure 38: Cold Wave Bayesian-Adjusted HLR – Population

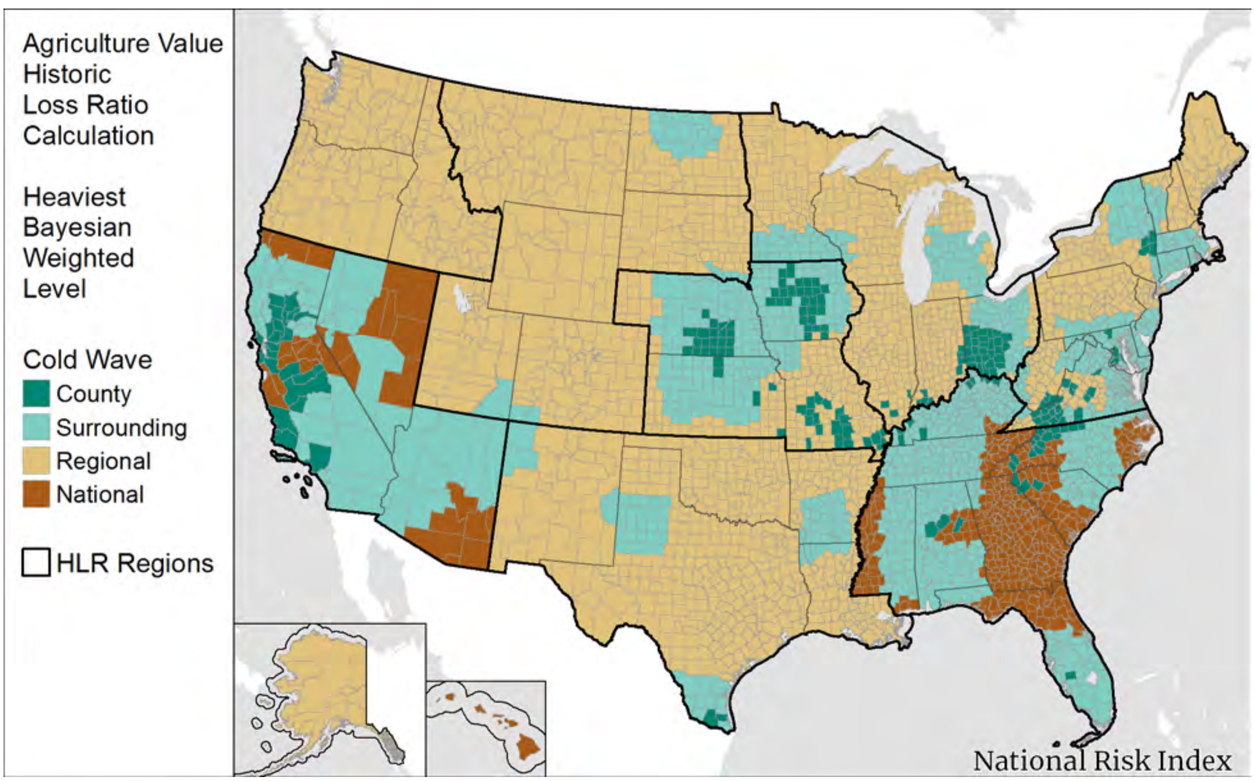

Figure 39: Cold Wave Heaviest Bayesian Weighted Level – Agriculture Value

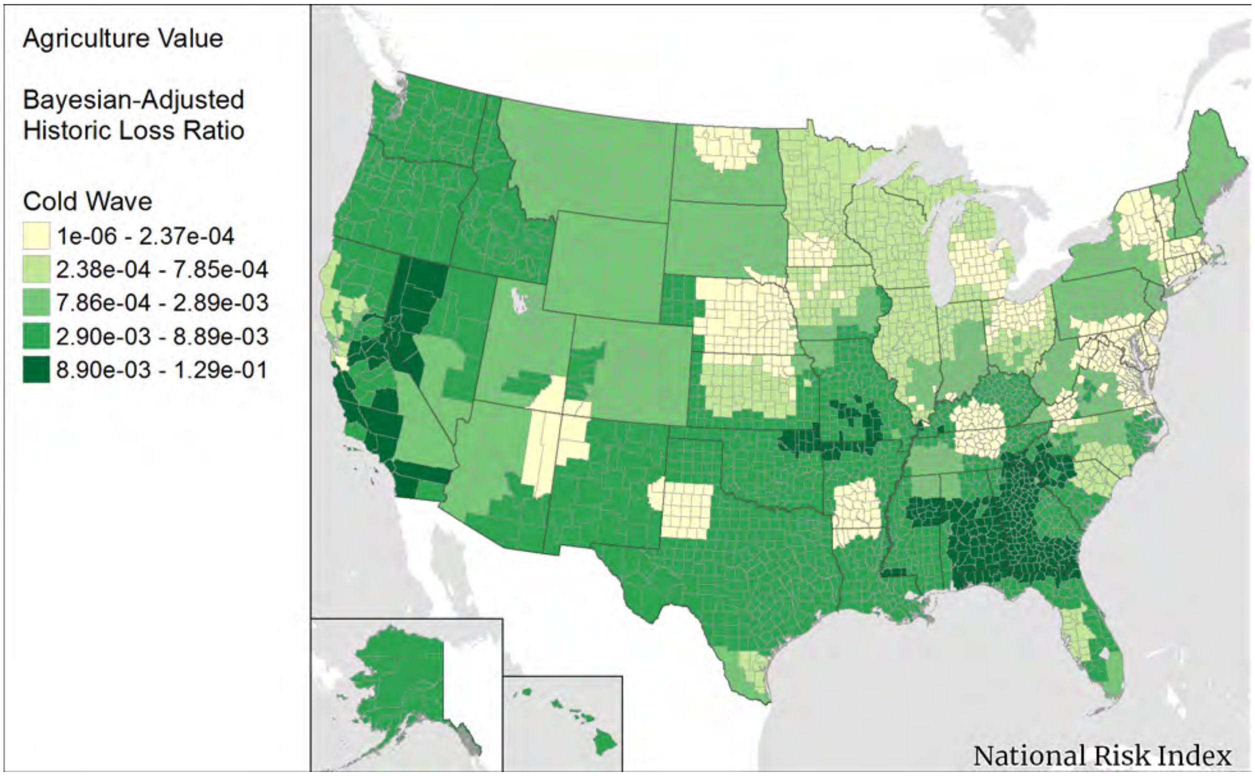

Figure 40: Cold Wave Bayesian-Adjusted HLR – Agriculture Value

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

8.8. Expected Annual Loss

Once exposure, annualized 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 building Expected Annual Loss due to Cold Wave occurrences for a specific Census block (in dollars).

$Exposure_{CWAV_{CB_{Bldg}}}$ is the building value exposed to Cold Wave occurrences in the Census block (in dollars).

$Freq_{CWAV_{CB}}$ is the Cold Wave annualized 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 population equivalence Expected Annual Loss value due to Cold Wave occurrences for a specific Census block (in dollars).

$Exposure_{CWAV_{CB_{Pop}}}$ is the population equivalence value exposed to Cold Wave occurrences 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 agriculture Expected Annual Loss due to Cold Wave occurrences for a specific Census block (in dollars).

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

$HLR_{CWAV_{CB_{Ag}}}$ is the Bayesian-adjusted agriculture HLR 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 building, population, and agriculture EAL values 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 occurrences for a specific Census tract (in dollars).

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

$\sum_{CB}^{CT} EAL_{CWAV}{}_{CB}{}_{Pop}$	is the summed population equivalence Expected Annual Loss due to Cold Wave occurrences for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{CWAV}{}_{CB}{}_{Ag}$	is the summed agriculture Expected Annual Loss due to Cold Wave occurrences for all Census blocks in the Census tract (in dollars).
$EAL_{CWAV}{}_{Co}$	is the total EAL due to Cold Wave occurrences for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{CWAV}{}_{CB}{}_{Bldg}$	is the summed building Expected Annual Loss due to Cold Wave occurrences for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{CWAV}{}_{CB}{}_{Pop}$	is the summed population equivalence Expected Annual Loss due to Cold Wave occurrences for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{CWAV}{}_{CB}{}_{Ag}$	is the summed agriculture Expected Annual Loss due to Cold Wave occurrences for all Census blocks in the county (in dollars).

Figure 41 shows the total EAL (building value, population equivalence, and agriculture value combined) to Cold Wave occurrences.

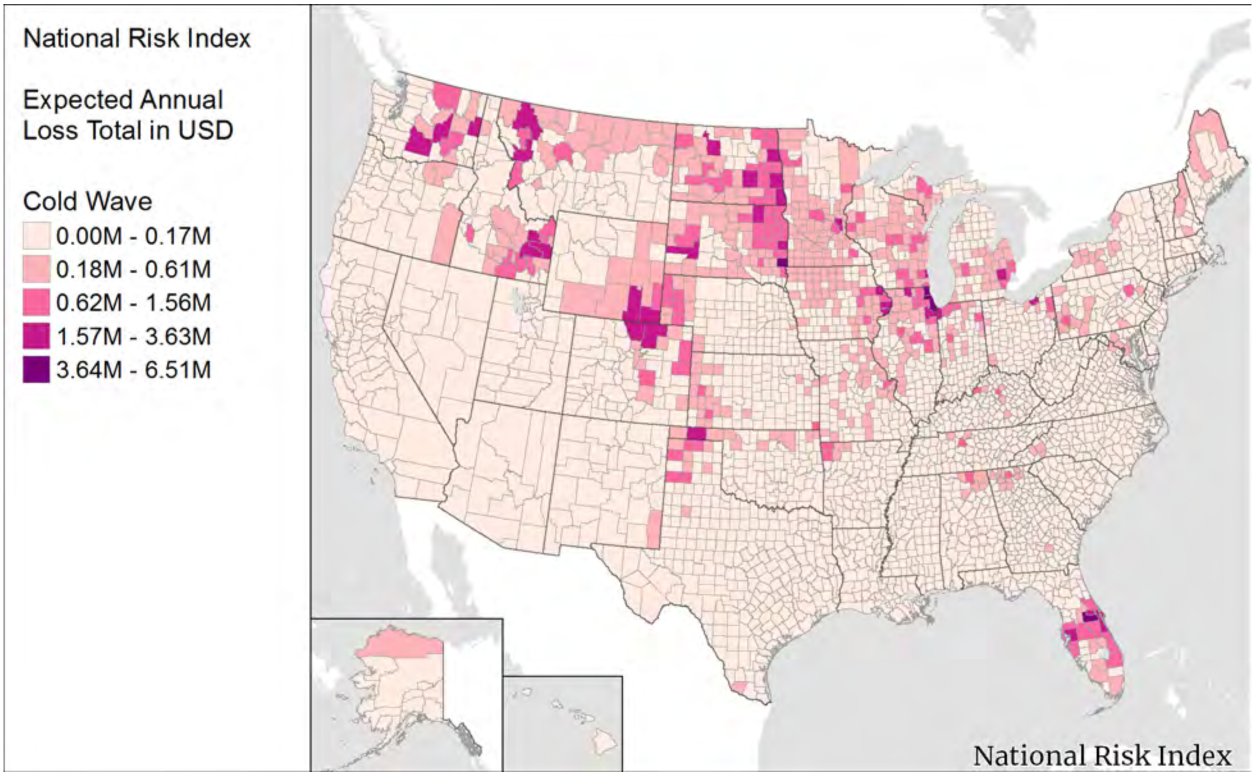

Figure 41: Total Expected Annual Loss by County to Cold Wave

With the Cold Wave total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same levels. 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 Occurrence Source: University of Nebraska-Lincoln National Drought Mitigation Center (NDMC), U.S. Drought Monitor[42]

The NDMC provides shapefiles representing areas experiencing Drought on a weekly basis since 2000 (see Figure 42). 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 26).

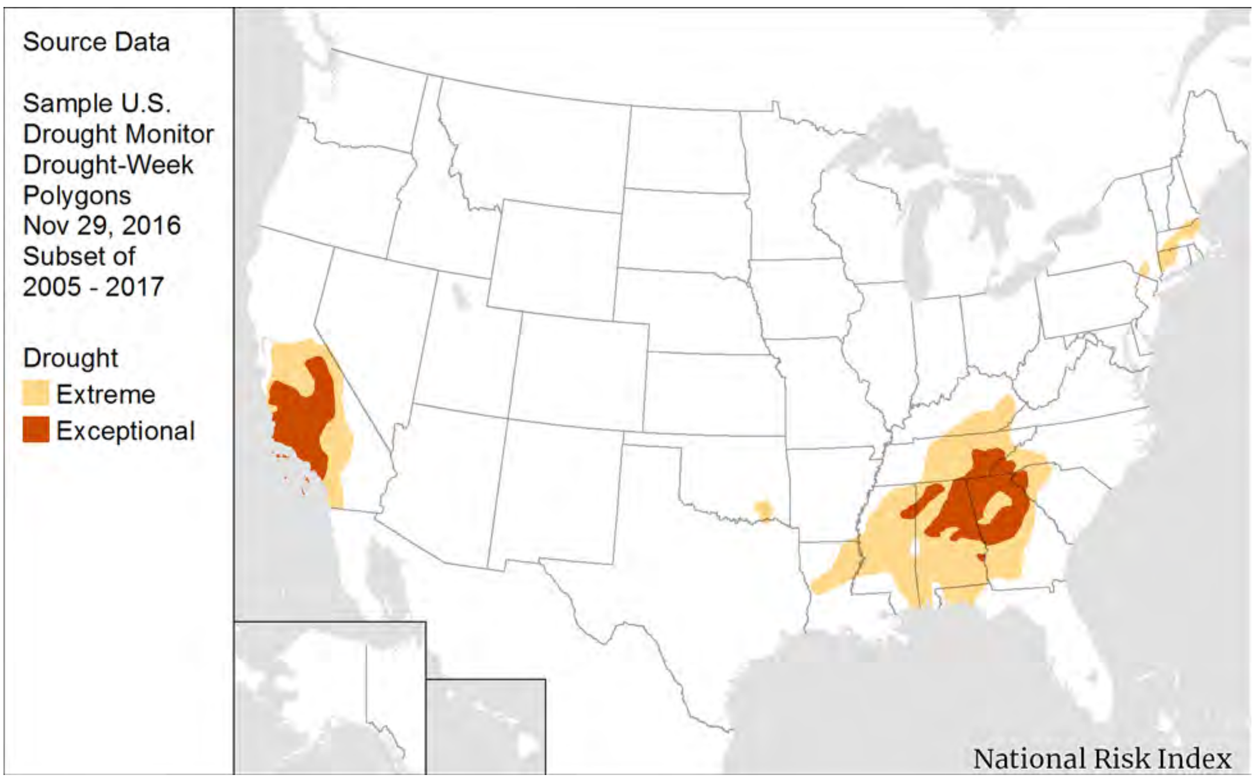

Figure 42: Sample Drought Shape

[42] 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 26: 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 processing database. The data initially consist of 10,010 drought-week records. Only the most severe Drought events are analyzed, 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 annualized 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 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 27). All areas are in square kilometers.

Table 27: 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 agriculture value density of the Census tract (see Equation 36). The Census tract agriculture value density has been calculated by dividing the total agriculture value of the Census tract by its agriculture land area (in square kilometers).

Equation 36: Census Tract Drought Exposure

$$Exposure_{DRGT_{CT}\,_{Ag}} = \frac{\sum IntsctArea_{DRGT_{CT}\,_{AG}}}{EventWeekCount_{DRGT_{CT}}} \times AgValueDen_{CT}$$

where:

$Exposure_{DRGT\,CT_{Ag}}$ is the agriculture 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-weeks with the Census tract (in square kilometers).

$EventWeekCount_{DRGT_{CT}}$ is the total number of Drought event-week polygons that intersect the Census tract.

$AgValueDen_{CT}$ is the agriculture value density of the Census tract (in dollars per square kilometer).

The crop value derived from USDA 2017 Census of Agriculture[43] and CropScape data 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

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

[43] U.S. Department of Agriculture. (2017). *2017 Census of Agriculture*. Retrieved from https://www.nass.usda.gov/Publications/AgCensus/2017/index.php.

where:

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

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

9.5. Historic Occurrence Count

The historic occurrence count of Drought, in 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 annualized 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. Annualized Frequency

The annualized frequency value represents the number of recorded Drought occurrences, in 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.

Annualized 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 Annualized 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. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized 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 annualized 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 Annualized Frequency

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

where:

$Freq_{DRGT\,Co}$	is the Drought annualized frequency calculated for a specific county (event-days per year).
$Freq_{DRGT\,CT}$	is the annualized frequency of Drought determined for 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 43 displays Drought annualized frequency at the county level.

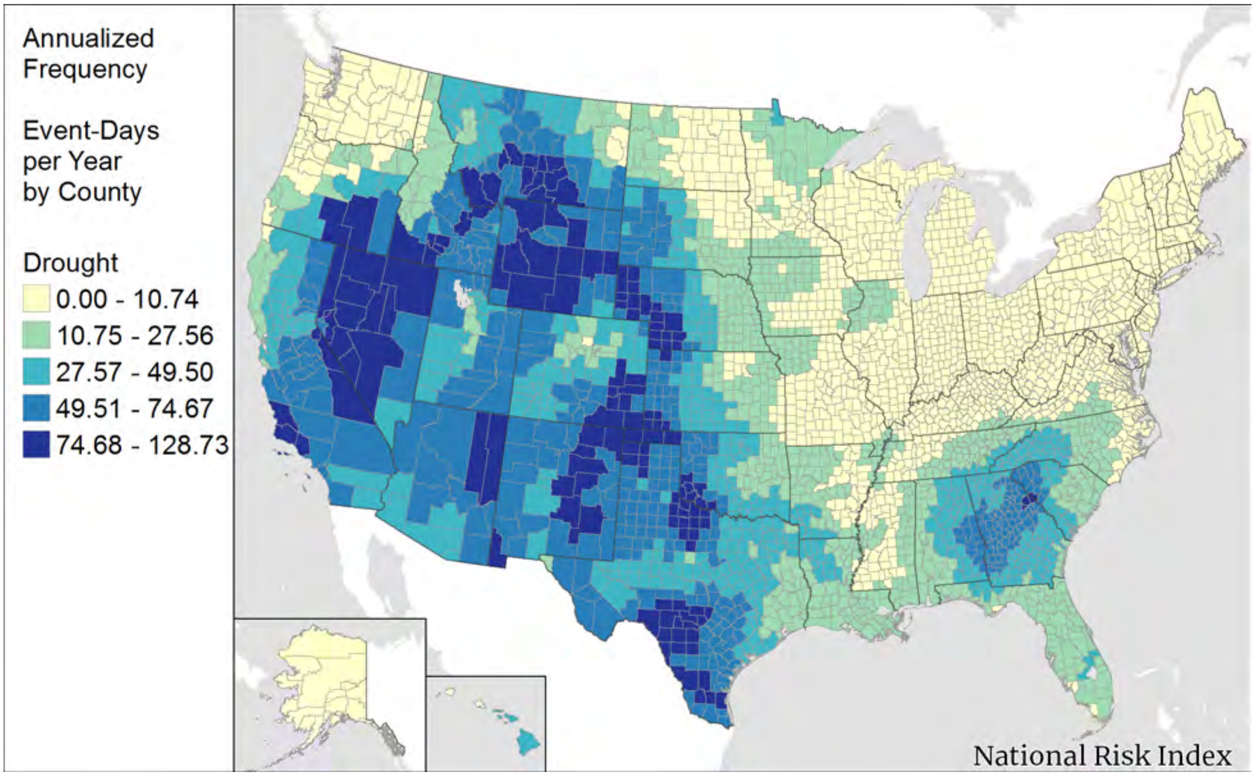

Figure 43: Drought Annualized Frequency by County

9.7. Historic Loss Ratio

The Drought HLR is the representative percentage of a location's Drought exposure 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 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Drought hazard type.

Loss data are provided by SHELDUS[44] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. One peril type is mapped to the hazard Drought (see Table 28). These native loss records are expanded on an event-day basis (to a maximum of 365 days) and are aggregated on a single-event-per-day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

Table 28: Drought Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Drought	5,232	145,001

[44] For Drought 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 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. Calculation is performed for agriculture.
$Loss_{DRGT\,Co_{Ag}}$	is the agriculture loss experienced from the Drought event-day documented to have occurred in the county (in dollars).
$HLRExposure_{Co_{Ag}}$	is the total agriculture 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 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 (1996 to 2019). For Drought, the historic event-day count is extracted using the intersection between the Drought event-week polygons and the Census tract used to calculate annualized frequency and multiplying by 7 to convert weeks into days. An annual rate is calculated as the event-day count divided by the period of record of 18 years, and this rate is multiplied by the SHELDUS period of record of 24 years to estimate a historic event-day count for the appropriate time range.

If the number of loss-causing Drought event-day records from SHELDUS is less than the scaled event-day count for the county, then a number of zero-loss records equal to the difference are 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 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

Figure 44 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 Bayesian-adjusted 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 Bayesian-adjusted HLR value, though its HLR may be influenced by other local or regional occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted 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 45 represents the final, Bayesian-adjusted county-level HLR values for Drought.

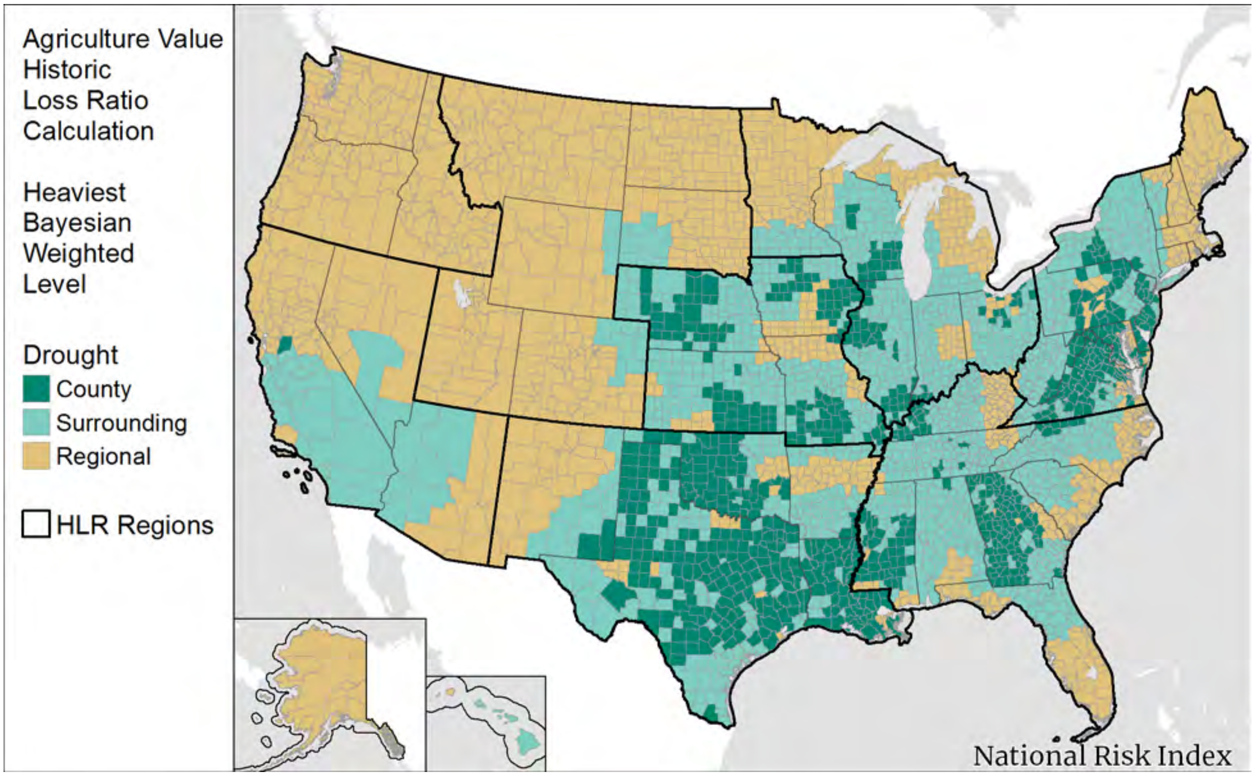

Figure 44: Drought Heaviest Bayesian Weighted Level – Agriculture Value

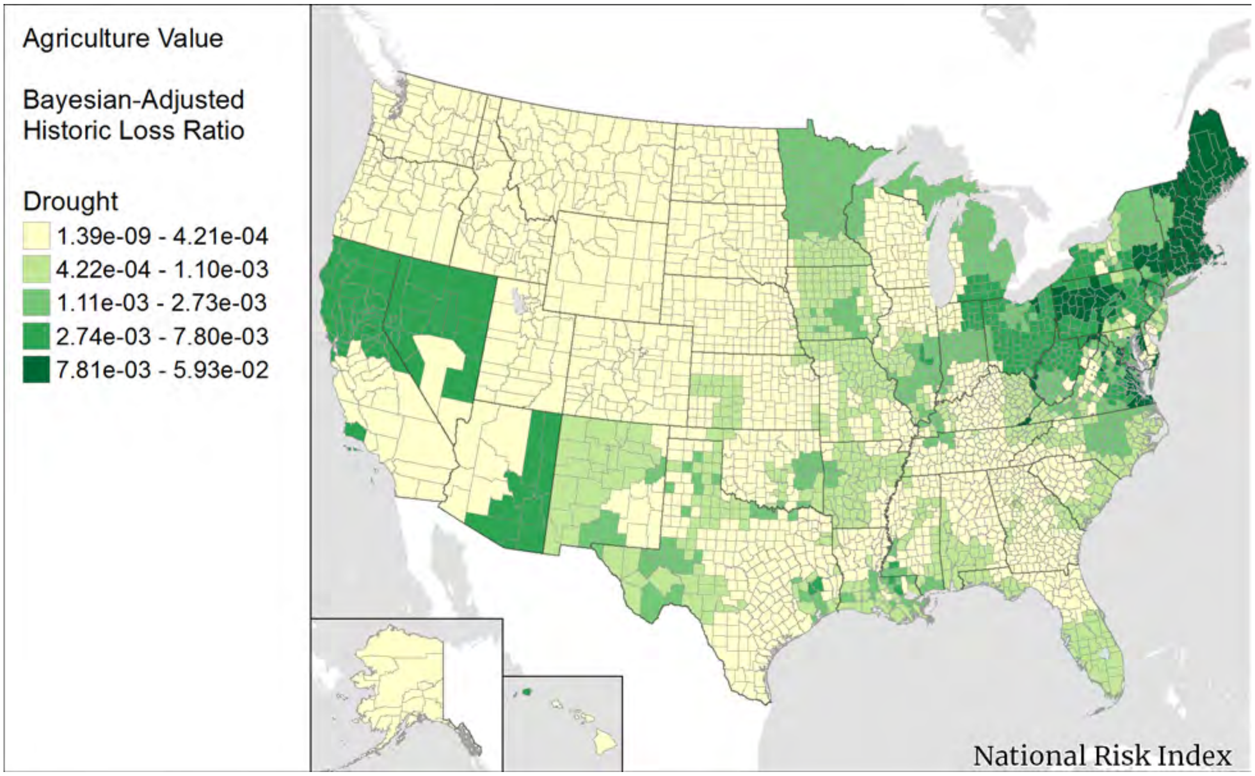

Figure 45: Drought Bayesian-Adjusted HLR – Agriculture Value

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

9.8. Expected Annual Loss

Once exposure, annualized 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 agriculture Expected Annual Loss due to Drought occurrences for a specific Census tract (in dollars).

$Exposure_{DRGT\,CT_{Ag}}$ is the agriculture value exposed to Drought occurrences in the Census tract (in dollars).

$Freq_{DRGT_{CT}}$	is the Drought annualized 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 agriculture EAL values 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 agriculture Expected Annual Loss to agriculture value due to Drought occurrences for all Census tracts in the county (in dollars).

Figure 46 shows the total EAL (agriculture only) to Drought occurrences.

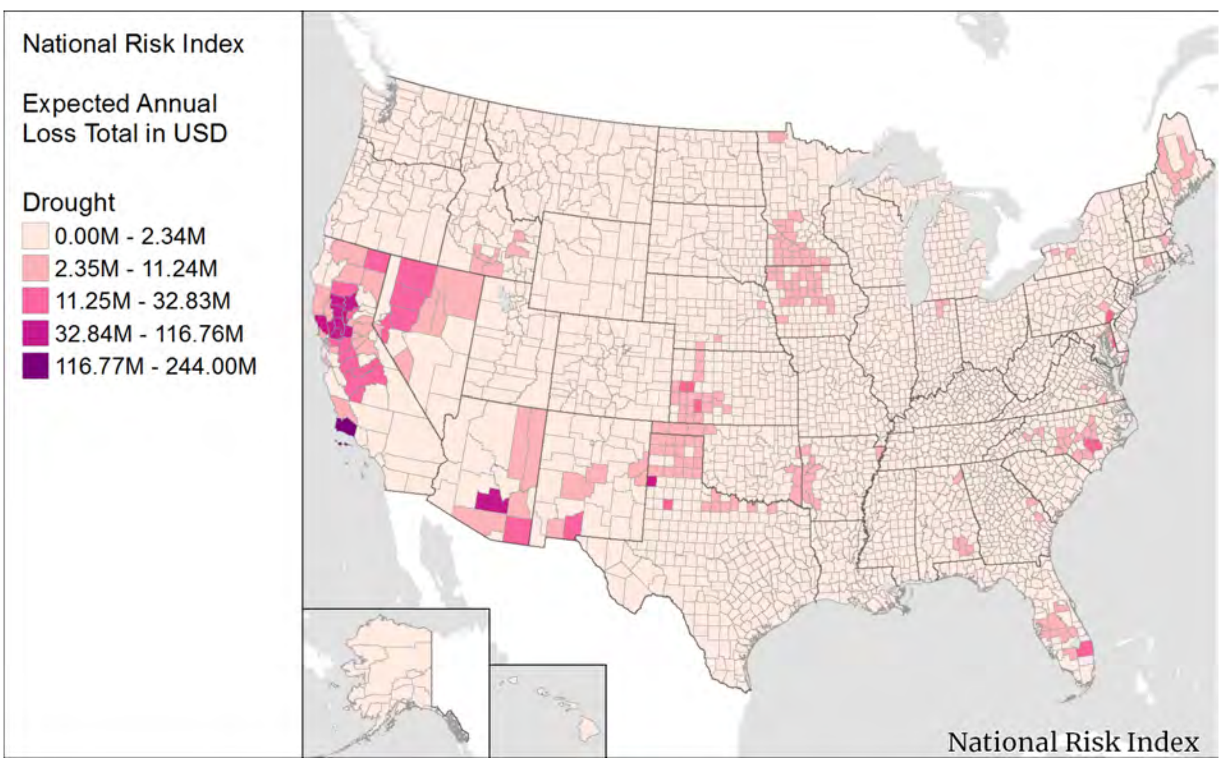

Figure 46: Total Expected Annual Loss by County to Drought

With the Drought total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 U.S. in which the cells give the 100-year probability of Minor-Damage Earthquake Shaking (see Figure 47). Cell values range from 0 to 100. These raster files are derived from the hazard model used to create USGS National Seismic Hazard Maps.[45]

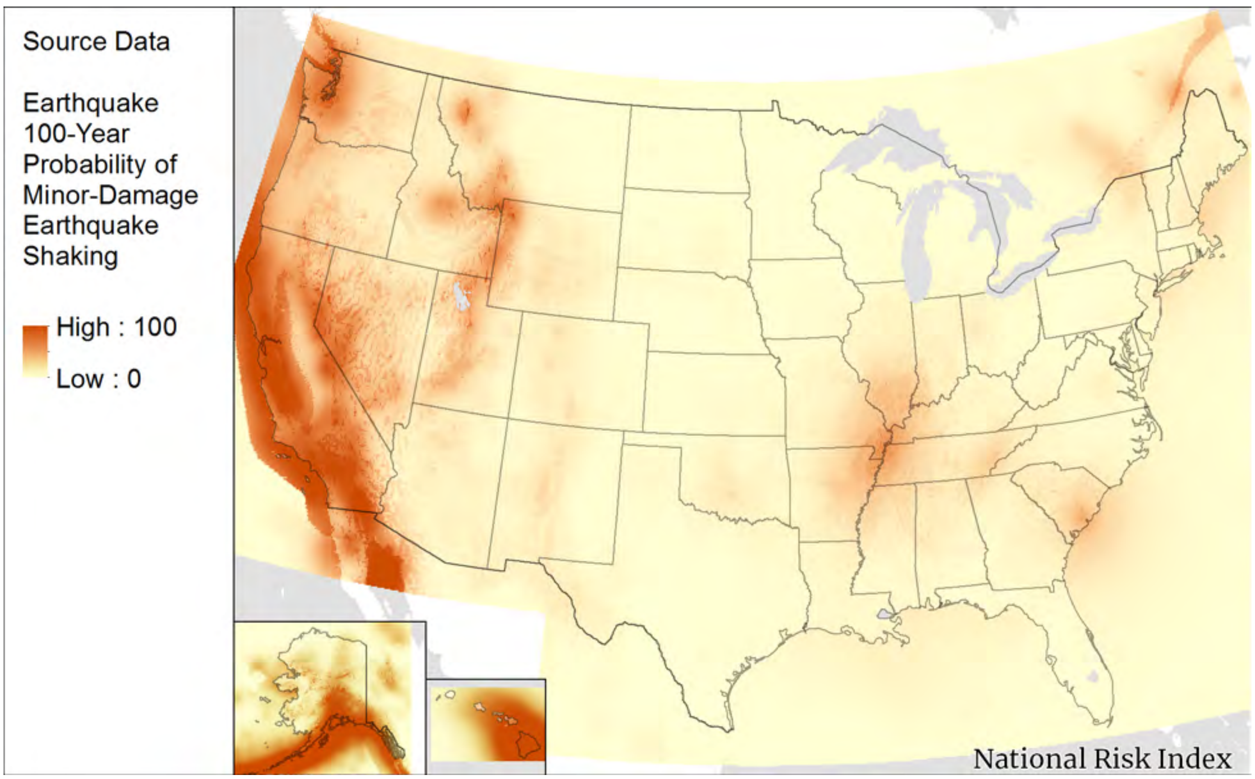

Figure 47: Map of Earthquake Probability Raster

Loss Quantification Source: Federal Emergency Management Agency, Hazus P-366 Study[46]

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

[46] 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 U.S. at both the Census tract and county levels (see Table 29 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 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 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 29: Sample Census Tract-Level Data from Hazus P-366

Census Tract	*County Name*	*State*	*TotalExp_Bldg_1k*	*Pop_2010*	*AEL_1mil*	*Level4Injury_2pm*
02013000100	Aleutians East	AK	479651	3141	0.366149	0.007988
06019004212	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 for exposure, annualized 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, the annualized frequency could not be extracted from the P-366 data as a simplified value. The raster datasets supplied by USGS allow for the computation of an annualized probability value to serve as annualized frequency surrogate, 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 processing database. A polygon fishnet in 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 48) that can then be intersected with the Census blocks to determine Earthquake annualized 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.

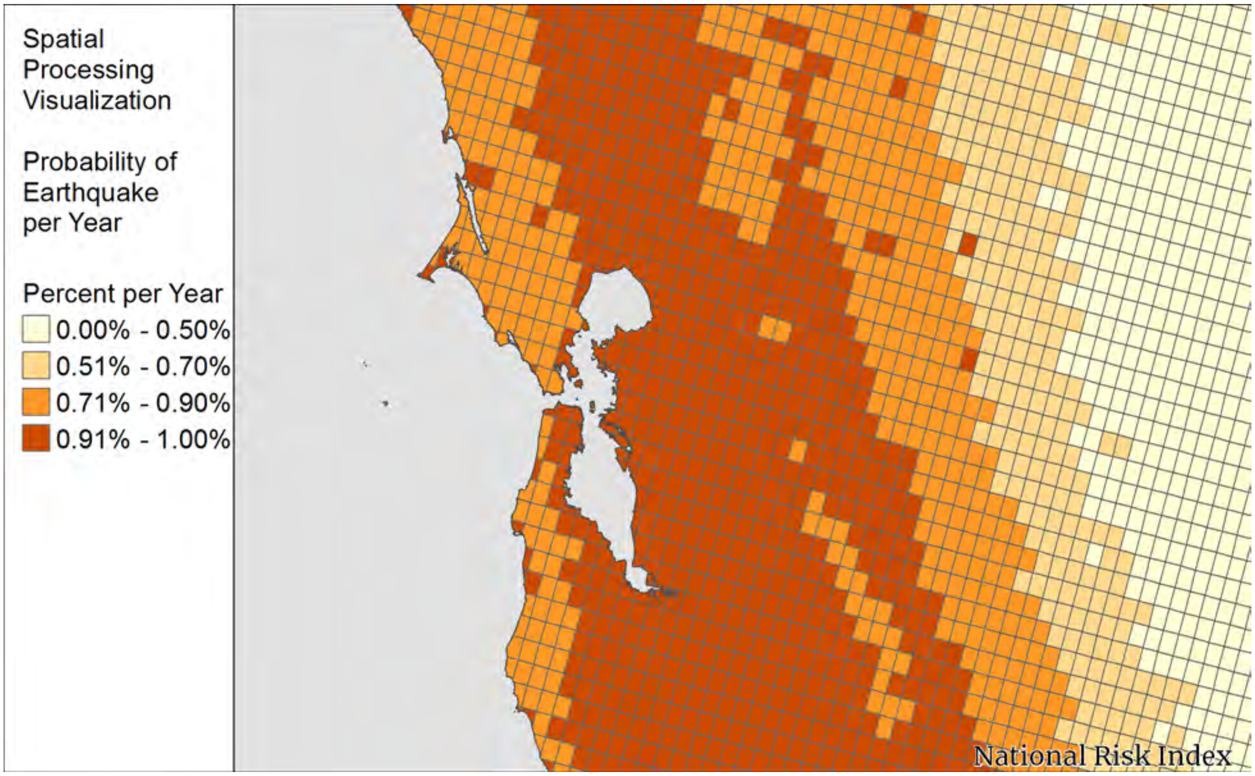

Figure 48: Map of Earthquake Fishnet

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, 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. Annualized Frequency

The annualized frequency value represents the area-weighted probability of Earthquake occurrences, in events, (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 processing database. The resulting table contains the fishnet polygon's unique identifier, Census block number, and the intersected area in square kilometers (see Table 30).

Table 30: Sample Data from the Earthquake Fishnet Census Block Intersection Table

EarthquakeFishnetID	*CensusBlock*	*IntersectedAreaKm2*
422655	191930036004217	0.003866
422655	191930036004221	0.010595
422655	191930036004225	0.019825

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

Equation 43: Census Block Area-Weighted Fishnet Earthquake Annualized 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 area-weighted annualized 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 event 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. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized 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 annualized frequency component from the P-366 data. The annualized 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 Annualized 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 area-weighted Earthquake annualized frequency calculated for a specific Census tract (probability per year).
$Freq_{ERQK\,CB}$	is the area-weighted annualized frequency of Earthquake determined for 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 area-weighted Earthquake annualized 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 49 displays Earthquake annualized frequency at the county level.

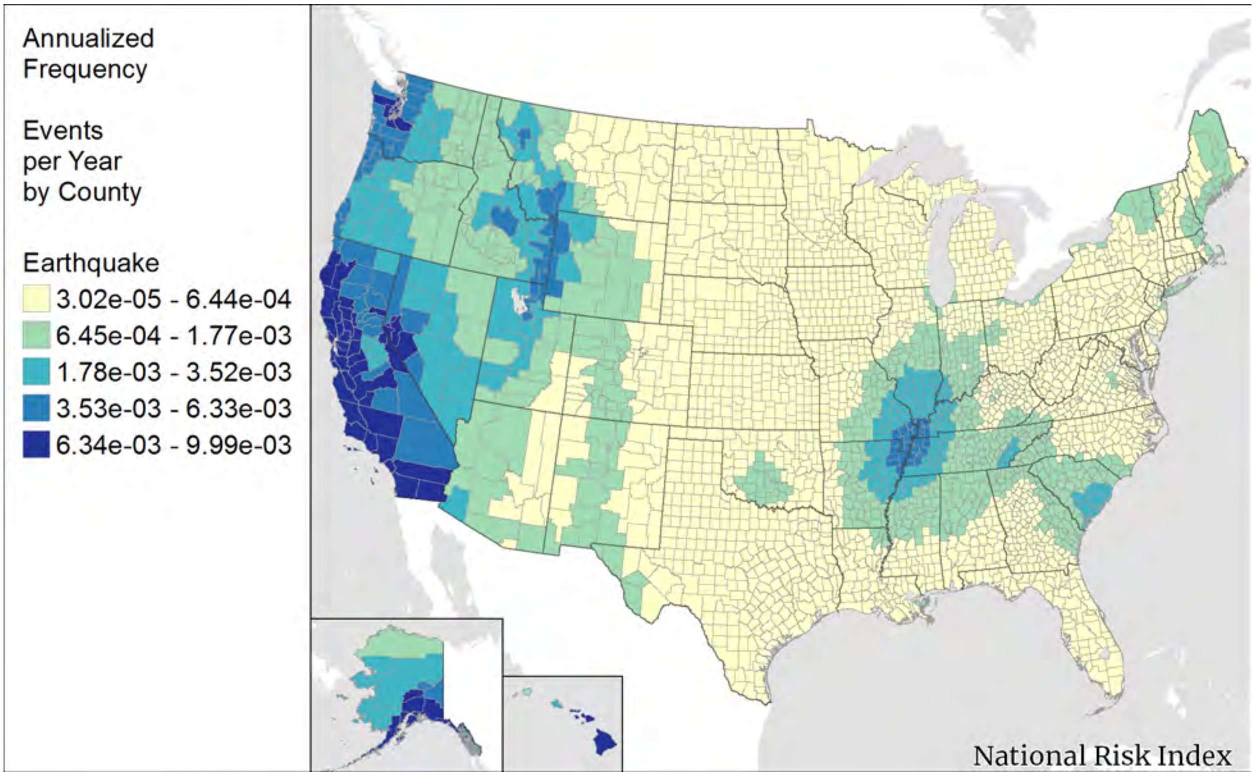

Figure 49: Earthquake Annualized Frequency by County

10.6. Historic Loss Ratio

The Earthquake HLR is the representative percentage of a location's hazard exposure that experiences loss due to an Earthquake occurrence, or the average rate of loss associated with an Earthquake occurrence. HLR values displayed 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 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Earthquake hazard type.

Loss data are provided by SHELDUS[47] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1960 to 2019 are included in the HLR calculation. Four peril types are mapped to the hazard Earthquake (see Table 31). These native records are aggregated on a timeframe basis (see Section 5.4.4 Historic Loss Ratio Methodology).

[47] 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 31: Earthquake Peril Types and Recorded Events from 1960-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Earthquake	210	206
Fire-following Earthquake	0	0
Landslide following Earthquake	2	1
Liquefaction	0	0

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 or impacted people).

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

Earthquake frequency is based on a probabilistic model, so no zero-loss occurrences 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 50 and Figure 52 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 Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Earthquake occurrences within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value, though its HLR may be influenced by other local or national occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing occurrences or have widely varying loss ratios get the most influence from national-level loss data. Figure 51 and Figure 53 represent the final, Bayesian-adjusted county-level HLR values for Earthquake.

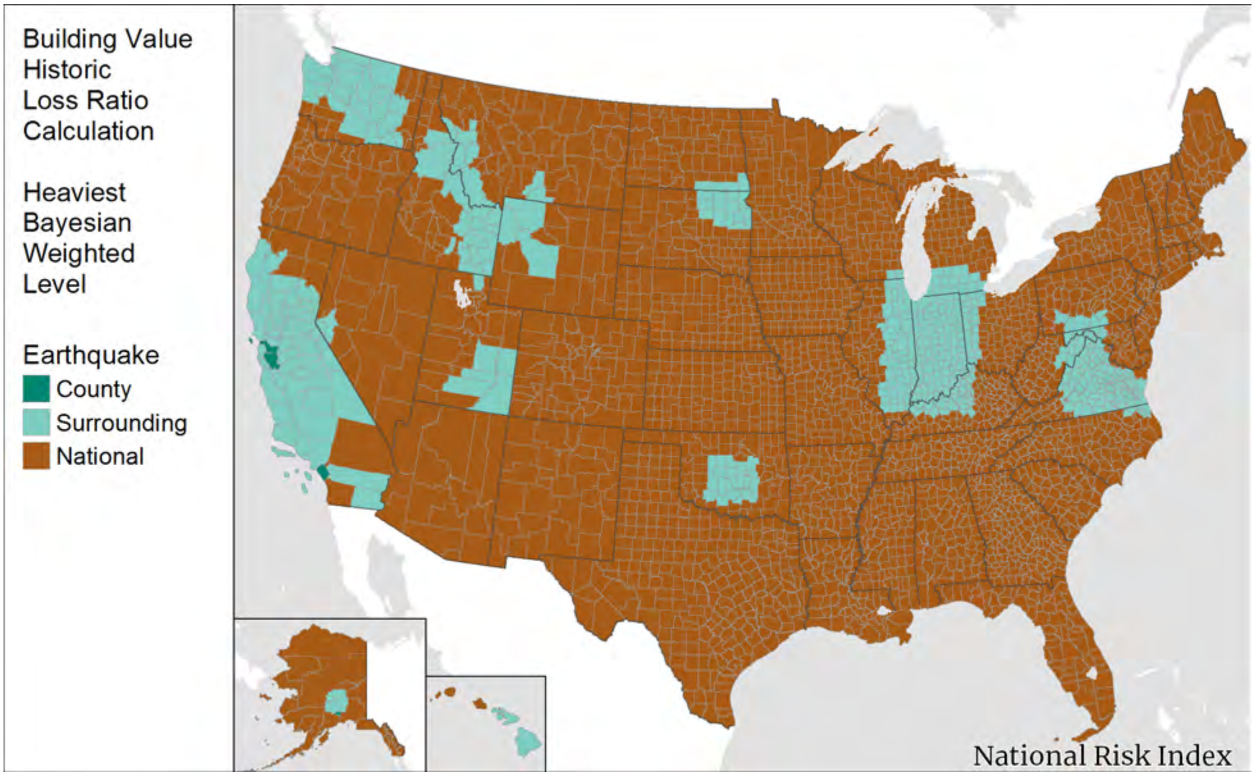

Figure 50: Earthquake Heaviest Bayesian Weighted Level – Building Value

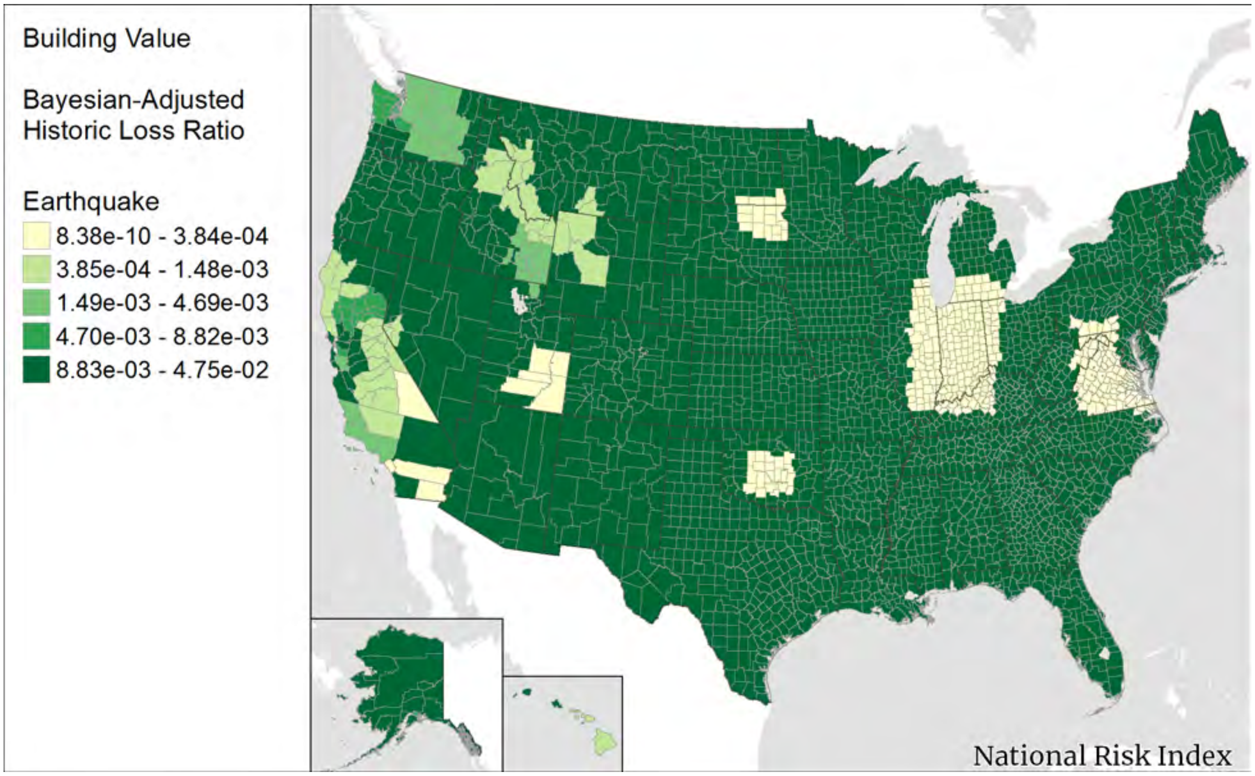

Figure 51: Earthquake Bayesian-Adjusted HLR – Building Value

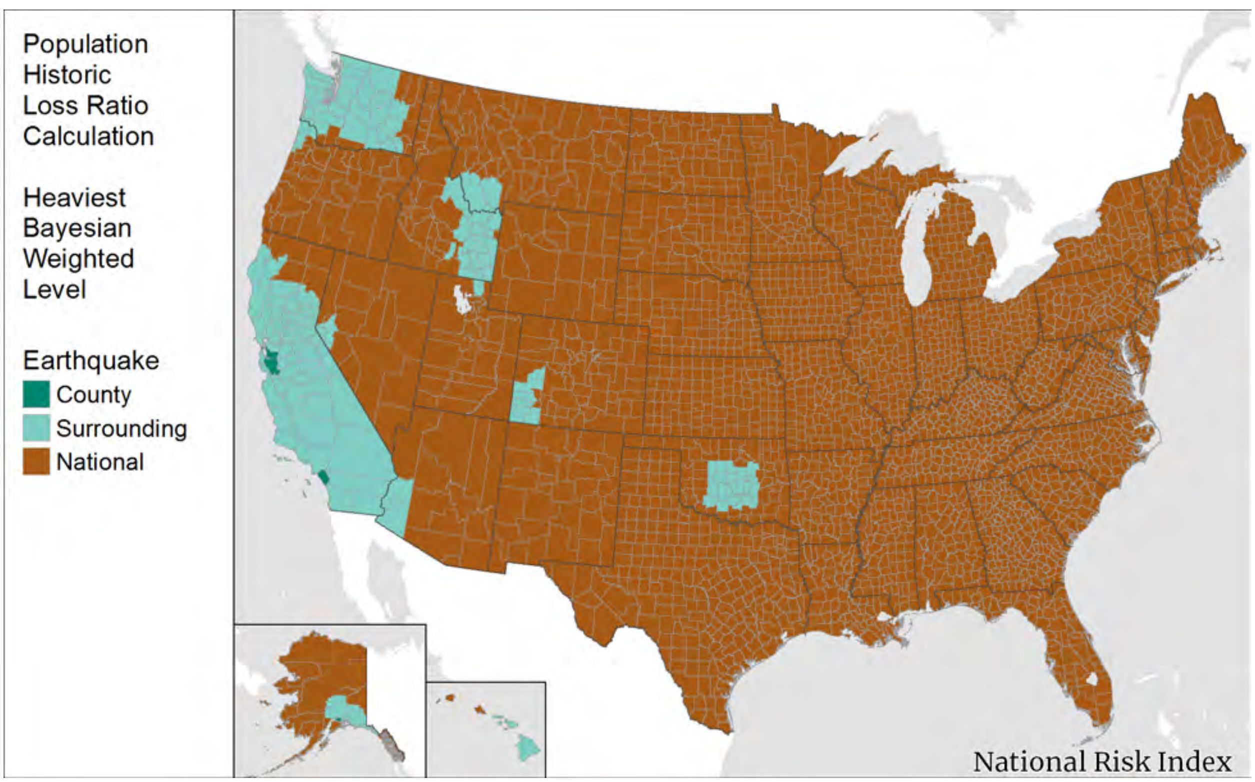

Figure 52: Earthquake Heaviest Bayesian Weighted Level – Population

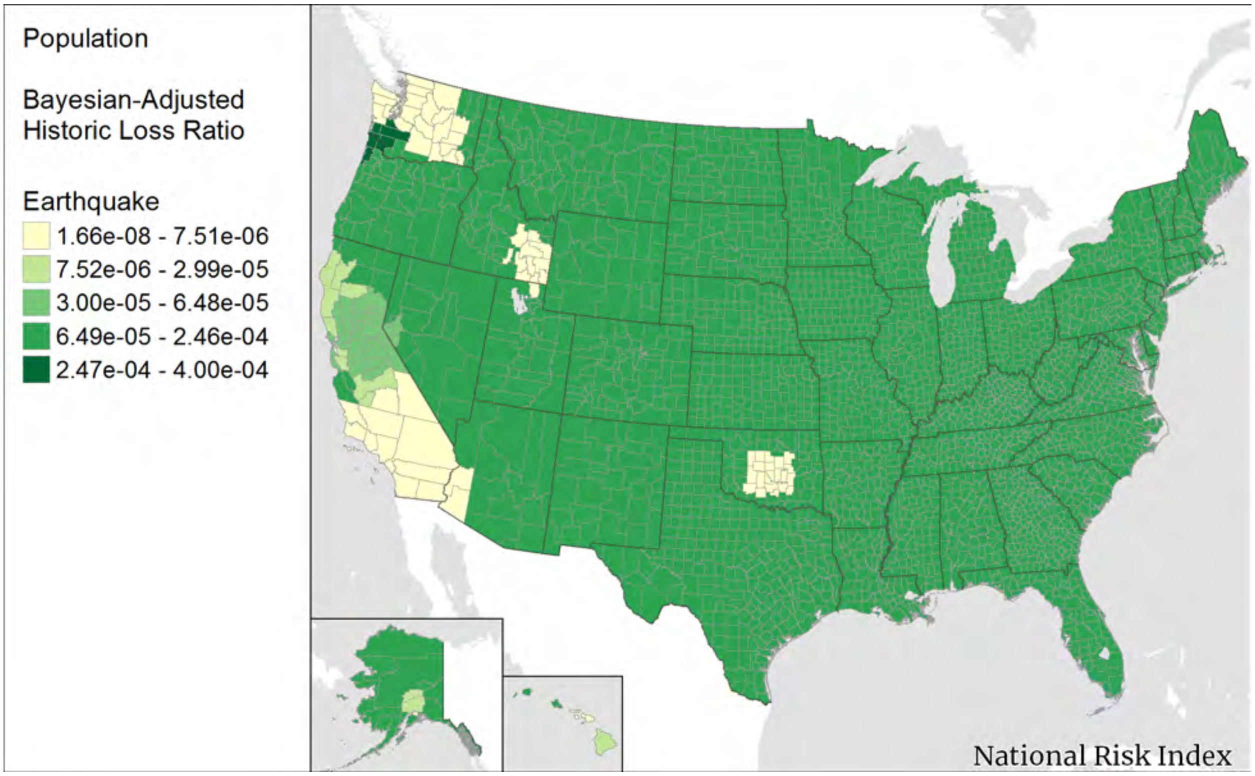

Figure 53: Earthquake Bayesian-Adjusted HLR – Population

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

10.7. Expected Annual Loss

EAL values are extracted from the P-366 study data at the Census tract and county levels. Exposure, annualized 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 annualized 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 occurrences 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 ($7.6M per person).

$EAL_{ERQK_{Co}}$ is the total Expected Annual Loss due to Earthquake occurrences 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 54 shows the total EAL (building value and population equivalence combined) to Earthquake occurrences.

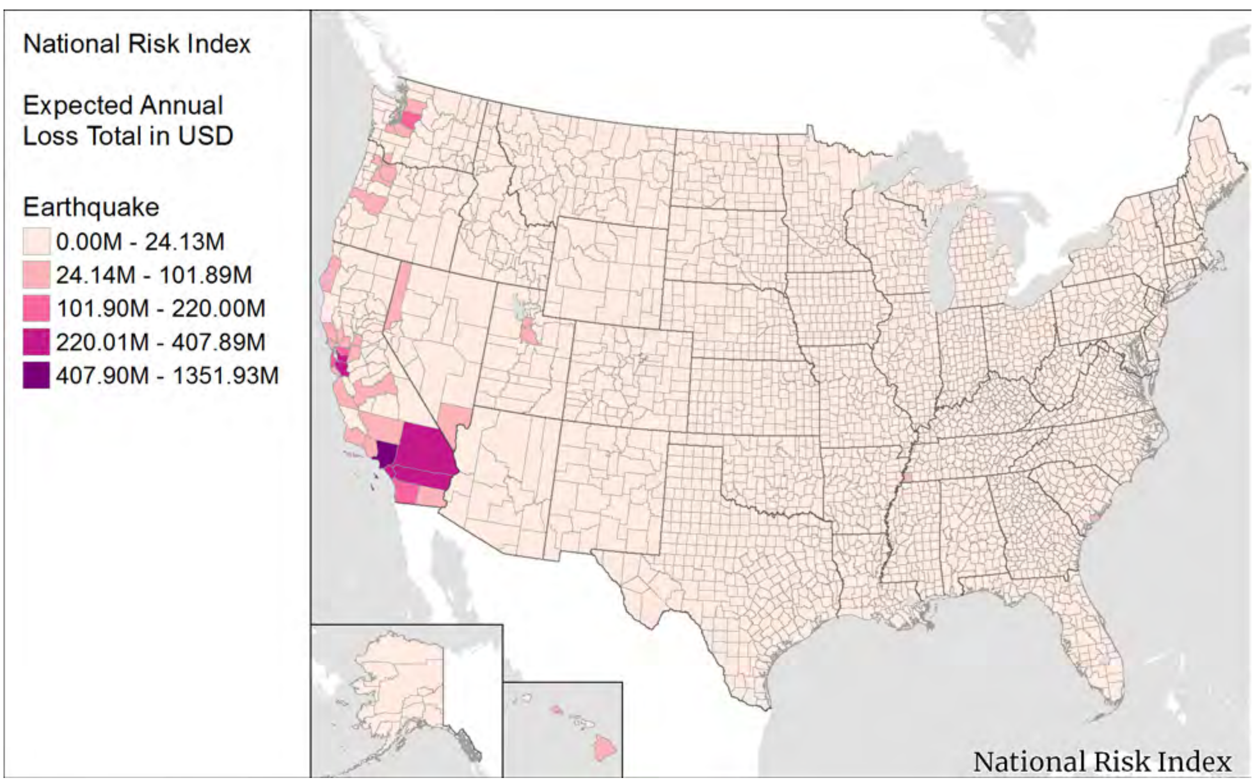

Figure 54: Total Expected Annual Loss by County to Earthquake

With the Earthquake total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all other communities at the same level. 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 Occurrence Source: *National Weather Service, Storm Prediction Center, Severe Weather Database Files*[48]

The Storm Prediction Center (SPC) 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 32 and Figure 55).

Table 32: Sample Hail Data from the 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 PM	AK	0.75	0	0	0	0	-150.22	65
317151	7/19/2011 2:50 PM	OR	1.00	1	0	0	0	45.3	-118.14
2016-06082	6/22/2016 2:19 AM	ND	1.75	0	0	25000	50000	-104.04	47.94

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

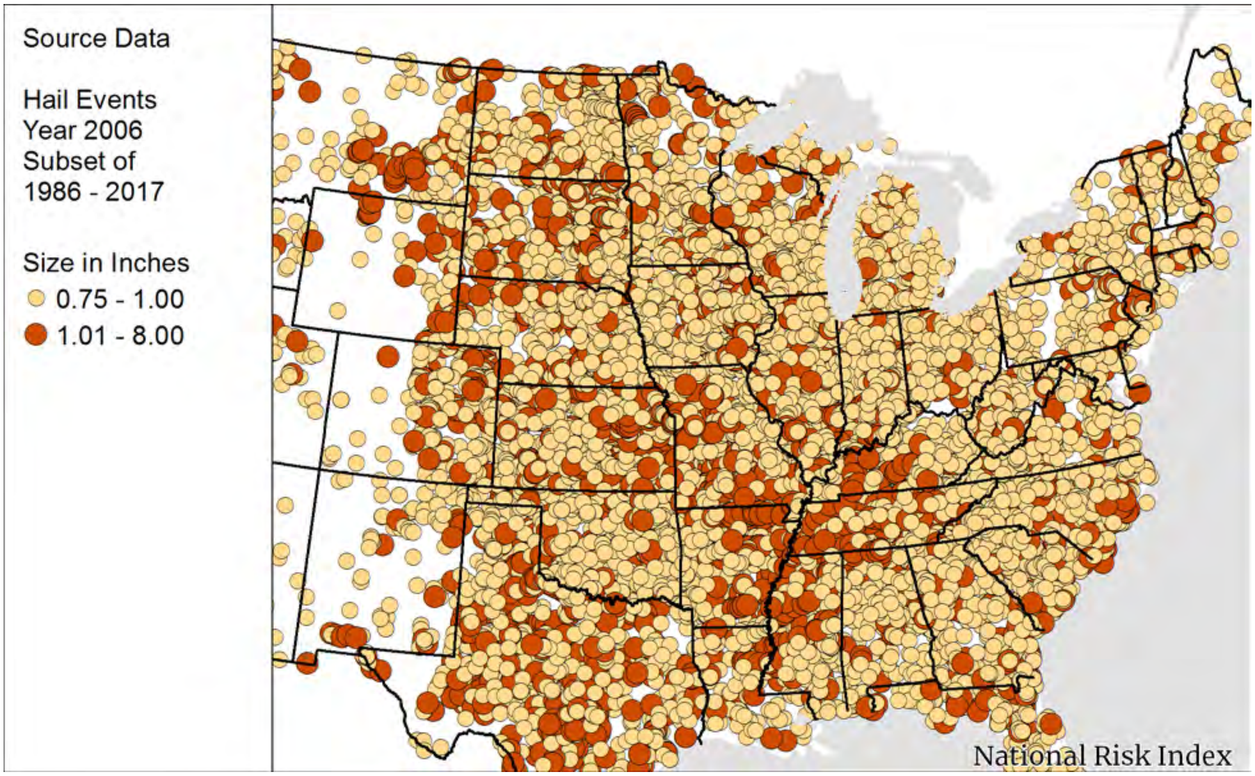

Figure 55: Map of Hail Source Data Points

11.1.1. PERIOD OF RECORD

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. The resulting Hail event polygons can then be used to estimate annualized 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 56).

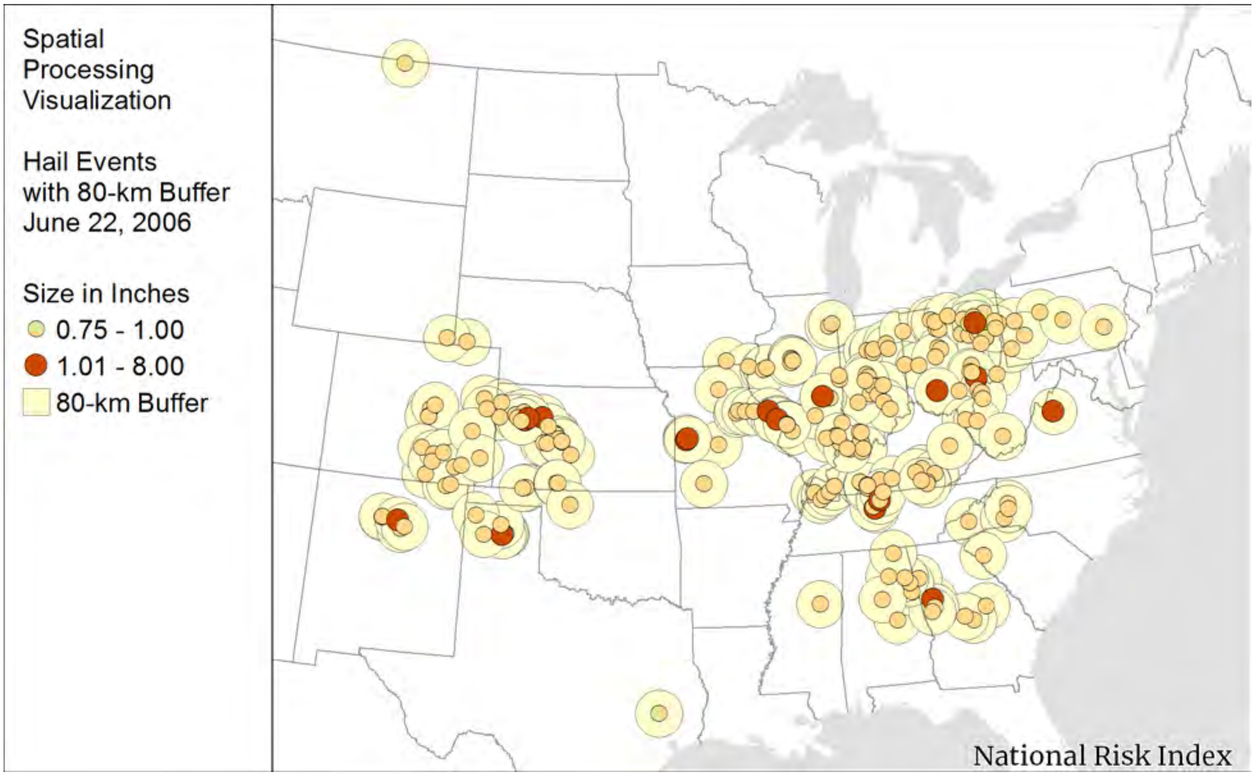

Figure 56: Map of Buffered Hail Points

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 agriculture value of a Census block, Census tract, and county are considered exposed to Hail. Population equivalence, which is used in select EAL calculations, is calculated by multiplying population by the VSL ($7.6M per person).

11.5. Historic Occurrence Count

The historic occurrence count of Hail, in events, is initially computed as the number of distinct Hail event polygons that intersect a 49-by-49-km fishnet grid cell. Buffering the Hail points and using the fishnet grid to count historic Hail events serves to spatially spread the influence of past Hail events to nearby areas that may also be susceptible to Hail but have not experienced Hail as frequently.

However, using these methods can overestimate Hail frequency. To adjust for this, a national scaling factor is calculated (see Equation 47).

Equation 47: National Scaling Factor for Hail Event Count

$$NatlScalingFactor_{HAIL} = \frac{EventCount_{HAIL_{Ntl}}}{\sum FishnetIntsctCount_{HAIL_{Ntl}}}$$

where:

$NatlScalingFactor_{HAIL}$	is the Hail scaling factor to be applied to the fishnet grid cell event count.
$EventCount_{HAIL_{Ntl}}$	is the count of distinct Hail events that have occurred in the U.S.
$\sum FishnetIntsctCount_{HAIL_{Ntl}}$	is the summed total of all Hail event polygon-fishnet grid cell intersections in the U.S.

The scaling factor is then applied to the fishnet grid Hail event count (see Equation 48).

Equation 48: Scaled Hail Event Fishnet Count

$$ScaledEventCount_{HAIL_{Fish}} = EventCount_{HAIL_{Fish}} \times NatlScalingFactor_{HAIL}$$

where:

$ScaledEventCount_{HAIL_{Fish}}$	is the scaled count of Hail events within a fishnet grid cell (in events per year).
$EventCount_{HAIL_{Fish}}$	is the count of Hail event polygons that intersect a 49-by-49-km fishnet grid cell.
$NatlScalingFactor_{HAIL}$	is the Hail scaling factor to be applied to the fishnet grid cell event count.

The Census block Hail event count is then computed as the scaled event count of the 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 Occurrence Count). This scaled count is then used to compute Hail event annualized frequency.

Historic event counts are also supplied at the Census tract and county levels as the scaled, area-weighted count of Hail events intersecting fishnet grid cells that intersect the Census tract and county, respectively.

11.6. Annualized Frequency

The number of recorded Hail occurrences, in events, each year over the period of record (32 years) is used to estimate the annualized frequency of Hail events 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.

Annualized frequency calculations use the Hail event polygons created from the source data (as described in Section 11.2 Spatial Processing), as well as their corresponding computed duration days from the pre-processing of the data. The Census block Hail event count computed using the scaled event counts of the fishnet grid cells intersecting the Census block is divided by the period of record to compute frequency as in Equation 49.

Equation 49: Census Block Hail Annualized Frequency

$$Freq_{HAIL_{CB}} = \frac{ScaledEventCount_{HAIL_{Fish}}}{PeriodRecord_{HAIL}}$$

where:

$Freq_{HAIL_{CB}}$	is the annualized frequency of Hail events determined for a specific Census block (events per year).
$ScaledEventCount_{HAIL_{Fish}}$	is the scaled count of Hail events calculated for the Census block.
$PeriodRecord_{HAIL}$	is the period of record for Hail (32 years).

11.6.1. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized frequency values at both the Census tract and county level. These values may not exactly match that of dividing the number of recorded Hail events at the Census tract and county level by the period of record, as the event count for annualized 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 annualized frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 50.

Equation 50: Census Tract and County Area-Weighted Hail Annualized Frequency Aggregation

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

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

where:

$Freq_{HAIL_{CT}}$	is the area-weighted Hail annualized frequency calculated for a specific Census tract (events per year).

$Freq_{HAIL_{CB}}$	is the annualized frequency of Hail events determined for a specific Census block (events per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	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 area-weighted Hail annualized 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 57 displays Hail annualized frequency at the county level.

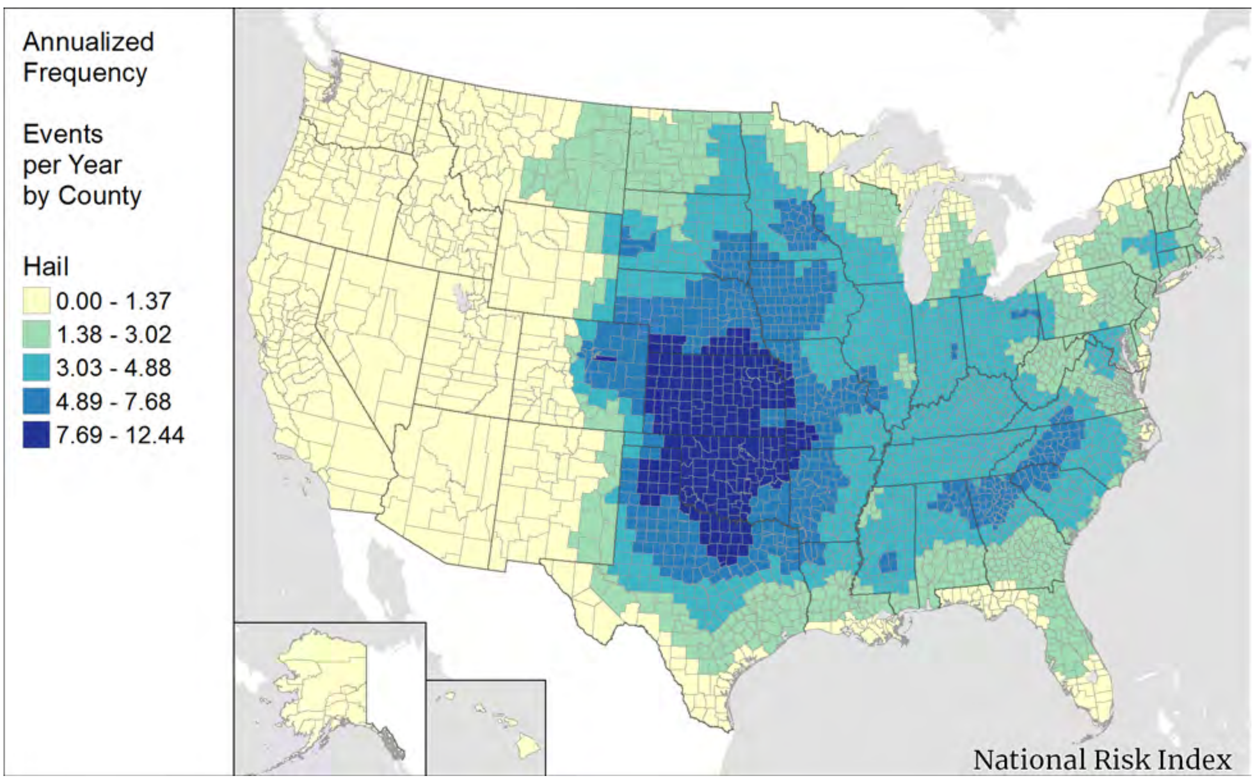

Figure 57: Hail Annualized Frequency by County

11.7. Historic Loss Ratio

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

Loss data are provided by SHELDUS[49] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. One peril type is mapped to the hazard Hail (see Table 33). Native records of Hail storms that caused loss over more than one day (such as those that occurred overnight) have their loss assigned to the first day, and all records are aggregated on a single-event-per-day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

Table 33: Hail Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Hail	27,522	18,719

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 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 51.

Equation 51: Loss Ratio per Basis Calculation for a Single Hail Event

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

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 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 (in dollars).

Hail events 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

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

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 (1996 to 2019). For Hail, the historic event count is extracted using an intersection between the Hail event polygons and the Census blocks. An annual rate is calculated as the event count divided by the period of record of 32 years, and this rate is multiplied by the SHELDUS period of record of 24 years to estimate a historic event count for the appropriate time range.

If the number of Hail event records from SHELDUS is less than the scaled event count for the county, then a number of zero-loss records equal to the difference are 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 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

Figure 58, Figure 60, and Figure 62 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 Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Hail events within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value, though its HLR may be influenced by other local, regional, or national occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted 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 LRBs get the most influence from regional or national-level loss data. Figure 59, Figure 61, and Figure 63 represent the final, Bayesian-adjusted county-level HLR values for Hail.

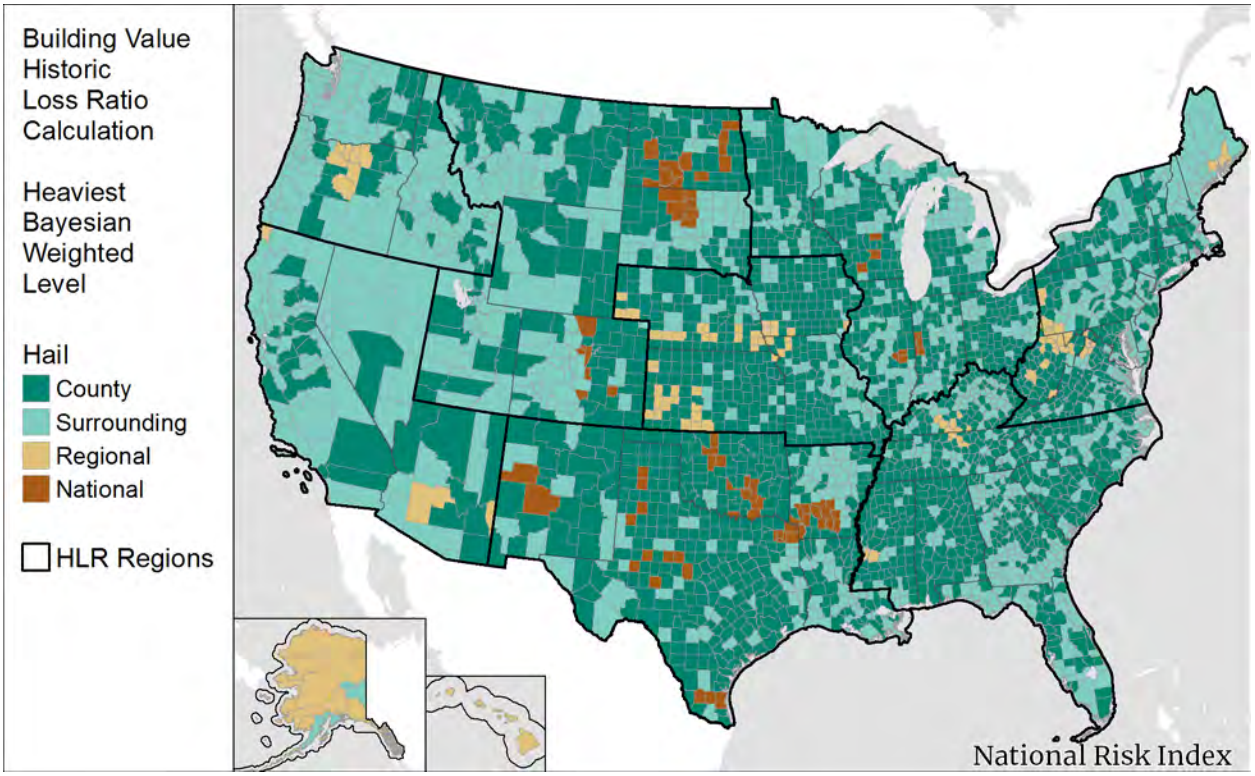

Figure 58: Hail Heaviest Bayesian Weighted Level – Building Value

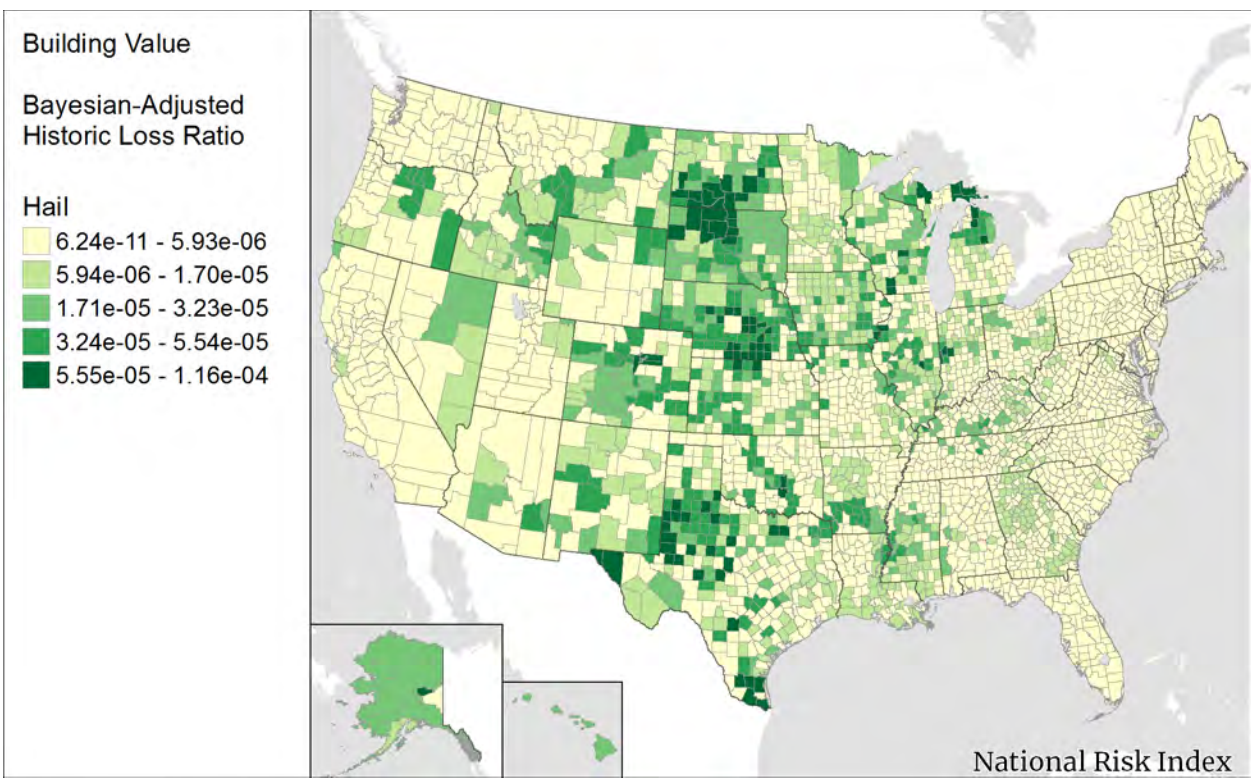

Figure 59: Hail Bayesian-Adjusted HLR – Building Value

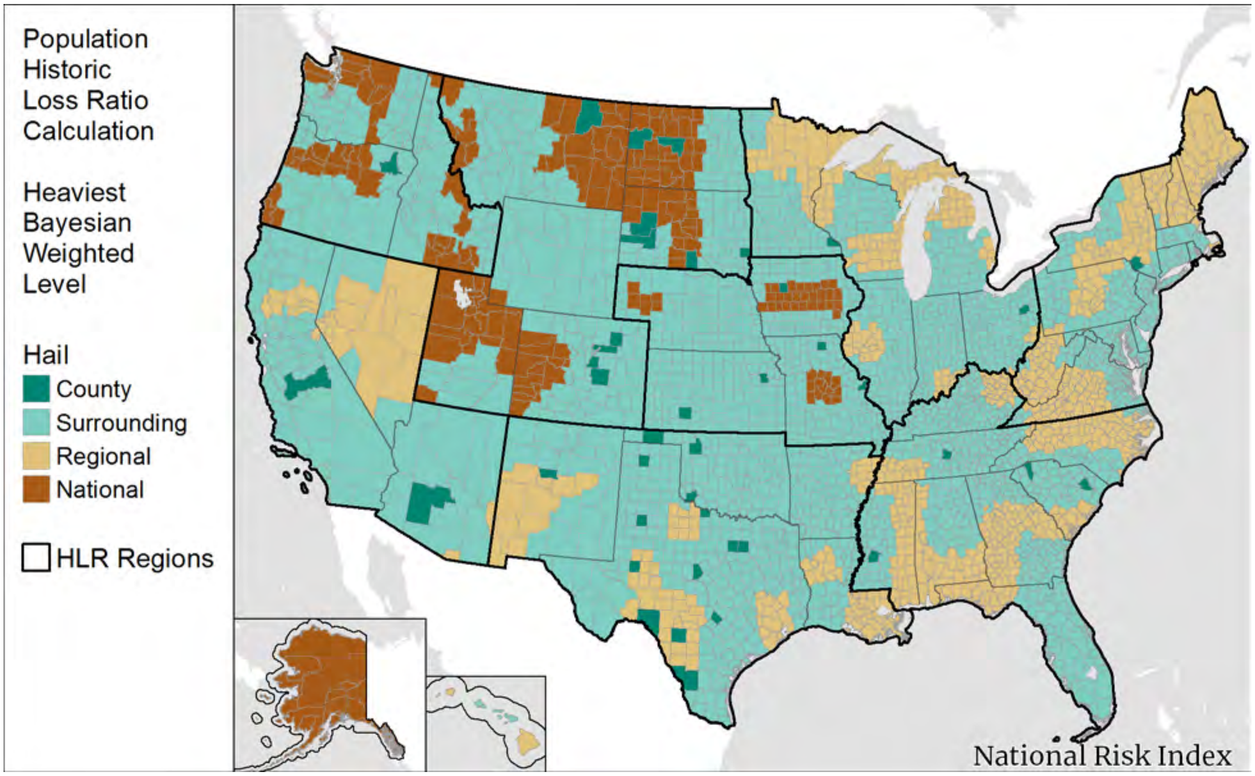

Figure 60: Hail Heaviest Bayesian Weighted Level -- Population

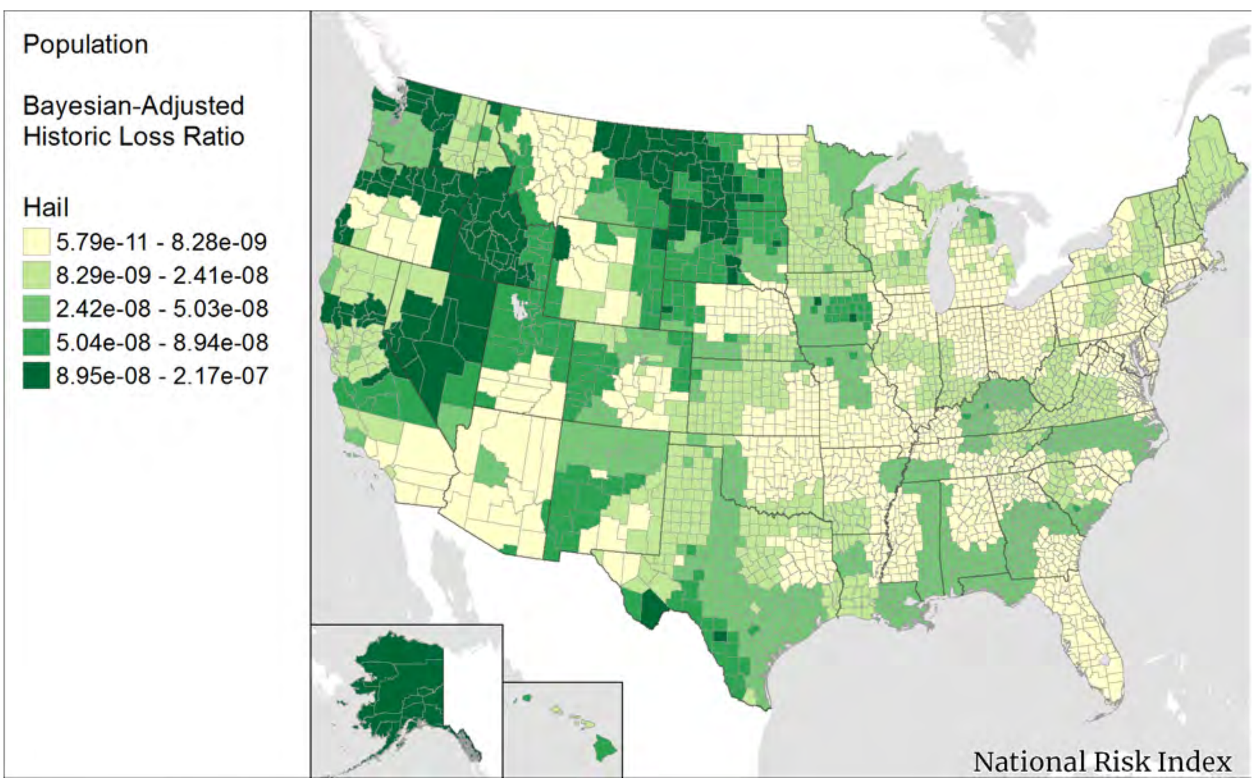

Figure 61: Hail Bayesian-Adjusted HLR – Population

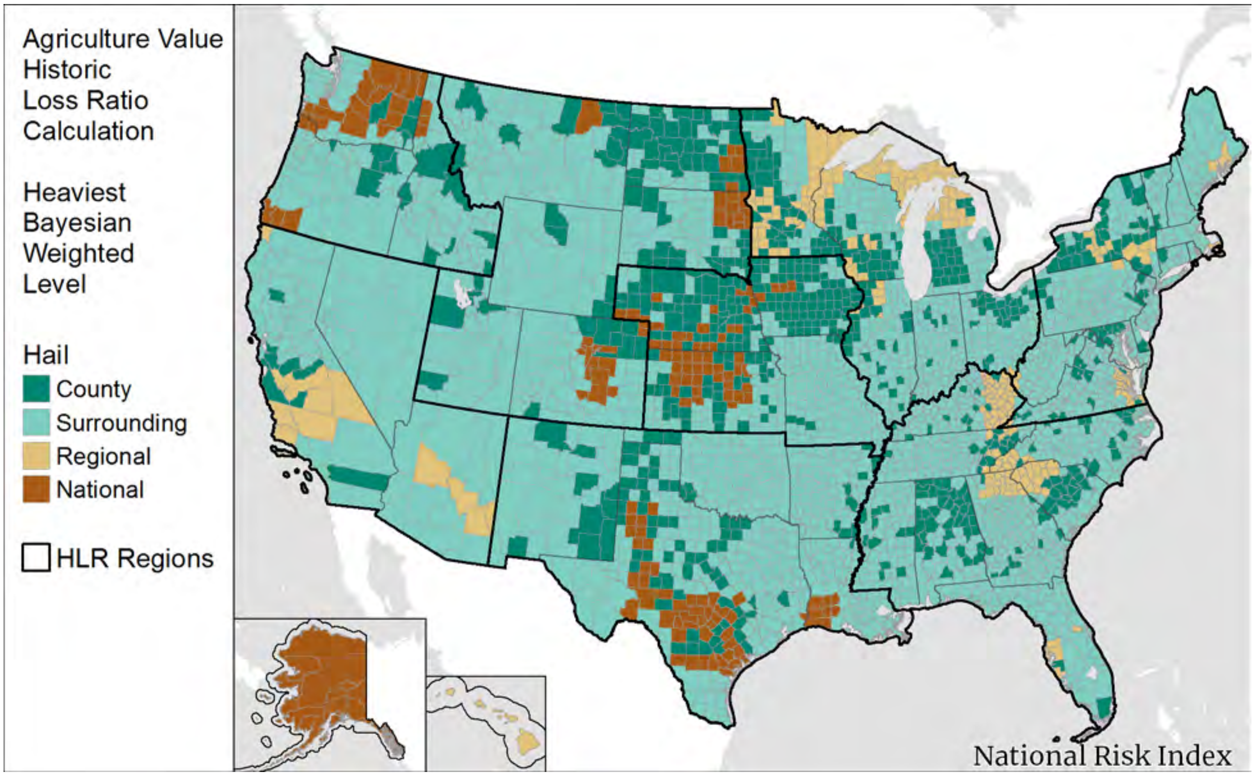

Figure 62: Hail Heaviest Bayesian Weighed Level – Agriculture Value

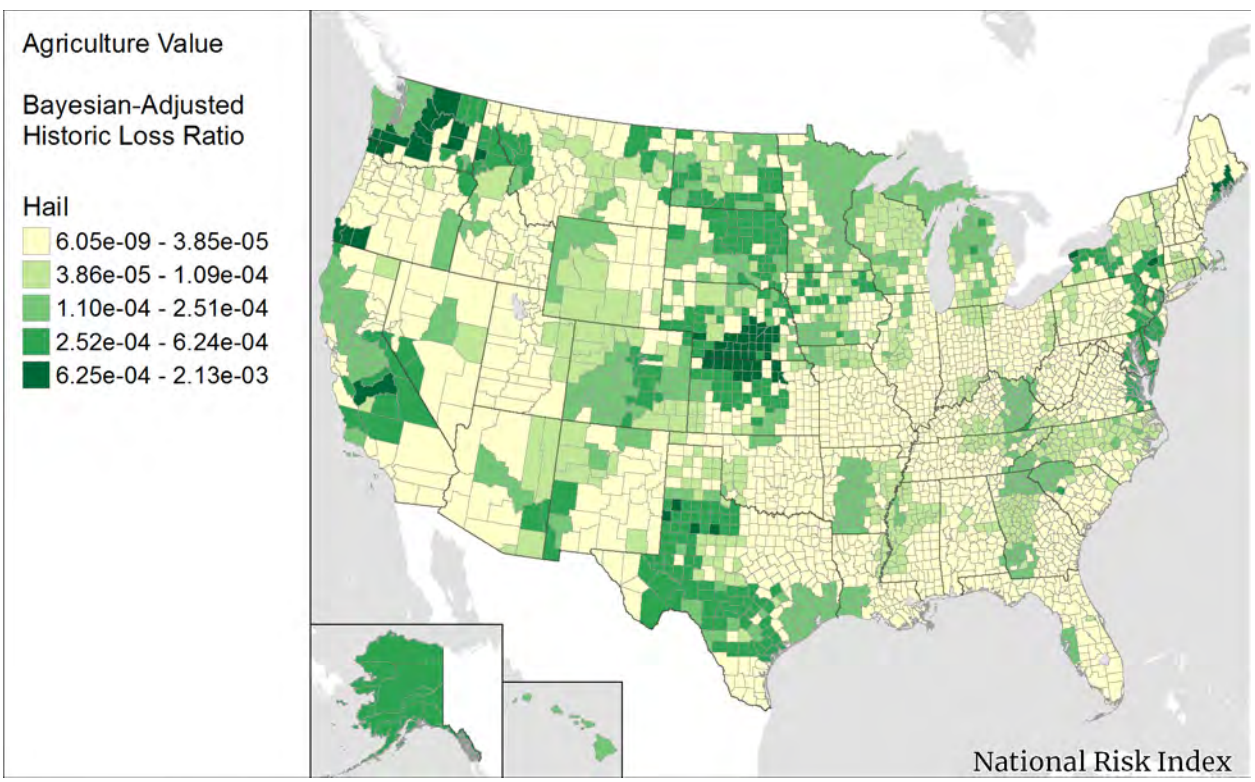

Figure 63: Hail Bayesian-Adjusted HLR – Agriculture Value

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

11.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level (see Equation 52). 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 52: 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 building Expected Annual Loss due to Hail occurrences for a specific Census block (in dollars).
$Exposure_{HAIL_{CB_{Bldg}}}$	is the building value exposed to Hail occurrences in the Census block (in dollars).
$Freq_{HAIL_{CB}}$	is the Hail annualized frequency calculated for the Census block (events 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 population equivalence Expected Annual Loss due to Hail occurrences for a specific Census block (in dollars).
$Exposure_{HAIL_{CB_{Pop}}}$	is the population equivalence value exposed to Hail occurrences 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 agriculture Expected Annual Loss due to Hail occurrences for a specific Census block (in dollars).

$Exposure_{HAIL_{CB_{Ag}}}$	is the agriculture value exposed to Hail occurrences in the Census block (in dollars).
$HLR_{HAIL_{CB_{Ag}}}$	is the Bayesian-adjusted agriculture 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 building, population equivalence, and agriculture EAL values at the Census block level as in Equation 53.

Equation 53: 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 occurrences for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{HAIL_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Hail occurrences for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{HAIL_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Hail occurrences for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{HAIL_{CB_{Ag}}}$	is the summed agriculture Expected Annual Loss due to Hail occurrences for all Census blocks in the Census tract (in dollars).
$EAL_{HAIL_{Co}}$	is the total Expected Annual Loss due to Hail occurrences for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{HAIL_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Hail occurrences for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{HAIL_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Hail events occurrences for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{HAIL_{CB_{Ag}}}$	is the summed agriculture Expected Annual Loss due to Hail occurrences for all Census blocks in the county (in dollars).

Figure 64 shows the total EAL (building value, population equivalence, and agriculture value combined) to Hail occurrences.

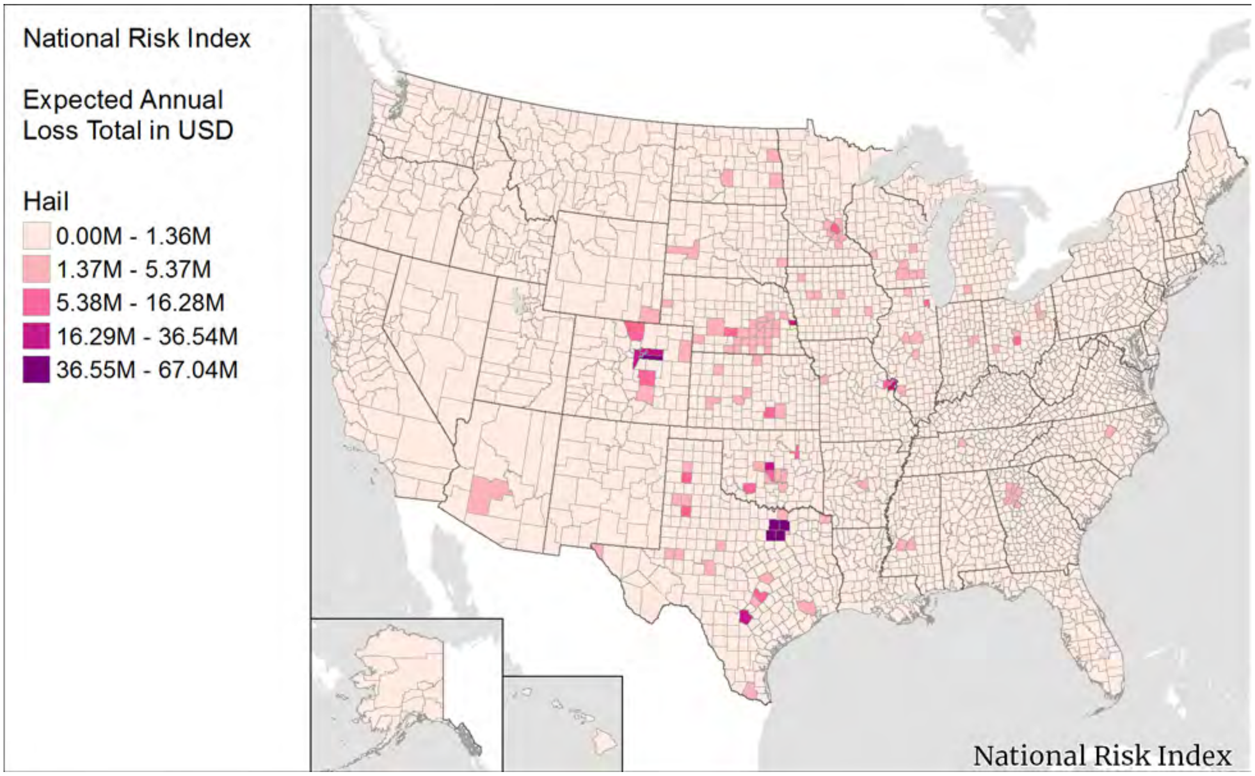

Figure 64: Total Expected Annual Loss by County to Hail

With the Hail total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 Occurrence Generating Source: National Weather Service, Weather Alerts[50]

Historical Occurrence Compiling Source: Iowa State University, Iowa Environmental Mesonet[51]

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 annualized 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[52] 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.

[50] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *Active Alerts* [online dataset]. Retrieved from *https://www.weather.gov/*.
[51] Department of Agronomy, Iowa State University. (2018). *Iowa Environmental Mesonet* [online database]. Retrieved from *https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml*.
[52] 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,[53] 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 distributions 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.

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 many 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.

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 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. See Figure 65 for an example of the differences in the spatial resolution of weather alert boundaries.

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

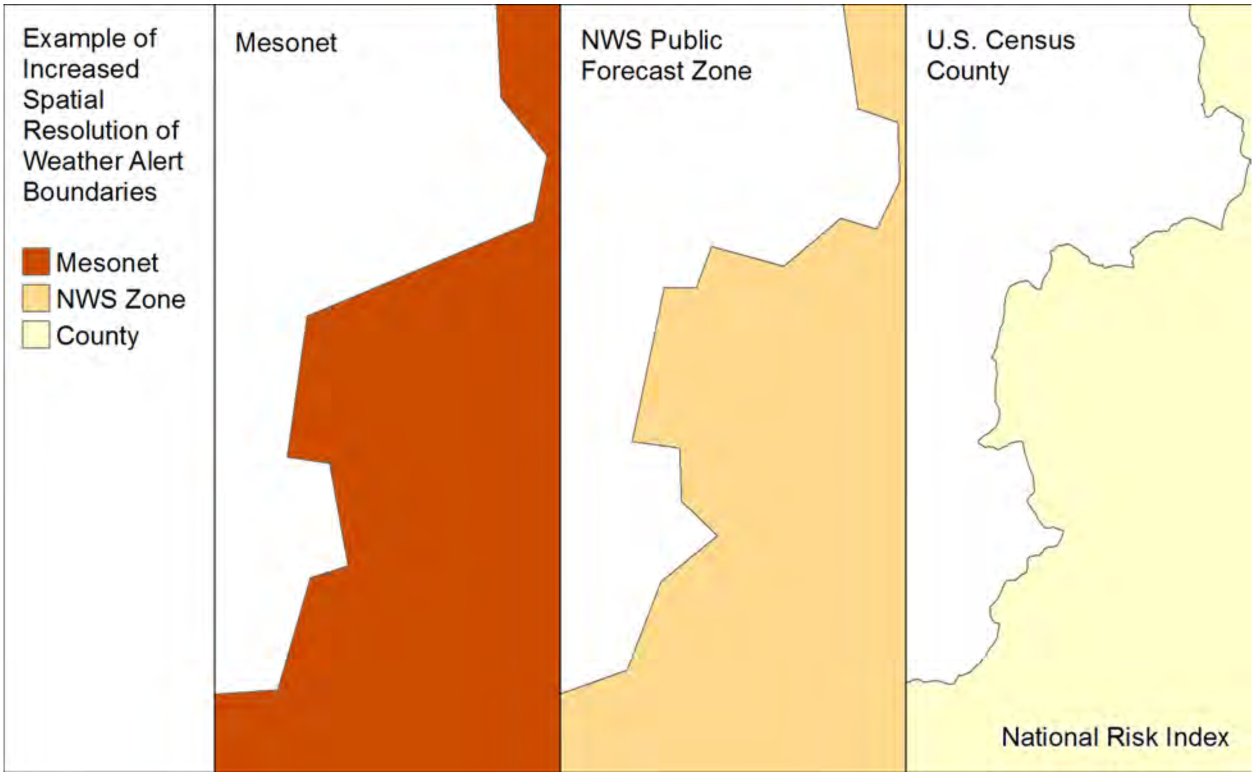

Figure 65: Three Boundary Definitions: Mesonet, Forecast Zone, and U.S. Census County

12.1.1. PERIOD OF RECORD

In the 1990s and early 2000s, the NWS's system of recording WWA made automated processing too difficult. So, in 2005, the 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 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 annualized 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 Heat Wave occurrences (see Table 34).

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 34: Original Mesonet Heat Wave Records

WFO	*ISSUED*	*EXPIRED*	*PHENOM*	*SIG*	*NWS_UGC*	*AREA_KM2*
PSR	6/4/2017 6:00 PM	6/8/2017 3:00 AM	EH	W	AZZ554	583.5392
MAF	6/17/2017 5:00 PM	6/18/2017 2:00 AM	EH	W	TXZ045	3894.574
VEF	6/17/2017 6:00 PM	6/27/2017 4:00 AM	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. To illustrate this concept, the Heat Wave events in Table 35 are expanded to create the Heat Wave event-day records in Table 36.

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.

Table 35: Sample Heat Wave Data after Zone Shape Re-Sourcing

HeatwaveID	*WFO*	*Issued*	*Expired*	*PHENOM*	*SIG*	*NWS_UGC*	*AreaKm2*	*NewShapeSource*
47081	PSR	6/4/2017 6:00 PM	6/8/2017 3:00 AM	EH	W	AZZ554	577.2512	NWS Forecast Zone
51174	TWC	6/7/2017 6:00 PM	6/6/2017 9:45 PM	EH	W	AZZ504	5763.599	NWS Forecast Zone

Table 36: Sample Data from the Heat Wave Date Expansion Table

HeatwaveDate ExpansionID	*HeatwaveID*	*Issued*	*Expired*	*DateType*	*HeatwaveHours*
2030	47081	6/4/2017 6:00 PM	6/5/2017 12:00 AM	Expanded Dates - Issued	6
2032	47081	6/5/2017 12:00 AM	6/6/2017 12:00 AM	Expanded Dates - New Dates	24
2031	47081	6/6/2017 12:00 AM	6/7/2017 12:00 AM	Expanded Dates - New Dates	24
2034	47081	6/7/2017 12:00 AM	6/8/2017 12:00 AM	Expanded Dates - New Dates	24
1	51174	6/7/2017 6:00 PM	6/7/2017 6:00 PM	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 annualized frequency.

12.3. Determination of Possibility of Hazard Occurrence

Heat Waves can occur almost anywhere in the U.S. 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 Spatial Processing) are intersected with the Census block polygons within the 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 37).

Table 37: Sample Data from the Heat Wave Expansion Census Block Intersection Table

HeatwaveDateExpansionID	*CensusBlock*	*IntersectedAreaKm2*
53297	040131167132017	0.080384
53297	040131167133000	0.313492
53297	040131167133001	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-day polygons that intersected the Census block and dividing this sum by the number of intersecting event-day polygons. This is multiplied by the developed area building value density, developed area population density, and the agriculture area value density of the Census block to model the conservative-case concentration of exposure within the Census block (see Equation 54). The densities for each consequence type in the Census block have been calculated by dividing the Census block total exposure values (as recorded in Hazus 4.2 SP1) by the developed or agriculture land area (in square kilometers). The VSL was used to express population equivalence exposure in terms of dollars.

Equation 54: Census Block Heat Wave Exposure

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

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

$$Exposure_{HWAV_{CB_{Ag}}} = \frac{\sum IntsctArea_{HWAV_{CB}}}{EventDayCount_{HWAV_{CB}}} \times AgValueDen_{CB}$$

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).

$EventDayCount_{HWAV_{CB}}$ is the total number of Heat Wave event-day polygons 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 equivalence 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 ($7.6M per person).

$Exposure_{HWAV_{CB_{Ag}}}$ is the agriculture value exposed to Heat 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, 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 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 building value exceeds the Hazus-recorded building value, then the Hazus-recorded building value is used as the building 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 Census tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see Equation 55).

Equation 55: Census Tract and County Heat Wave Exposure Aggregations

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

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

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

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

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

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

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 equivalence 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 equivalence exposed to Heat Wave for each Census block within the Census tract (in dollars).

$Exposure_{HWAV_{Co_{Pop}}}$ is the population equivalence 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 equivalence exposed to Heat Wave for each Census block within the county (in dollars).

$Exposure_{HWAV_{CT_{Ag}}}$ is the agriculture value exposed to Heat Wave event-days in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{HWAV_{CB_{Ag}}}$ is the summed value of all agriculture areas exposed to Heat Wave for each Census block within the Census tract (in dollars).

$Exposure_{HWAV_{Co_{Ag}}}$ is the agriculture value exposed to Heat Wave event-days in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{HWAV_{CB_{Ag}}}$ is the summed value of all agriculture areas exposed to Heat Wave for each Census block within the county (in dollars).

12.5. Historic Occurrence Count

The historic occurrence count of Heat Wave, in 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 Census 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 annualized 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. Annualized Frequency

The number of recorded Heat Wave occurrences, in event-days, each year over the period of record (12.14 years) is used to estimate the annualized frequency of Heat Waves in an area. Because a Heat Wave event can last over several days or a single day, an event-day basis was used to estimate annualized 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.

Annualized 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 56.

Equation 56: Census Block Heat Wave Annualized Frequency

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

where:

$Freq_{HWAV_{CB}}$	is the Heat Wave annualized frequency calculated for a specific Census block (event-days per year).
$EventDayCount_{HWAV_{CB}}$	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. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized 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 event-days at the Census tract and county level by the period of record, as the annualized frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 57.

Equation 57: Census Tract and County Area-Weighted Heat Wave Annualized 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 area-weighted Heat Wave annualized frequency calculated for a specific Census tract (event-days per year).
$Freq_{HWAV_{CB}}$	is the Heat Wave annualized 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 area-weighted Heat Wave annualized 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 66 displays Heat Wave annualized frequency at the county level.

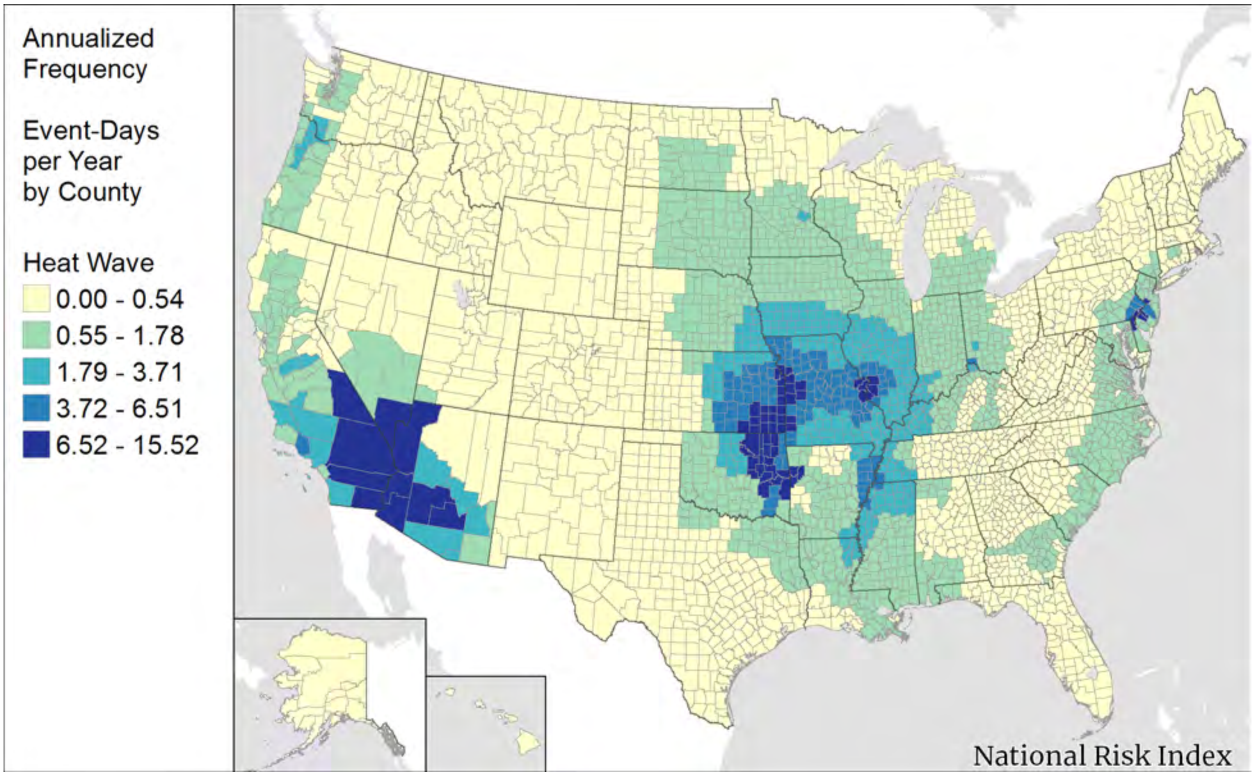

Figure 66: Heat Wave Annualized Frequency by County

12.7. Historic Loss Ratio

The Heat Wave HLR is the representative percentage of a location's hazard exposure 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 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Heat Wave hazard type.

Loss data are provided by SHELDUS[54] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Two peril types are mapped to the hazard Heat Wave (see Table 38). These native records are expanded on an event-day basis (to a maximum of 31 event-days) and aggregated on a single-event-per-day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

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

Table 38: Heat Wave Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Heat	2,610	11,780
Heat Wave	1	1

The HLR exposure value used in the formula below is a county-level value that represents the dollar value of the total building value, the entire population, or the total agriculture value of a county as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event-day and each consequence type (building, population, and agriculture) is calculated using Equation 58.

Equation 58: 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, population, and agriculture).

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

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

Heat Wave event-days can occur with a high frequency in areas, but often result in no recorded loss to building value, population, or agriculture value. 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 (1996 to 2019). For Heat Wave, the historic event-day count is extracted using the intersection between the Heat Wave event-day polygons and the Census block polygons used to calculate exposure and annualized frequency (see Table 37). An annual rate is calculated as the event-day count divided by the period of record of 12.14 years, and this rate is multiplied by the SHELDUS period of record of 24 years to estimate a historic event-day count for the appropriate time range.

If the number of Heat Wave event-day records from SHELDUS is less than the scaled event-day count for the county, then a number of zero-loss records equal to the difference are 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 Heat Wave is derived from the FEMA regions with Regions 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

Figure 67, Figure 69, and Figure 71 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 Bayesian-adjusted 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 Bayesian-adjusted HLR value, though its HLR may be influenced by other local or regional occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted 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 68, Figure 70, and Figure 72 represent the final, Bayesian-adjusted county-level HLR values for Heat Wave.

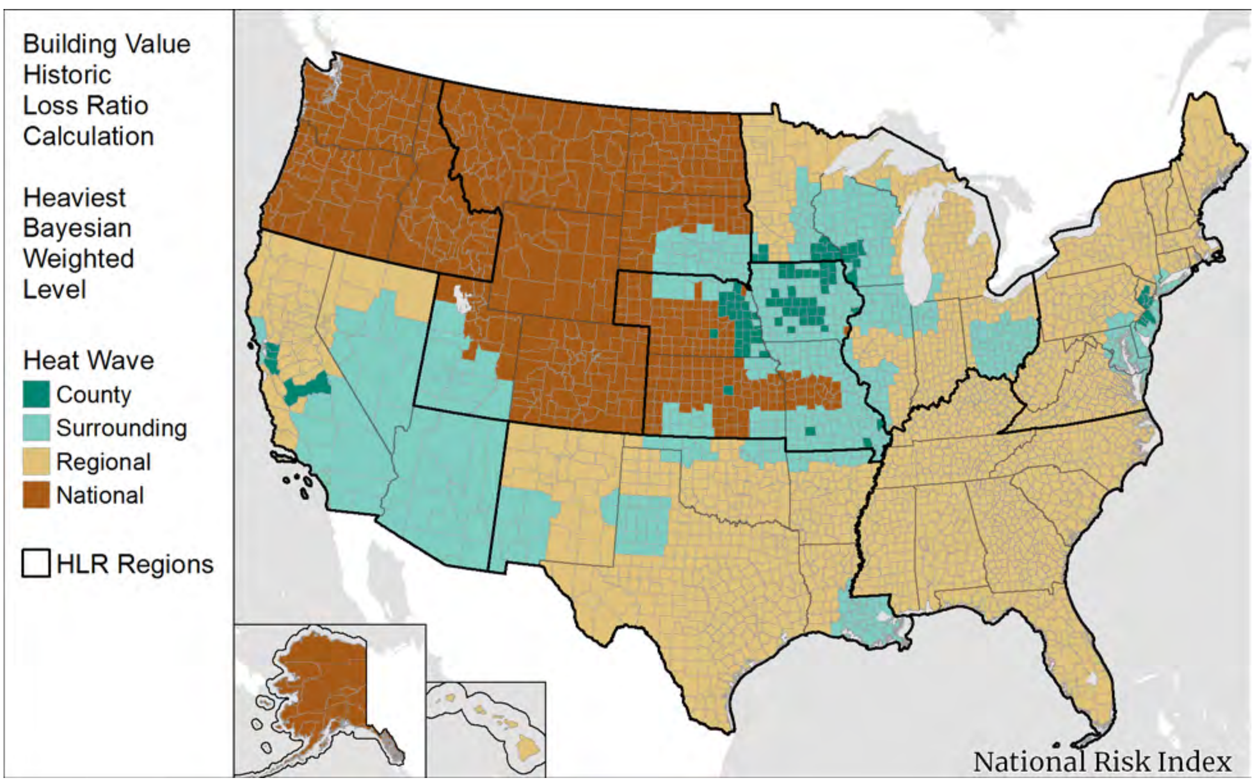

Figure 67: Heat Wave Maximum Weighting Factor Contributor – Building Value

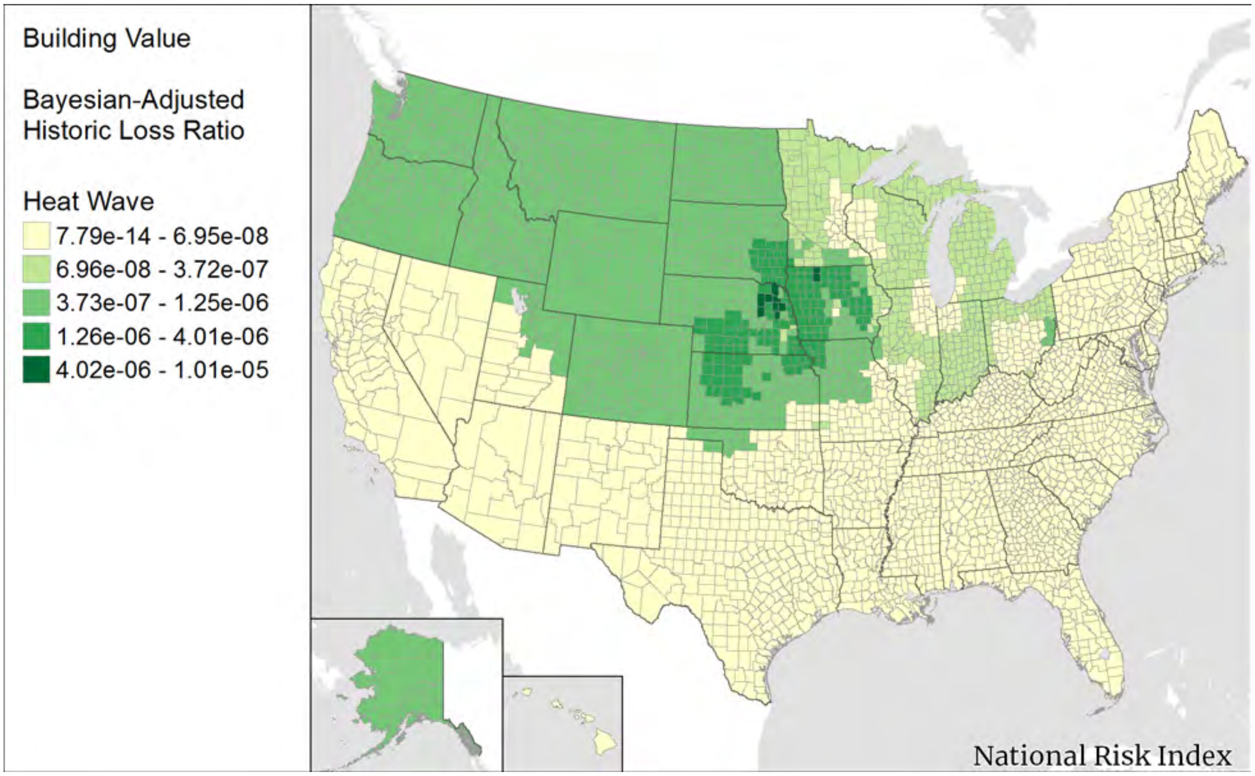

Figure 68: Heat Wave Bayesian-Adjusted HLR – Building Value

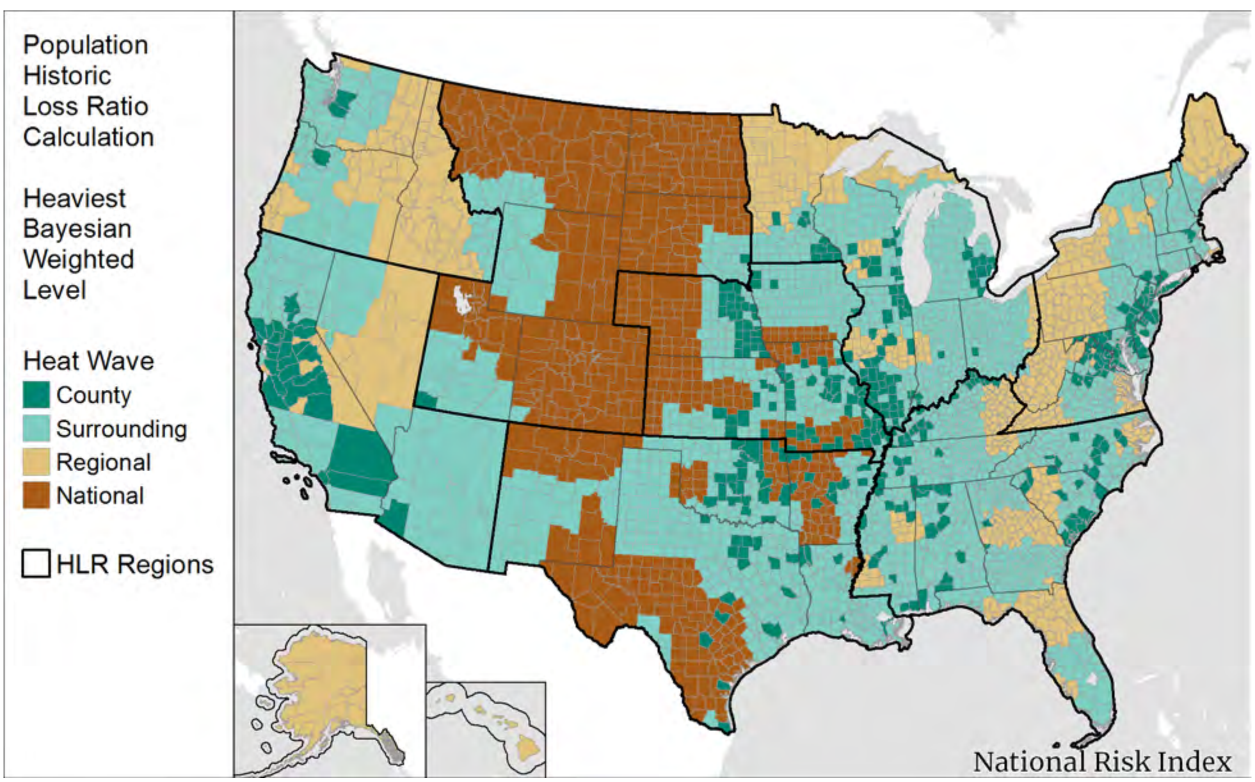

Figure 69: Heat Wave Maximum Weighting Factor Contributor – Population

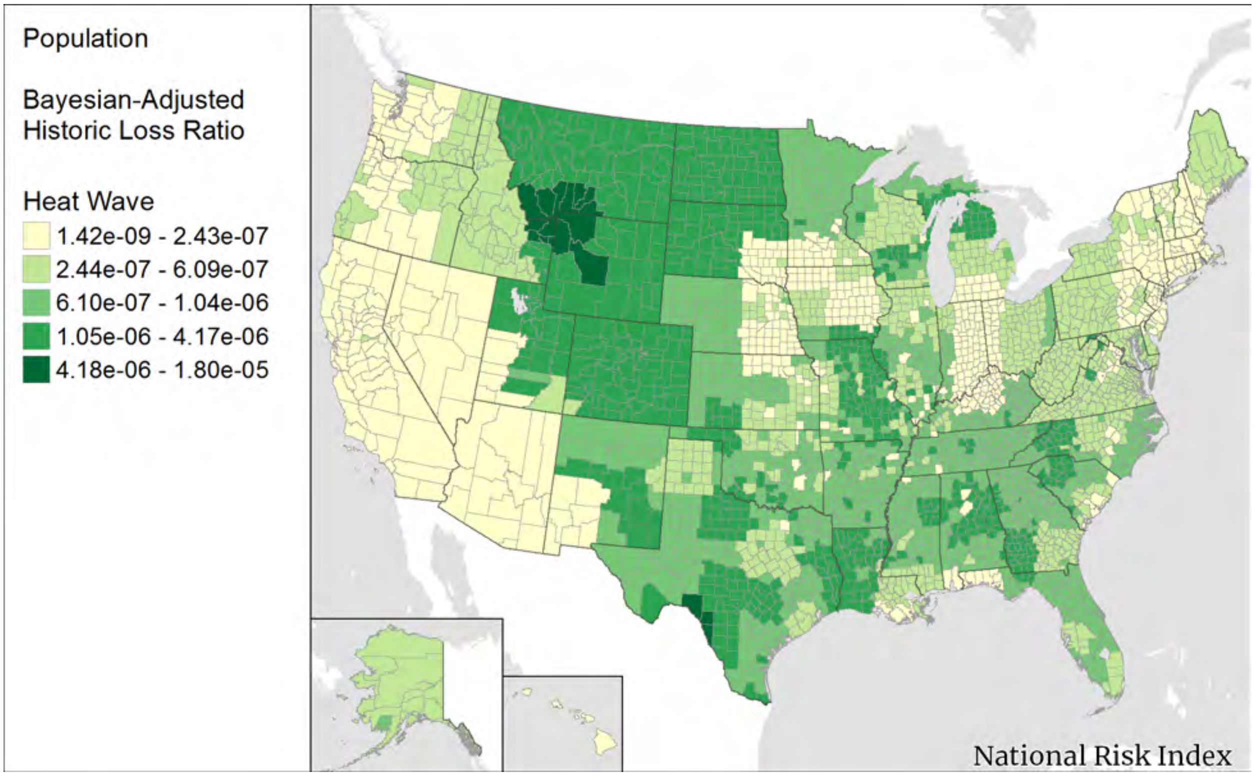

Figure 70: Heat Wave Bayesian-Adjusted HLR – Population

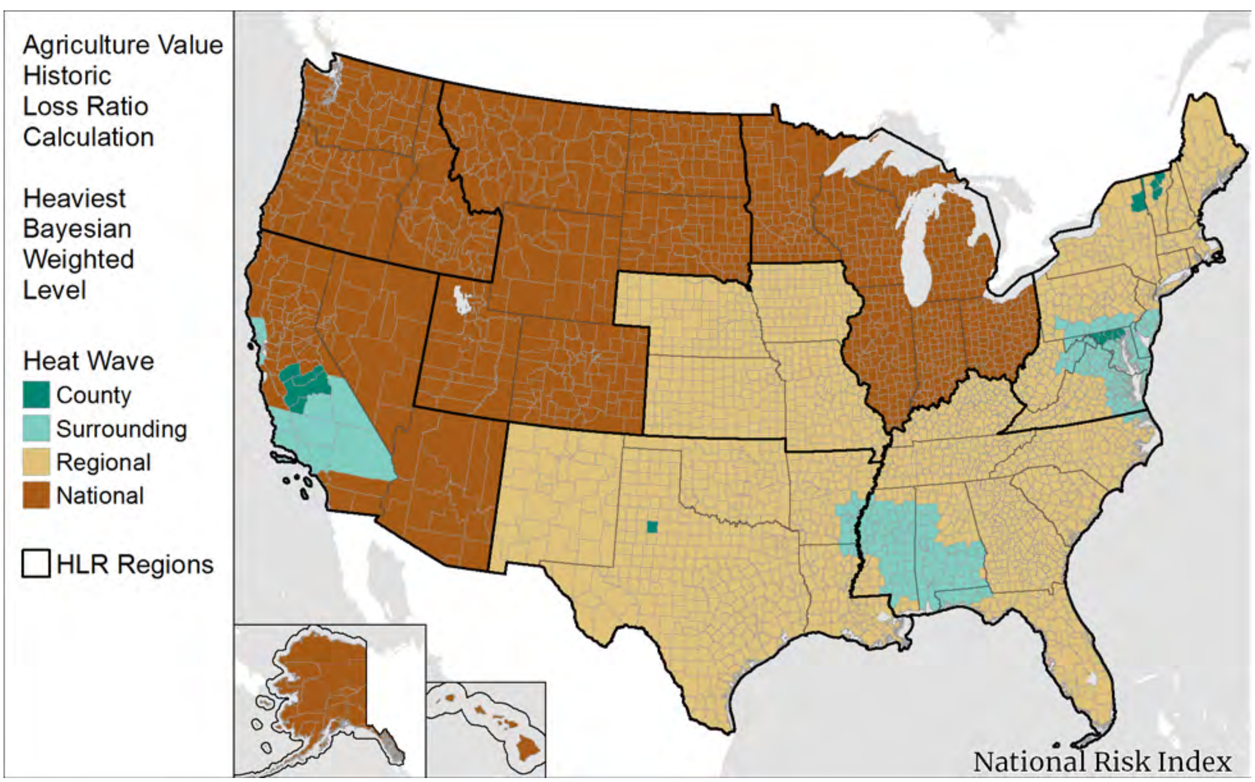

Figure 71: Heat Wave Maximum Weighting Factor Contributor – Agriculture Value

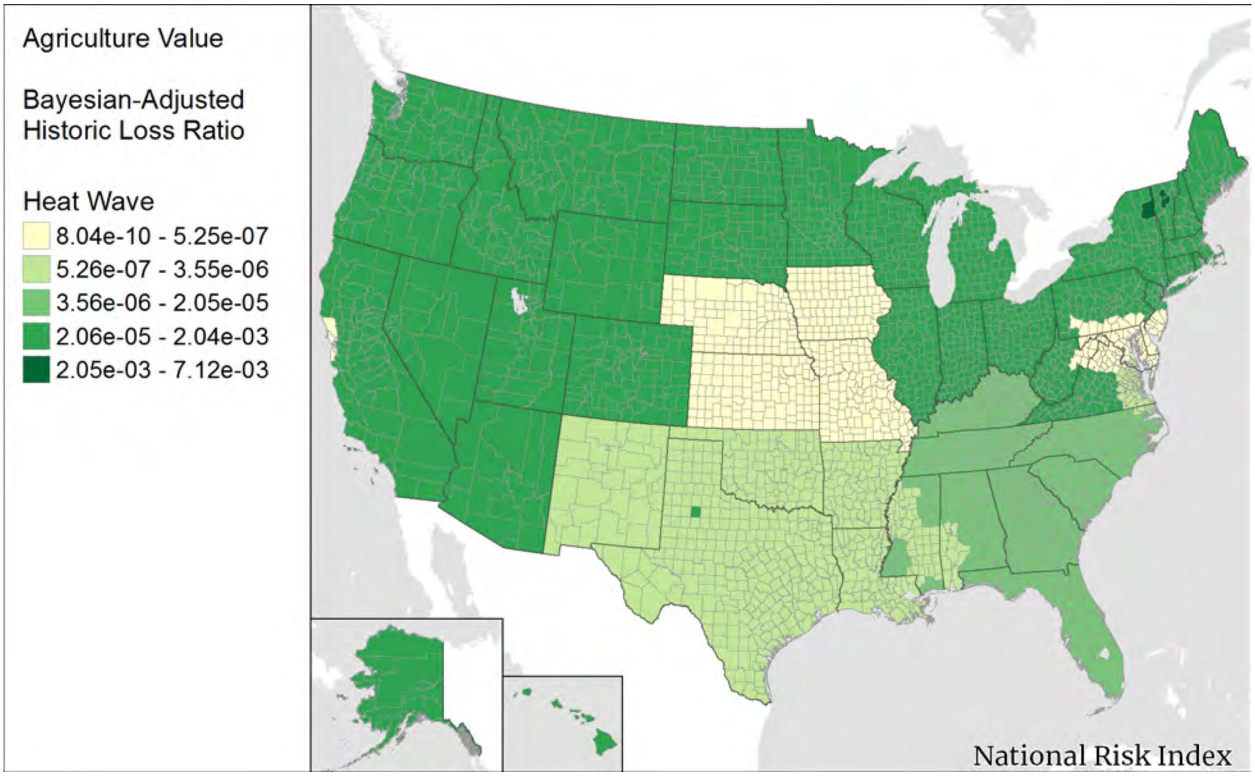

Figure 72: Heat Wave Bayesian-Adjusted HLR – Agriculture Value

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

12.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 59. 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 59: Census Block Expected Annual Loss to Heat Wave

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

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

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

where:

$EAL_{HWAV_{CB_{Bldg}}}$	is the building Expected Annual Loss due to Heat Wave occurrences for a specific Census block (in dollars).
$Exposure_{HWAV_{CB_{Bldg}}}$	is the building value exposed to Heat Wave occurrences in the Census block (in dollars).
$Freq_{HWAV_{CB}}$	is the Heat Wave annualized 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 population equivalence Expected Annual Loss due to Heat Wave occurrences for a specific Census block (in dollars).
$Exposure_{HWAV_{CB_{Pop}}}$	is the population equivalence value exposed to Heat Wave occurrences 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.
$EAL_{HWAV_{CB_{Ag}}}$	is the agriculture Expected Annual Loss due to Heat Wave occurrences for a specific Census block (in dollars).
$Exposure_{HWAV_{CB_{Ag}}}$	is the agriculture value exposed to Heat Wave occurrences in the Census block (in dollars).
$HLR_{HWAV_{CB_{Ag}}}$	is the Bayesian-adjusted agriculture 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 building, population equivalence, and agriculture EAL values at the Census block level as in Equation 60.

Equation 60: Census Tract and County Expected Annual Loss to Heat Wave

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

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

where:

$EAL_{HWAV_{CT}}$	is the total EAL due to Heat Wave occurrences for a specific Census tract (in dollars).

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

$\sum_{CB}^{CT} EAL_{HWAV_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Heat Wave occurrences for all Census blocks in the Census tract (in dollars).

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

$EAL_{HWAV_{Co}}$ is the total Expected Annual Loss due to Heat Wave occurrences for a specific county (in dollars).

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

$\sum_{CB}^{Co} EAL_{HWAV_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Heat Wave occurrences for all Census blocks in the county (in dollars).

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

Figure 73 shows the total EAL (building value, population equivalence, and agriculture value combined) to Heat Wave occurrences.

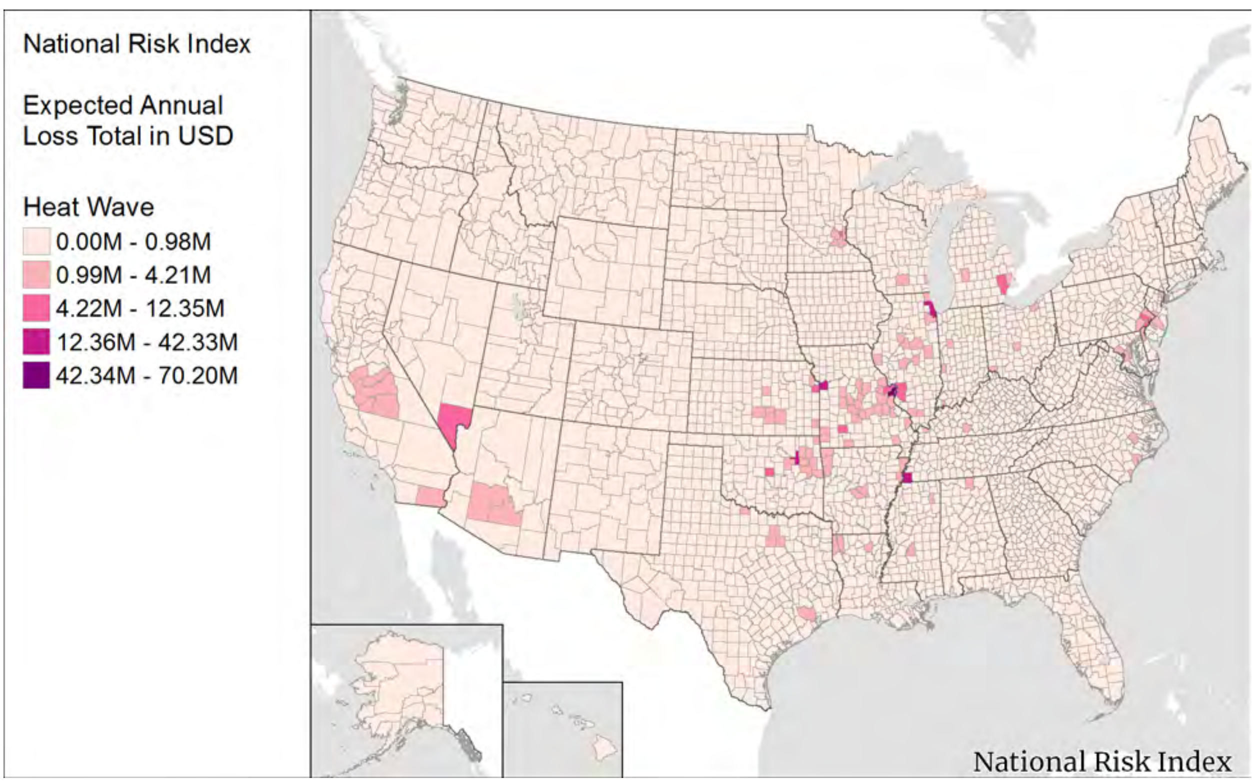

Figure 73: Total Expected Annual Loss by County to Heat Wave

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 in comparison to all other communities at the same level. 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 Hurricane data also include tropical storms for which wind speeds range from 39 to 74 mph.

13.1. Spatial Source Data

Historical Occurrence Source: NOAA, National Hurricane Center, HURDAT2 Best Track Data[55]

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.[56] 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 39 and Figure 74). 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 39: Sample Data from HURDAT2

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

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

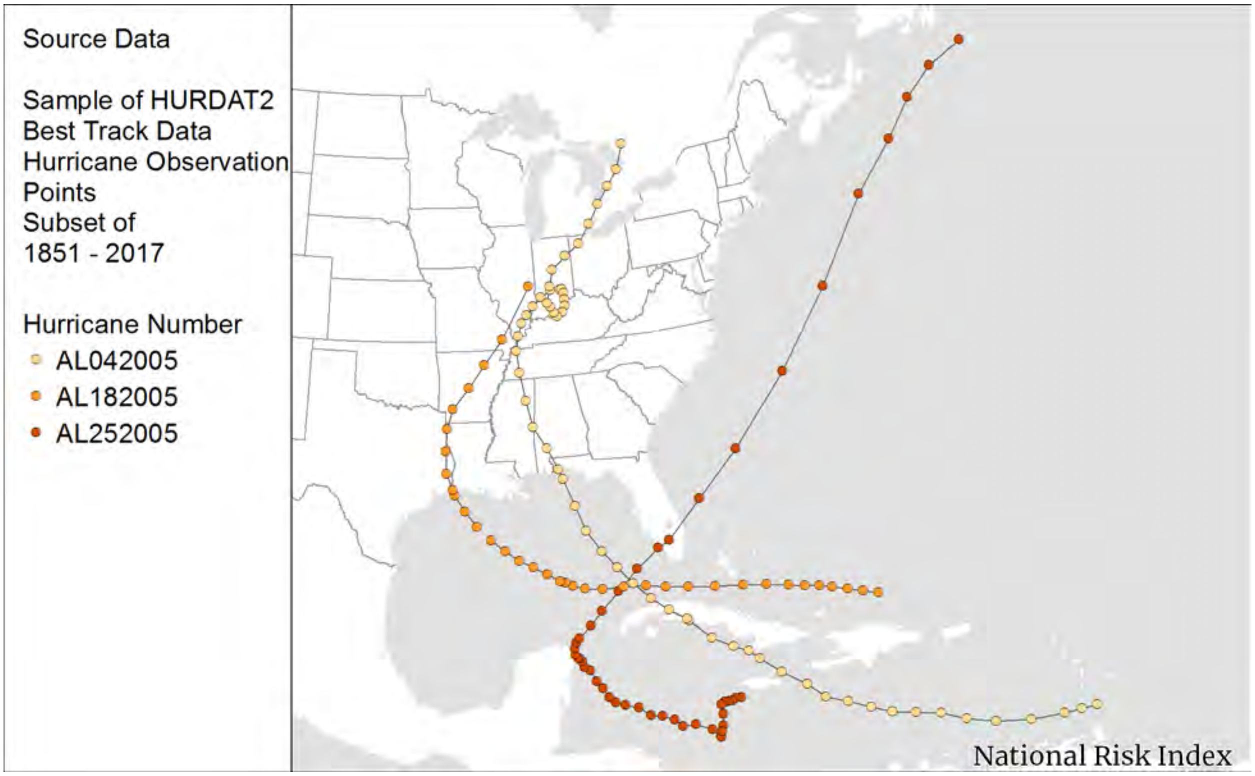

Figure 74: Map of HURDAT2 Points

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 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 wind speeds (based on the Saffir-Simpson Hurricane Wind Scale).[57] 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

[57] 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 40 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).[58]

Table 40: Hurricane Categorization

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)*
Other	0	38.9	0	32.9	0
Tropical Storm	39	73.9	33	63.9	15
Category 1	74	95.9	64	82.9	26.45
Category 2	96	110.9	83	95.9	39.1
Category 3	111	129.9	96	112.9	43.7
Category 4	130	156.9	113	136.9	50.03
Category 5	157	9999	137	9999	54.04

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 75, Table 41, and Figure 76).

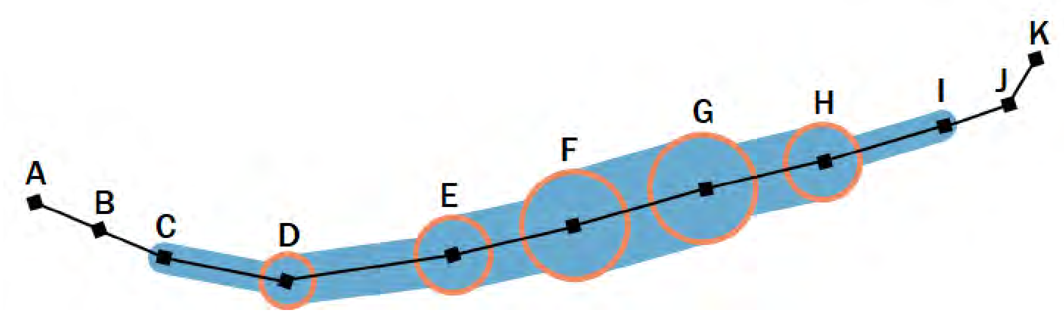

Figure 75: Notional Example Hurricane Event Path Polygon

58 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 41: Notional Example Hurricane Storm Observations

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
J	30	Other
K	15	Other

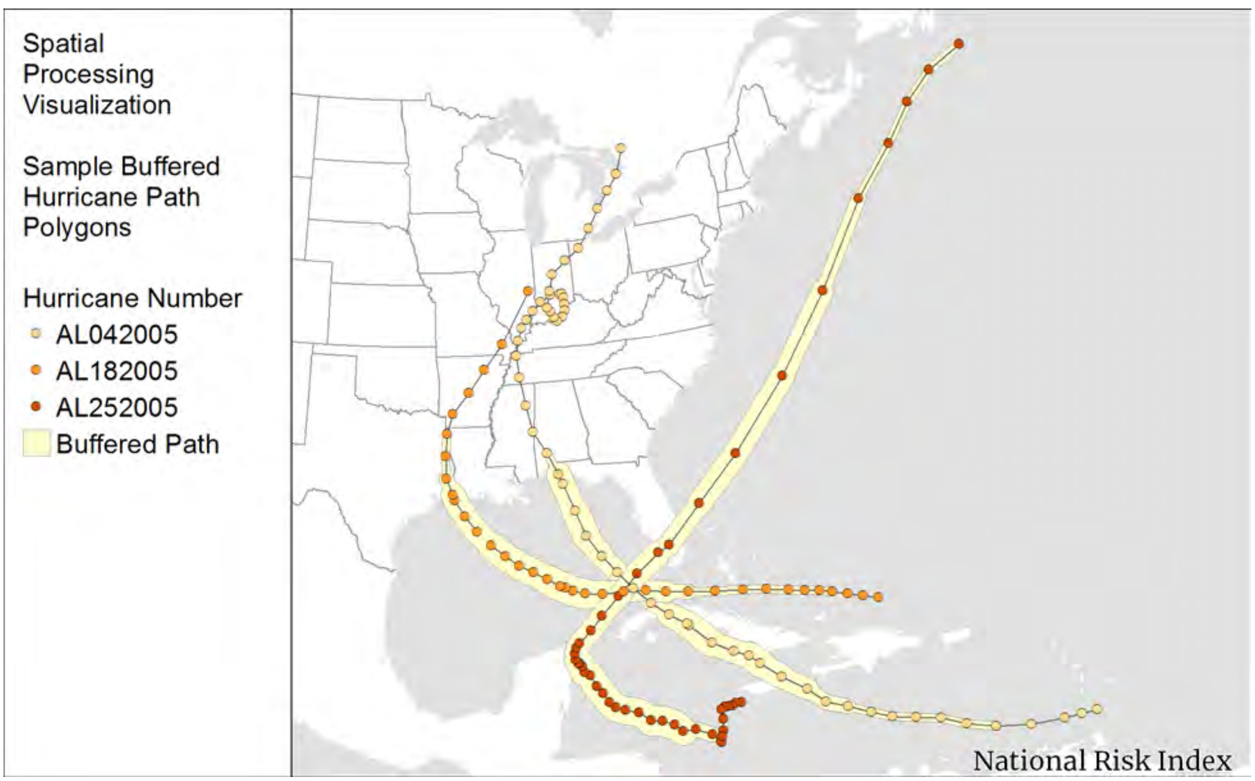

Figure 76: Sample Buffered Hurricane Event Path Polygons

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 Spatial Processing 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 77).

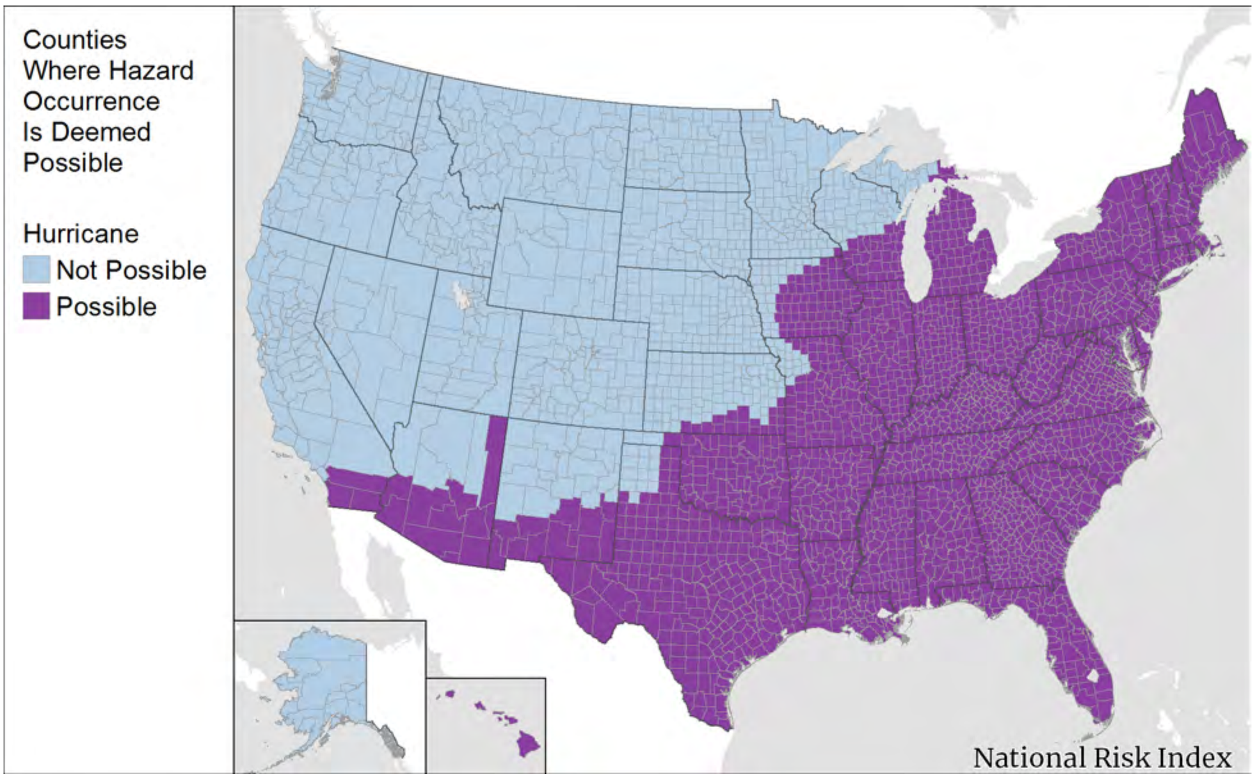

Figure 77: Map of Counties Deemed Possible for Hurricane Occurrence

13.4. Exposure

To identify areas of exposure, the Hurricane event path polygons are intersected with the Census block polygons within the processing database. The resulting table contains the storm's unique identifier, Census block number, and the intersected area in square kilometers (see Table 42).

Table 42: 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 occurrence 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, the developed area population density, and the agriculture area value density of the Census block to model the conservative-case concentration of exposure within the Census block (see Equation 61). These densities in the Census block have been calculated by dividing the total exposure values (as recorded in Hazus 4.2 SP1) by the developed or agriculture land area (in square kilometers). The VSL was used to express population equivalence exposure in terms of dollars.

Equation 61: Census Block Hurricane Exposure

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

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

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

where:

$Exposure_{HRCN_{CB_{Bldg}}}$	is the building value exposed to Hurricanes in a specific Census block (in dollars).
$\sum IntsctArea_{HRCN_{CB}}$	is the sum of the intersected areas of past Hurricanes with the Census block (in square kilometers).
$EventCount_{HRCN_{CB}}$	is the total number of Hurricanes 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 equivalence value exposed to Hurricanes 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 ($7.6M per person).
$Exposure_{HRCN_{CB_{Ag}}}$	is the agriculture value exposed to Hurricanes in a specific Census block (in dollars).
$AgValueDen_{CB}$	is the agriculture value density of the Census block (in dollars per square kilometer).

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 occurrences 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 annualized 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 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 building value exceeds the Hazus-recorded building value, then the Hazus-recorded building value is used as the building 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 Census tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see Equation 62).

Equation 62: Census Tract and County Hurricane Exposure Aggregation

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

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

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

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

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

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

where:

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

$Exposure_{HRCN_{CT_{Ag}}}$	is the agriculture value exposed to Hurricanes in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{HRCN_{CB_{Ag}}}$	is the summed value of all agriculture areas exposed to Hurricane for each Census block within the Census tract (in dollars).
$Exposure_{HRCN_{Co_{Ag}}}$	is the agriculture value exposed to Hurricanes in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{HRCN_{CB_{Ag}}}$	is the summed value of all agriculture areas exposed to Hurricane for each Census block within the county (in dollars).

13.5. Historic Occurrence Count

Historic occurrence counts of Hurricanes, in events, are supplied at the Census tract and county levels as the number of distinct Hurricane event path polygons (see Section 13.2 Spatial Processing) that intersect the Census tract and county, respectively. This count uses the same Hurricane Census block intersection table used to calculate exposure.

13.6. Annualized Frequency

The annualized frequency value represents the estimated number of recorded Hurricane occurrences, in 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.

Annualized 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 Occurrence 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 63.

Equation 63: Census Block Hurricane Annualized 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 annual frequency is set at 0.01 (1 in 100 years). This was determined by subject matter experts to be an acceptable assumption.

13.6.2. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized 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 annualized 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 annualized frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 64.

Equation 64: Census Tract and County Area-Weighted Hurricane Annualized 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 area-weighted Hurricane annualized frequency calculated for a specific Census tract (events per year).
$Freq_{HRCN_{CB}}$	is the annualized frequency of Hurricane events determined for a specific Census block (events per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	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 area-weighted Hurricane annualized 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 78 displays Hurricane annualized frequency at the county level.

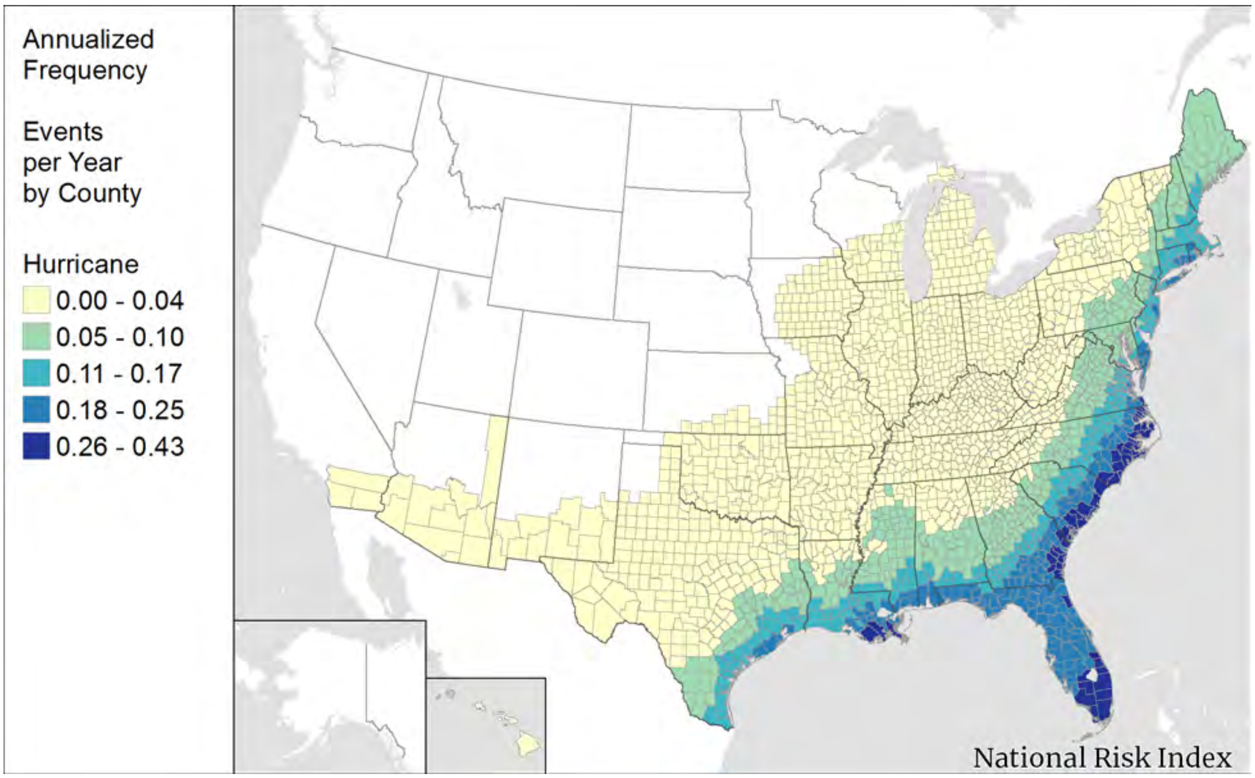

Figure 78: Hurricane Annualized Frequency by County

13.7. Historic Loss Ratio

The Hurricane HLR is the representative percentage of a location's hazard exposure that experiences loss due to a Hurricane occurrence, or the average rate of loss associated with the Hurricane occurrence. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Hurricane hazard type.

Loss data are provided by SHELDUS[59] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Eight peril

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

types are mapped to the hazard Hurricane (see Table 43). These native records are aggregated on a consecutive day basis (see Section 5.4.4 Historic Loss Ratio Methodology). Note that recorded Hurricane events only include those that made landfall as a Tropical Storm or Hurricane.

Table 43: Hurricane Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Cyclone-Extratropical	0	0
Cyclone-Subtropical	0	0
Cyclone-Unspecified	1	1
Hurricane/Tropical Storm	1,429	1,139
Nor'easter	0	0
Storm Surge	599	496
Tropical Depression	175	165
Tropical Storm	2,505	1,871

The HLR exposure value used in the formula below is a county-level value that represents the dollar value of the total building value, the entire population of a county, or the dollar value of the total agriculture value as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event and each consequence type (building, population, and agriculture) is calculated using Equation 65.

Equation 65: 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, population, and agriculture).

$Loss_{HRCN\,Co_{CnsqType}}$ is the loss (by consequence type) experienced from the Hurricane event documented to have occurred in the county (in dollars or impacted people).

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

Hurricane events (particularly tropical storms) 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 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 (1996 to 2019). For Hurricane, the historic event count is extracted using the intersection between the Hurricane event path polygons and the Census block polygons used to calculate exposure (see Table 42). Unlike the count used for annualized frequency, this count is simply the number of distinct Hurricane event path polygons that have intersected Census blocks in the county. An annual rate is calculated as the event count divided by the period of record of 167.11 years for the Atlantic basin or 69.04 years for the Pacific basin. This rate is multiplied by the SHELDUS period of record of 24 years to estimate a historic event-day count for the appropriate time range.

If the number of loss-causing Hurricane event records from SHELDUS is less than the scaled event count for the county, a number of zero-loss records equal to the difference are 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 1, 2, and 3 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[60] (Figure 14). This region definition was introduced specifically 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 79, Figure 81, and Figure 83 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 Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Hurricane occurrences within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value, though its HLR may be influenced by other local or regional occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing occurrences or have widely varying loss ratios get the most influence from regional-level loss data. Figure 80, Figure 82, and Figure 84 represent the final, Bayesian-adjusted county-level HLR values for Hurricane.

[60] 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.

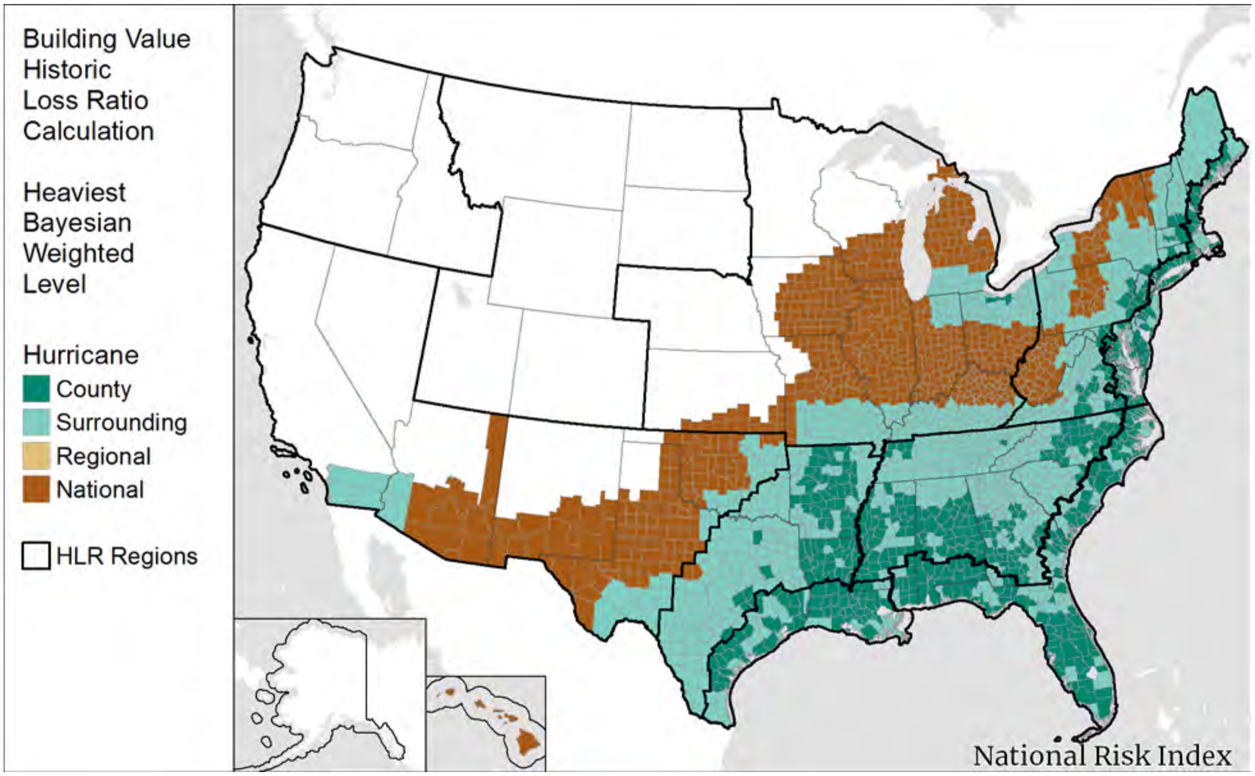

Figure 79: Hurricane Heaviest Bayesian Weighted Level – Building Value

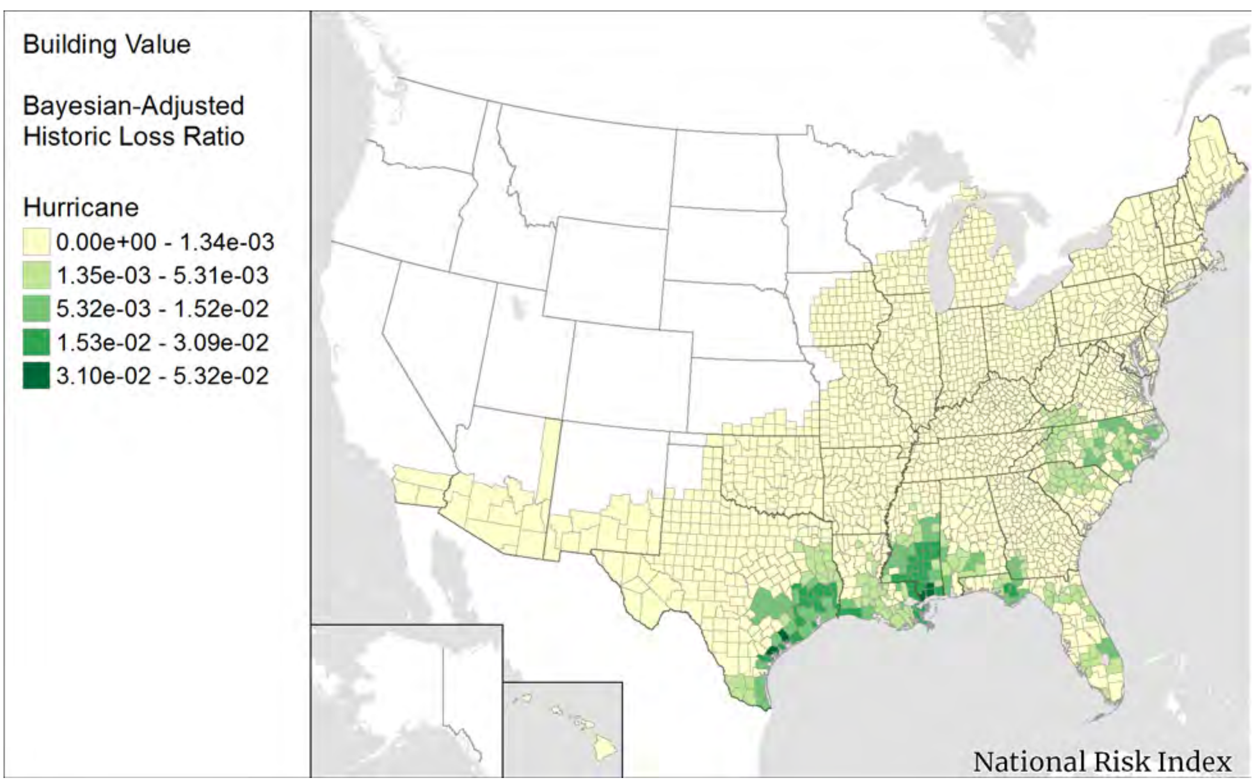

Figure 80: Hurricane Bayesian-Adjusted HLR – Building Value

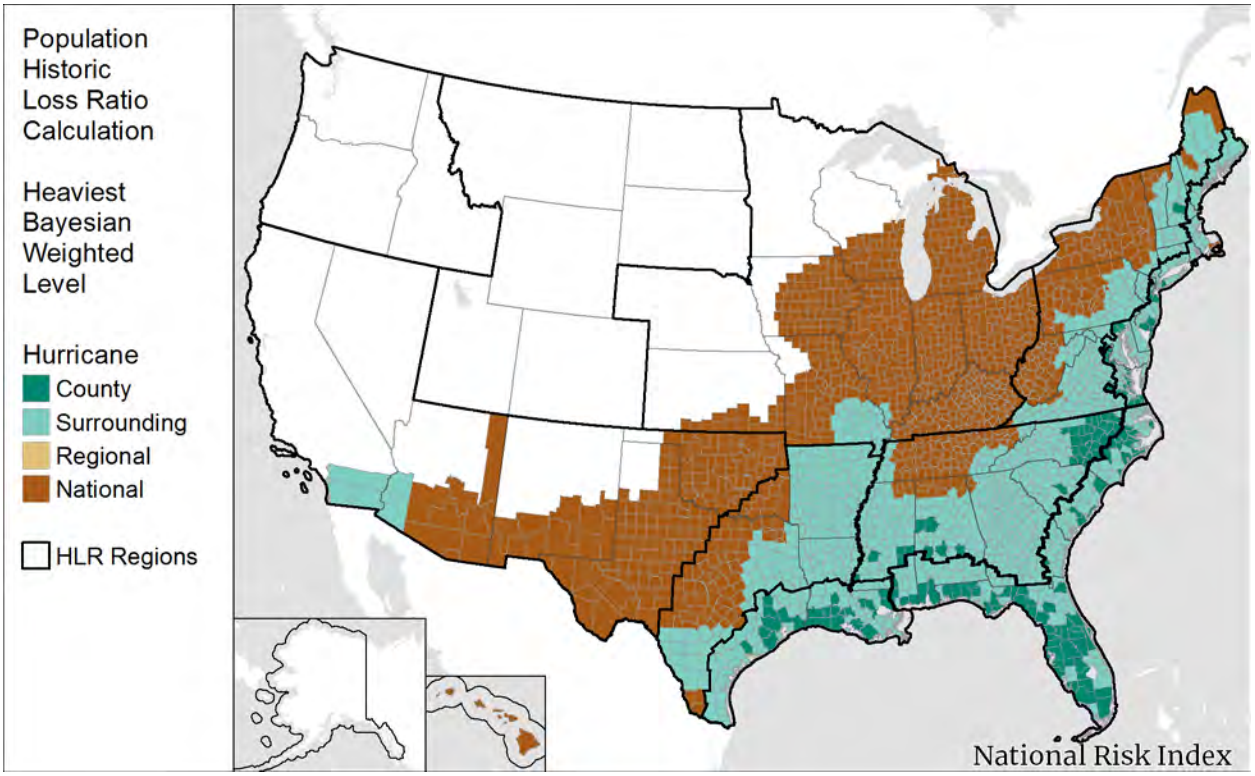

Figure 81: Hurricane Maximum Weighting Factor Contributor – Population

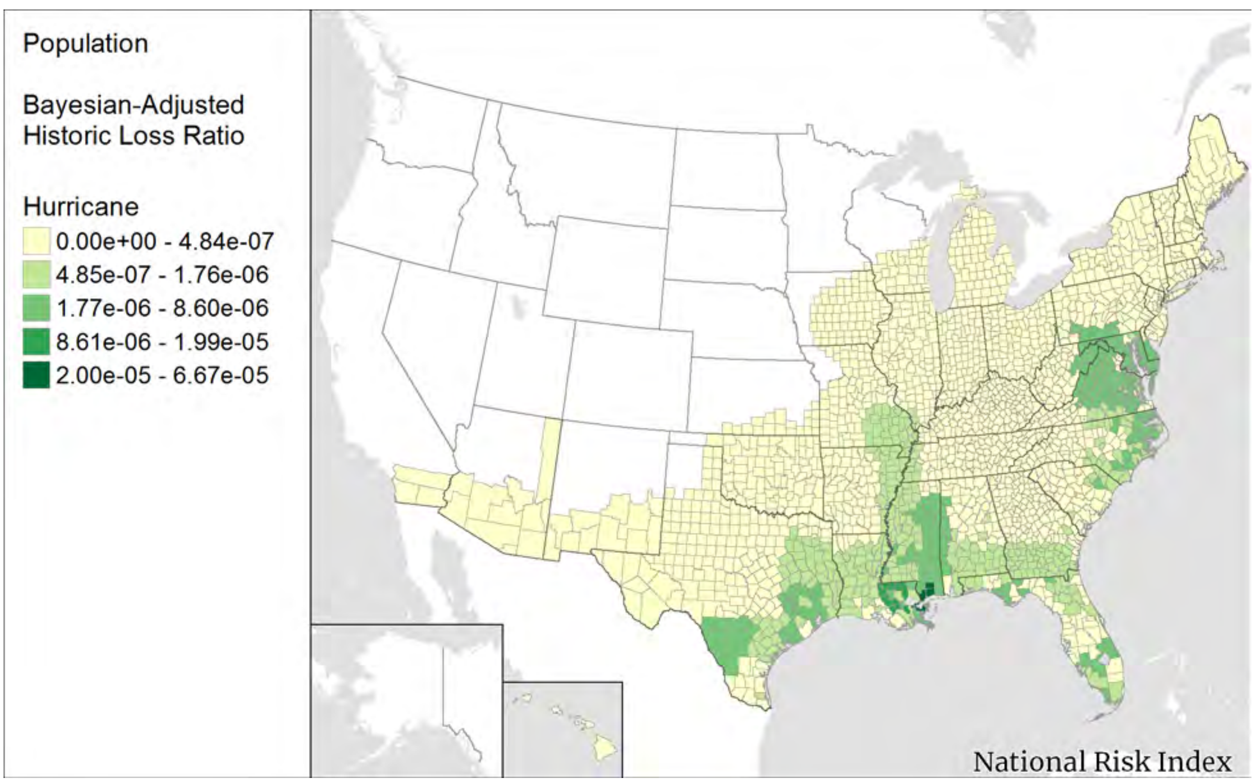

Figure 82: Hurricane Bayesian-Adjusted HLR – Population

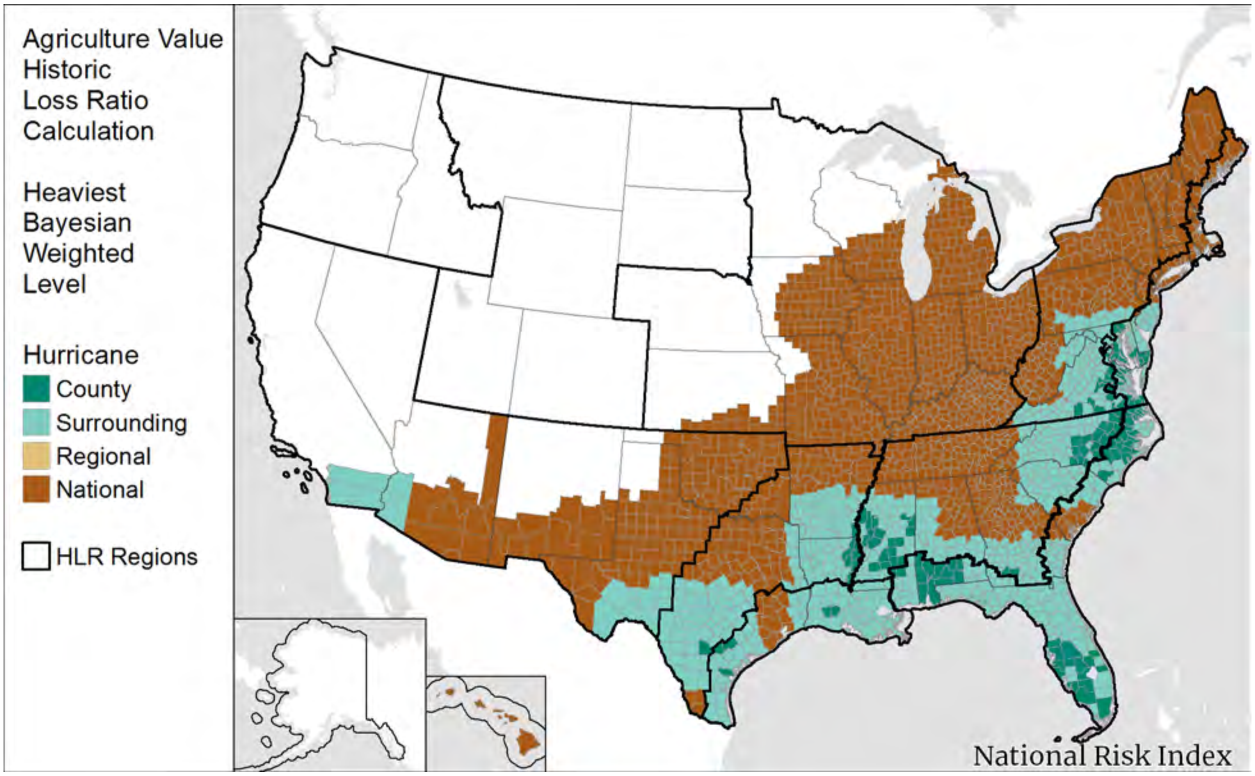

Figure 83: Hurricane Maximum Weighting Factor Contributor – Agriculture Value

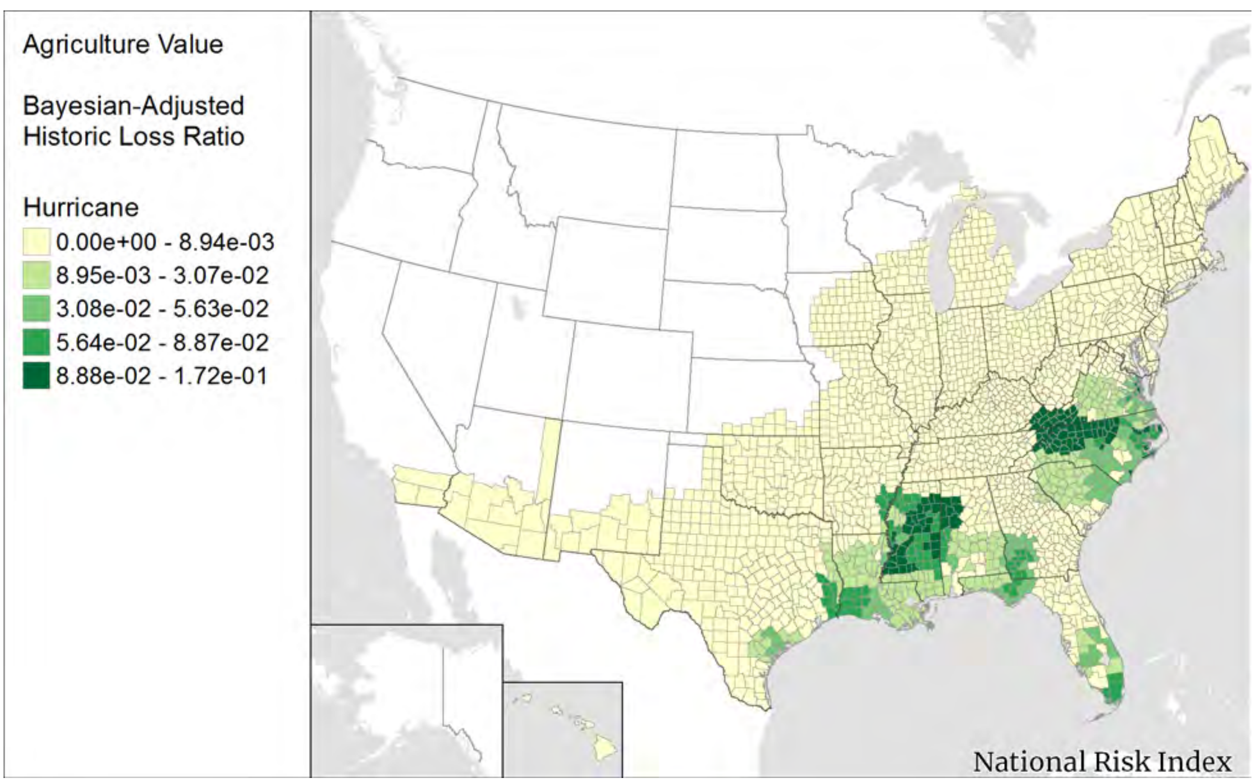

Figure 84: Hurricane Bayesian-Adjusted HLR – Agriculture Value

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

13.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 66. 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 66: Census Block Expected Annual Loss to Hurricanes

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

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

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

where:

$EAL_{HRCN_{CB_{Bldg}}}$ is the building Expected Annual Loss due to Hurricane occurrences for a specific Census block (in dollars).

$Exposure_{HRCN_{CB_{Bldg}}}$ is the building value exposed to Hurricane occurrences in the Census block (in dollars).

$Freq_{HRCN_{CB}}$ is the Hurricane annualized 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 population equivalence Expected Annual Loss due to Hurricane occurrences for a specific Census block (in dollars).

$Exposure_{HRCN_{CB_{Pop}}}$ is the population equivalence value exposed to Hurricane occurrences in the Census block (in dollars).

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

$EAL_{HRCN_{CB_{Ag}}}$ is the agriculture Expected Annual Loss due to Hurricane occurrences for a specific Census block (in dollars).

$Exposure_{HRCN_{CB_{Ag}}}$ is the agriculture value exposed to Hurricane occurrences in the Census block (in dollars).

$HLR_{HRCN_{CB_{Ag}}}$ is the Bayesian-adjusted agriculture 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 building, population equivalence, and agriculture EAL values at the Census block level as in Equation 67.

Equation 67: Census Tract and County Expected Annual Loss to Hurricanes

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

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

where:

$EAL_{HRCN_{CT}}$ is the total Expected Annual Loss due to Hurricane occurrences for a specific Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{HRCN_{CB_{Bldg}}}$ is the summed building EAL due to Hurricane occurrences for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{HRCN_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Hurricane occurrences for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{HRCN_{CB_{Ag}}}$ is the summed agriculture Expected Annual Loss due to Hurricane occurrences for all Census blocks in the Census tract (in dollars).

$EAL_{HRCN_{Co}}$ is the total Expected Annual Loss due to Hurricane occurrences for a specific county (in dollars).

$\sum_{CB}^{Co} EAL_{HRCN_{CB_{Bldg}}}$ is the summed building Expected Annual Loss due to Hurricane occurrences for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{HRCN_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Hurricane occurrences for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{HRCN_{CB_{Ag}}}$ is the summed agriculture Expected Annual Loss due to Hurricane occurrences for all Census blocks in the county (in dollars).

Figure 85 shows the total EAL (building value, population equivalence, and agriculture combined) to Hurricane occurrences.

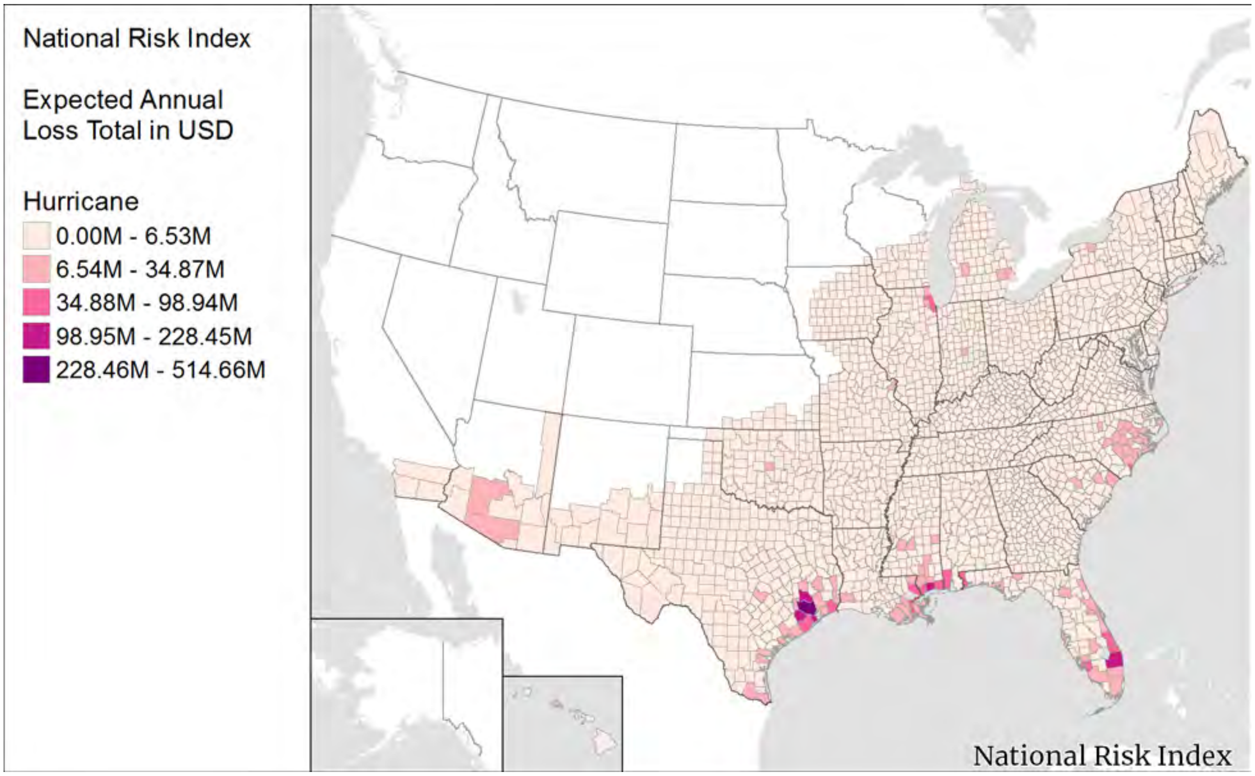

Figure 85: Total Expected Annual Loss by County to Hurricane

With the Hurricane total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all other communities at the same level. 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[61]

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 86). Start and end dates for Ice Storm occurrences 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.

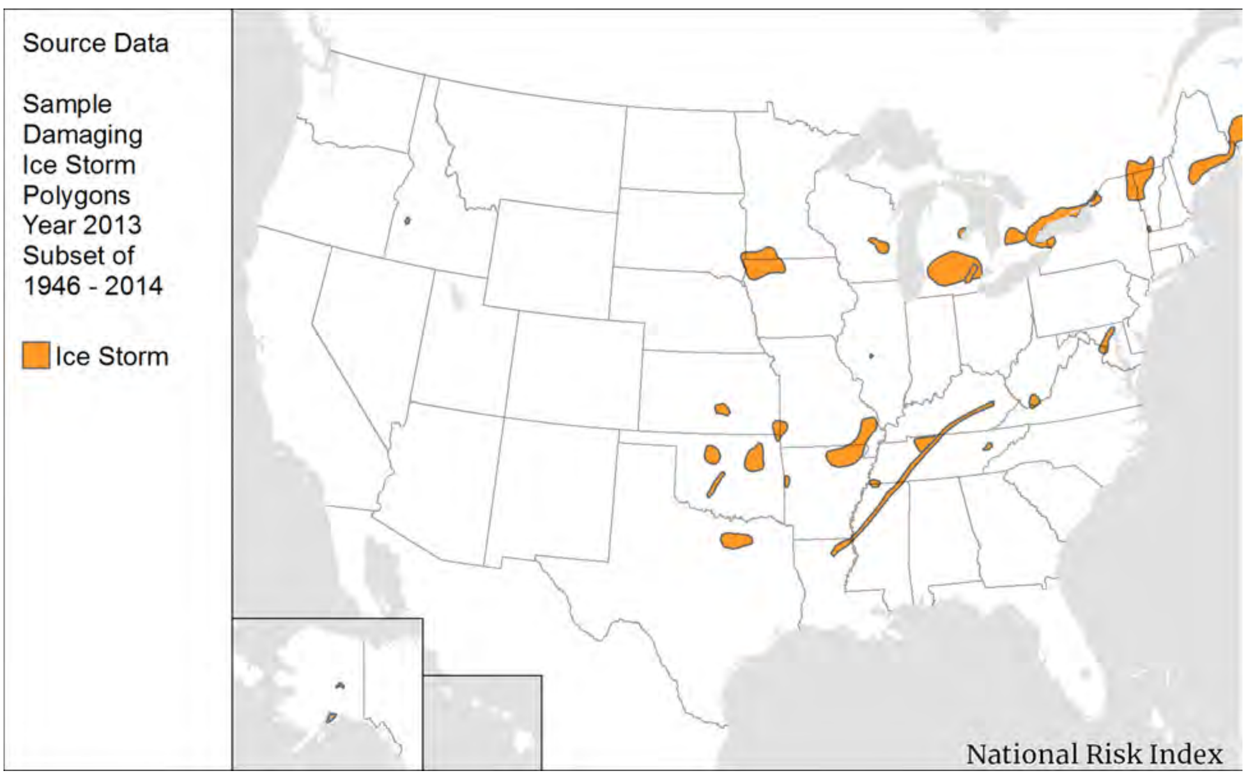

Figure 86: Map of Sample Damaging Ice Storm Polygons

[61] Cold Regions Research and Engineering Laboratory, U.S. 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, 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 annualized frequency.

14.3. Determination of Possibility of Hazard Occurrence

To distinguish between areas with no Ice Storm occurrences and those where such occurrences 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, except 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 87).

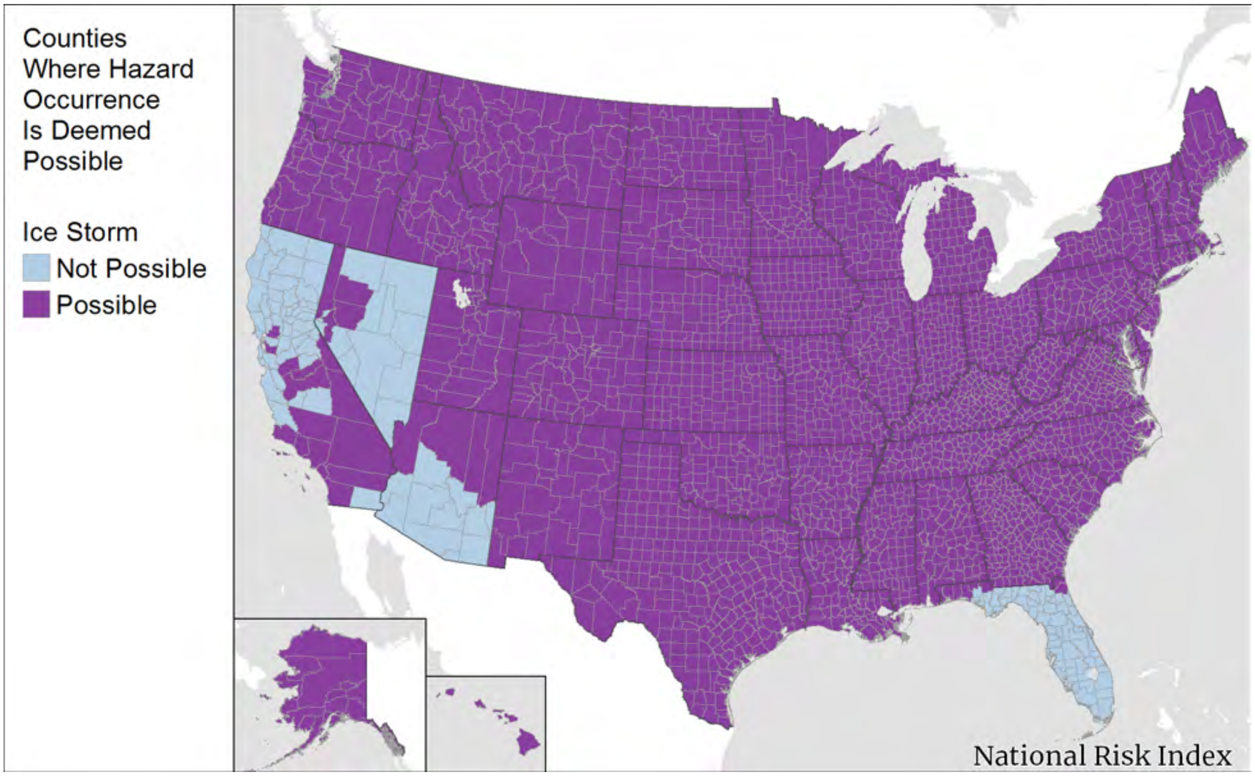

Figure 87: Map of Counties Deemed Possible for Ice Storm Occurrence

14.4. Exposure

To identify areas of exposure, the Ice Storm event-day polygons are intersected with the Census block polygons within the processing database. The resulting table contains the storm's unique identifier, Census block number, and the intersected area in square kilometers (see Table 44).

Table 44: Sample Data from the Ice Storm Census Block Intersection Table

IceStormID	*CensusBlock*	*IntersectedAreaKm2*
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 annualized frequency as this method better captures the variability in duration between occurrences. 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 divided by the total area of the Census block to calculate the average Ice Storm event-day coverage percentage and 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 (see Equation 68). These Census block densities have been calculated by dividing the total exposure values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers). The VSL was used to express population equivalence exposure in terms of dollars.

Equation 68: Census Block Ice Storm Exposure

$$Exposure_{ISTM\,CB_{Bldg}} = \frac{\sum_{ISTM}^{CB}\left(IntsctArea_{ISTM_{CB}} \times Days_{ISTM}\right)}{\sum_{ISTM}^{CB}(Days_{ISTM})} \Big/ Area_{CB} \times DevAreaDen_{CB_{Bldg}}$$

$$Exposure_{ISTM\,CB_{Pop}} = \left(\frac{\sum_{ISTM}^{CB}\left(IntsctArea_{ISTM_{CB}} \times Days_{ISTM}\right)}{\sum_{ISTM}^{CB}(Days_{ISTM})} \Big/ Area_{CB} \times DevAreaDen_{CB_{Pop}} \right) \times VSL$$

where:

$Exposure_{ISTM\,CB_{Bldg}}$	is the building value exposed to Ice Storm event-days for a specific Census block (in dollars).
$IntsctArea_{ISTM_{CB}}$	is the intersected area 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).
$\sum_{ISTM}^{CB}$	is the sum for all Ice Storm event polygons intersecting the Census block.
$Area_{CB}$	is the total area of 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).
$Exposure_{ISTM\,CB_{Pop}}$	is the population equivalence 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 ($7.6M 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 building value exceeds the Hazus-recorded building value, then the Hazus-recorded building value is used as the building 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 Census tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see Equation 69).

Equation 69: 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 equivalence 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 equivalence exposed to Ice Storms for each Census block within the Census tract (in dollars).

$Exposure_{ISTM\,Co_{Pop}}$ is the population equivalence 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 equivalence exposed to Ice Storms for each Census block within the county (in dollars).

14.5. Historic Occurrence Count

The historic occurrence count of Ice Storm, in 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 occurrence (see Equation 70).

Equation 70: 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. Annualized Frequency

The annualized frequency value represents the estimated number of recorded Ice Storm occurrences, in 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.

Annualized 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 70). If the Census block intersects multiple fishnet grid cells, an area-weighted average count is calculated (see Appendix D – Fishnet Occurrence Count). Using this count, the Census block annualized frequency is calculated as in Equation 71.

Equation 71: Census Block Ice Storm Annualized Frequency

$$Freq_{ISTM_{CB}} = \frac{EventCount_{ISTM_{CB}}}{PeriodRecord_{ISTM}}$$

where:

$Freq_{ISTM_{CB}}$	is the area-weighted annualized 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 annual frequency is set at 0.01489, or once in the period of record (1 in 67.16 years).

14.6.2. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized 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 annualized 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 annualized frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 72.

Equation 72: Census Tract and County Area-Weighted Ice Storm Annualized 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 area-weighted annualized frequency of Ice Storm event-days determined for a specific Census tract (event-days per year).
$Freq_{ISTM_{CB}}$	is the area-weighted annualized frequency of Ice Storm event-days 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 area-weighted Ice Storm annualized 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 88 displays Ice Storm annualized frequency at the county level.

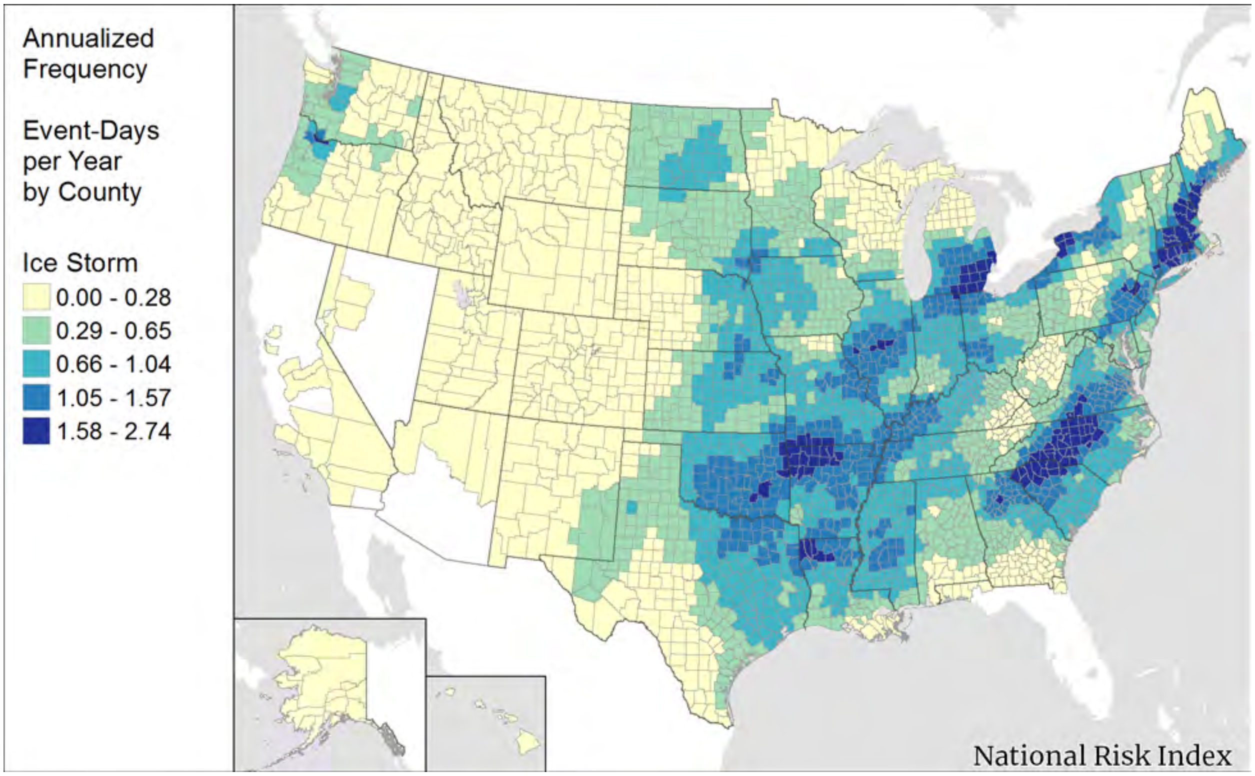

Figure 88: Ice Storm Annualized Frequency by County

14.7. Historic Loss Ratio

The Ice Storm HLR is the representative percentage of a location's hazard exposure 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 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Ice Storm hazard type.

Loss data are provided by SHELDUS[62] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. One peril type is mapped to the hazard Ice Storm (see Table 45). These native records are expanded on an event-day basis (to a maximum of 31 event-days) and aggregated on a single-event-per-day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

Table 45: Ice Storm Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Ice	3,888	6,671

[62] For Ice Storm 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 73.

Equation 73: 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 or impacted people).
$HLRExposure_{Co_{CnsqType}}$	is the total value (by consequence type) of the county estimated to have been exposed to the Ice Storm event-day (in dollars or people).

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 (1996 to 2019). For Ice Storm, the historic event-day count is extracted using an intersection between the Ice Storm event-day polygons and the Census blocks. Unlike the count used for annualized frequency, this count is simply the summed duration days of distinct Ice Storm polygons that have intersected Census blocks in the county. An annual rate is calculated as the event-day count divided by the period of record of 67.16 years, and this rate is multiplied by the SHELDUS period of record of 24 years to estimate a historic event-day count for the appropriate time range.

If the number of loss-causing Ice Storm event-day records from SHELDUS is less than the scaled event-day count for the county, then a number of zero-loss records equal to the difference are 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 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

In an effort to correct for urban bias, a ceiling is applied to the Bayesian-adjusted population HLR for Ice Storm. This is calculated as the average number of people (excluding zero population loss events) impacted by past Ice Storms per county divided by the county population. This affects a few highly populated counties where the Bayesian influence of injuries and fatalities in less populated surrounding counties may overinflate the HLR of urban counties.

Figure 89 and Figure 91 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 Bayesian-adjusted 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 Bayesian-adjusted HLR value, though its HLR may be influenced by other local, regional, or national occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted 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 90 and Figure 92 represent the final, Bayesian-adjusted county-level HLR values for Ice Storm.

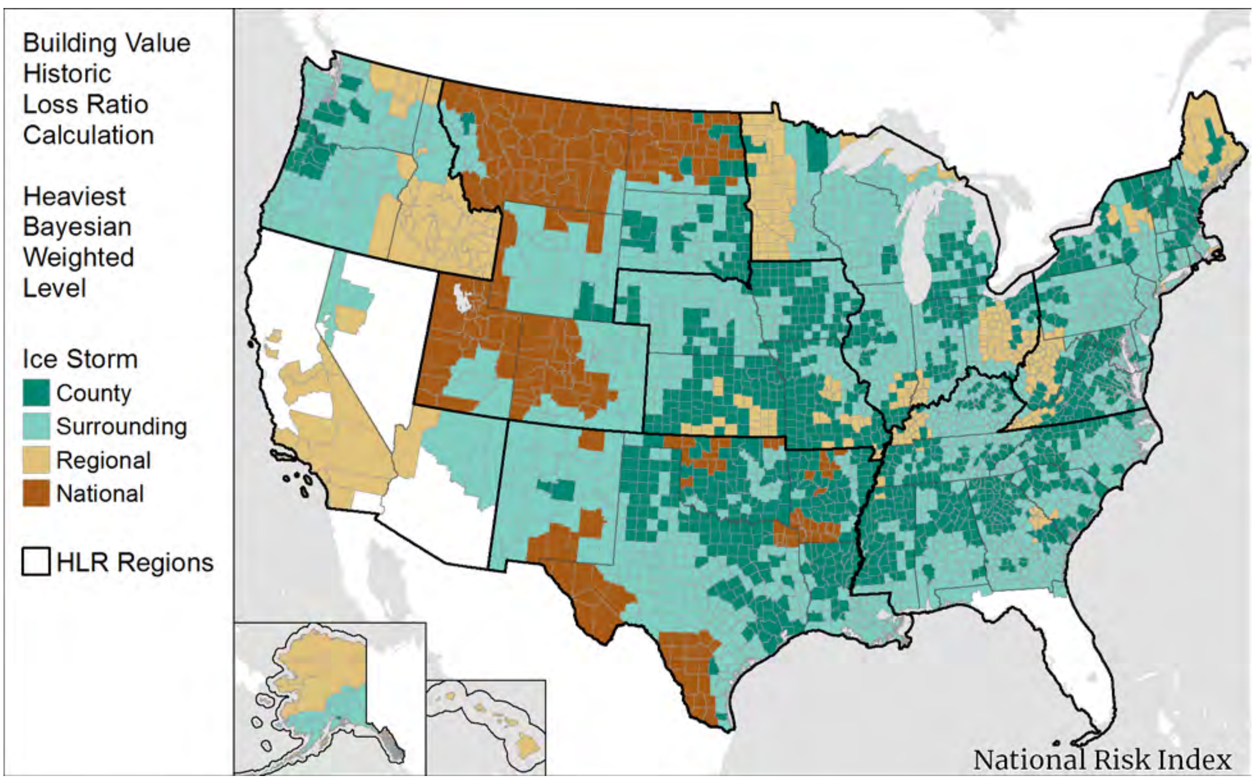

Figure 89: Ice Storm Heaviest Bayesian Weighted Level – Building Value

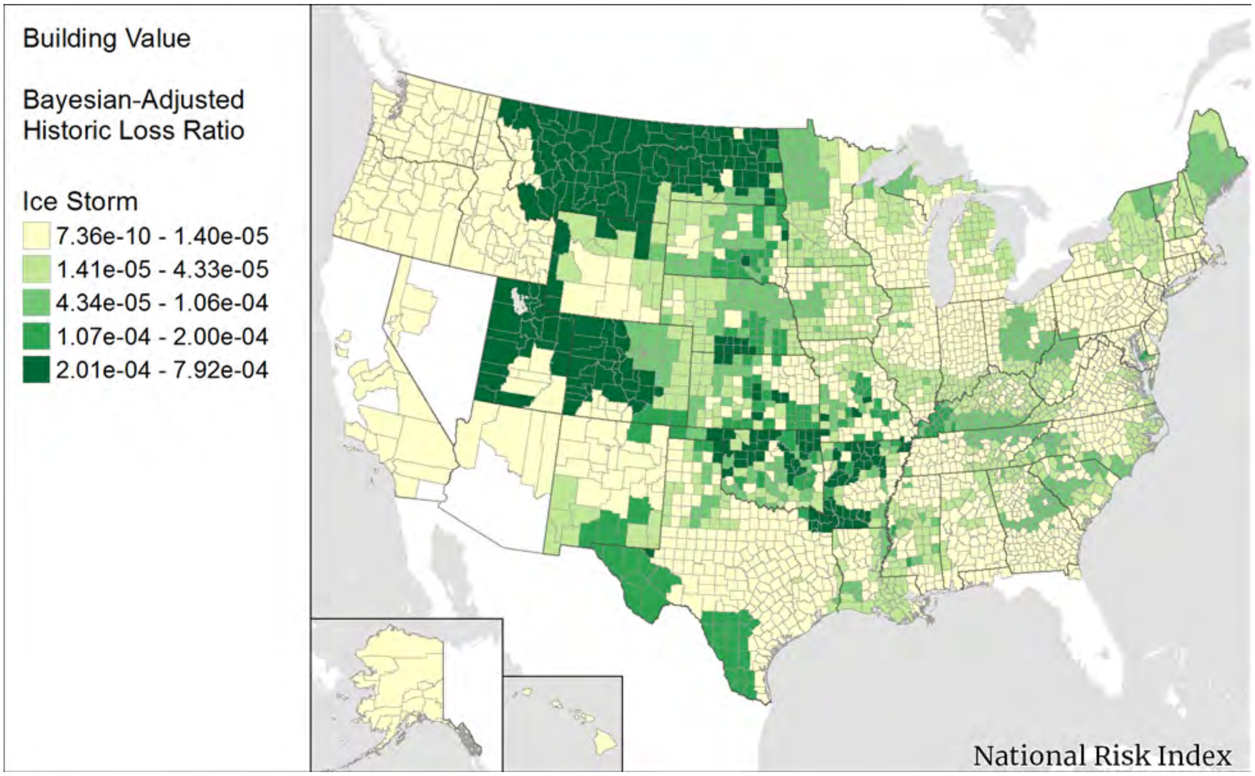

Figure 90: Ice Storm Bayesian-Adjusted HLR – Building Value

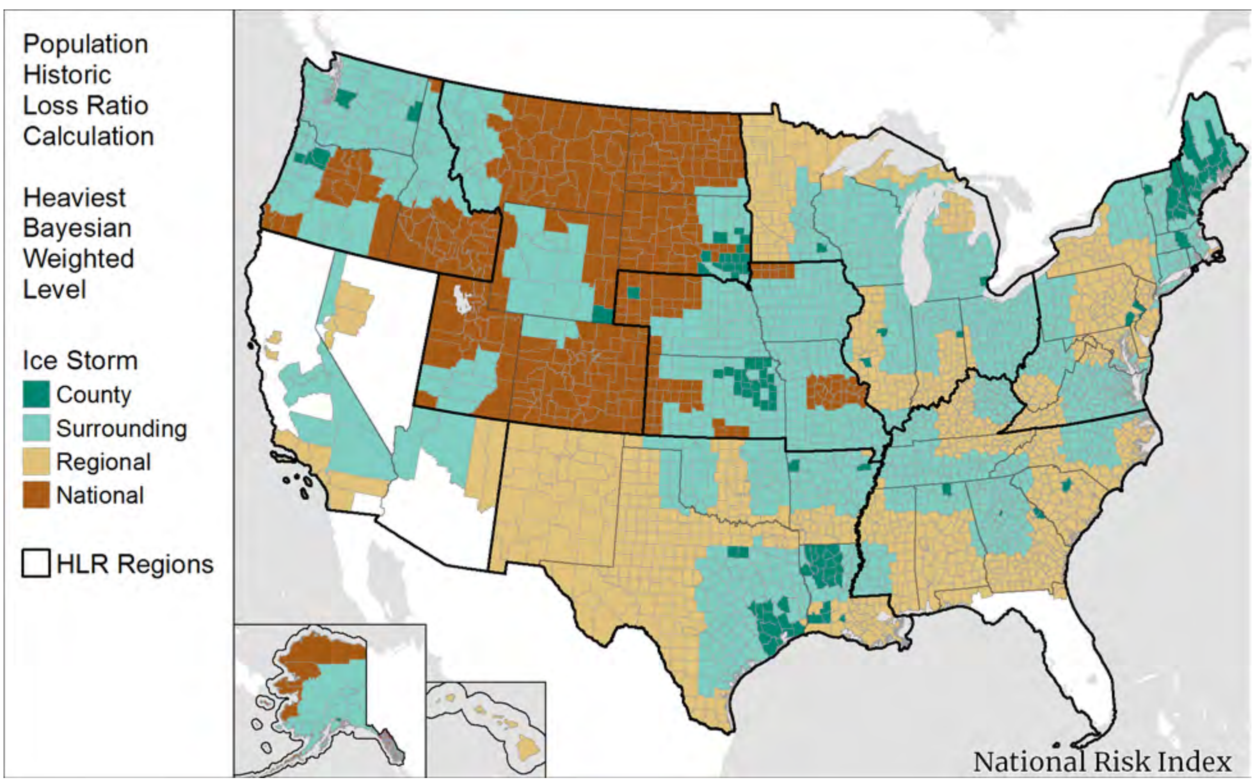

Figure 91: Ice Storm Heaviest Bayesian Weighted Level – Population

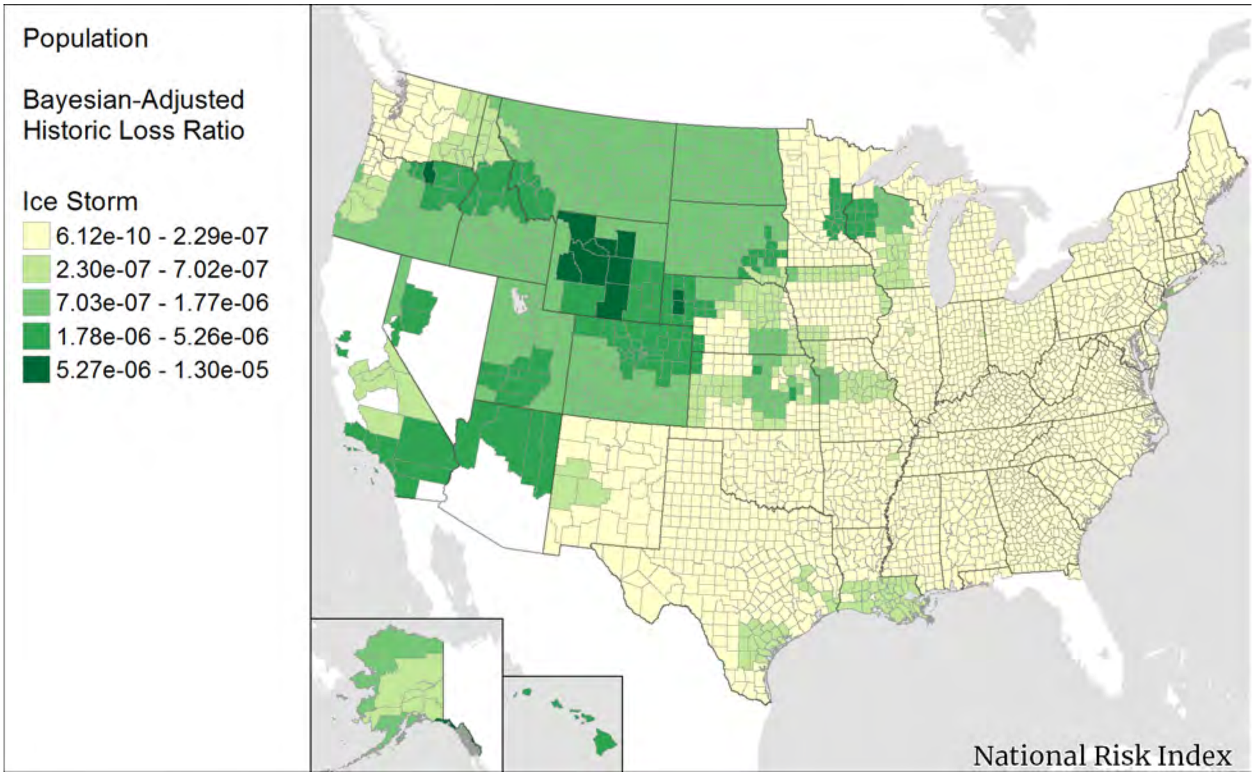

Figure 92: Ice Storm Bayesian-Adjusted HLR – Population

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

14.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 74. 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 74: 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 building Expected Annual Loss due to Ice Storm occurrences for a specific Census block (in dollars).

$Exposure_{ISTM_{CB_{Bldg}}}$	is the building value exposed to Ice Storm occurrences in the Census block (in dollars).
$Freq_{ISTM_{CB}}$	is the Ice Storm annualized 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 population equivalence Expected Annual Loss due to Ice Storm occurrences for a specific Census block (in dollars).
$Exposure_{ISTM_{CB_{Pop}}}$	is the population equivalence value exposed to Ice Storm occurrences 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 building and population equivalence EAL values at the Census block level as in Equation 75.

Equation 75: 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 occurrences for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{ISTM_{CB_{Bldg}}}$	is the summed building Expected Annual Loss to Ice Storm occurrences for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{ISTM_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Ice Storm occurrences for all Census blocks in the Census tract (in dollars).
$EAL_{ISTM_{Co}}$	is the total Expected Annual Loss due to Ice Storm occurrences for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{ISTM_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Ice Storm occurrences for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{ISTM_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Ice Storm events for all Census blocks in the county (in dollars).

Figure 93 shows the total EAL (building value and population equivalence combined) to Ice Storm occurrences.

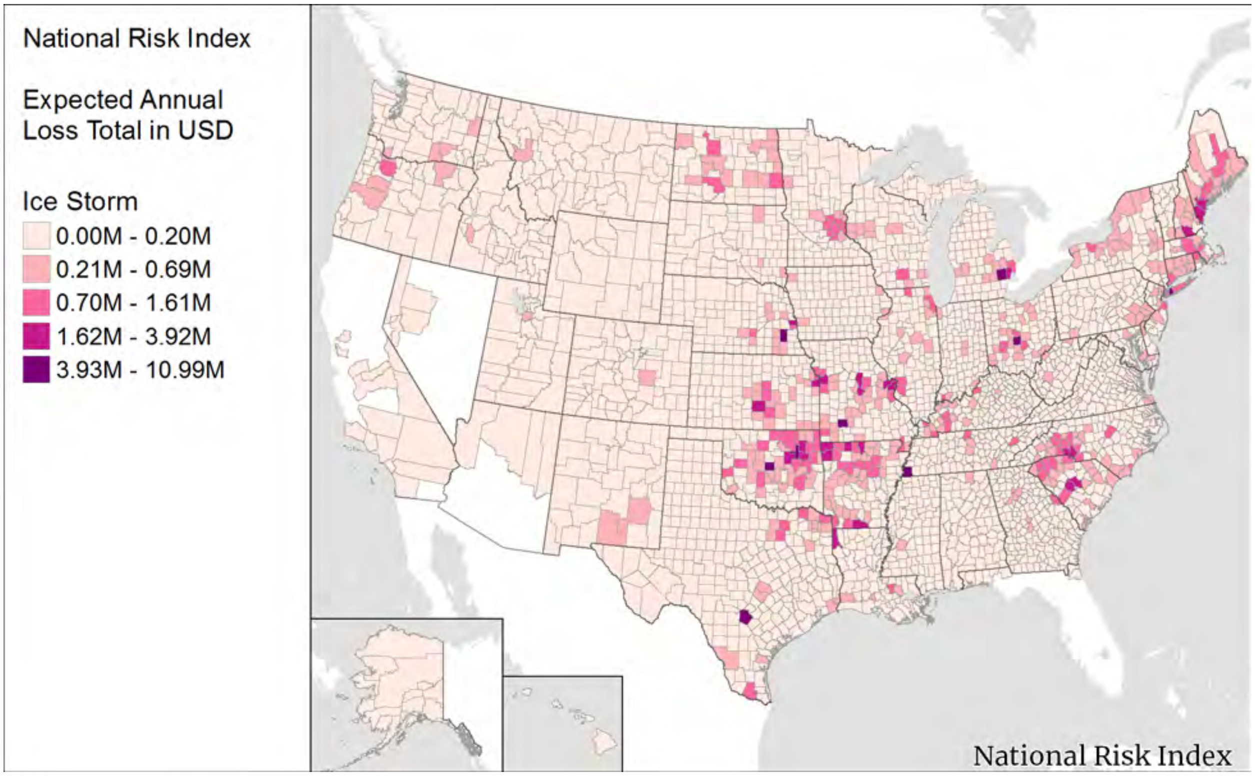

Figure 93: Total Expected Annual Loss by County to Ice Storm

With the Ice Storm total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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[63]

A conterminous U.S. 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 U.S. 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 94.)

Note: Because Landslide susceptibility data are not available for Alaska and Hawaii, exposure and, therefore, EAL values cannot be computed for these states.

[63] 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.

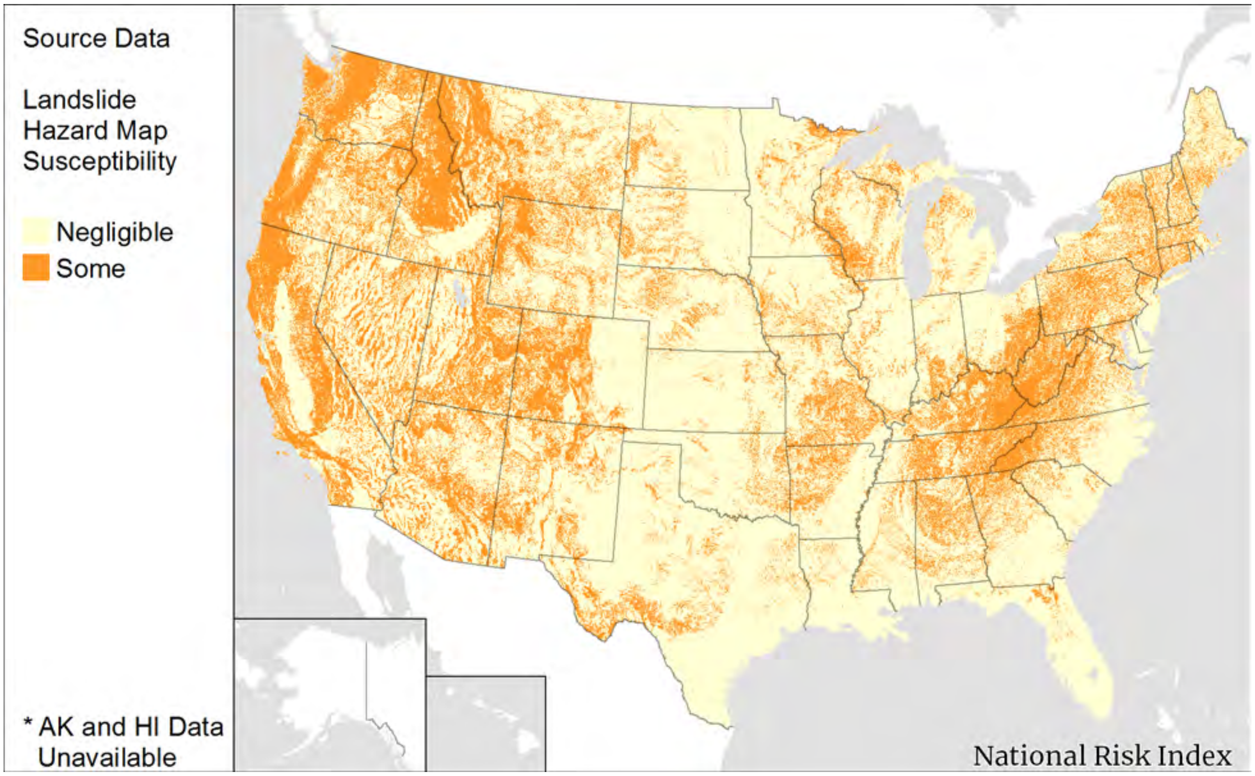

Figure 94: Map of Landslide Raster

Historical Occurrence Source: National Aeronautics and Space Administration (NASA), Cooperative Open Online Landslide Repository (COOLR)[64]

NASA has combined its Global Landslide Catalog (GLC)[65] with the Landslide Reporter Catalog (LRC), a dataset formed by citizen scientists submitting landslide observations to NASA's Landslide Report application, to create the Cooperative Open Online Landslide Repository (COOLR).[66] The dataset includes spatiotemporal records of worldwide historical Landslide events dating from 1915 to 2021. Data were available for download in multiple formats, including file geodatabase format (see Figure 95). 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.

[64] National Aeronautics and Space Administration. (2021). *Cooperative Open Online Landslide Repository (COOLR).* [cartographic dataset]. Retrieved from https://maps.nccs.nasa.gov/arcgis/apps/webappviewer/index.html?id=824ea5864ec8423fb985b33ee6bc05b7 on 4/15/2021.

[65] Kirschbaum, D.B., Stanley, T., & Zhou, Y. (2015). Spatial and temporal analysis of a global landslide catalog. *Geomorphology*, 249, 4-15. doi:10.1016/j.geomorph.2015.03.016

[66] Juang, C.S., Stanley, T.A., & Kirschbaum, D.B. (2019). Using citizen science to expand the global map of landslides: Introducing the Cooperative Open Online Landslide Repository (COOLR). *PLoS ONE*, 14(7), e0218657. doi:10.1371/journal.pone.0218657

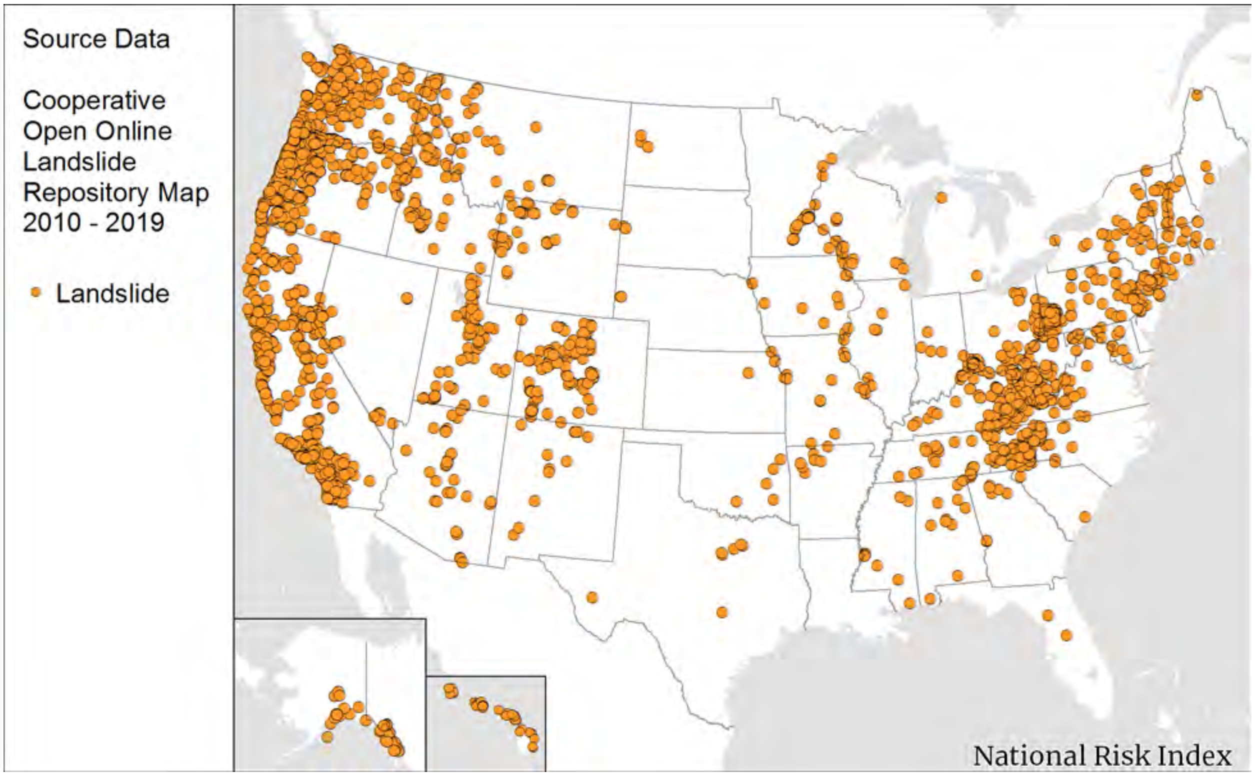

Figure 95: Map of Landslide Points

15.1.1. PERIOD OF RECORD

All Landslide records in the U.S. between 1/1/2010 and 12/31/2019 are included in the calculation of annualized frequency, so the period of record for which Landslide data are utilized is 10 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 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.

To determine Landslide event count and frequency, the Landslide points are intersected with Census blocks, so that each Landslide event is associated with a single Census block.

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 U.S. 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 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 processing database. The resulting table contains the fishnet polygon's unique identifier, Census block number, and the intersected area in square kilometers (see Table 46).

Table 46: 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 (see Equation 76). These Census block 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). The VSL was used to express population equivalence exposure in terms of dollars.

Equation 76: 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 equivalence 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 ($7.6M 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 building value exceeds the Hazus-recorded building value, then the Hazus-recorded building value is used as the building 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 Census tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see Equation 77).

Equation 77: 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 equivalence 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 equivalence exposed to Landslide susceptibility for each Census block within the Census tract (in dollars).

$Exposure_{LNDS_{Co_{Pop}}}$ is the population equivalence 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 equivalence exposed to Landslide susceptibility for each Census block within the county (in dollars).

15.5. Historic Occurrence Count

The historic occurrence count of Landslide, in events, is computed as the number of distinct Landslide event points (from COOLR, see Section 15.1 Spatial Source Data) 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. Annualized Frequency

The annualized frequency value represents the estimated number of recorded Landslide occurrences, in 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 78), and the Census block inherits this value. The Census block value is used in the EAL calculations.

Annualized frequency calculations use the source data points from COOLR. The Landslide event count is the total number of Landslide points that intersect the Census tract.

Equation 78: Census Tract Landslide Annualized 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 (10 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 annual frequency is set at 0.01 (1 in 100 years).

15.6.2. ANNUALIZED FREQUENCY INHERITANCE AND AGGREGATION

The Census block inherits its annualized frequency value from the Census tract that contains it as in Equation 79.

Equation 79: 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 annualized frequency value (excluding Census blocks with no frequency) 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 annualized frequency values at the Census block level are rolled up to the county level using area-weighted aggregations as in Equation 80.

Equation 80: County Area-Weighted Landslide Annualized 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 area-weighted annualized frequency of Landslide events determined for a specific county (events per year).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Freq_{LNDS_{CB}}$	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).
$Area_{Co}$	Is the total area of the county (in square kilometers).

Figure 96 displays Landslide annualized frequency at the county level.

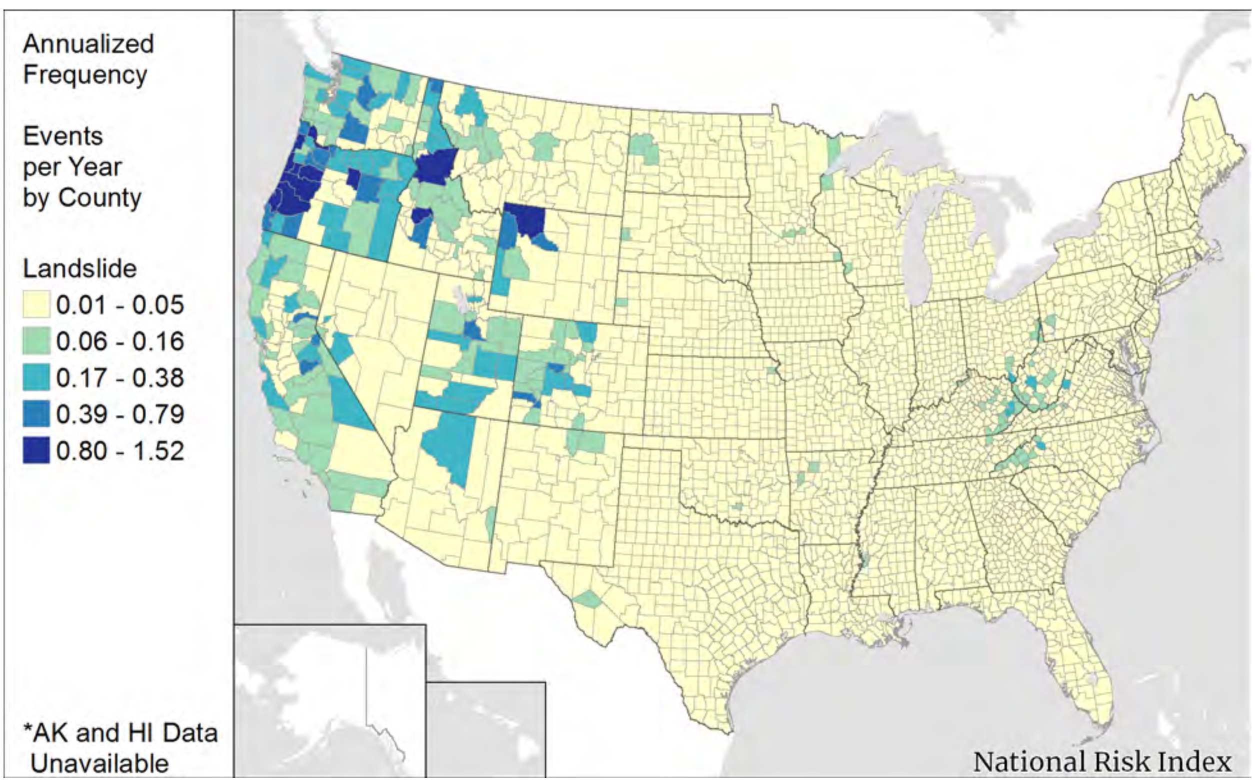

Figure 96: Landslide Annualized Frequency by County

15.7. Historic Loss Ratio

The Landslide HLR is the representative percentage of a location's hazard exposure that experiences loss due to a Landslide occurrence, or the average rate of loss associated with a Landslide occurrence. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Landslide hazard type.

Loss data are provided by SHELDUS[67] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Five peril types are mapped to the hazard Landslide (see Table 47).

Table 47: Landslide Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Landslide	615	416
Landslide-Slump	1	1
Mud Flow	0	0
Mudslide	174	172
Rock Slide	62	60

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 81.

Equation 81: 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).

[67] 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

$Loss_{LNDS\,Co_{CnsqType}}$ is the loss (by consequence type) experienced from the Landslide event documented to have occurred in the county (in dollars or impacted people).

$HLRExposure_{LNDS\,Co_{CnsqType}}$ is the total value (by consequence type) of the county estimated to have been exposed to the Landslide event (in dollars or people).

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 building loss, a dollar amount based on the total building value of the county (see Table 48). This artificial loss creation is an attempt to supplement the historic event data, which only exist for the ten (10) years from 2010 through 2019. 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 48: Default Landslide Building Loss

Default Loss	*Total County Building Value Range*
$300,000	$0-$5B
$7M	$5B-$25B
$9M	$25B+

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 HLR by consequence type is then inherited by the Census blocks and Census tracts within the parent county. Figure 97 and Figure 98 represent the final county-level HLR values for Landslide.

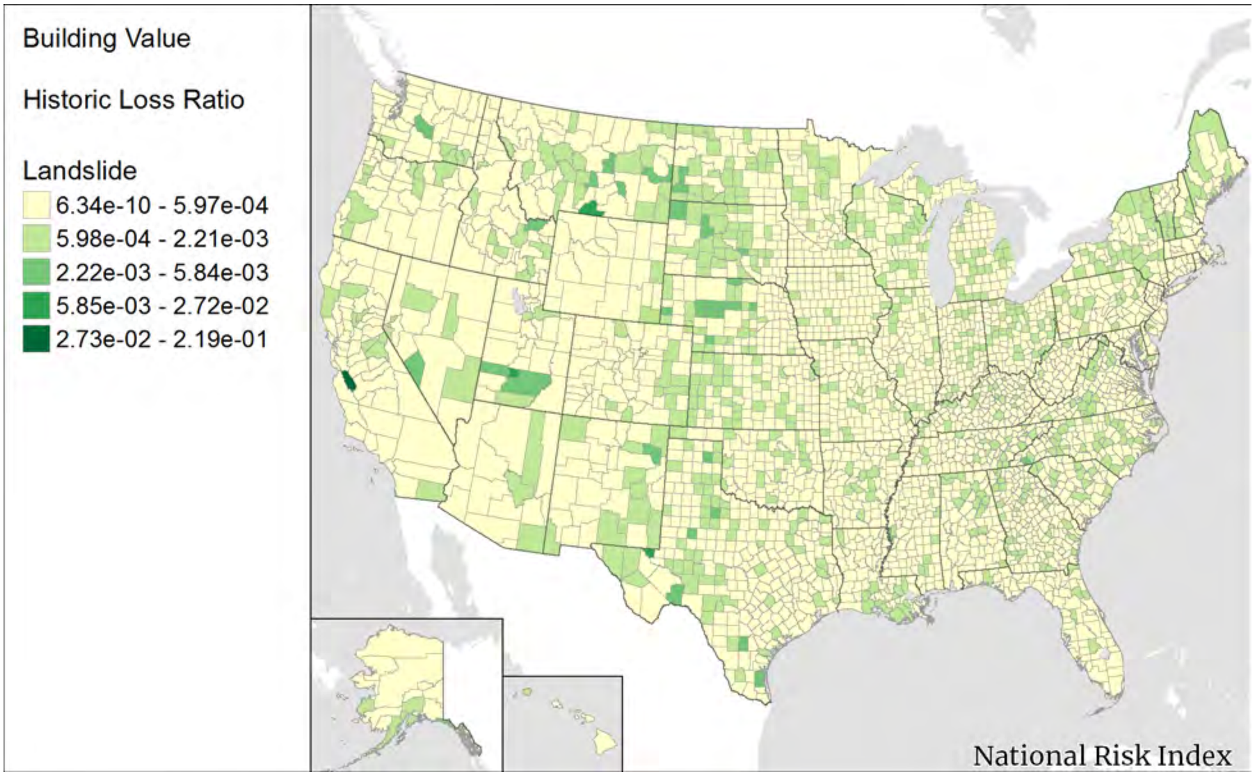

Figure 97: Landslide HLR – Building Value

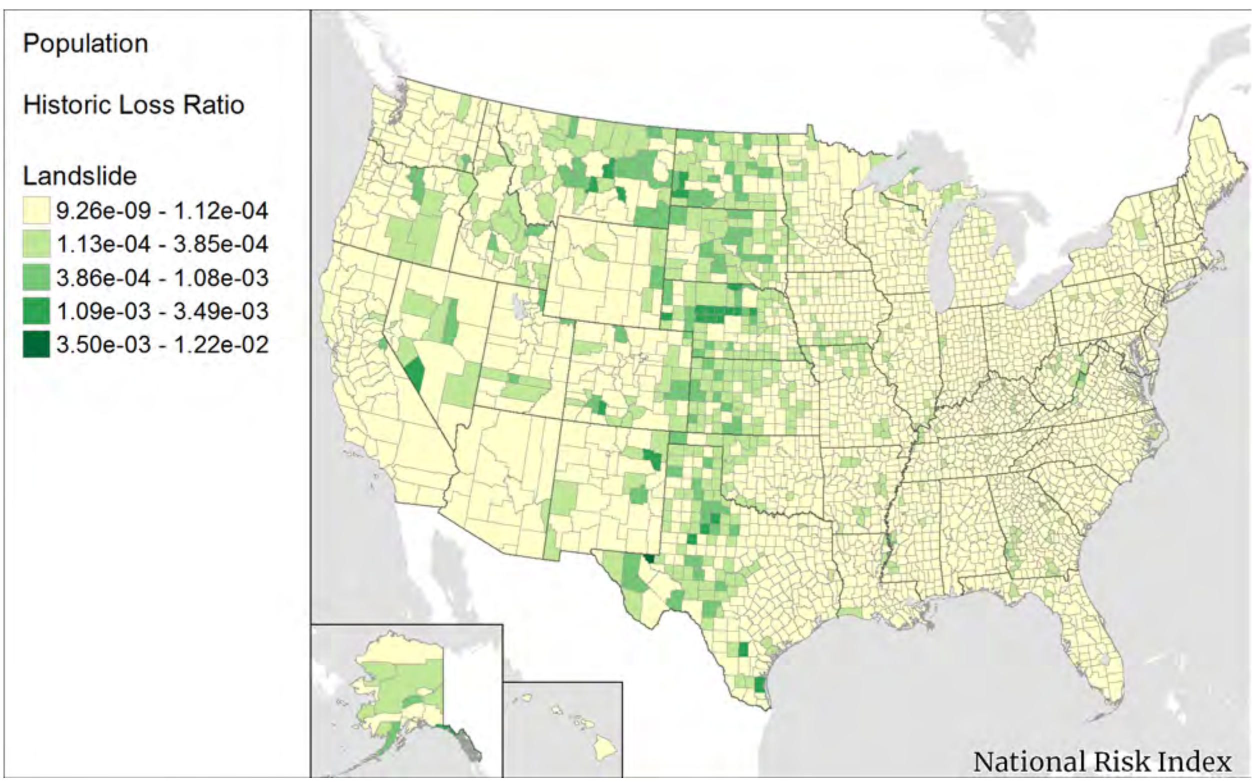

Figure 98: Landslide HLR – Population

15.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 82. 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 82: 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 building Expected Annual Loss due to Landslide occurrences 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 frequency of Landslide events determined for a specific 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 population equivalence Expected Annual Loss due to Landslide occurrences for a specific Census block (in dollars).
$Exposure_{LNDS_{CB_{Pop}}}$	is the population equivalence 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 building and population equivalence EAL values at the Census block level as in Equation 83.

Equation 83: 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 occurrences for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{LNDS_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Landslide occurrences for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{LNDS_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Landslide occurrences for all Census blocks in the Census tract (in dollars).
$EAL_{LNDS_{Co}}$	is the total Expected Annual Loss due to Landslide occurrences for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{LNDS_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Landslide occurrences for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{LNDS_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Landslide occurrences for all Census blocks in the county (in dollars).

Figure 99 shows the total EAL (building value and population equivalence combined) to Landslide occurrences.

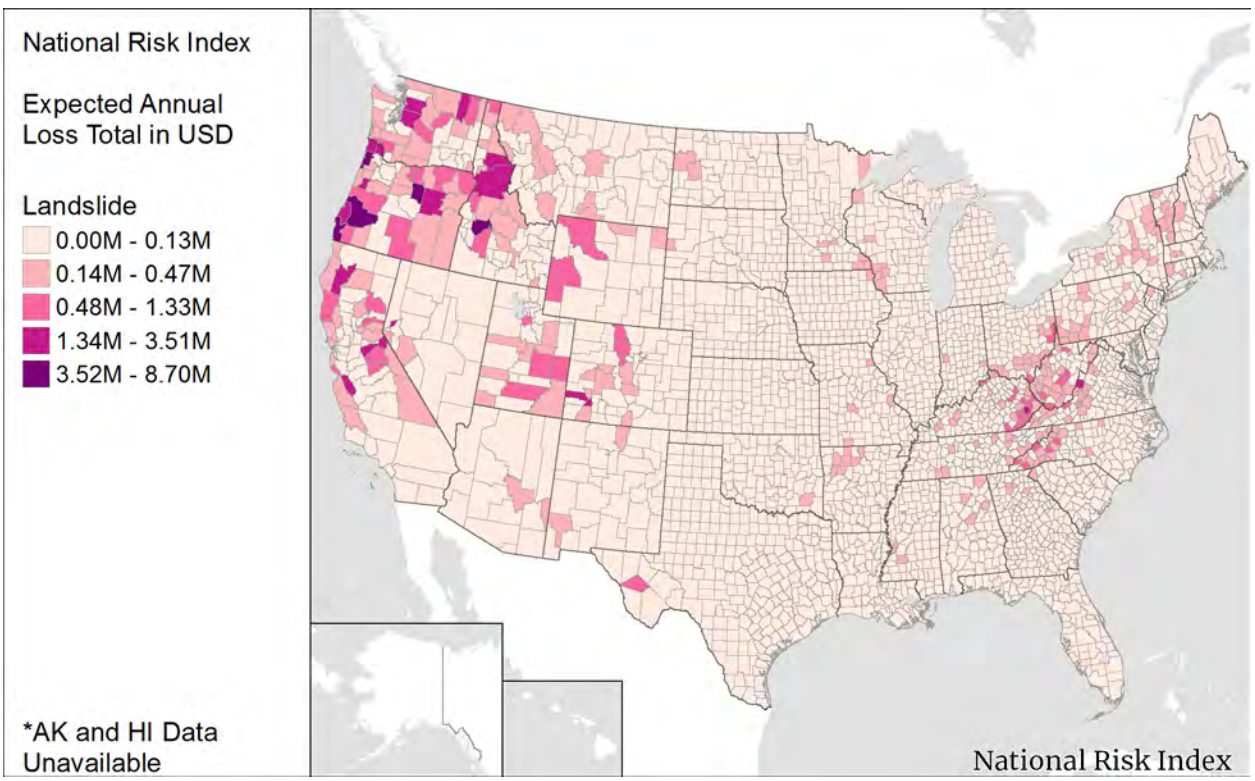

Figure 99: Total Expected Annual Loss by County to Landslide

With the Landslide total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 Occurrence Source: NOAA, National Centers for Environmental Information (NCEI), Cloud-to-Ground Lightning Strikes[68]

NCEI currently maintains a prototype dataset with all recorded cloud-to-ground Lightning strikes in the conterminous U.S. 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 100). Each cell summarizes Lightning strikes for each hour, day, month, or year. The files aggregating Lightning strikes per year are used to calculate annualized frequency at the Census block level.

Note: Because Lightning strike data are not available for Alaska and Hawaii, annualized frequency and, therefore, EAL cannot be computed for these states.

[68] 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.

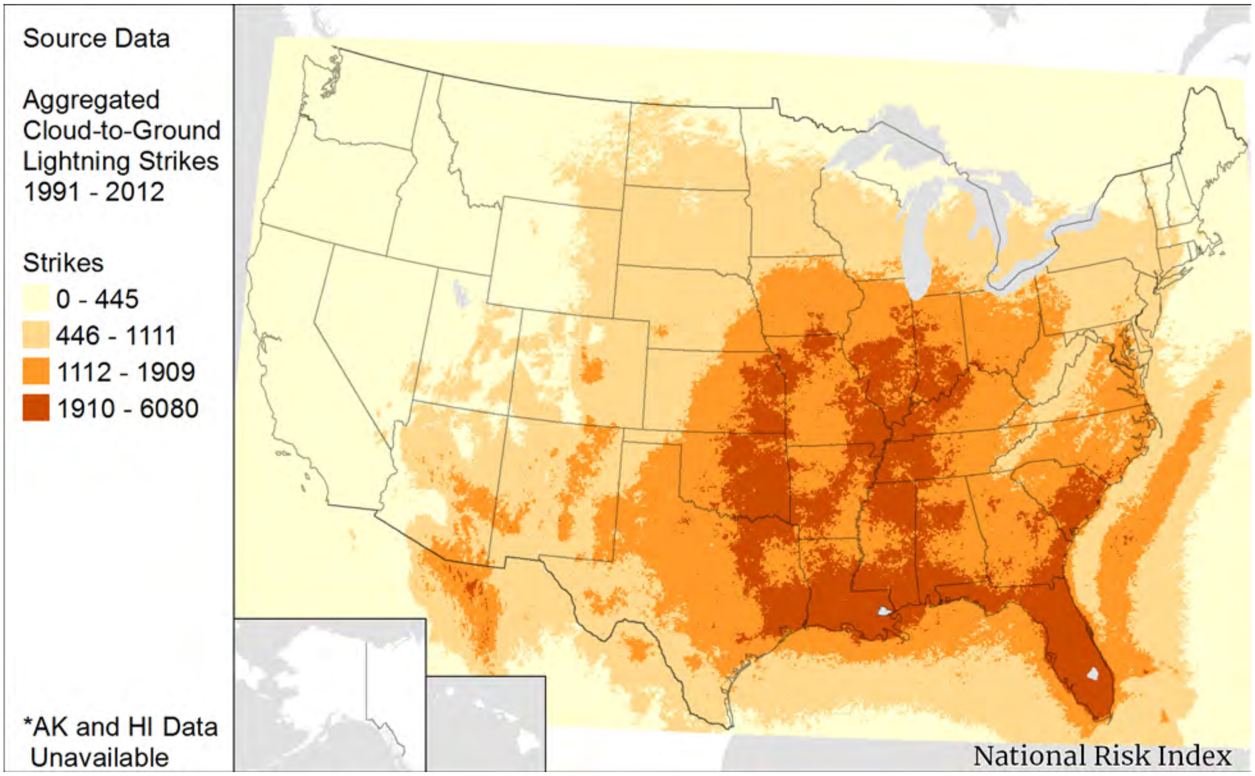

Figure 100: Map of Lightning Strikes

16.1.1. PERIOD OF RECORD

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 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 49). Polygons imported into the processing database can then be intersected with the Census-block polygons.

Table 49: 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. Population equivalence, which is used in select EAL calculations, is calculated by multiplying population by the VSL ($7.6M per person).

16.5. Historic Occurrence Count

The historic occurrence count of Lightning strikes, in events, 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 84). Historic event 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 84: 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. Annualized Frequency

The annualized 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 annualized frequencies of its intersecting fishnet cells. The Census block value is used in the EAL calculations.

Annualized 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 85.

Equation 85: Fishnet Cell Lightning Annualized 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 annualized frequency at the Census block level, the Lightning fishnet polygons are first intersected with the Census block polygons within the processing database. The resulting table contains the polygon's unique identifier, Census block number, and the intersected area in square kilometers (see Table 50).

Table 50: 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 86.

Equation 86: Census Block Area-Weighted Fishnet Lightning Annualized 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 area-weighted annualized 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. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized 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 annualized frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 87.

Equation 87: Census Tract and County Area-Weighted Lightning Annualized 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 area-weighted Lightning annualized frequency for a specific Census tract.
$Freq_{LTNG_{CB}}$	is the area-weighted annualized frequency of Lightning strikes determined for the 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).
$Freq_{LTNG_{Co}}$	is the area-weighted Lightning annualized 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 101 displays Lightning annualized frequency at the county level.

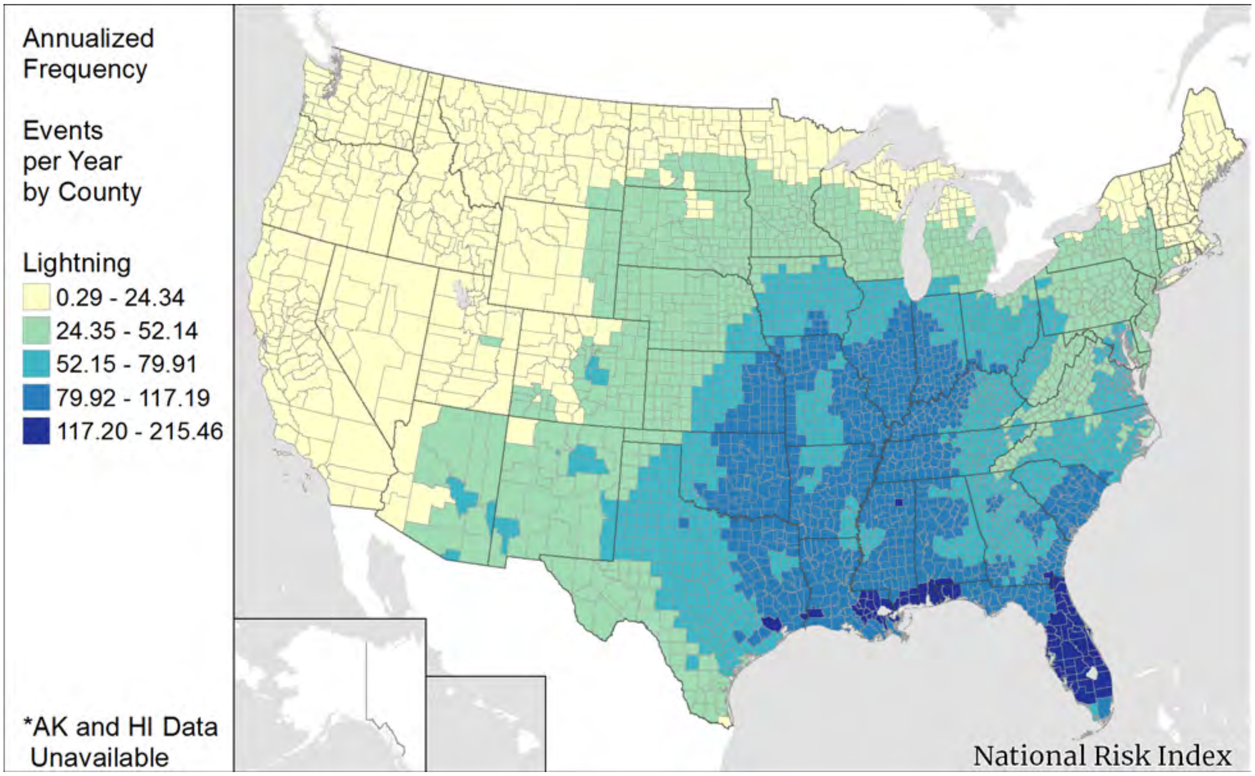

Figure 101: Lightning Annualized Frequency by County

16.7. Historic Loss Ratio

The Lightning HLR is the representative percentage of a location's hazard exposure that experiences loss due to a Lightning strike occurrence, or the average rate of loss associated with a Lightning strike occurrence. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Lightning hazard type.

Loss data are provided by SHELDUS[69] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Two peril types are mapped to the hazard Lightning (see Table 51). Native records of Lightning events that caused loss over more than one day have their loss assigned to the first day, and all records are aggregated on a single event-per-day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

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

Table 51: Lightning Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Fire-St Elmo's	0	0
Lightning	14,439	13,232

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 88.

Equation 88: 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 or impacted people).

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

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 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 (1996 to 2019). For Lightning, the historic event count is extracted using the intersection between the Lightning fishnet polygons and the Census block polygons used to calculate annualized frequency (see Table 50). The area-weighted count of all Lightning fishnet-Census block polygon intersections within the county for each record year is used as the historic event count. An annual rate is calculated as the event count divided by the period of record of 22 years, and this rate is multiplied by the SHELDUS period of record of 24 years to estimate a historic event-day count for the appropriate time range.

If the number of loss-causing Lightning event records from SHELDUS is less than the scaled event count for the county, then a number of zero-loss records equal to the difference are 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 102 and Figure 104 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 Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Lightning occurrences within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value, though its HLR may be influenced by other local or national occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing occurrences or have widely varying loss ratios get the most influence from national-level loss data. Figure 103 and Figure 105 represent the final, Bayesian-adjusted county-level HLR values for Lightning.

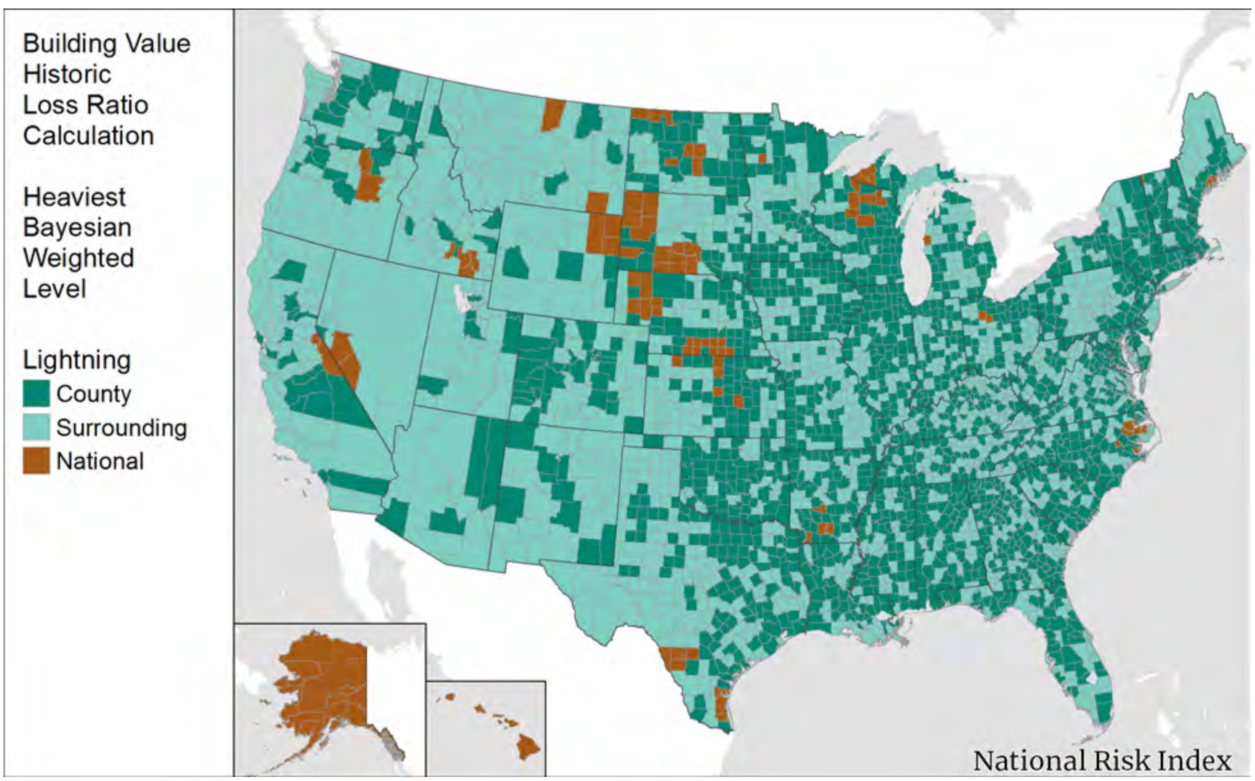

Figure 102: Lightning Heaviest Bayesian Weighted Level – Building Value

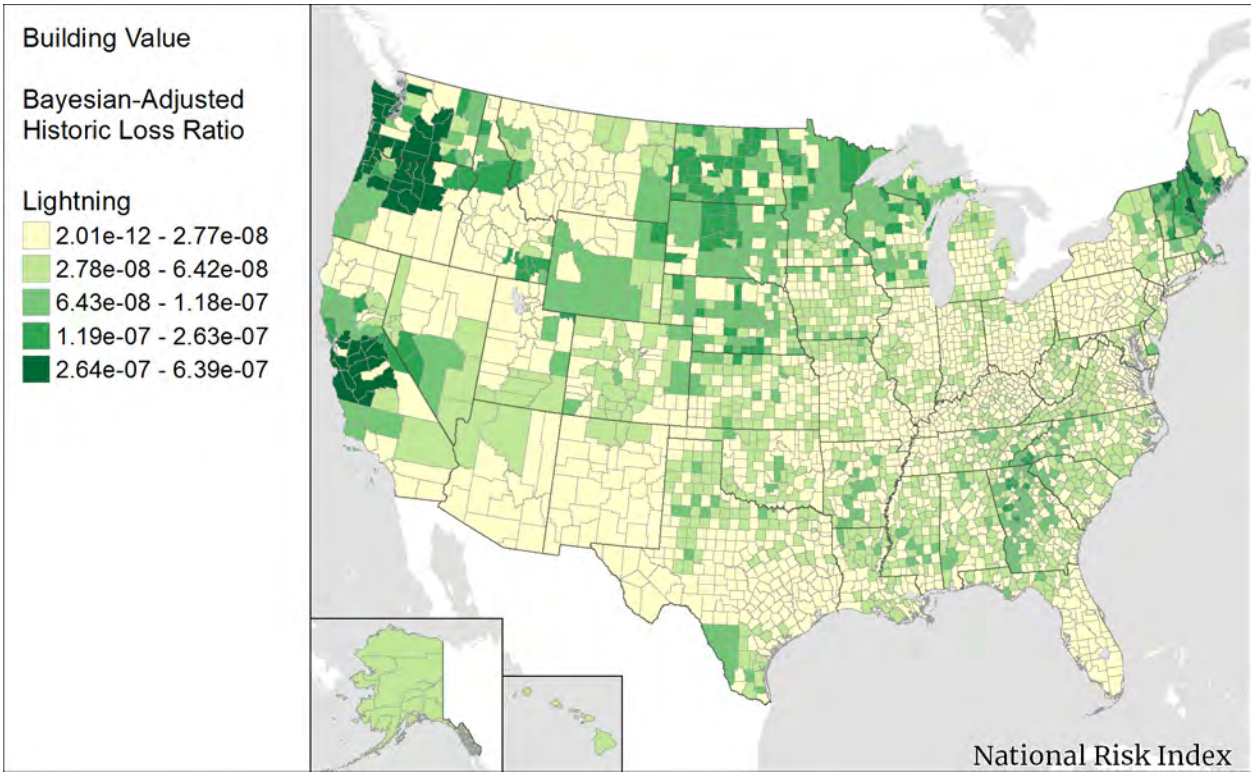

Figure 103: Lightning Bayesian-Adjusted HLR – Building Value

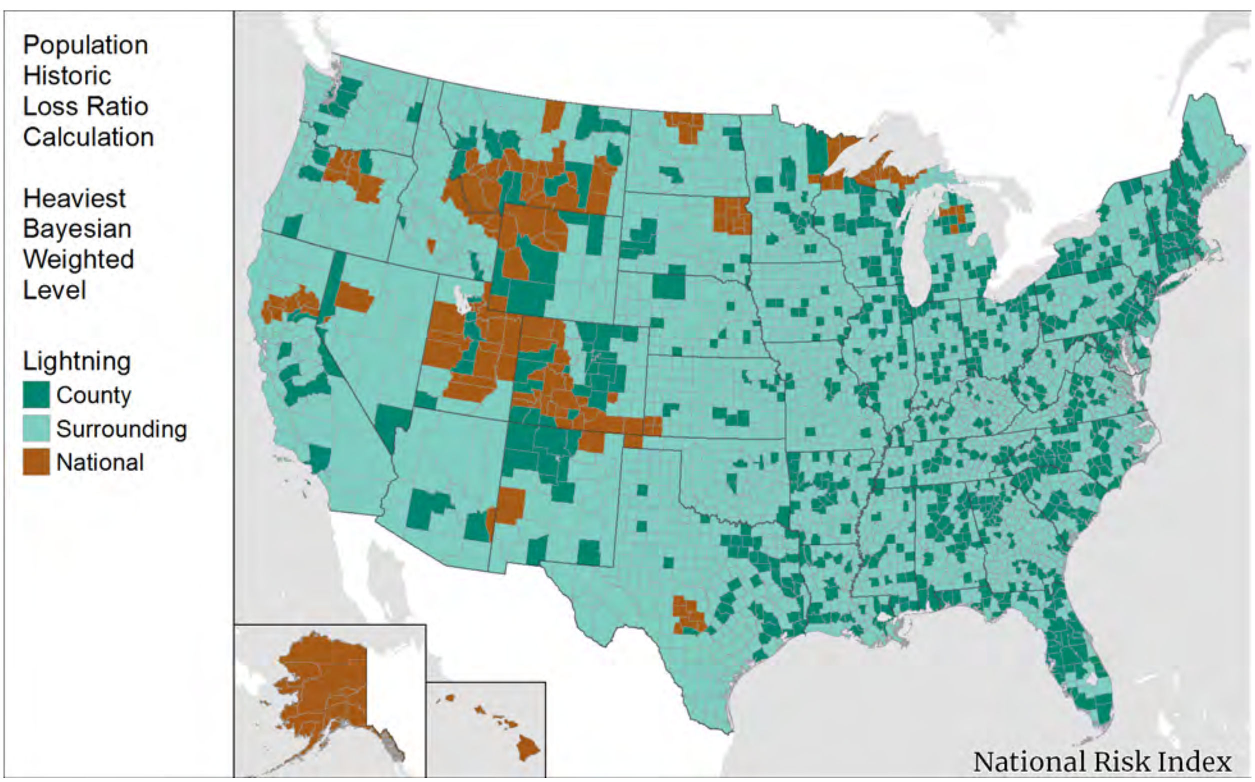

Figure 104: Lightning Heaviest Bayesian Weighted Level – Population

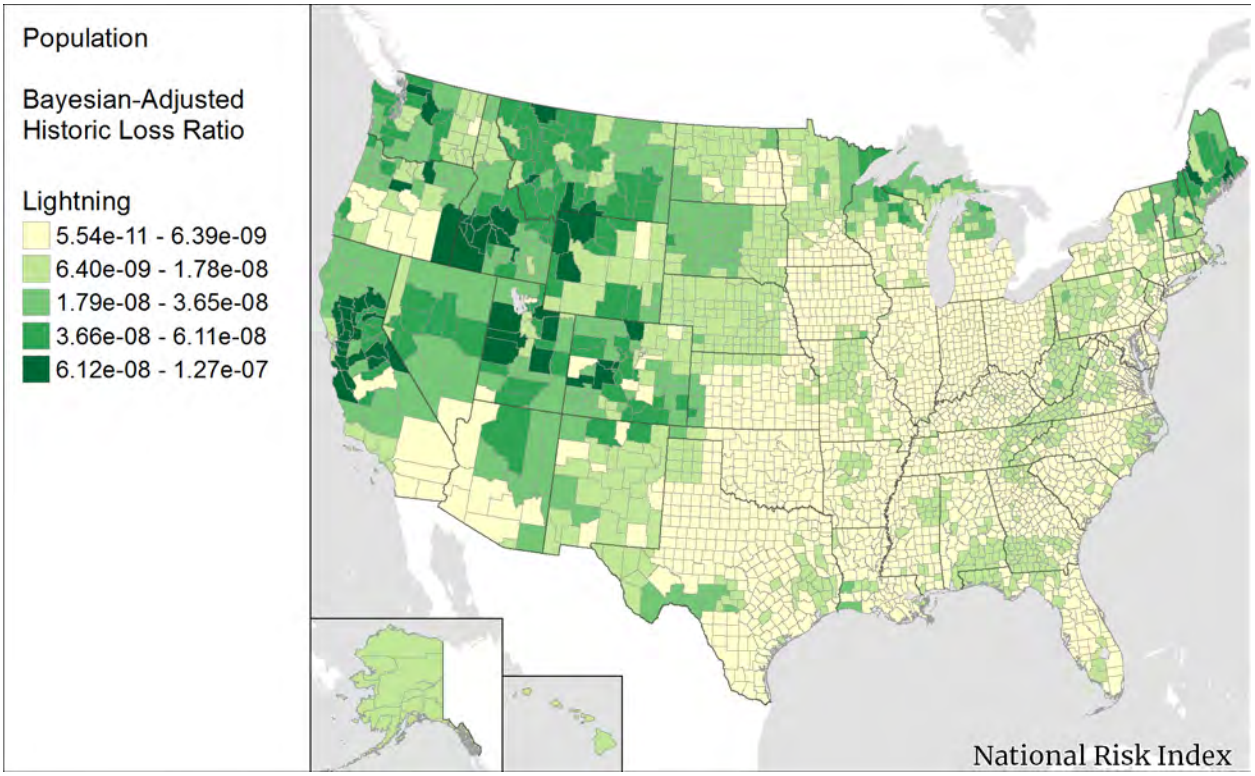

Figure 105: Lightning Bayesian-Adjusted HLR – Population

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

16.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 89. 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 89: 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 building Expected Annual Loss due to Lightning occurrences for a specific Census block (in dollars).

$Exposure_{LTNG_{CB_{Bldg}}}$	is the building value exposed to Lightning occurrences in the Census block (in dollars).
$Freq_{LTNG_{CB}}$	is the Lightning annualized 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 population equivalence Expected Annual Loss due to Lightning occurrences for a specific Census block (in dollars).
$Exposure_{LTNG_{CB_{Pop}}}$	is the population equivalence value exposed to Lightning occurrences 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 building and population equivalence EAL values at the Census block level as in Equation 90.

Equation 90: 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 occurrences for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{LTNG_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Lightning occurrences for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{LTNG_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Lightning occurrences for all Census blocks in the Census tract (in dollars).
$EAL_{LTNG_{Co}}$	is the total Expected Annual Loss due to Lightning occurrences for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{LTNG_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Lightning occurrences for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{LTNG_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Lightning occurrences for all Census blocks in the county (in dollars).

Figure 106 shows the total EAL (building value and population equivalence combined) to Lightning occurrences.

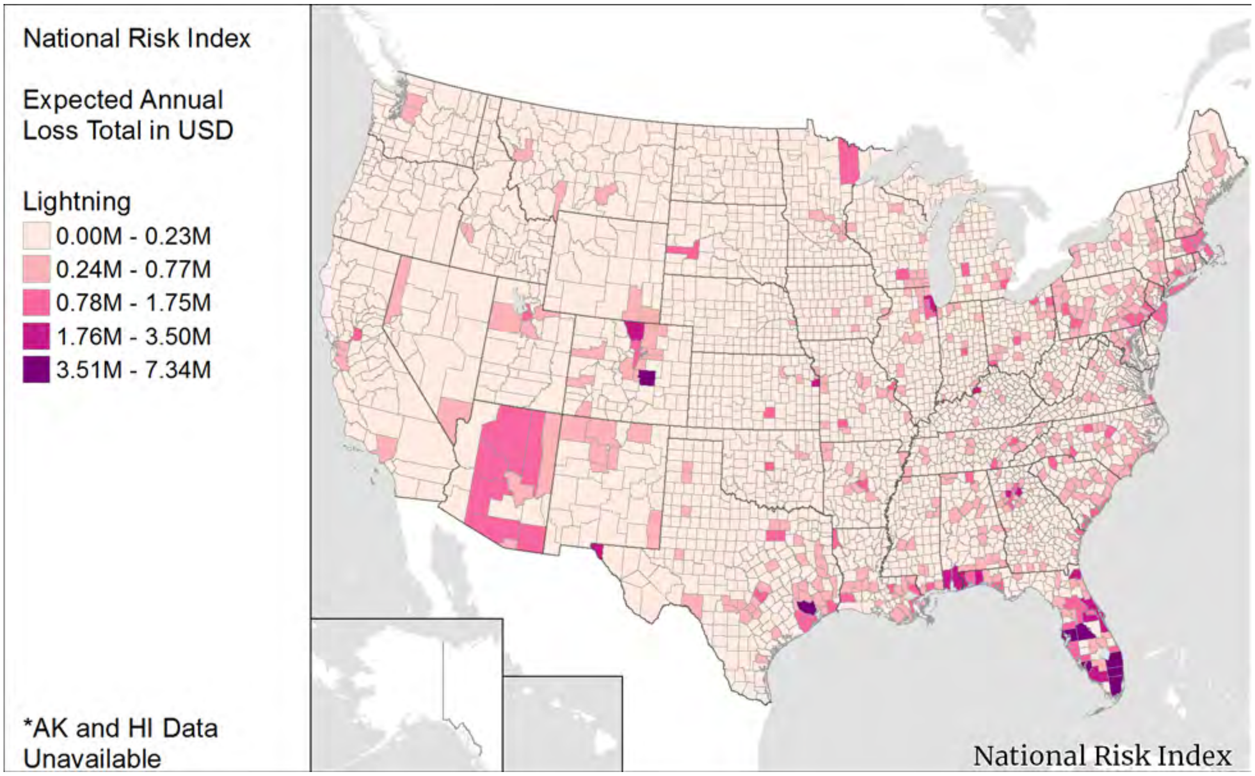

Figure 106: Total Expected Annual Loss by County to Lightning

With the Lightning total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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[70]

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 107) for use in the calculation of Riverine Flooding exposure.

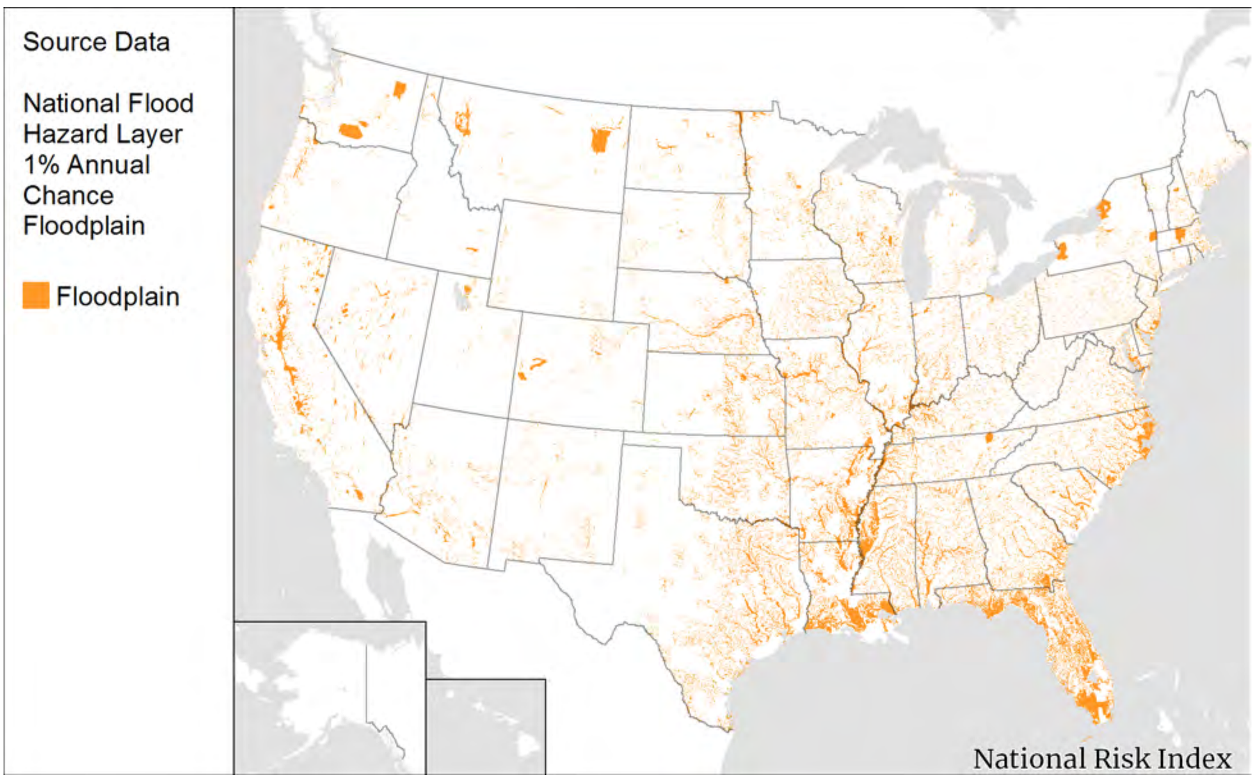

Figure 107: Map of 1% Annual Chance Floodplain

Susceptible Area Source: CoreLogic Special Flood Hazard Area Layer

[70] 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 Centers for Environmental Information, Storm Events Database[71]

The NCEI Storm Events Database contains records of the occurrence of storms and other significant weather phenomena, including flooding events, since January 1950. Each flooding event record includes the affected counties, the dates of the event occurrence, and any reported loss. These records are used to calculate the annualized frequency for Riverine Flooding.

17.1.1. PERIOD OF RECORD

The Riverine Flooding annualized frequency calculation is based on the number of recorded Riverine Flooding events in the NCEI Storm Events Database from 1/1/1996 to 12/31/2019, so the period of record is 24 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 U.S. had sustained some form of loss due to Riverine Flooding occurrences, 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 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 52). All area values are in square kilometers.

[71] National Centers for Environmental Information. (2020). *Storm Events Database, Version 3.1.* [online database]. Retrieved from https://www.ncdc.noaa.gov/stormevents/.

Table 52: 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 agriculture area intersecting the riverine floodplain polygons for each Census block is multiplied by the total agriculture area value density (see Equation 91). These densities have been calculated by dividing the total exposure values (as recorded in Hazus 4.2 SP1) by the developed area or agriculture land area (in square kilometers). The VSL was used to express population equivalence exposure in terms of dollars.

Equation 91: 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 equivalence 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 ($7.6M per person).
$Exposure_{RFLD_{CB_{Ag}}}$	is the agriculture value exposed to Riverine Flooding in a specific Census block (in dollars).
$\sum IntsctArea_{RFLD_{Ag_{CB}}}$	is the sum of the intersected agriculture 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 building value exceeds the Hazus-recorded building value, then the Hazus-recorded building value is used as the building 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 Census tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see Equation 92).

Equation 92: 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 equivalence 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 equivalence exposed to Riverine Flooding for each Census block within the Census tract (in dollars).
$Exposure_{RFLD\,Co_{Pop}}$	is the population equivalence 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 equivalence exposed to Riverine Flooding for each Census block within the county (in dollars).
$Exposure_{RFLD\,CT_{Ag}}$	is the agriculture 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 agriculture value exposed to Riverine Flooding for each Census block within the Census tract (in dollars).
$Exposure_{RFLD\,Co_{Ag}}$	is the agriculture value exposed to Riverine Flooding in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{RFLD\,CB_{Ag}}$	is the summed value of all agriculture value exposed to Riverine Flooding for each Census block within the county (in dollars).

17.5. Historic Occurrence Count

The historic occurrence count of Riverine Flooding, in event-days, is computed as the number of days in which 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) were recorded in the NCEI Storm Events Database within the county from January 1996 to December 2019. 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-day counts are also supplied at the Census tract level. These values are inherited from the parent county as the exact location of the occurrence within the county cannot always be determined from the NCEI Storm Events Database record.

17.6. Annualized Frequency

The annualized frequency value represents the number of Riverine Flooding occurrences, in event-days, each year over the period of record (24 years). Annualized frequency is initially calculated at the county level. The Census tracts and Census blocks inherit annualized frequency values from the counties that contain them, and the Census block-level value is used in the EAL calculations.

Annualized frequency calculations use the NCEI Storm Events Database Riverine Flooding events for the county (see Section 17.5 Historic Occurrence Count) and divide by the period of record as in Equation 93. Multiple event records that occur on the same day in the same county are counted as a single Riverine Flooding occurrence.

Equation 93: County Riverine Flooding Annualized Frequency

$$Freq_{RFLD_{Co}} = \frac{EventDayCount_{RFLD_{Co}}}{PeriodRecord_{RFLD}}$$

where:

$Freq_{RFLD_{Co}}$	is the annualized frequency of Riverine Flooding events determined for a specific county (event-days per year).
$EventDayCount_{RFLD_{Co}}$	is the total number of Riverine Flooding event-days (from the NCEI Storm Events Database) that have impacted the county.
$PeriodRecord_{RFLD}$	is the period of record for Riverine Flooding (24 years).

17.6.1. MINIMUM ANNUAL FREQUENCY

If a county intersects the 1% annual chance riverine floodplain but has not experienced a Riverine Flooding event-day, it is assigned a minimum annual frequency of 0.01 or once in 100 years.

17.6.2. ANNUALIZED FREQUENCY INHERITANCE

The Census tracts and Census blocks inherit their annualized frequency values from the parent counties that contain them as in Equation 94.

Equation 94: Census Block and Tract Riverine Flooding Annualized Frequency Inheritance

$$Freq_{RFLD_{CB}} = Freq_{RFLD_{CT}} = Freq_{RFLD_{Co}}$$

where:

$Freq_{RFLD_{CB}}$	is the inherited annualized frequency of Riverine Flooding event-days for a specific Census block within the parent county.
$Freq_{RFLD_{CT}}$	is the inherited annualized frequency of Riverine Flooding event-days for a specific Census tract within the parent county.
$Freq_{RFLD_{Co}}$	is the annualized frequency of Riverine Flooding event-days associated with a specific county.

Figure 108 displays Riverine Flooding annualized frequency at the county level.

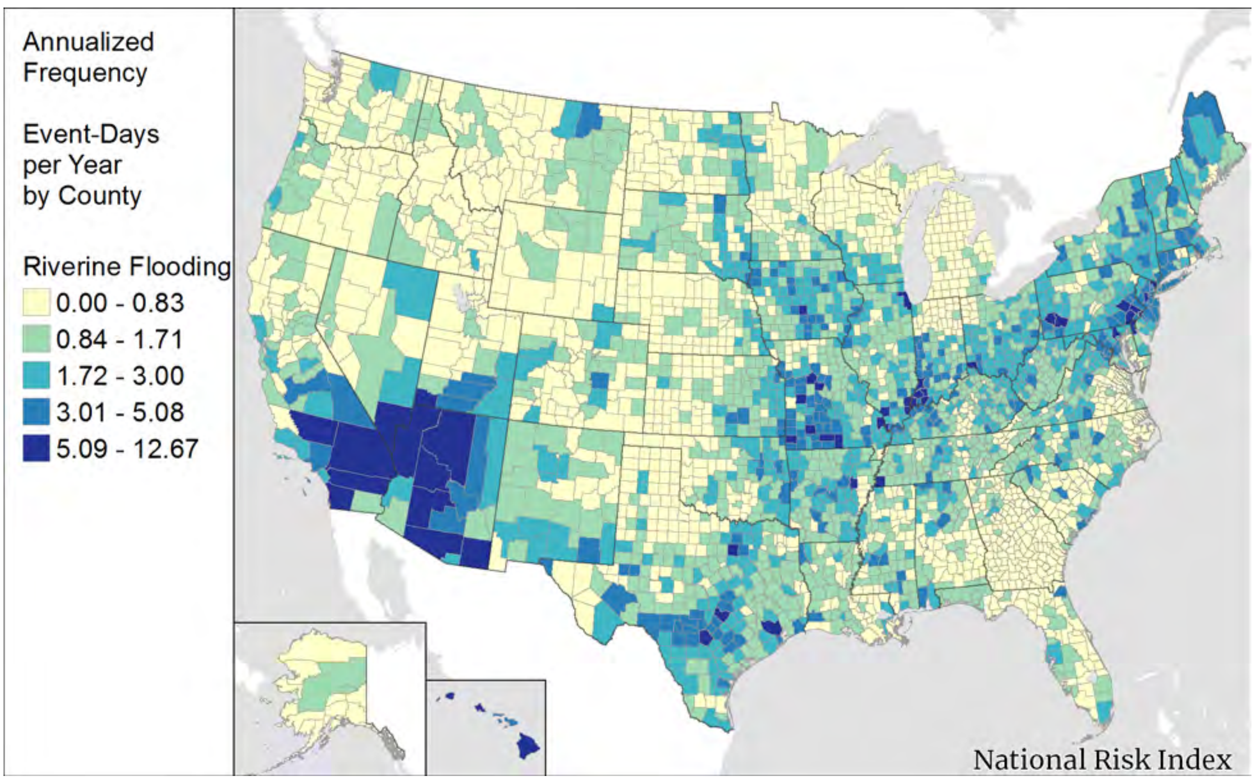

Figure 108: Riverine Flooding Annualized Frequency by County

17.7. Historic Loss Ratio

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

Riverine Flooding occurrence. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Riverine Flooding hazard type.

Loss data are provided by SHELDUS[72] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Eight peril types are mapped to the hazard Riverine Flooding (see Table 53). These native records are expanded on an event-day basis (to a maximum of 31 days) and aggregated on a single-event-per-day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

Table 53: Riverine Flooding Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Flood-Flash	29,522	26,395
Flood-Ice Jam	4	12
Flooding	22,149	91,029
Flood-Lakeshore	112	1,119
Flood-Lowland	0	0
Flood-Riverine	60	495
Flood-Small Stream	256	277
Flood-Snowmelt	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 agriculture area density exposure values of the Census blocks that intersect the layer of the 1% annual chance floodplain (see Section 17.4 Exposure). 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 agriculture 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-day and each consequence type (building, population, and agriculture) is calculated using Equation 95.

Equation 95: Loss Ratio per Basis Calculation for a Single Riverine Flooding Event-Day

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

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

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-day. 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-day documented to have occurred in the county (in dollars or impacted people).
$HLRExposure_{RFLD\,Co_{CnsqType}}$	is the value (by consequence type) of the susceptible area estimated to have been exposed to the Riverine Flooding event-day (in dollars or people).

Riverine Flooding event-days may occur in areas without resulting in recorded loss to buildings, population, or agriculture. SHELDUS does not record event-days 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 (1996 to 2019). For Riverine Flooding, the historic event-day count is computed as the number of Riverine Flooding event-days recorded in the NCEI 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-day.) The period of record for both the SHELDUS and NCEI data is the same 24 years, so the count does not need to be scaled by an annual rate.

If the number of loss-causing Riverine Flooding event-day records from SHELDUS is less than the historic event-day count for the county, then a number of zero-loss records equal to the difference are 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 two levels: county and regional. The regional definition for Riverine Flooding is derived from the FEMA regions with Regions 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

To address overestimation of population impacts, the Bayesian-adjusted population HLRs are compared to the ratio of the average number of people impacted (excluding zero population loss events) divided by the county population. The smaller of these two values is used as the county's population HLR.

Figure 109, Figure 111, and Figure 113 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 Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough River Flooding occurrences within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value, though its HLR may be influenced by regional occurrences. Counties that have experienced few loss-causing Riverine Flooding occurrences or have widely varying LRBs get the most influence from regional-level loss data.

Figure 110, Figure 112, and Figure 114 represent the final, Bayesian-adjusted county-level HLR values for Riverine Flooding.

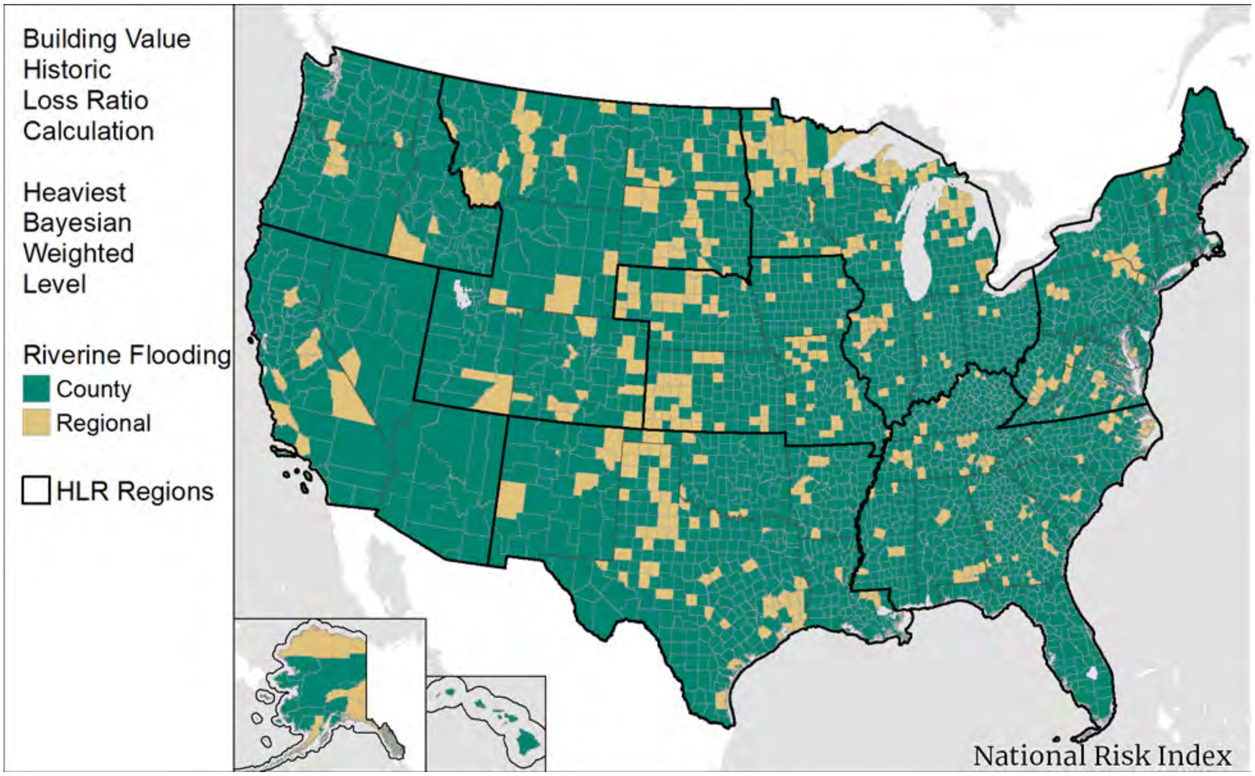

Figure 109: Riverine Flooding Heaviest Bayesian Influence Level – Building Value

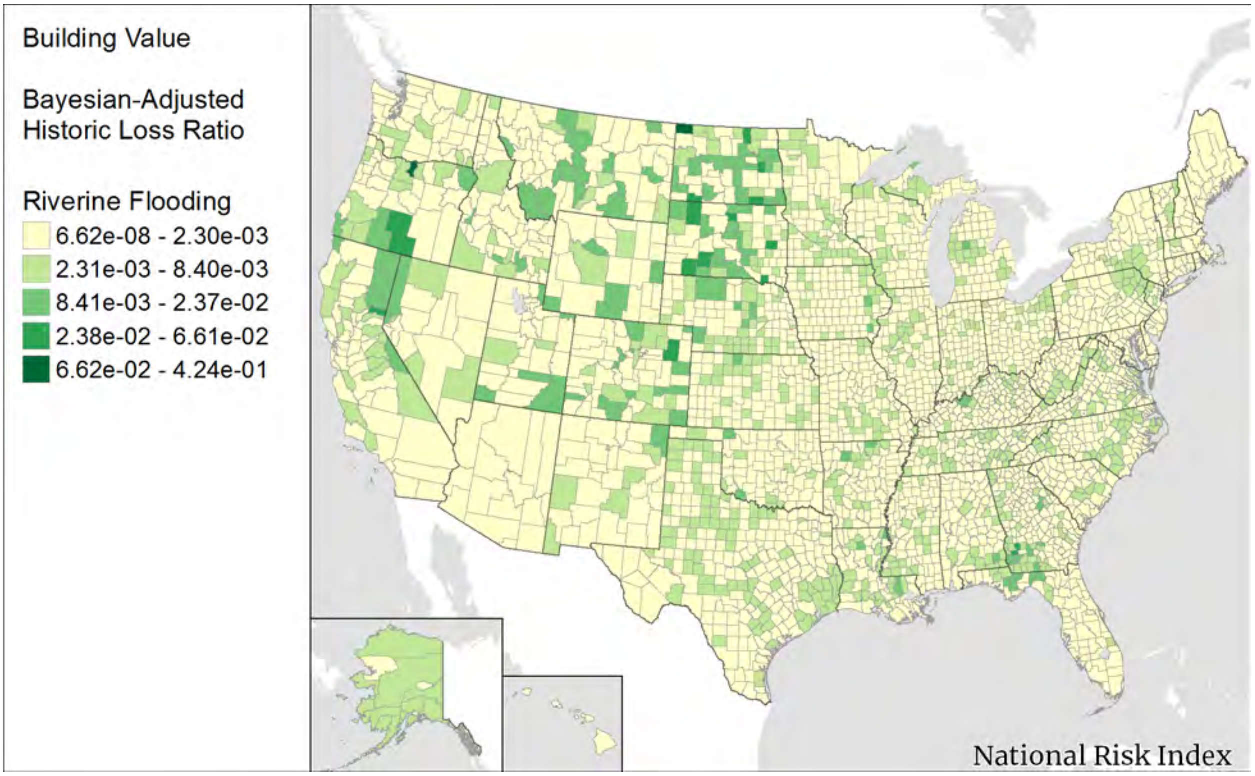

Figure 110: Riverine Flooding Bayesian-Adjusted HLR – Building Value

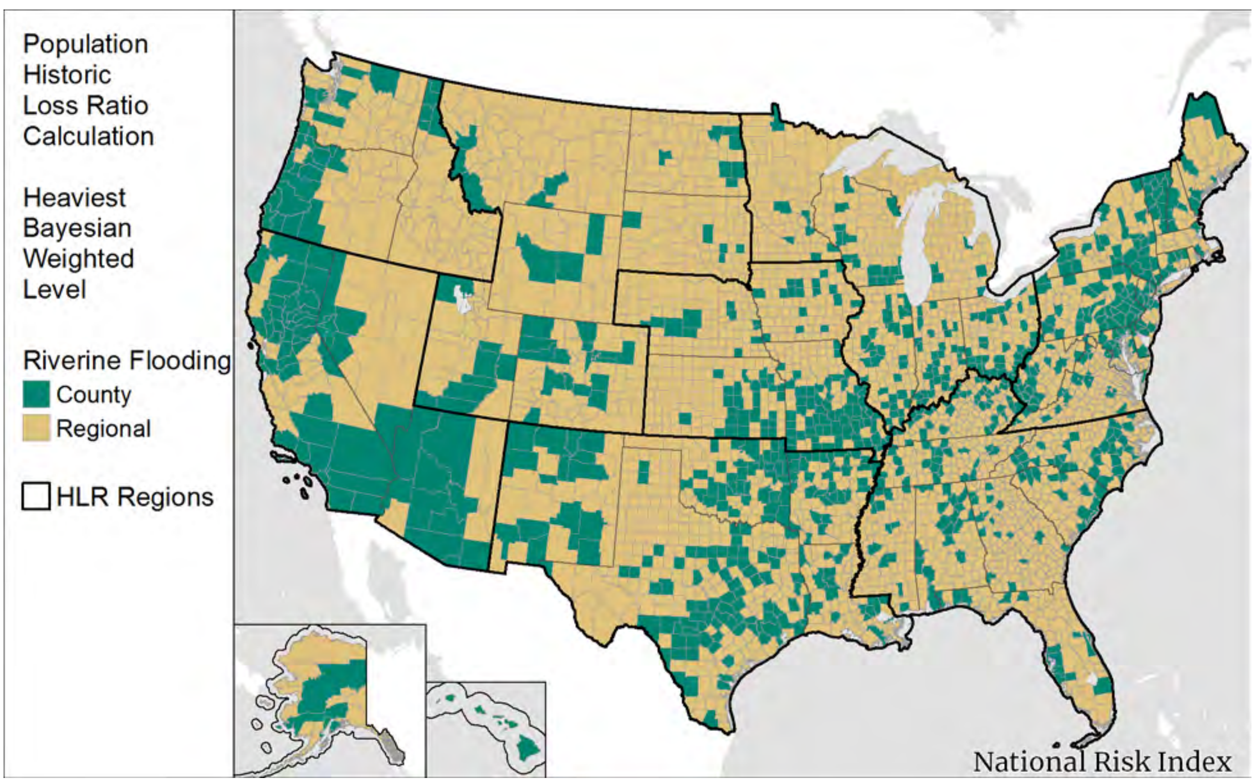

Figure 111: Riverine Flooding Heaviest Bayesian Influence Level – Population

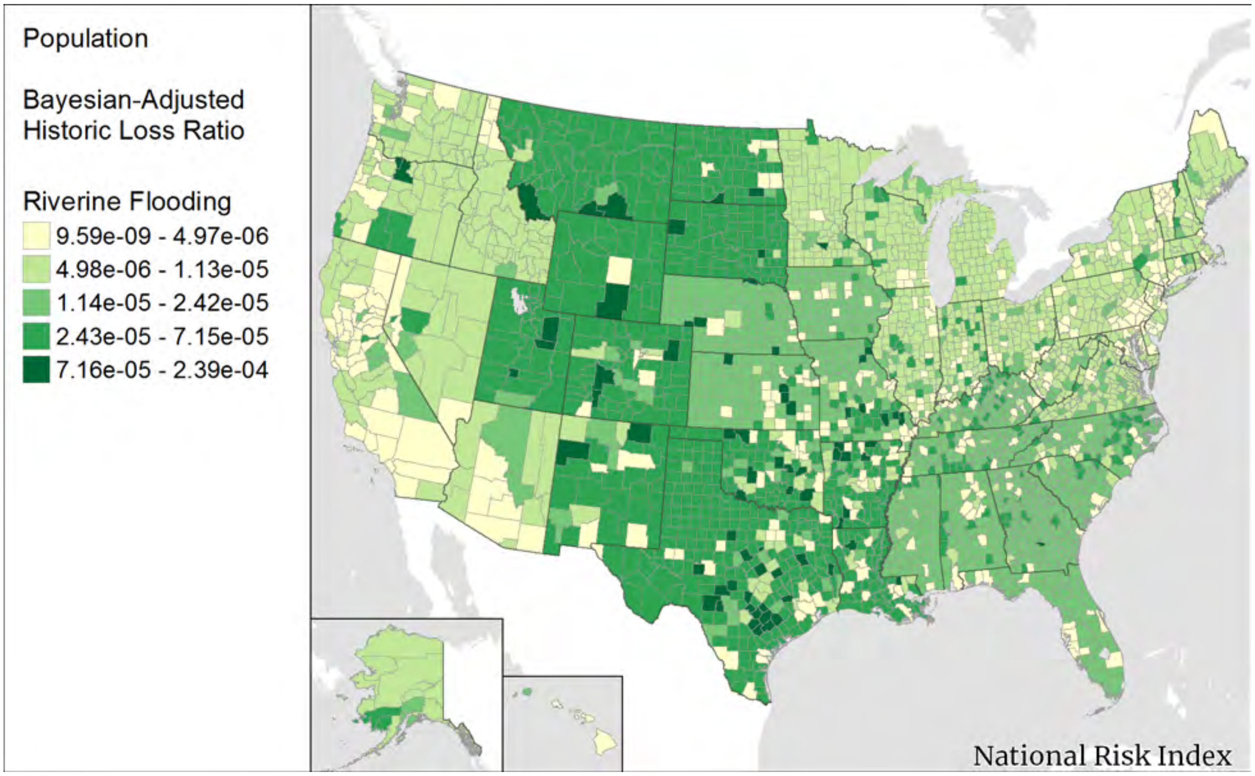

Figure 112: Riverine Flooding Bayesian-Adjusted HLR – Population

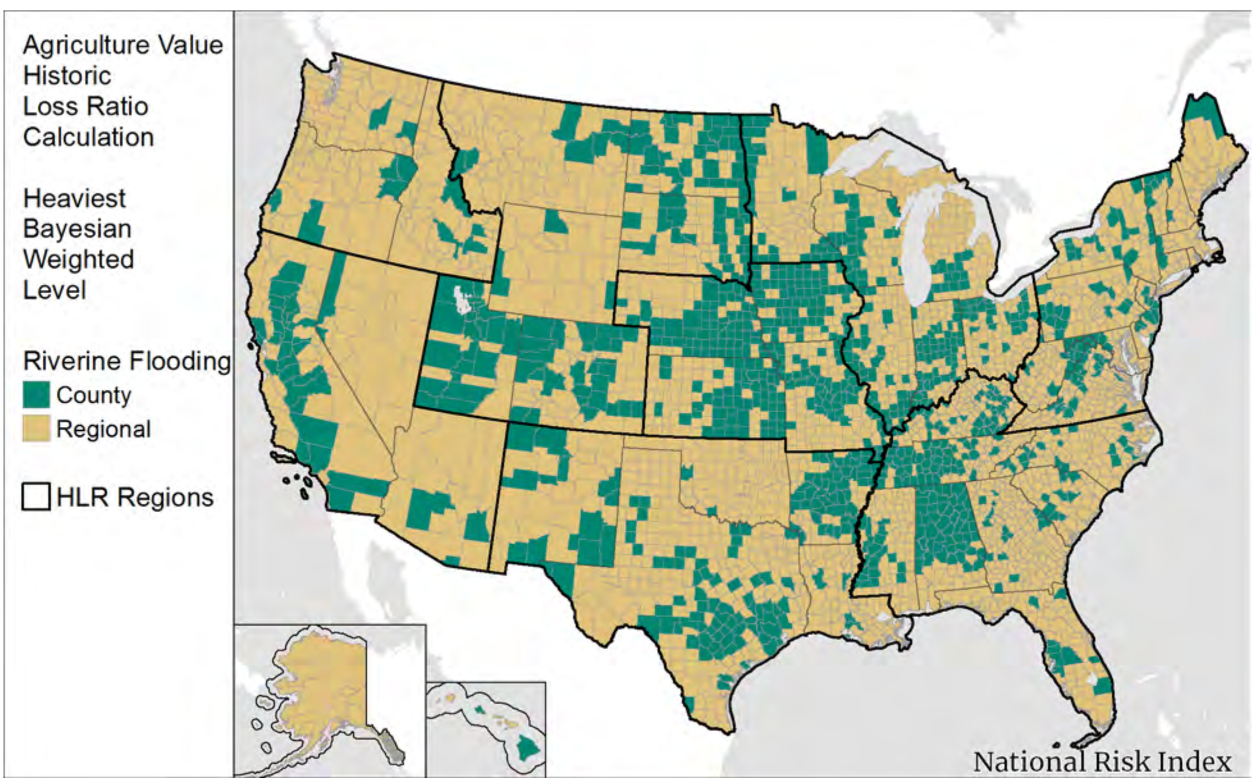

Figure 113: Riverine Flooding Heaviest Bayesian Influence Level – Agriculture Value

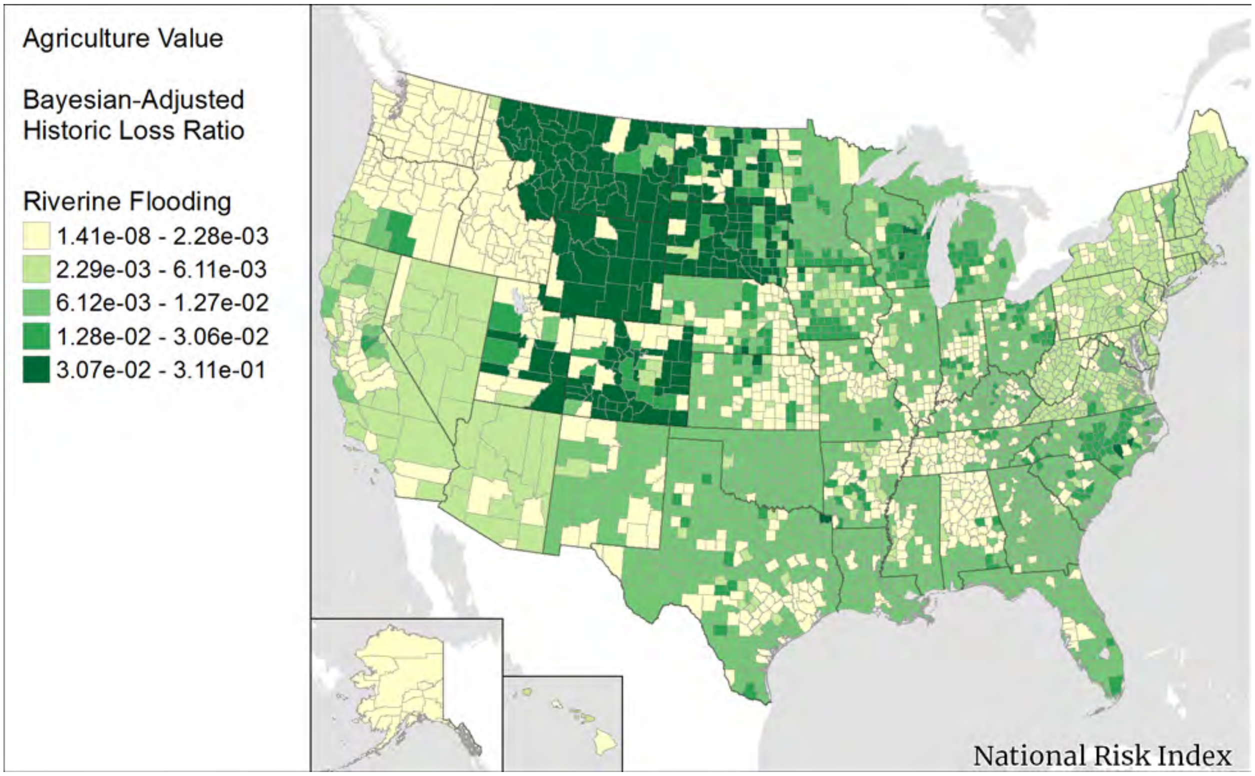

Figure 114: Riverine Flooding Bayesian-Adjusted HLR – Agriculture Value

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

17.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 96. 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 96: 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 building Expected Annual Loss due to Riverine Flooding occurrences for a specific Census block (in dollars).

$Exposure_{RFLD_{CB_{Bldg}}}$ is the building value exposed to Riverine Flooding occurrences in the Census block (in dollars).

$Freq_{RFLD_{CB}}$ is the Riverine Flooding annualized 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 population equivalence Expected Annual Loss due to Riverine Flooding occurrences for a specific Census block (in dollars).

$Exposure_{RFLD_{CB_{Pop}}}$ is the population equivalence value exposed to Riverine Flooding occurrences 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 agriculture Expected Annual Loss due to Riverine Flooding occurrences for a specific Census block (in dollars).

$Exposure_{RFLD_{CB_{Ag}}}$ is the agriculture value exposed to Riverine Flooding occurrences 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 building, population equivalence, and agriculture EAL values at the Census block level as in Equation 97.

Equation 97: 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 occurrences for a specific Census tract (in dollars).

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

$\sum_{CB}^{CT} EAL_{RFLD_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Riverine Flooding for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{RFLD\,CB_{Ag}}$ is the summed agriculture Expected Annual Loss 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 occurrences for a specific county (in dollars).

$\sum_{CB}^{Co} EAL_{RFLD\,CB_{Bldg}}$ is the summed building Expected Annual Loss due to Riverine Flooding for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{RFLD\,CB_{Pop}}$ is the summed population equivalence Expected Annual Loss due to Riverine Flooding for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{RFLD\,CB_{Ag}}$ is the summed agriculture Expected Annual Loss due to Riverine Flooding for all Census blocks in the county (in dollars).

Figure 115 shows the total EAL (building value, population equivalence, and agriculture value combined) to Riverine Flooding occurrences.

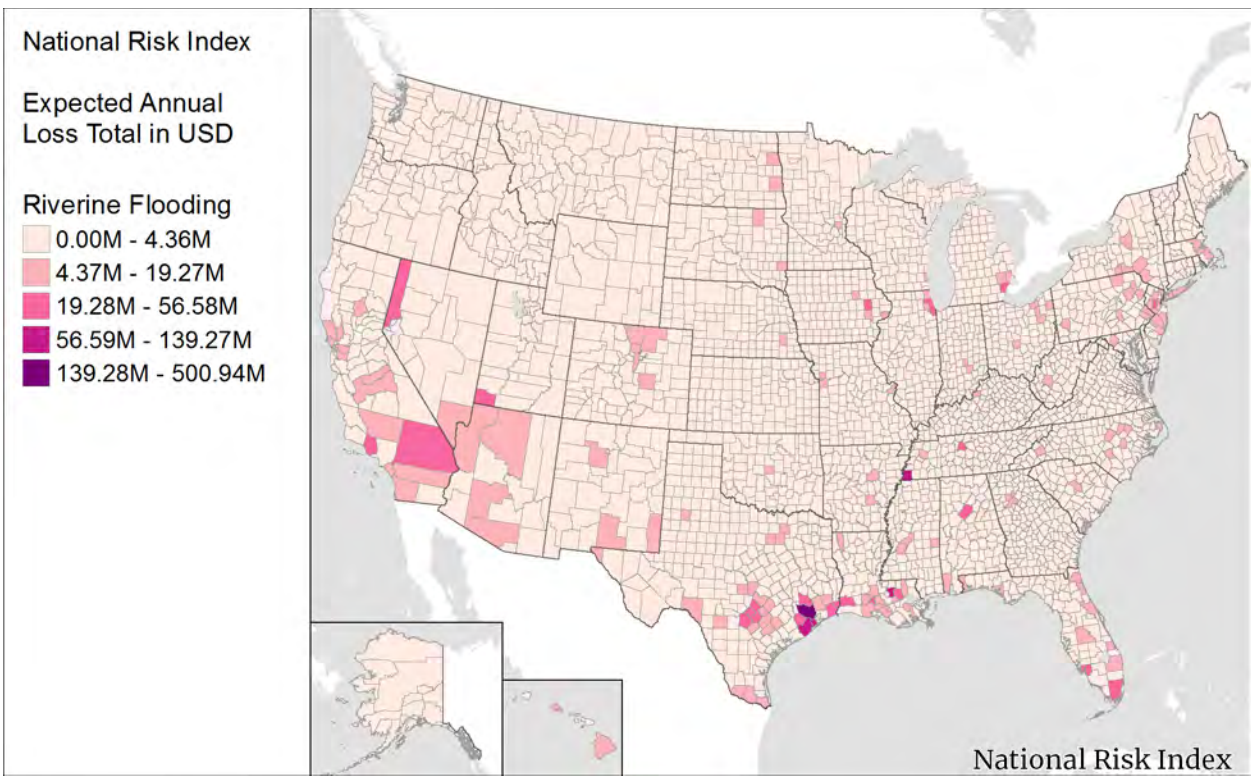

Figure 115: Total Expected Annual Loss by County to Riverine Flooding

With the Riverine Flooding total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 Occurrence Source: National Weather Service, Storm Prediction Center, Severe Weather Database Files[73]

The SPC 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 54 and Figure 116). Many fields are empty for older records, especially those before 1985.

Table 54: 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 7:00 PM	MT	0	-84.58	43.28	0	0
553	2/6/1999 10:37 PM	AR	52	-93.92	33.93	0	0
636896	6/9/2017 1:59 AM	MI	100	-111.86	48.85	-111.86	48.85

[73] 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/.

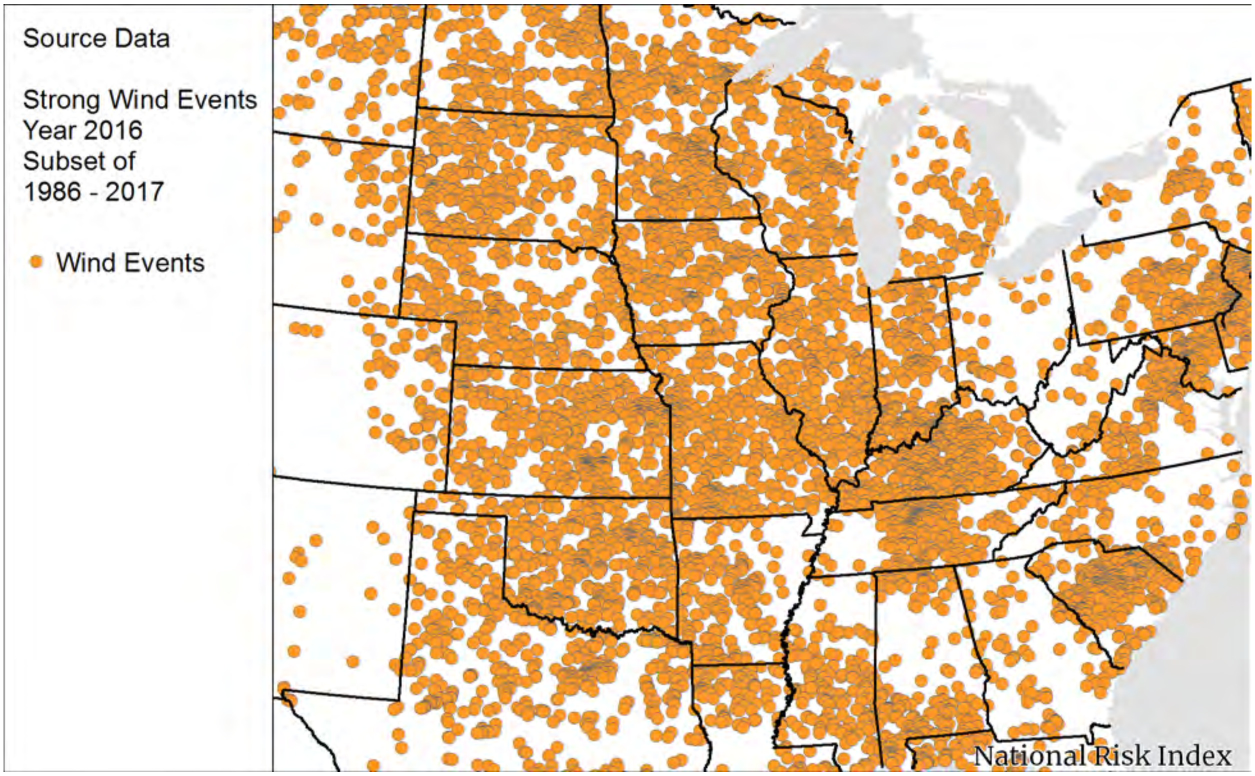

Figure 116: Map of Wind Points

18.1.1. PERIOD OF RECORD

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)[74] are filtered out. An 80-km buffer was created from the remaining points to produce a layer of Strong Wind event polygons (see Figure 117). The 80-km 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 Strong Wind event polygons can then be used to estimate annualized frequency at the Census block level.

[74] This threshold is used by NOAA and the National Weather Service as the minimum wind gust criterion for a Severe Thunderstorm Watch.

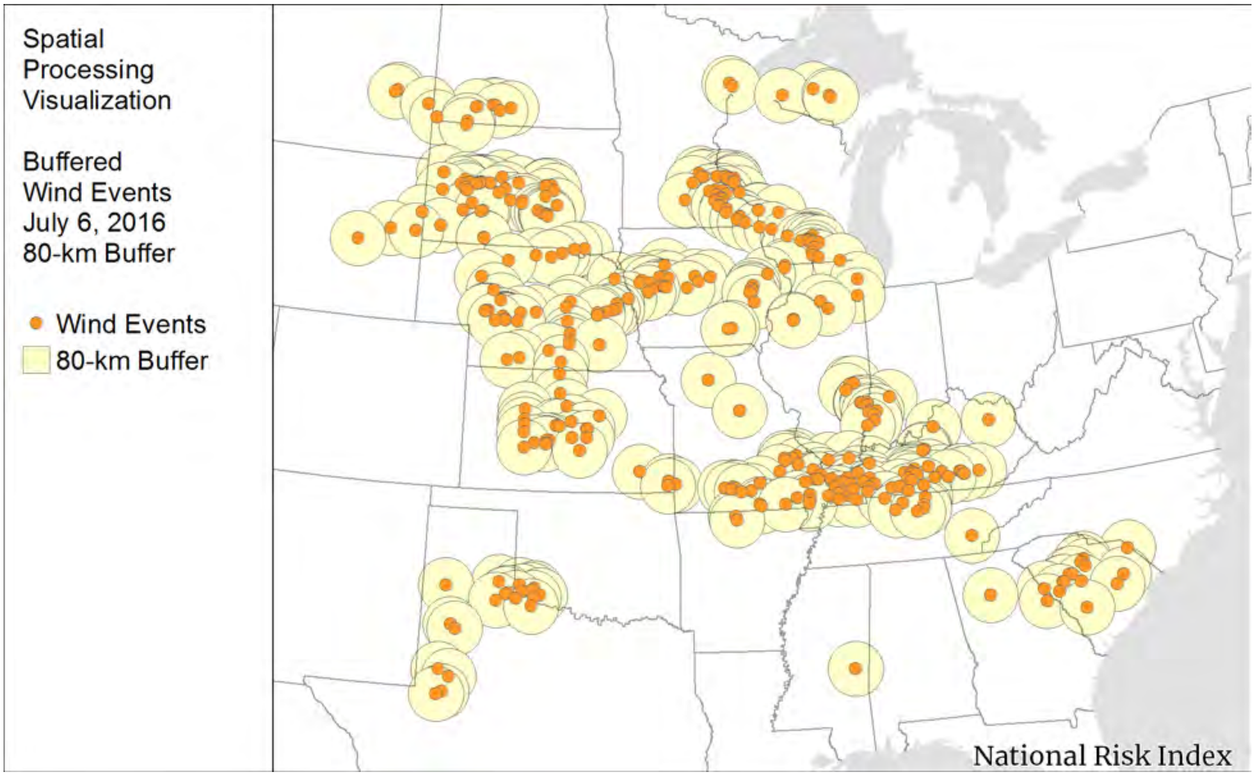

Figure 117: Map of Buffered Wind Points

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 agriculture value of a Census block, Census tract, and county is considered exposed to Strong Wind. Agriculture value is included as a consequence type for Strong Wind because more than 1% of economic loss due to Strong Wind recorded in SHELDUS impacted agriculture. Population equivalence, which is used in select EAL calculations, is calculated by multiplying population by the VSL ($7.6M per person).

18.5. Historic Occurrence Count

The historic occurrence count of Strong Wind, in events, is initially computed as the number of distinct Strong Wind event polygons that intersect a 49-by-49-km fishnet grid cell. Buffering the Strong Wind points and using the fishnet grid to count historic Strong Wind events serves to spatially spread the influence of past Strong Wind events to nearby areas that may also be susceptible to Strong Wind but have not experienced Strong Wind as frequently. However, using these methods can overestimate Strong Wind frequency. To adjust for this, a national scaling factor is calculated (see Equation 102).

Equation 98: National Scaling Factor for Strong Wind Event Count

$$NatlScalingFactor_{SWND} = \frac{EventCount_{SWND_{Ntl}}}{\sum FishnetIntsctCount_{SWND_{Ntl}}}$$

where:

$NatlScalingFactor_{SWND}$	is the Strong Wind scaling factor to be applied to the fishnet grid cell event count.
$EventCount_{SWND_{Ntl}}$	is the count of distinct Strong Wind events which have occurred in the U.S.
$\sum FishnetIntsctCount_{SWND_{Ntl}}$	is the summed total of all Strong Wind event polygon-fishnet grid cell intersections in the U.S.

The scaling factor is then applied to the fishnet grid Strong Wind event count (see Equation 99).

Equation 99: Scaled Strong Wind Event Fishnet Count

$$ScaledEventCount_{SWND_{Fish}} = EventCount_{SWND_{Fish}} \times NatlScalingFactor_{SWND}$$

where:

$ScaledEventCount_{SWND_{Fish}}$	is the scaled count of Strong Wind events within a fishnet grid cell (in events per year).
$EventCount_{SWND_{Fish}}$	is the count of Strong Wind event polygons that intersect a 49-by-49 km fishnet grid cell.
$NatlScalingFactor_{SWND}$	is the Strong Wind scaling factor to be applied to the fishnet grid cell event count.

The Census block Strong Wind event count is then computed as the scaled event count of the 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 Occurrence Count). This scaled count is used to compute Strong Wind event annualized frequency.

Historic event counts are also supplied at the Census tract and county levels as the scaled, area-weighted count of Strong Wind events intersecting fishnet grid cells that intersect the Census tract and county, respectively.

18.6. Annualized Frequency

The number of recorded Strong Wind occurrences, in events, each year over the period of record (32 years) is used to estimate the annualized frequency of Strong Wind events 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.

Annualized frequency calculations use the Strong Wind event polygons created from the source data (as described in Section 18.2 Spatial Processing), as well as their corresponding computed duration days from the pre-processing of the data. The Census block Strong Wind event count computed using the scaled event counts of the fishnet grid cells intersecting the Census block is divided by the period of record to compute frequency as in Equation 100.

Equation 100: Census Block Strong Wind Annualized Frequency

$$Freq_{SWND_{CB}} = \frac{ScaledEventCount_{SWND_{Fish}}}{PeriodRecord_{SWND}}$$

where:

$Freq_{SWND_{CB}}$	is the annualized frequency of Strong Wind events determined for a specific Census block (events per year).
$ScaledEventCount_{SWND_{Fish}}$	is the scaled count of Strong Wind events calculated for the Census block.
$PeriodRecord_{SWND}$	is the period of record for Strong Wind (32 years).

18.6.1. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized 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 annualized 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 annualized frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 101.

Equation 101: Census Tract and County Area-Weighted Strong Wind Annualized 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 area-weighted Strong Wind annualized frequency for a specific Census tract (events per year).
$Freq_{SWND_{CB}}$	is the annualized frequency of Strong Wind events determined for a specific Census block (events per year).
$Area_{CB}$	is the total area of the Census block (in square kilometers).
$\sum_{CB}^{CT}$	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 area-weighted Strong Wind annualized frequency 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 118 displays Strong Wind annualized frequency at the county level.

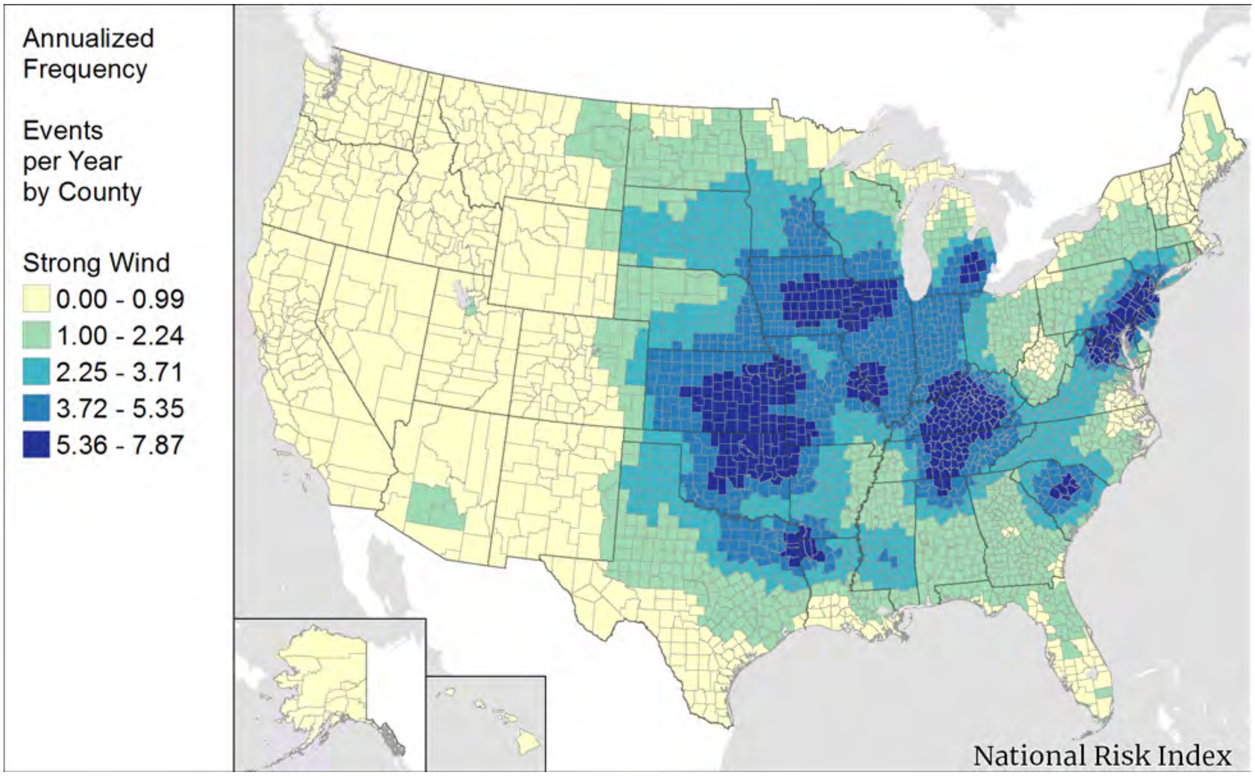

Figure 118: Strong Wind Annualized Frequency by County

18.7. Historic Loss Ratio

The Strong Wind HLR is the representative percentage of a location's hazard exposure that experiences loss due to a Strong Wind event, or the average rate of loss associated with the occurrence of a Strong Wind event. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Strong Wind hazard type.

Loss data are provided by SHELDUS[75] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Three peril types are mapped to the hazard Strong Wind (see Table 55). Native records of Strong Wind events that caused loss over more than one day have their loss assigned to the first day, and all records are aggregated on a single-event-per-day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

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

Table 55: Strong Wind Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Derecho	1	1
Wind	200,254	148,723
Wind-Straight Line	0	0

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 102.

Equation 102: Loss Ratio per Basis Calculation for a Single Strong Wind Event

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

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. 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 documented to have occurred in the county (in dollars or impacted people).

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

Strong Wind events 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 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 (1996 to 2019). For Strong Wind, the historic event count is extracted using an intersection between the Strong Wind event polygons and the Census blocks. An annual rate is calculated as the event count divided by the period of record of 32 years, and this rate is multiplied by the SHELDUS period of record of 24 years to estimate a historic event count for the appropriate time range.

If the number of loss-causing Strong Wind event records from SHELDUS is less than the scaled event count for the county, then a number of zero-loss records equal to the difference are 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 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

Figure 119, Figure 121, and Figure 123 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 Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Strong Wind events within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value, though its HLR may be influenced by other local, regional, or national occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted 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 120, Figure 122, and Figure 124 represent the final, Bayesian-adjusted county-level HLR values for Strong Wind.

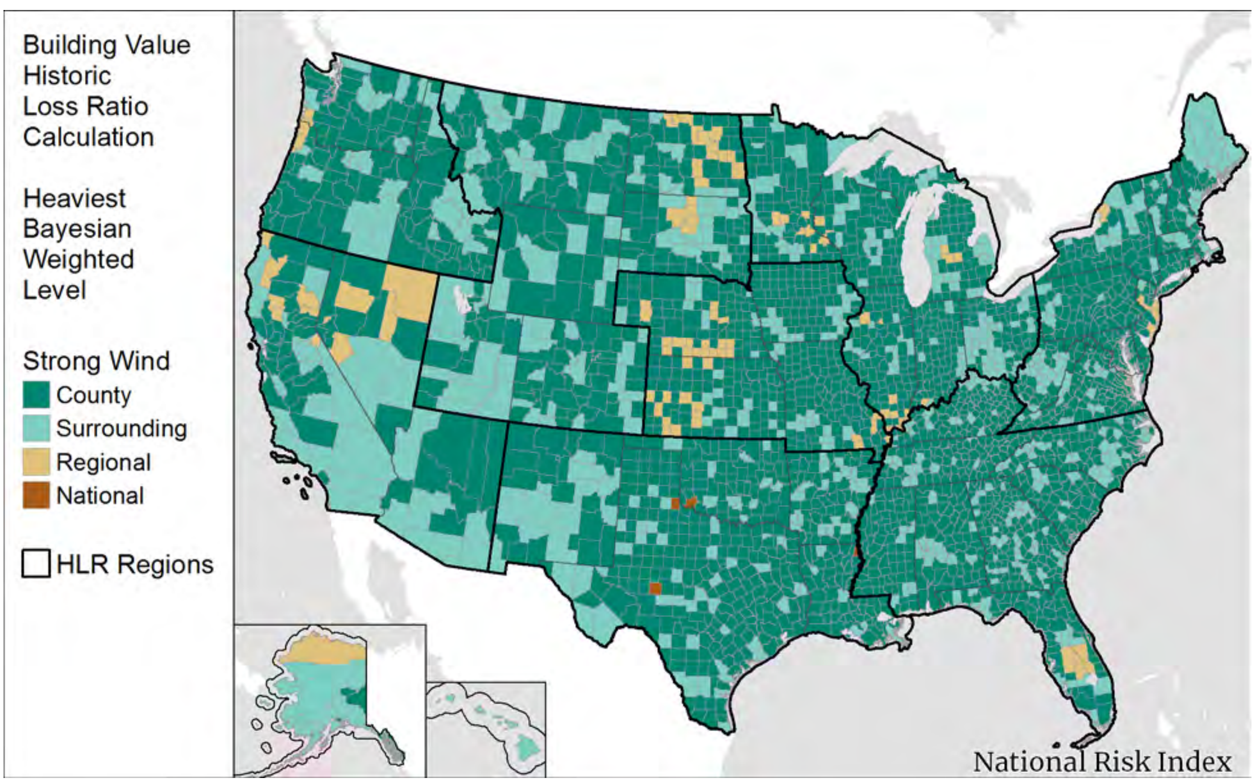

Figure 119: Strong Wind Heaviest Bayesian Influence Level – Building Value

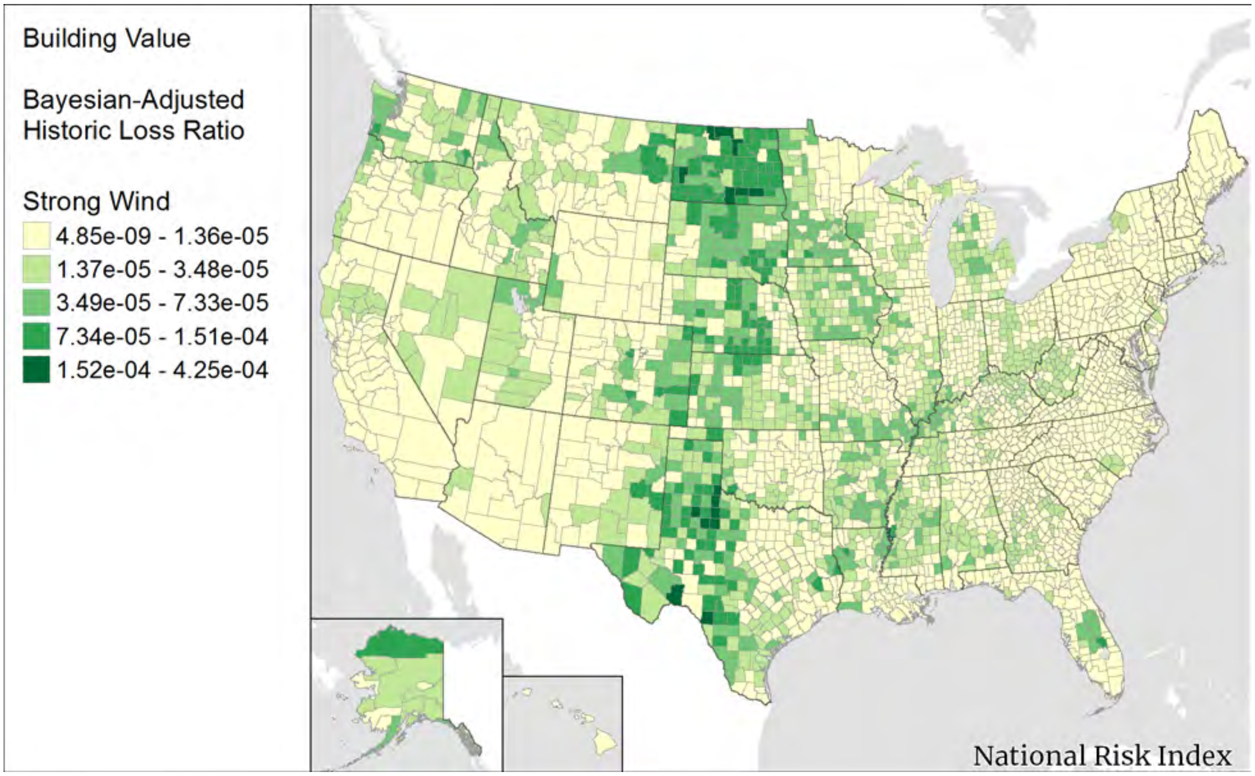

Figure 120: Strong Wind Bayesian-Adjusted HLR – Building Value

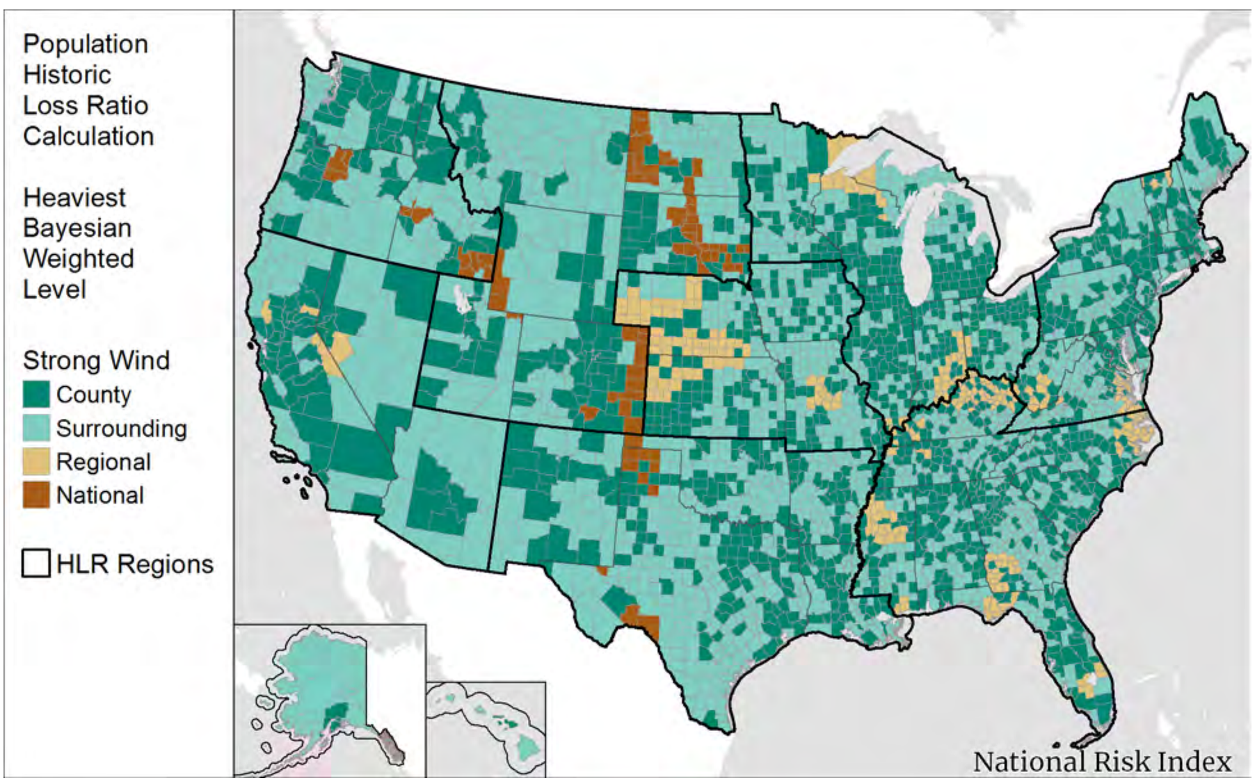

Figure 121: Strong Wind Heaviest Bayesian Influence Level – Population

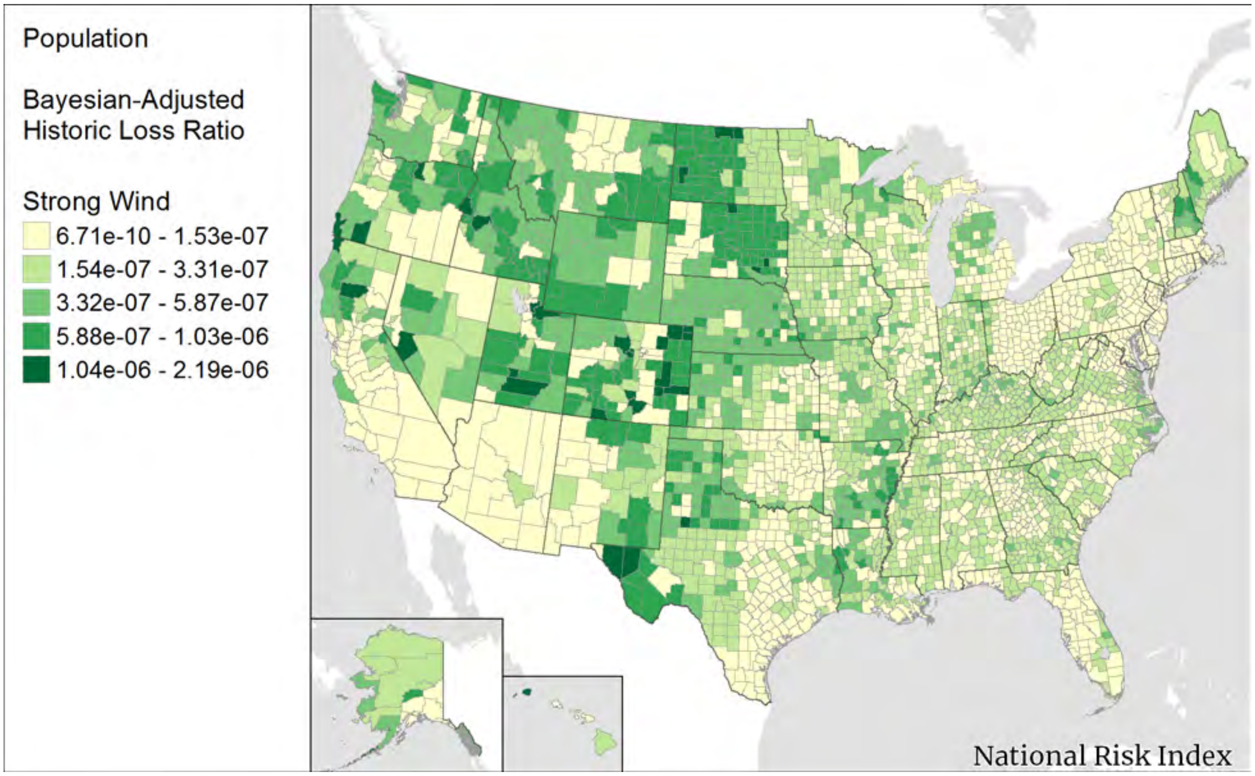

Figure 122: Strong Wind Bayesian-Adjusted HLR – Population

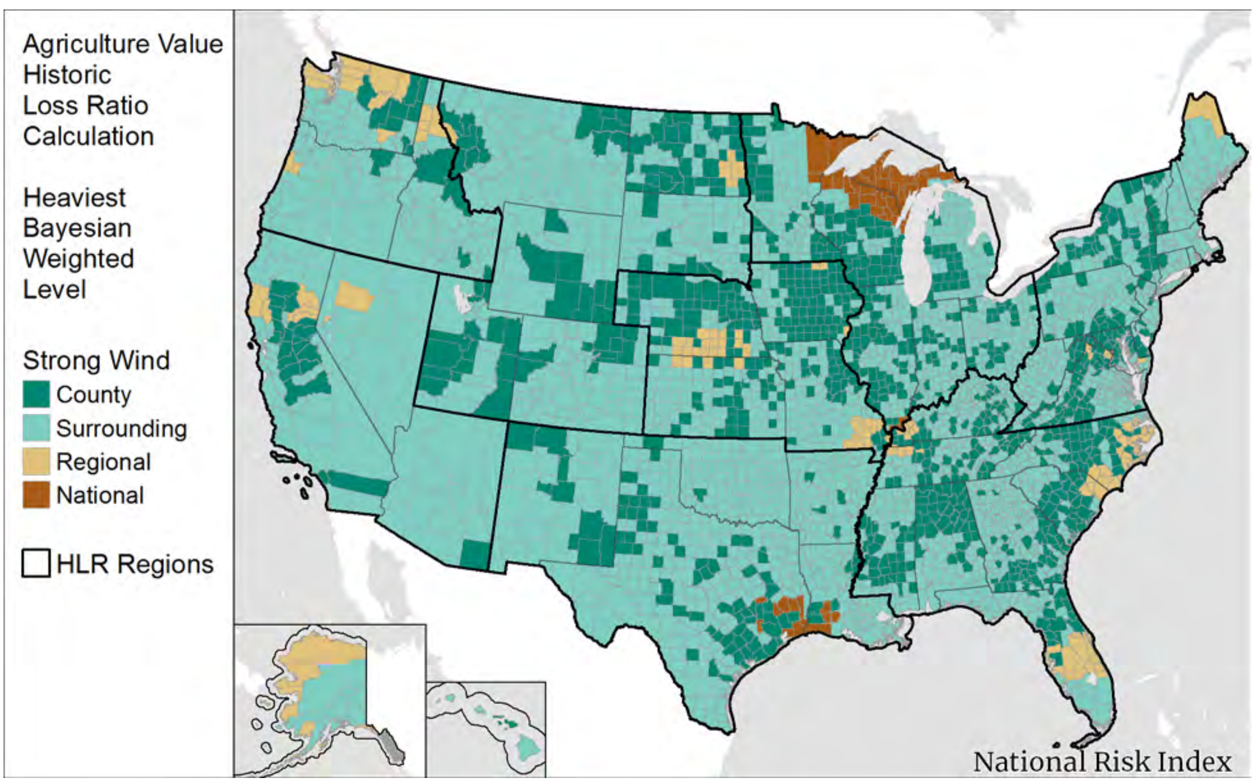

Figure 123: Strong Wind Heaviest Bayesian Influence Level – Agriculture Value

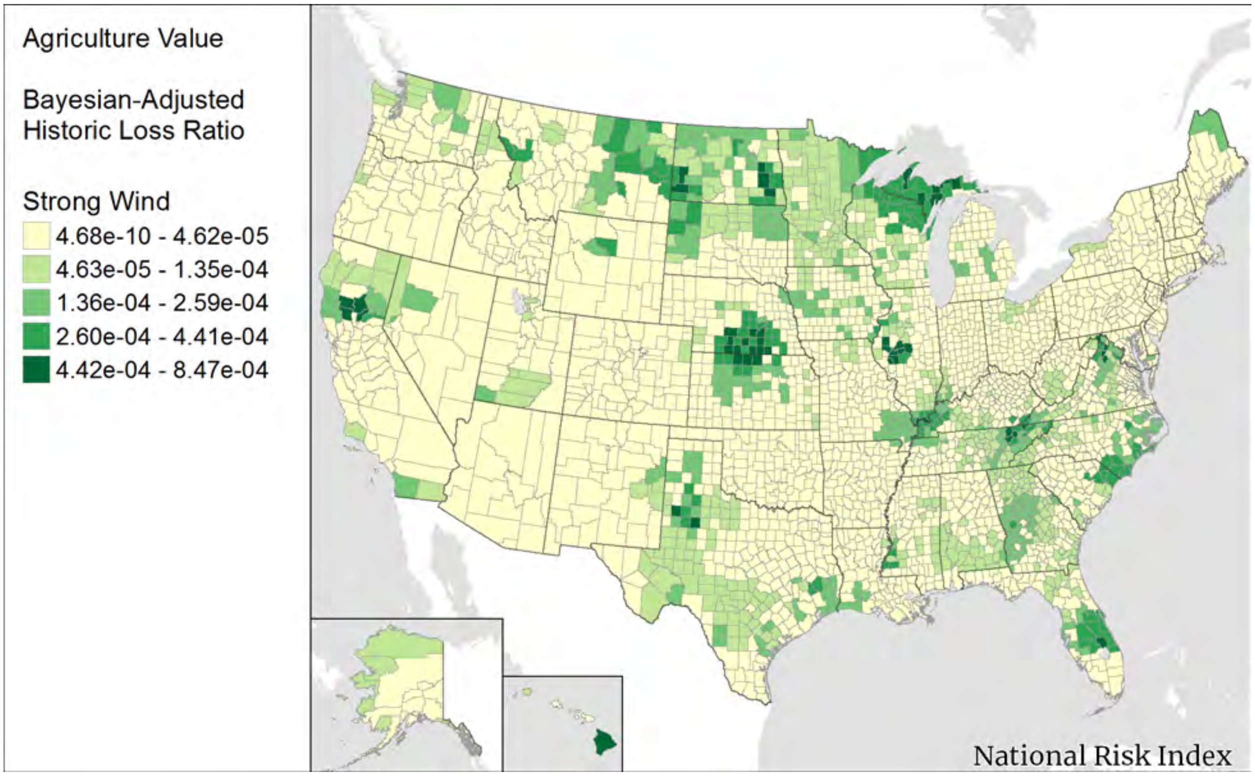

Figure 124: Strong Wind Bayesian-Adjusted HLR – Agriculture Value

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

18.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 103. 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 103: 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 building Expected Annual Loss due to Strong Wind occurrences for a specific Census block (in dollars).

$Exposure_{SWND_{CB_{Bldg}}}$	is the building value exposed to Strong Wind occurrences in the Census block (in dollars).
$Freq_{SWND_{CB}}$	is the Strong Wind annualized frequency for the Census block (events 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 population equivalence Expected Annual Loss due to Strong Wind occurrences for a specific Census block (in dollars).
$Exposure_{SWND_{CB_{Pop}}}$	is the population equivalence value exposed to Strong Wind occurrences 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 agriculture Expected Annual Loss to due to Strong Wind occurrences for a specific Census block (in dollars).
$Exposure_{SWND_{CB_{Ag}}}$	is the agriculture value exposed to Strong Wind occurrences 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 building, population equivalence, and agriculture EAL values at the Census block level as in Equation 104.

Equation 104: 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 occurrences for a specific Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{SWND_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Strong Wind for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{SWND_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Strong Wind for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{SWND_{CB_{Ag}}}$	is the summed agriculture Expected Annual Loss 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 occurrences for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{SWND_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Strong Wind for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{SWND_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Strong Wind for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{SWND_{CB_{Ag}}}$	is the summed agriculture Expected Annual Loss due to Strong Wind for all Census blocks in the county (in dollars).

Figure 125 shows the total EAL (building value, population equivalence, and agriculture value combined) to Strong Wind occurrences.

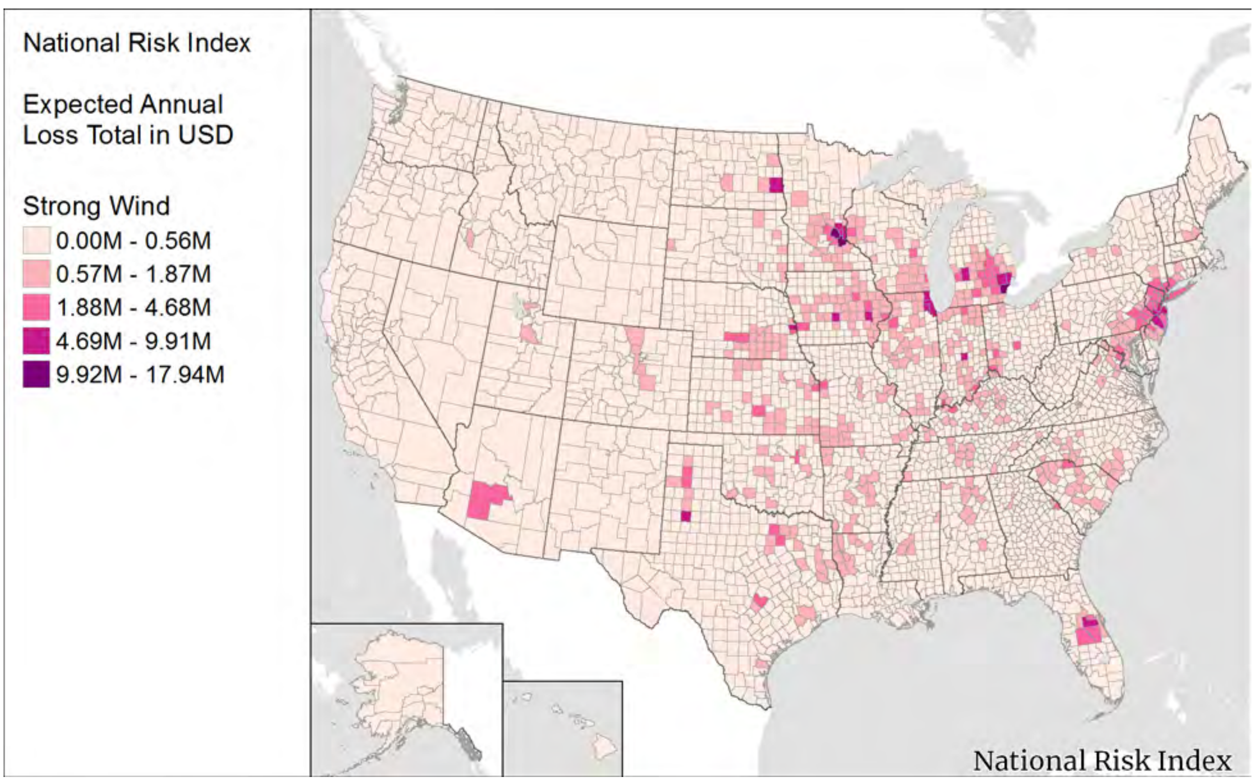

Figure 125: Total Expected Annual Loss by County to Strong Wind

With the Strong Wind total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 Occurrence Source: National Weather Service, Storm Prediction Center, Severe Weather Database Files[76]

The SPC compiles all records of Tornadoes from the NWS's monthly Storm Data publication and makes them available in CSV and shapefile format on the Warning Coordination Meteorologist's (WCM) website. Shapefiles representing Tornadoes as both points (initial touchdown points) and lines (paths) were downloaded. 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 56 and Figure 126). Economic loss information is recorded as either a predefined category of loss (1950-1995), a value representing loss in millions of dollars (1996-2015), or the loss in dollars (2016-present). 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 56: Sample Tornado Data from the SPC

om (Tornado Number [before 2007])	*Date*	*St (State)*	*Mag (F/EF Scale)*	*Inj (Injuries)*	*Fat (Fatalities)*	*loss (Loss Category or $)*	*len (Path Length in Miles)*	*wid (Path Width in Yards)*
1	1/3/1950 11:00 AM	MO	3	3	0	6	9.5	150
241	5/15/1989 3:35 PM	TX	1	3	0	5	5.5	80
0	12/20/2017 12:15 PM	GA	0	0	0	30000	3.17	125

[76] Storm Prediction Center, National Weather Service. (2020). Severe Weather Database files, Tornado, 1950-2019 [online dataset]. Retrieved from http://www.spc.noaa.gov/wcm/.

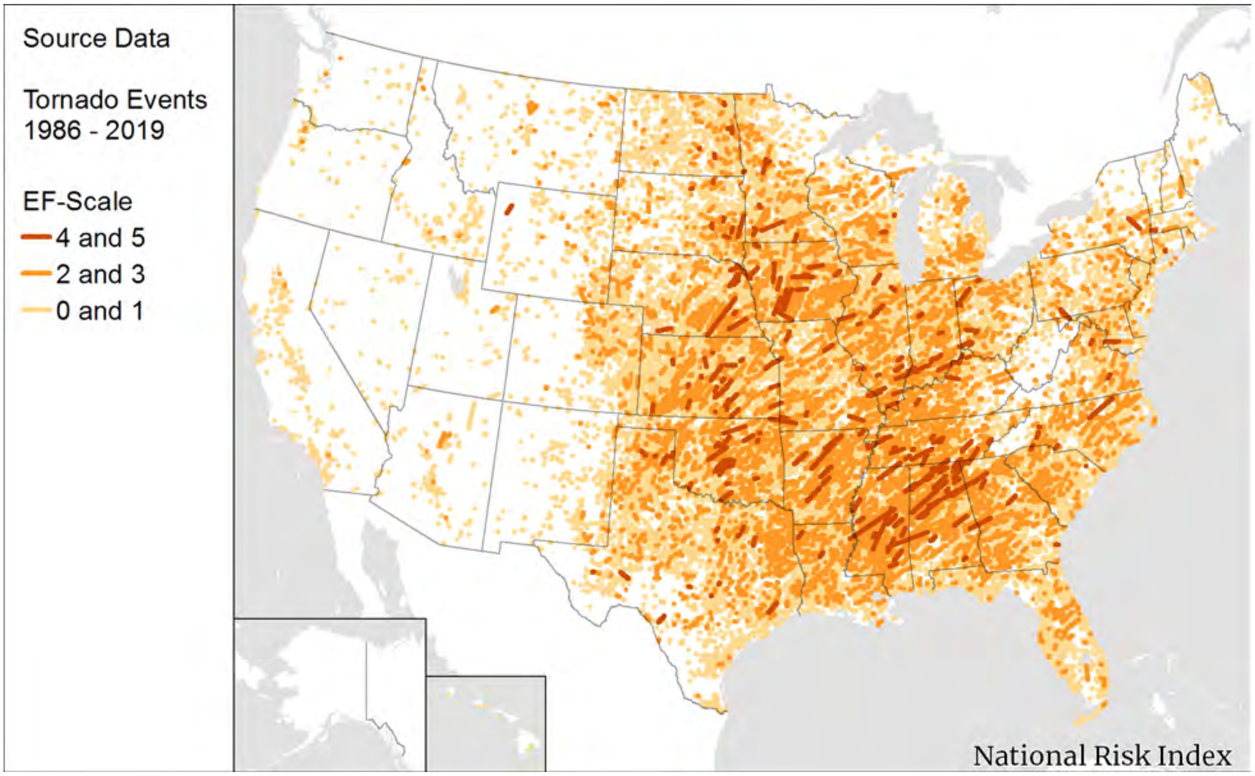

Figure 126: Map of Tornado Source Data

19.1.1. PERIOD OF RECORD

Tornado data between 1/1/1986 and 12/31/2019 are analyzed, so the period of record for which Tornado data are utilized is 34 years.

19.2. Spatial Processing

Tornado records in the path shapefile provided by the SPC may have empty geometries if the path information is incomplete. To form a complete set of geometries for all Tornadoes within the period of record, path records with empty geometries are replaced by the record with the same unique ID in the point shapefile. Any Tornadoes outside the period of record or that have an F- or EF-scale of -9 to signify insufficient data are filtered out.

With the intended spatial processing goal of intersecting Tornado events to determine the Census block (and parent county) that the Tornado traversed, Tornado path lines and touchdown points are buffered to create tornado event path polygons. To conservatively estimate the largest area for each Tornado polygon, even those without a complete path geometry from the source data, three methods are used to calculate a possible buffer radius. Whichever method yields the largest radius is used to buffer the given line or point. Options for buffer radii are:

- Half of the Tornado width as specified in Table 56 (converted from yards to meters);

- The calculated radius of the Tornado as extrapolated from its length and width (converted to meters) as provided in the source data; or
- The average radius of impact for a storm of that magnitude based on F- or EF-scale category according to Table 57.

Table 57: 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	1,233

The resulting category-buffered Tornado event path polygons are intersected with the Census blocks to determine the counties that might have experienced loss from each Tornado event. This relationship is used in the HLR calculation, as well as for determining historic Tornado event counts at the Census tract and county level.

Because Tornado occurrences are recorded at distinct locations and multiple Tornadoes are often reported on the same day in near proximity, it was necessary for annualized 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 127). 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 are intersected with the 49-by-49-km fishnet grid and used to estimate annualized frequency at the Census tract level.

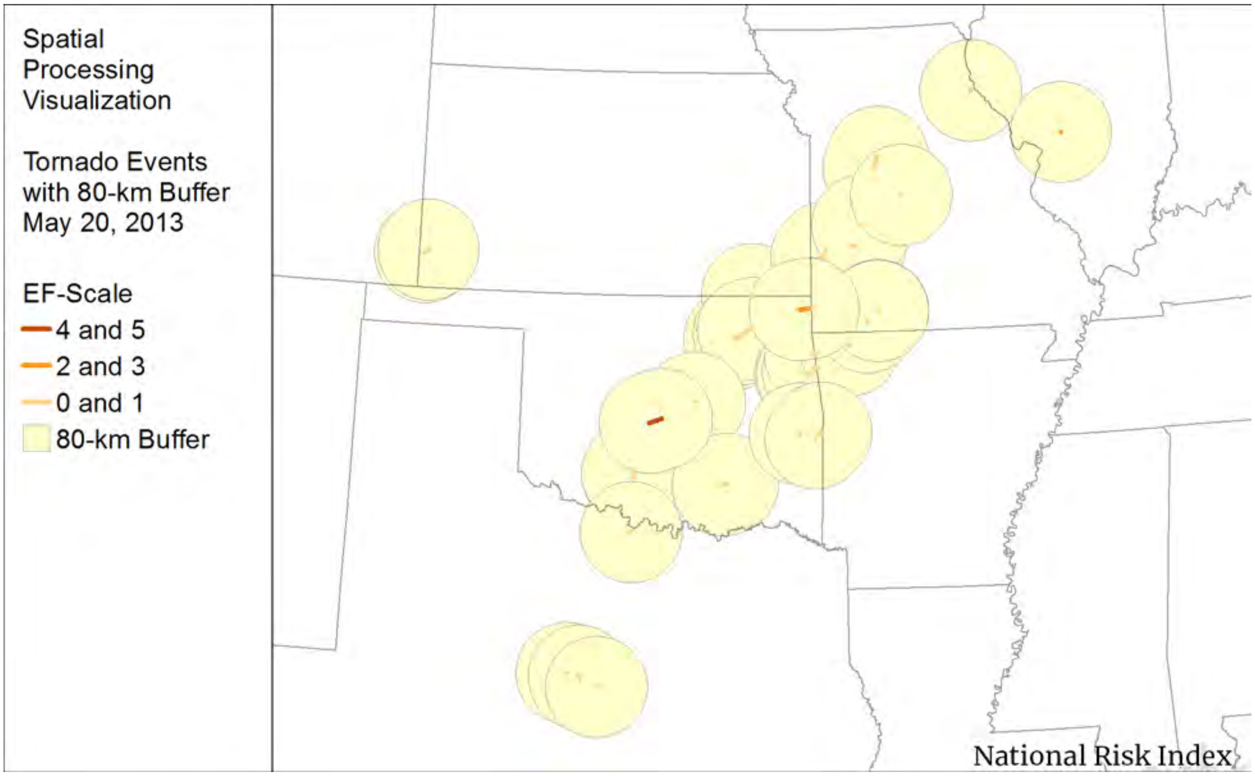

Figure 127: Map of Buffered Tornadoes

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

The size of the damage area caused by a Tornado can vary greatly depending on its magnitude or EF-scale. For this reason, exposure is calculated for three sub-types: 1) EF-scale 0 and 1; 2) EF-scale 2 and 3; and 3) EF-scale 4 and 5. An average historical Tornado damage area is assigned to each Tornado sub-type (see Table 58). These average damage area values were calculated from the historical set of Tornado event path polygons generated according to one of the three methods described in Section 19.2 Spatial Processing and not from the subsequent 80-km buffer applied to the Tornado event path polygon used for frequency estimation.

Table 58: Average Historical Damage Area by Tornado Sub-Type

Tornado Sub-Type	*Average Historical Damage Area*
EF-Scale 0 and 1	0.78 km^2
EF-Scale 2 and 3	13 km^2
EF-Scale 4 and 5	79 km^2

Because a Tornado could occur anywhere in the Census tract, the Census tract average density (the Census tract's total building value, population equivalence, or agriculture value divided by the total area of the Census tract) is applied. Therefore, the exposure area of a Census tract is calculated using Equation 105 and the exposure area of a county is calculated using Equation 106.

Equation 105: Census Tract Tornado Sub-Type Exposure

$$Exposure_{TRNDSub\,CT_{Bldg}} = DamageArea_{TRNDSub} \times AvgDen_{CT_{Bldg}}$$

$$Exposure_{TRNDSub\,CT_{Pop}} = \left(DamageArea_{TRNDSub} \times AvgDen_{CT_{Pop}}\right) \times VSL$$

$$Exposure_{TRNDSub_{CT_{Ag}}} = DamageArea_{TRNDSub} \times AvgDen_{CT_{Ag}}$$

where:

$Exposure_{TRNDSub\,CT_{Bldg}}$	is the building value exposed to Tornadoes of a sub-type in a specific Census tract (in dollars).
$DamageArea_{TRNDSub}$	is the average damage area of a Tornado sub-type (in square kilometers).
$AvgDen_{CT_{Bldg}}$	is the average building value density of the Census tract (in dollars per square kilometer).
$Exposure_{TRNDSub\,CT_{Pop}}$	is the population equivalence exposed to Tornadoes of a sub-type 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 ($7.6M per person).
$Exposure_{TRNDSub_{CT_{Ag}}}$	is the agriculture value exposed to Tornadoes of a sub-type in a specific Census tract (in dollars).

$AvgDen_{CT_{Ag}}$	is the average agriculture value density of the Census tract (in dollars per square kilometer).

Equation 106: County Tornado Sub-Type Exposure

$$Exposure_{TRNDSub_{Co_{Bldg}}} = DamageArea_{TRNDSub} \times AvgDen_{Co_{Bldg}}$$

$$Exposure_{TRNDSub_{Co_{Pop}}} = \left(DamageArea_{TRNDSub} \times AvgDen_{Co_{Pop}}\right) \times VSL$$

$$Exposure_{TRNDSub_{Co_{Ag}}} = DamageArea_{TRNDSub} \times AvgDen_{Co_{Ag}}$$

where:

$Exposure_{TRNDSub_{Co_{Bldg}}}$	is the building value exposed to Tornadoes of a sub-type in a specific county (in dollars).
$DamageArea_{TRNDSub}$	is the average damage area of a Tornado sub-type (in square kilometers).
$AvgDen_{Co_{Bldg}}$	is the average building value density of the county (in dollars per square kilometer).
$Exposure_{TRNDSub_{Co_{Pop}}}$	is the population equivalence value exposed to Tornadoes of a sub-type 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 ($7.6M per person).
$Exposure_{TRNDSub_{Co_{Ag}}}$	is the agriculture value exposed to Tornadoes of a sub-type in a specific county (in dollars).
$AvgDen_{Co_{Ag}}$	is the average agriculture value density of the county (in dollars per square kilometer).

Note that exposure values for each sub-type are multiplied by their respective sub-type annualized frequency and HLR to calculate the sub-type EAL. Exposure values displayed in the application are surrogates representing the entire building value, population, and agriculture value of the Census tract or county.

19.5. Historic Occurrence Count

The historic occurrence count of Tornado, in events, is computed as the number of distinct Tornado event path polygons that intersect a Census block. Historic event 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 application but that this count is not used to calculate annualized frequency.

19.6. Annualized Frequency

The annualized frequency value represents the estimated number of recorded Tornado occurrences, in events, each year for a specific area. Annualized frequency is calculated for each Tornado sub-type at the county and Census tract levels, which are used in the EAL calculations.

Annualized frequency calculations are determined by intersecting the 80-km buffered Tornado event path polygons generated in Section 19.2 Spatial Processing with a 49-by-49-km fishnet grid. The count of distinct Tornado event path polygons of each sub-type intersecting each grid cell is recorded (see Appendix D – Fishnet Occurrence Count).

Buffering the Tornado paths and using the 49-by-49-km fishnet grid to count historic Tornado events serves to spatially spread the influence of past events to nearby areas that may also be susceptible to Tornadoes but have not experienced as many. However, using these methods can overestimate Tornado annualized frequency. To adjust for this, a national scaling factor is calculated for each Tornado sub-type (see Equation 107).

Equation 107: National Scaling Factor by Tornado Sub-Type

$$NatlScalingFactor_{TRNDSub} = \frac{EventCount_{TRNDSub_{Ntl}}}{FishnetIntsctCount_{TRNDSub_{Ntl}}}$$

where:

$NatlScalingFactor_{TRNDSub}$	is the Tornado sub-type scaling factor to be applied to fishnet grid cell frequency.
$EventCount_{TRNDSub_{Ntl}}$	is the count of distinct Tornado events of a sub-type that have occurred in the U.S.
$FishnetIntsctCount_{TRNDSub_{Ntl}}$	is the summed total count of all 80-km buffered Tornado-fishnet grid cell intersections of a Tornado sub-type in the U.S.

A minimum scaling factor is also calculated for fishnet grid cells that do not intersect a historic Tornado path. This scaling factor is set to 1/939 or one divided by the total count of all 49-by-49-km fishnet grid cells that do not intersect a historic Tornado path but intersect one or more U.S. counties (see Table 59).

Table 59: National Scaling Factor by Tornado Sub-Type

Tornado Sub-Type	*National Tornado Event Count*	*National Fishnet Intersect Count*	*National Scaling Factor*
EF-Scale 0 and 1	34,935	565,926	0.06173
EF-Scale 2 and 3	4,304	75,080	0.05733
EF-Scale 4 and 5	226	4,590	0.04923
No historic Tornado events	1	939	0.00053

This national scaling factor is applied to each grid cell sub-type event count and divided by the period of record to calculate a grid cell sub-type annualized frequency. This is then divided by the representative area associated with the grid cell to produce a sub-type annualized frequency rate per square kilometer (see Equation 108). By definition the 49-by-49-km fishnet grid cells are equally sized at 2,401 square kilometers; however the land area a grid cell covers varies by location. Grid cells along the coasts can have significant portions covering water and grid cells along the United States border can have significant portions covering foreign lands. Both cases would result in overestimating frequency for the counties and Census tracts associated with these grid cells. To balance these situations, the area associated with the fishnet grid cell is defined as the average of the fishnet grid size and the area covering United States land. This assists with the apportionment of the fishnet frequency rate per square kilometer.

Equation 108: Scaled Tornado Sub-Type Fishnet Annualized Frequency and Annualized Frequency Rate

$$Freq_{TRNDSub_{Fish}} = \frac{EventCount_{TRNDSub_{Fish}} \times NatlScalingFactor_{TRNDSub}}{PeriodRecord_{TRND}}$$

$$FreqRate_{TRNDSub_{Fish}} = \frac{Freq_{TRNDSub_{Fish}}}{RepresentativeArea_{Fish}}$$

where:

$Freq_{TRNDSub_{Fish}}$	is the annualized frequency of Tornado sub-type events within a fishnet grid cell (in events per year).
$EventCount_{TRNDSub_{Fish}}$	is the count of distinct Tornado path polygons that intersect a 49-by-49 km fishnet grid cell.
$NatlScalingFactor_{TRNDSub}$	is the Tornado sub-type scaling factor to be applied to fishnet grid cell frequency.
$PeriodRecord_{TRND}$	is the period of record for Tornado (34 years).
$FreqRate_{TRNDSub_{Fish}}$	is the Tornado sub-type annualized frequency rate of the fishnet grid cell (in annualized frequency per square kilometer).

$RepresentativeArea_{Fish}$	is the average of the fishnet grid cell size (2,401 square kilometers) and the United States land area within the fishnet grid cell (in square kilometers).

Area-weighted Tornado sub-type annualized frequency rates are then calculated at the Census tract and county levels (see Equation 109).

Equation 109: Census Tract and County Tornado Sub-Type Area-Weighted Annualized Frequency Rates

$$FreqRate_{TRNDSub_{CT}} = \sum_{CB}^{CT} \frac{\left(FreqRate_{TRNDSub_{Fish}} \times IntsctArea_{CB_{Fish}}\right)}{Area_{CT}}$$

$$FreqRate_{TRNDSub_{Co}} = \sum_{CB}^{Co} \frac{\left(FreqRate_{TRNDSub_{Fish}} \times IntsctArea_{CB_{Fish}}\right)}{Area_{Co}}$$

where:

$FreqRate_{TRNDSub_{CT}}$	is the Tornado sub-type annualized frequency rate of the Census tract (in annualized frequency per square kilometer).
$\sum_{CB}^{CT}$	is the sum for all Census blocks in the Census tract.
$FreqRate_{TRNDSub_{Fish}}$	is the Tornado sub-type annualized frequency rate of the fishnet grid cell (in annualized frequency per square kilometer).
$IntsctArea_{CB_{Fish}}$	is the intersected area of the Census block with a specific fishnet grid cell (in square kilometers).
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$FreqRate_{TRNDSub_{Co}}$	is the Tornado sub-type annualized frequency rate of the county (in annualized frequency per square kilometer).
$\sum_{CB}^{Co}$	is the sum for all Census blocks in the county.
$Area_{Co}$	is the total area of the county (in square kilometers).

In rare cases, a Census tract or county may have experienced more high-magnitude Tornado events than low-magnitude events. To treat these statistical anomalies, lower magnitude sub-type annualized frequency rates are scaled up to at least match the next highest magnitude sub-type annualized frequency rate. For example, if an EF-scale 2 and 3 annualized frequency rate for a county is 1×10^{-6} and its EF-scale 4 and 5 has a higher annualized frequency rate of 5×10^{-6}, the EF-scale 2 and 3 annualized frequency rate is set to 5×10^{-6}. Additionally, if there is a gap in sub-types, then the missing sub-type is inserted and assigned the annualized frequency rate of the higher magnitude sub-type. These actions ensure that, as the sub-type magnitude increase, the annualized frequency rate is less than or equal to the previous sub-type rate.

The Census tract and county annualized frequencies are then calculated as the Tornado sub-type annualized frequency rate multiplied by the area for the Census tract or county as in Equation 110. Note that if the Census tract or county area is less than the average damage area for the tornado sub-type, then the annualized frequency is calculated as the annualized frequency rate multiplied by the average damage area for the tornado sub-type. This is done to match the assumptions made for exposure to annualized frequency.

Equation 110: Census Tract and County Tornado Sub-Type Annualized Frequency

$$Freq_{TRNDSub_{CT}} = FreqRate_{TRNDSub_{CT}} \times Area_{CT}$$

$$Freq_{TRNDSub_{Co}} = FreqRate_{TRNDSub_{Co}} \times Area_{Co}$$

where:

$Freq_{TRNDSub_{CT}}$	is the scaled annualized frequency of Tornado sub-type events within a Census tract (in events per year).
$FreqRate_{TRNDSub_{CT}}$	is the Tornado sub-type annualized frequency rate of the Census tract (in frequency per square kilometer).
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$Freq_{TRNDSub_{Co}}$	is the scaled annualized frequency of Tornado sub-type events within a county (in events per year).
$FreqRate_{TRNDSub_{Co}}$	is the Tornado sub-type annualized frequency rate of the county (in frequency per square kilometer).
$Area_{Co}$	is the total area of the county (in square kilometers).

19.6.1. MINIMUM ANNUAL FREQUENCY

A minimum annual frequency is calculated for Census tracts and counties that do not intersect a fishnet grid cell that has experienced a past Tornado event. This is calculated in the same way as other sub-type frequencies with the minimum historic Tornado event count set to 1 and uses the smallest average damage area (0.78 km^2 for EF-scale 0 and 1) to multiply by the annualized frequency rate as in Equation 111.

Equation 111: Census Tract and County Tornado Minimum Annual Frequency

$$Freq_{TMAF} = \frac{1 \times NatlScalingFactor_{TMAF}}{PeriodRecord_{TRND}}$$

$$FreqRate_{TMAF_{CT}} = \frac{Freq_{TMAF}}{Area_{CT}}$$

$$FreqRate_{TMAF_{Co}} = \frac{Freq_{TMAF}}{Area_{Co}}$$

$$Freq_{TMAF_{CT}} = FreqRate_{TMAF_{CT}} \times DamageArea_{EF0\&1}$$

$$Freq_{TMAF_{Co}} = FreqRate_{TMAF_{Co}} \times DamageArea_{EF0\&1}$$

where:

$Freq_{TMAF}$	is the scaled minimum annual frequency of Tornado events (in events per year).
$NatlScalingFactor_{TMAF}$	is the minimum scaling factor to be applied to fishnet grid cell Tornado frequency.
$PeriodRecord_{TRND}$	is the period of record for Tornado (34 years).
$FreqRate_{TMAF_{CT}}$	is the minimum Tornado annualized frequency rate of the Census tract (in frequency per square kilometer).
$Area_{CT}$	is the total area of the Census tract (in square kilometers).
$FreqRate_{TMAF_{Co}}$	is the minimum Tornado frequency rate of the county (in frequency per square kilometer).
$Area_{Co}$	is the total area of the county (in square kilometers).
$Freq_{TMAF_{CT}}$	is the minimum annualized frequency of Tornado events within a Census tract (in events per year).
$DamageArea_{EF0\&1}$	is the average damage area for EF-scale 0 and 1 Tornadoes (0.78 km^2).
$Freq_{TMAF_{Co}}$	is the minimum annualized frequency of Tornado events within a county (in events per year).

19.6.2. ANNUALIZED FREQUENCY AGGREGATION

Annualized frequency values for each Tornado sub-type are multiplied by their respective sub-type exposure and HLR to calculate the sub-type EAL. Annualized frequency values displayed in the application are a surrogate value calculated as the sum of all sub-type frequencies at the Census tract and county levels as in Equation 112. Census tracts and counties with a frequency of 0 for all sub-types use the minimum annual frequency.

Equation 112: Census Tract and County Tornado Sub-Type Annualized Frequency Aggregation

$$Freq_{TRND_{CT}} = Freq_{EF0\&1_{CT}} + Freq_{EF2\&3_{CT}} + Freq_{EF4\&5_{CT}}$$

$$Freq_{TRND_{Co}} = Freq_{EF0\&1_{Co}} + Freq_{EF2\&3_{Co}} + Freq_{EF4\&5_{Co}}$$

where:

$Freq_{TRND_{CT}}$	is the Tornado annualized frequency calculated for a specific Census tract (events per year).
$Freq_{EF0\&1_{CT}}$	is the EF-scale 0 and 1 Tornado annualized frequency calculated for a specific Census tract (events per year).
$Freq_{EF2\&3_{CT}}$	is the EF-scale 2 and 3 Tornado annualized frequency calculated for a specific Census tract (events per year).
$Freq_{EF4\&5_{CT}}$	is the EF-scale 4 and 5 Tornado annualized frequency calculated for a specific Census tract (events per year).
$Freq_{TRND_{Co}}$	is the Tornado annualized frequency calculated for a specific county (events per year).
$Freq_{EF0\&1_{Co}}$	is the EF-scale 0 and 1 Tornado annualized frequency calculated for a specific county (events per year).
$Freq_{EF2\&3_{Co}}$	is the EF-scale 2 and 3 Tornado annualized frequency calculated for a specific county (events per year).
$Freq_{EF4\&5_{Co}}$	is the EF-scale 4 and 5 Tornado annualized frequency calculated for a specific county (events per year).

Figure 128 displays Tornado annualized frequency at the county level.

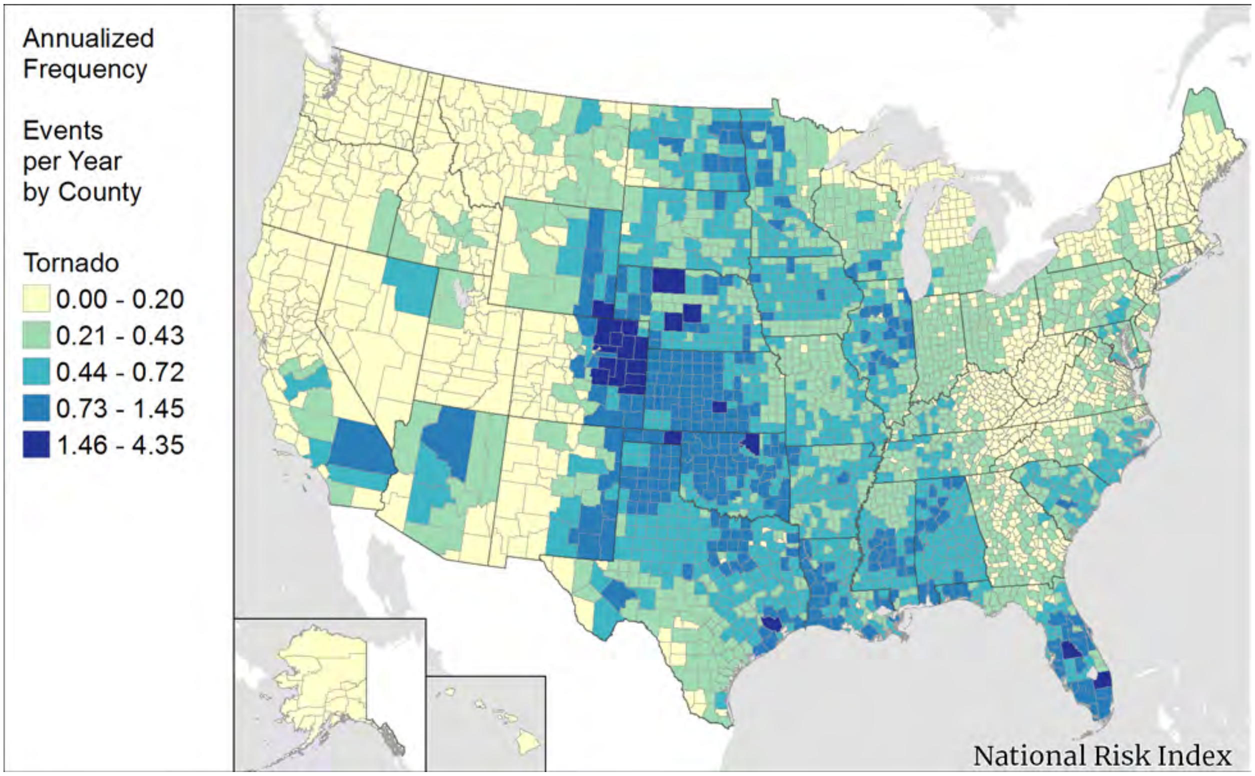

Figure 128: Tornado Annualized Frequency by County

19.7. Historic Loss Ratio

The Tornado HLR is the representative percentage of a location's hazard exposure that experiences loss due to a Tornado occurrence, or the average rate of loss associated with a Tornado occurrence. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Tornado hazard type.

Loss data are provided by SHELDUS[77] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Five peril types are mapped to the hazard Tornado (see Table 60). Native records of Tornadoes that caused loss over more than one day (such as those that occurred overnight) have their loss assigned to the first day (see Section 5.4.4 Historic Loss Ratio Methodology).

Table 60: Tornado Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Fire-Tornado	0	0
Tornado	17,698	17,663

[77] For Tornado 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
Waterspout	10	10
Wind-Tornadic	0	0
Wind-Vortex	2	2

Tornado EAL calculations require sub-type specific HLR values. To accomplish this, native SHELDUS loss records are matched to specific Tornados, so that each LRB is calculated using loss attributed to a specific Tornado and its exposure within a county as determined by the tornado event-path polygon and Census block intersects. In most cases, a single Tornado event occurs on a single day in a single county. However, multiple Tornadoes can occur in the same county on the same day and a single Tornado may cause damage in multiple counties. To make this matching as precise as possible, several strategies were implemented.

SHELDUS Tornado records from 2000 forward typically include a unique identifier to link them to records in the NCEI Storm Events Database. The NCEI records have additional information that is not in the SHELDUS data but is often present in the Tornado spatial source data. This includes event timestamps, EF-scale, length and width of the Tornado path, begin and end coordinates of the path, and the full Tornado event loss data. A fuzzy logic approach was used to map as many historic Tornado paths as possible to their county-specific loss in SHELDUS using these fields held in common between the spatial source data and NCEI data. For example, it could be assumed that if a Tornado path record occurred on the same day with the same timestamp and had the same recorded EF-scale, physical dimensions, and geographic coordinates as an NCEI record, both sources were describing the same Tornado event. This approach was iterated multiple times, each time using less stringent requirements for matching. By matching an NCEI record to a Tornado path, the exposure of a specific Tornado within a county could be matched to its SHELDUS county loss data.

Tornadoes with an EF-scale of 4 or 5 are rare and have much larger damage areas. They often occur during particularly bad storms, which can spawn multiple Tornadoes and can have long paths that impact multiple counties. Some of these Tornadoes may not be matched in the source data using the fuzzy logic approach, which could reduce their impact in the HLR and give an inaccurate estimate of EAL. A decision was made to manually inspect Tornado records of this sub-type and ensure that the loss of each of these Tornado events was appropriately matched to the correct path.

The Tornado match results where reviewed and analyzed. The aggregated total loss (from the multiple county SHELDUS loss records attributed to the same Tornado event) was compared to the loss reported for the tornado path in the source data (from the Storm Prediction Center). When averaging the ratio of SHELDUS loss to Tornado path loss (from the Storm Prediction Center) among the matched records, a strong correlation can be seen (see Table 61).

Table 61: Ratio of SHELDUS Loss to Tornado Path Loss Among Matched Tornado Records

EF-Scale	*Average Fatality Ratio*	*Average Injury Ratio*	*Average Building Damage Ratio*	*Average Agriculture Damage Ratio*
0	0.875	0.988	1.179	0.994
1	0.985	0.993	1.164	0.983
2	0.99	0.993	1.0394	1.054
3	0.962	0.991	1.204	0.973
4	0.988	0.987	1.094	0.99
5	1.0	0.998	0.959	1.0

LRBs are calculated for each matched Tornado event occurring in a county. The HLR exposure value used in the LRB calculation is calculated for each Tornado as the average value density of the consequence of the exposed Census blocks multiplied by the area of intersection, and then summed to the county level. The SHELDUS-recorded loss is divided by the consequence value exposed to the Tornado path to calculate the LRB as in Equation 113.

Equation 113: Loss Ratio per Basis Calculation for a Single Tornado Event

$$LRB_{TRND_{Co_{CnsqType}}} = \frac{Loss_{TRND_{Co_{CnsqType}}}}{HLRExposure_{TRNDSub_{Co_{CnsqType}}}}$$

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, population, and agriculture).

$Loss_{TRND_{Co_{CnsqType}}}$ is the loss (by consequence type) experienced from the Tornado event documented to have occurred in the county (in dollars or impacted people).

$HLRExposure_{TRNDSub_{Co_{CnsqType}}}$ is the value (by consequence type) of the area estimated to have been exposed to the Tornado sub-type event based on the path of the historic Tornado (in dollars or people).

Tornado 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 (1996 to 2019). For Tornado, the historic event count by sub-type 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 Spatial Processing) and the Census blocks. Using the path loss data, the percentage of past Tornadoes that caused no loss is calculated by sub-type. This percentage is multiplied by the sub-type count of Tornadoes that were matched to SHELDUS loss records in the county. For each sub-type (except EF-scale 4 and 5), a number of zero-loss records equal to the resulting product are inserted into the Loss Ratio per Basis table with zero values 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 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

Figure 129, Figure 131, Figure 133, Figure 135, Figure 137, Figure 139, Figure 141, Figure 143, and Figure 145 display the largest weighting factor contributor in the Bayesian credibility calculation for the Tornado sub-type HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Tornado occurrence within the county that its loss data are the dominant driver for its Bayesian-adjusted 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 Bayesian-adjusted 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 130, Figure 132, Figure 134, Figure 136, Figure 138, Figure 140, Figure 142, Figure 144, and Figure 146 represent the final, Bayesian-adjusted county-level HLR values for each Tornado sub-type.

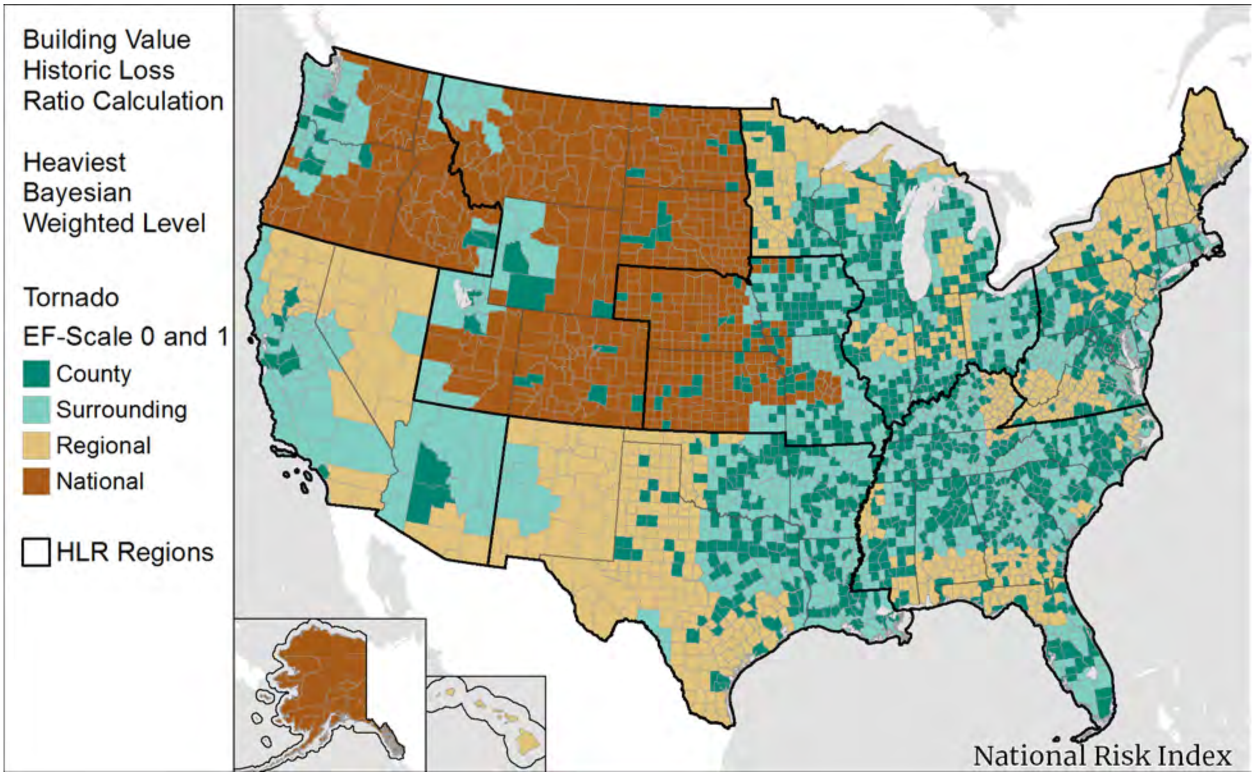

Figure 129: Tornado EF-Scale 0 and 1 Heaviest Bayesian Influence Level – Building Value

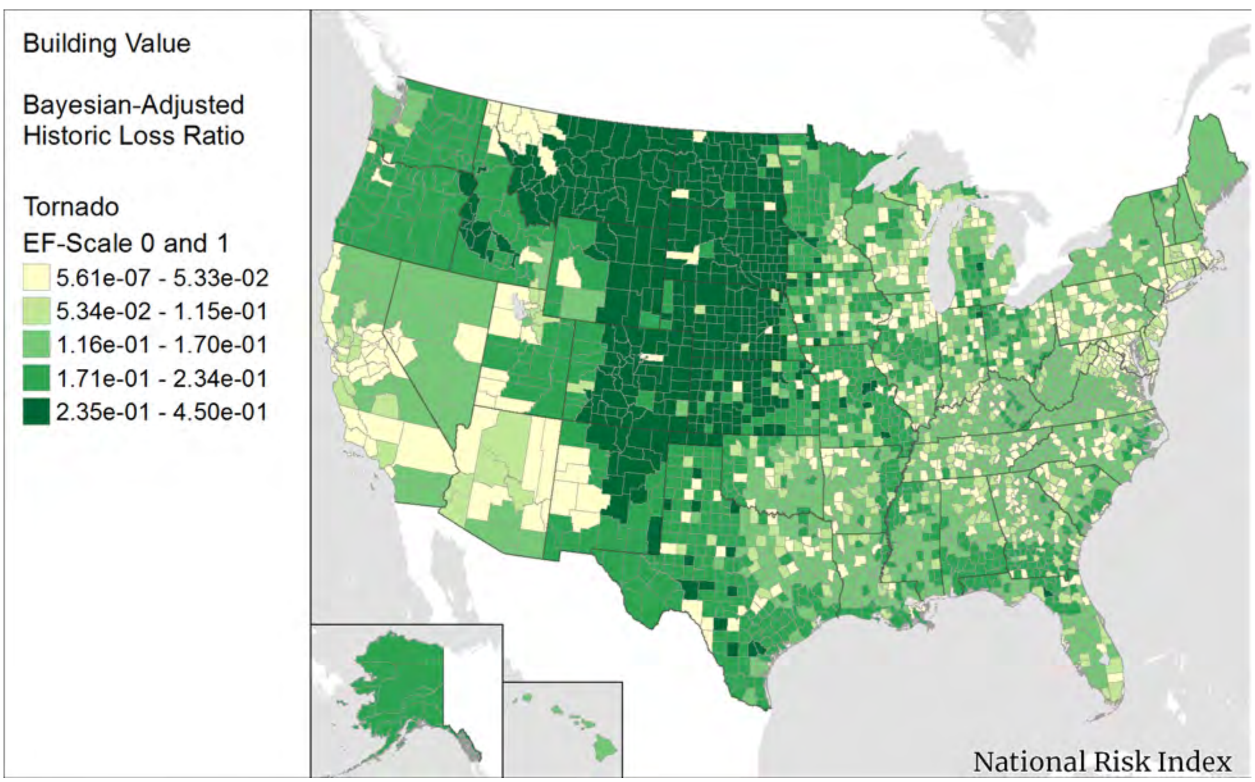

Figure 130: Tornado EF-Scale 0 and 1 Bayesian-Adjusted HLR – Building Value

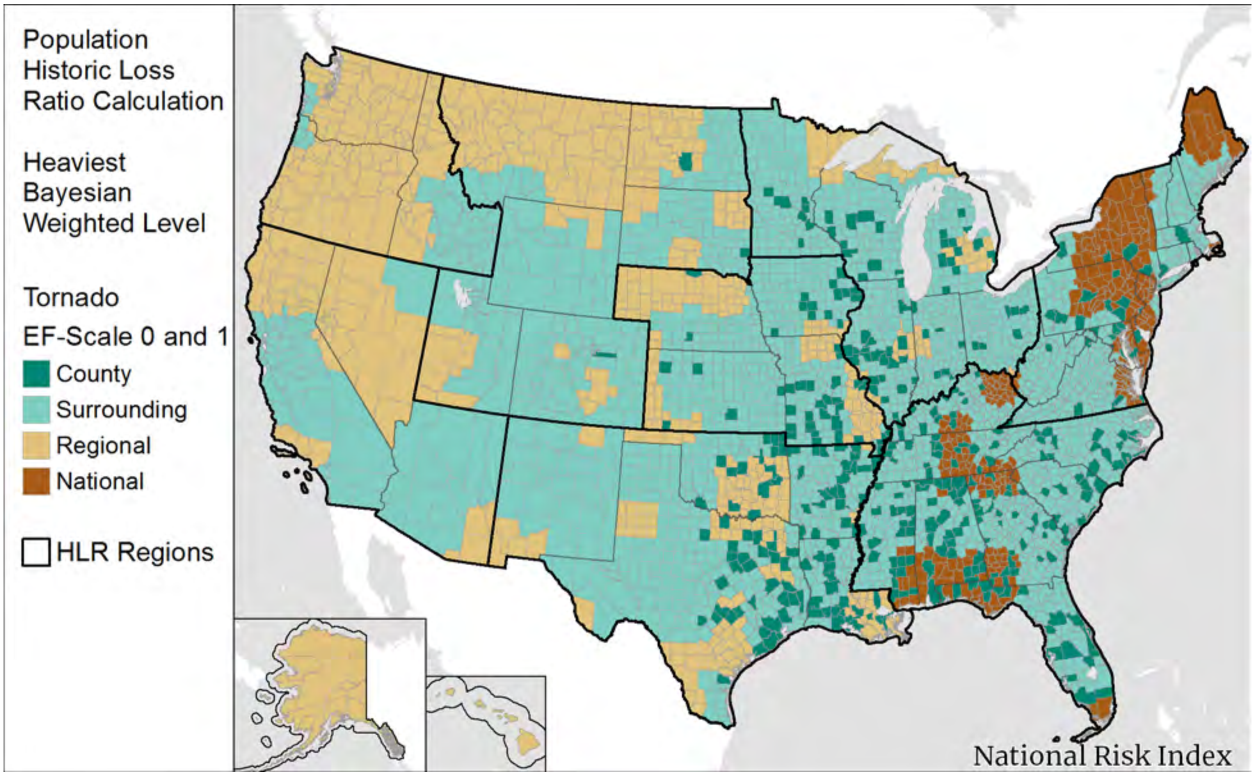

Figure 131: Tornado EF-Scale 0 and 1 Heaviest Bayesian Influence Level – Population

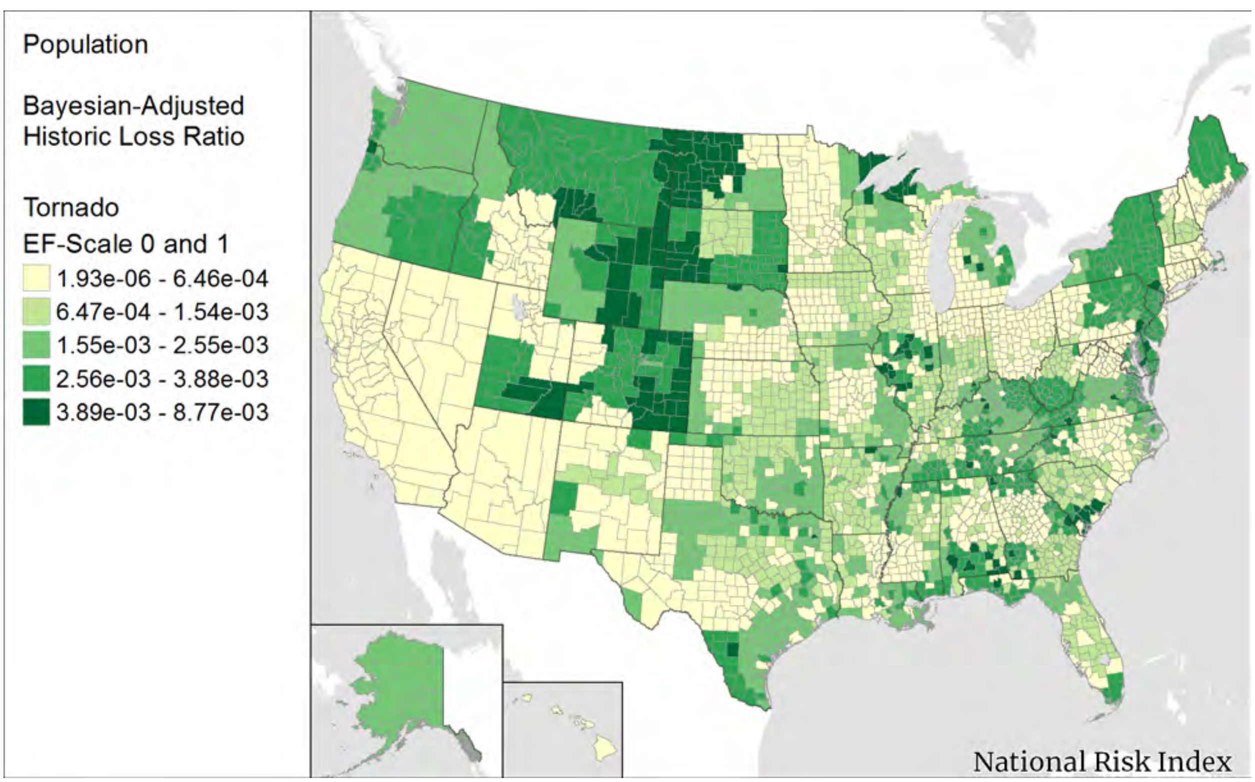

Figure 132: Tornado EF-Scale 0 and 1 Bayesian-Adjusted HLR – Population

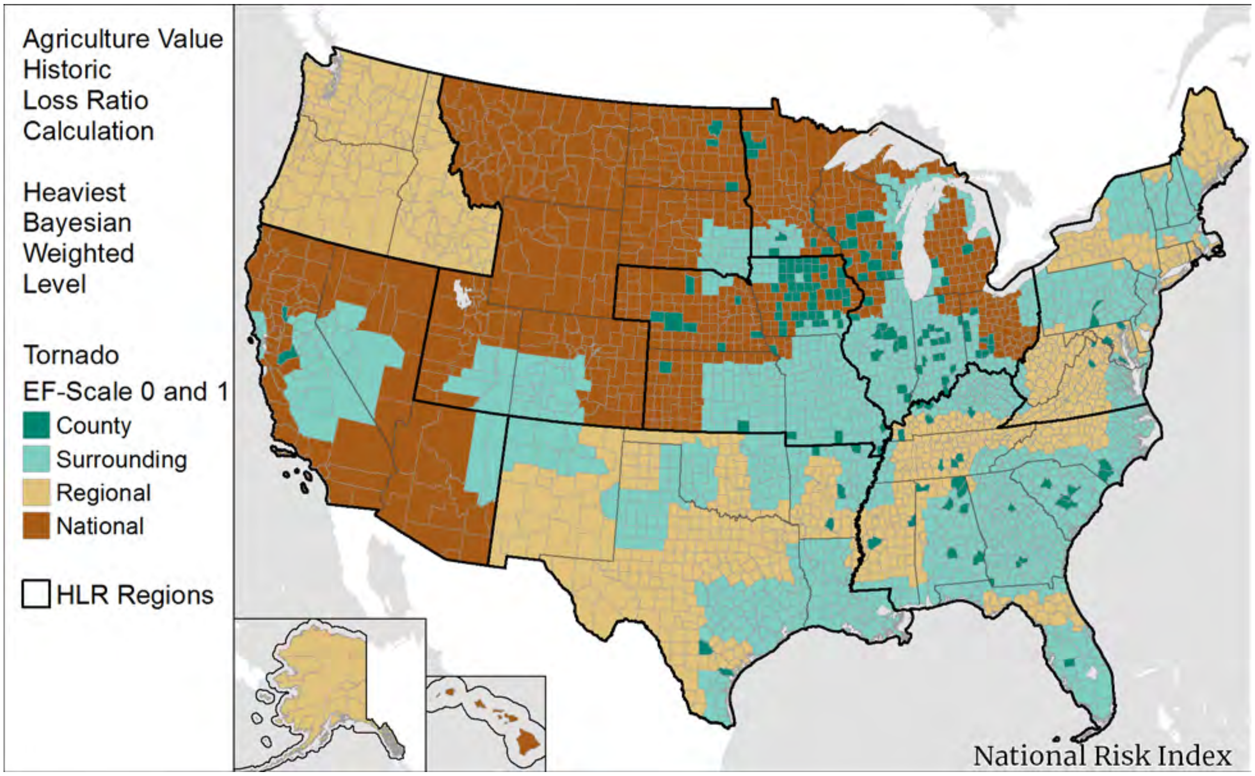

Figure 133: Tornado EF-Scale 0 and 1 Heaviest Bayesian Influence Level – Agriculture

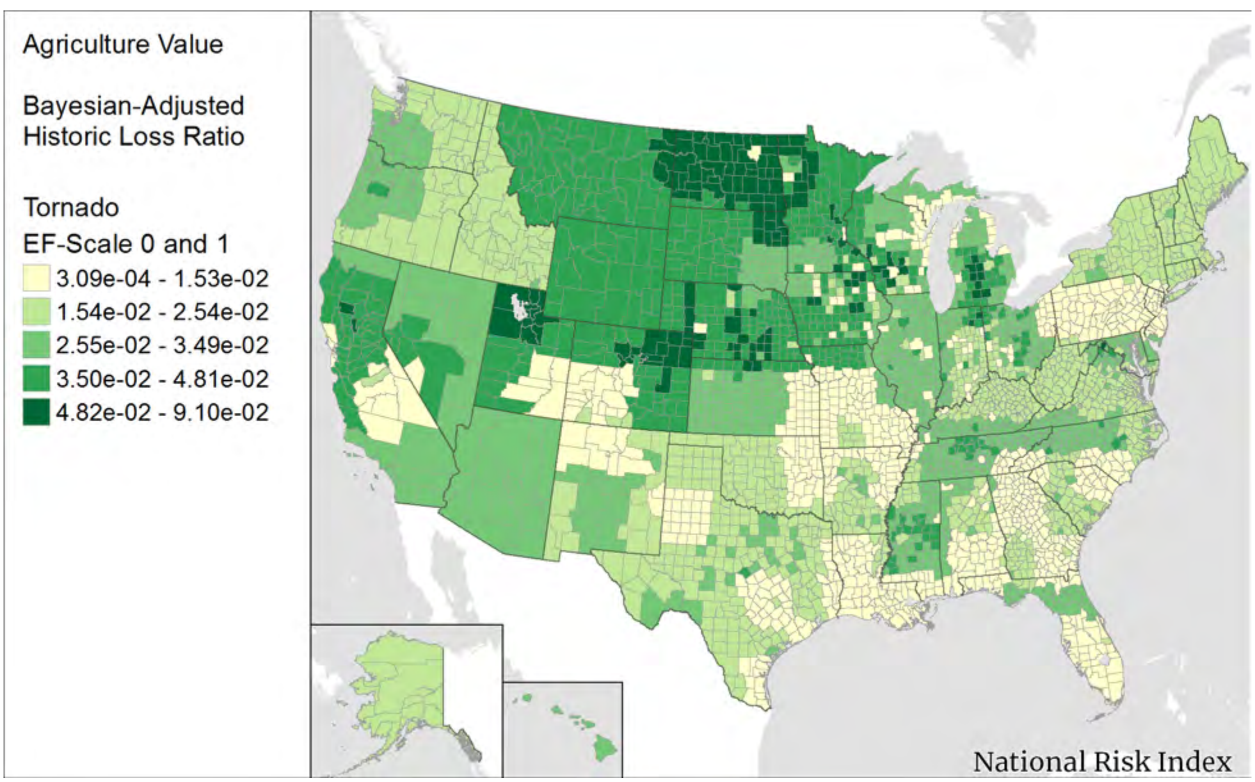

Figure 134: Tornado EF-Scale 0 and 1 Bayesian-Adjusted HLR – Agriculture

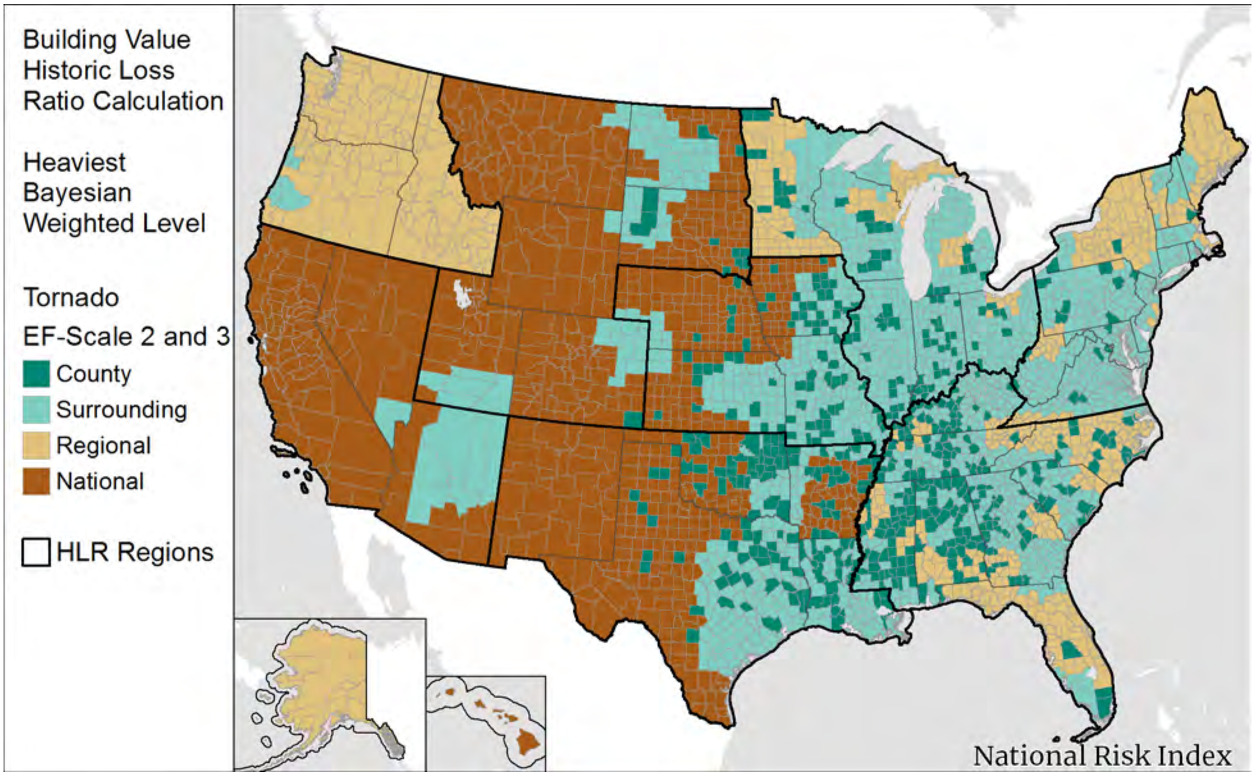

Figure 135: Tornado EF-Scale 2 and 3 Heaviest Bayesian Influence Level – Building Value

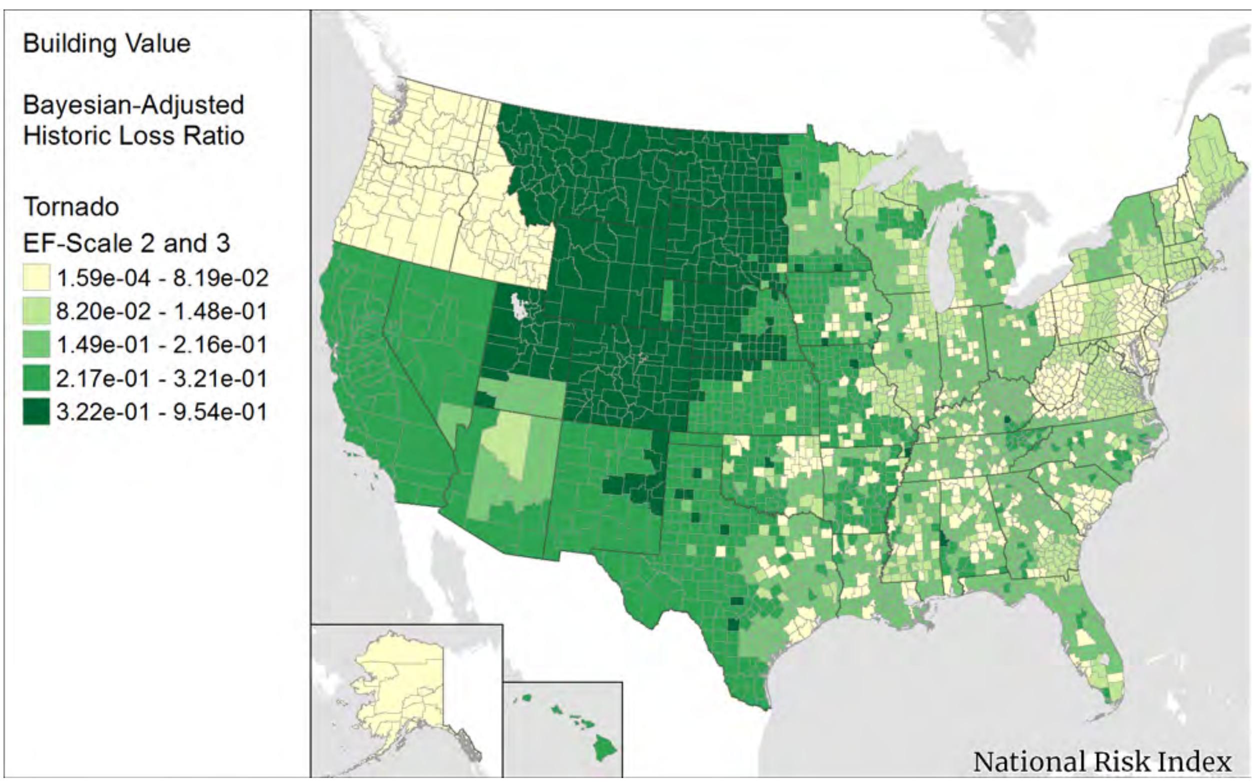

Figure 136: Tornado EF-Scale 2 and 3 Bayesian-Adjusted HLR – Building Value

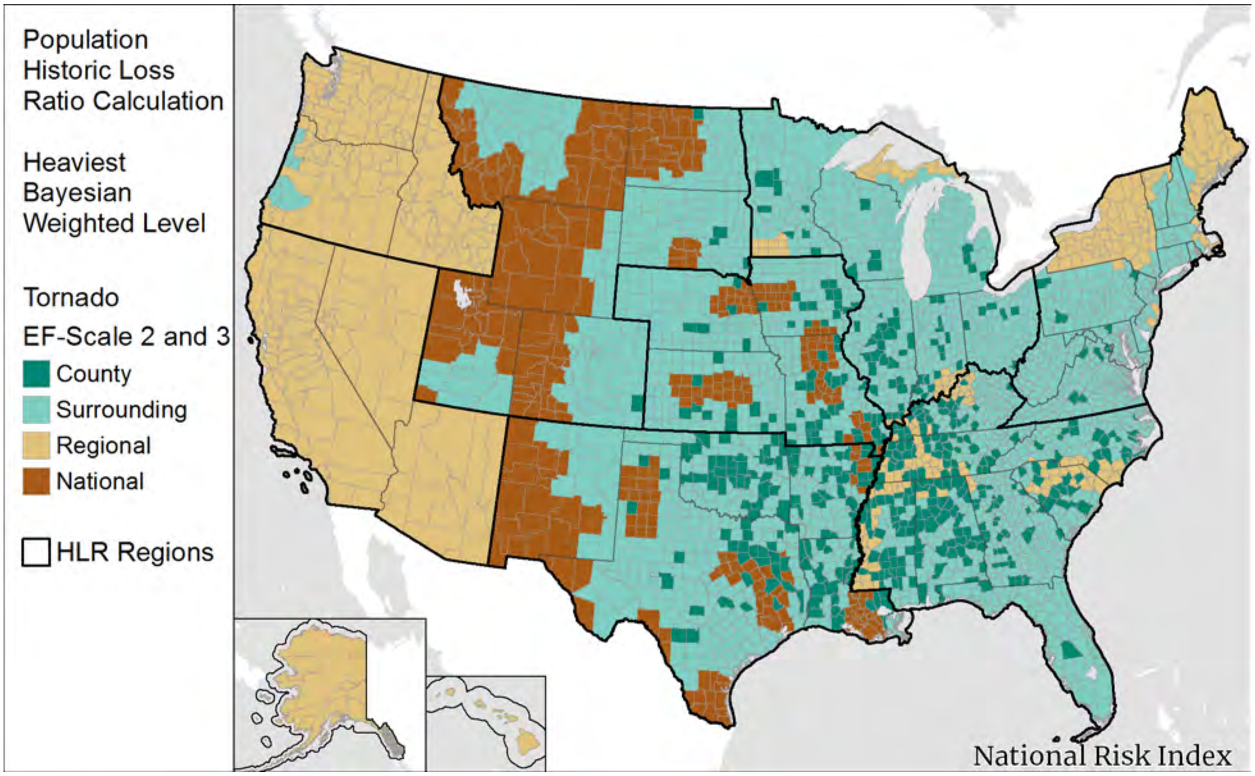

Figure 137: Tornado EF-Scale 2 and 3 Heaviest Bayesian Influence Level – Population

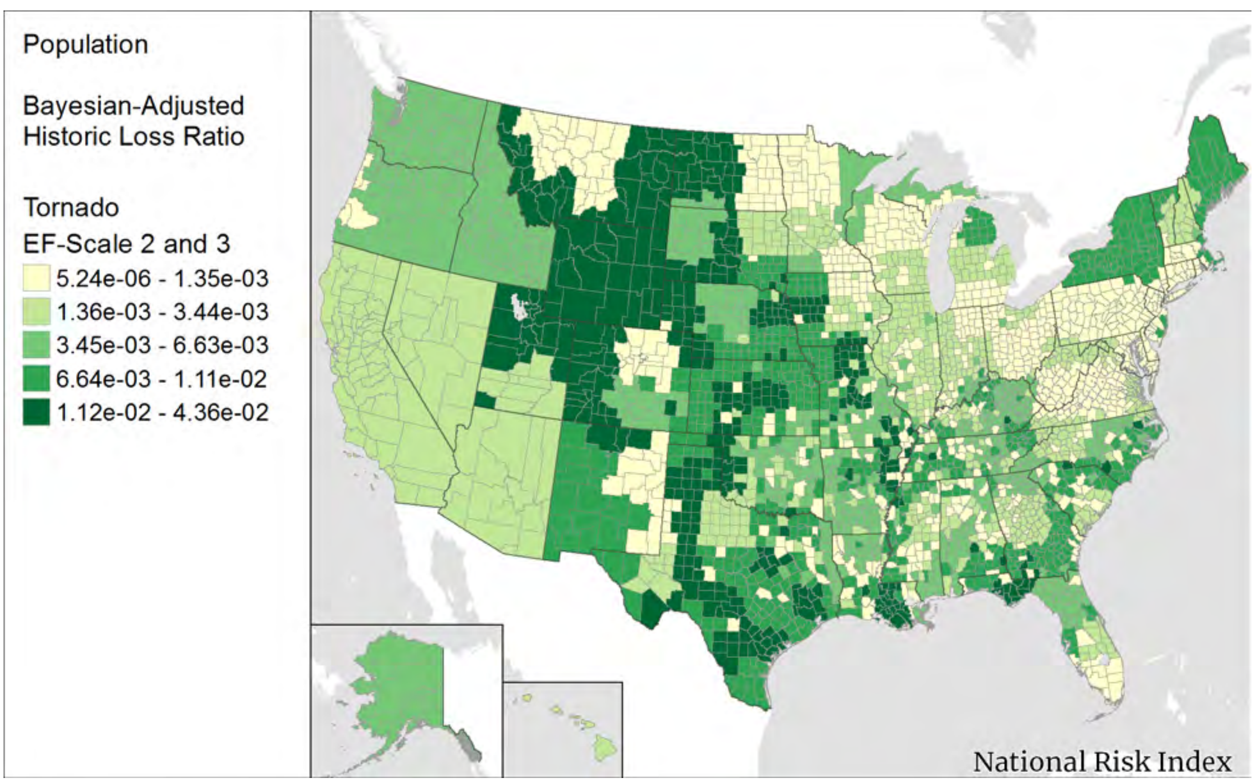

Figure 138: Tornado EF-Scale 2 and 3 Bayesian-Adjusted HLR – Population

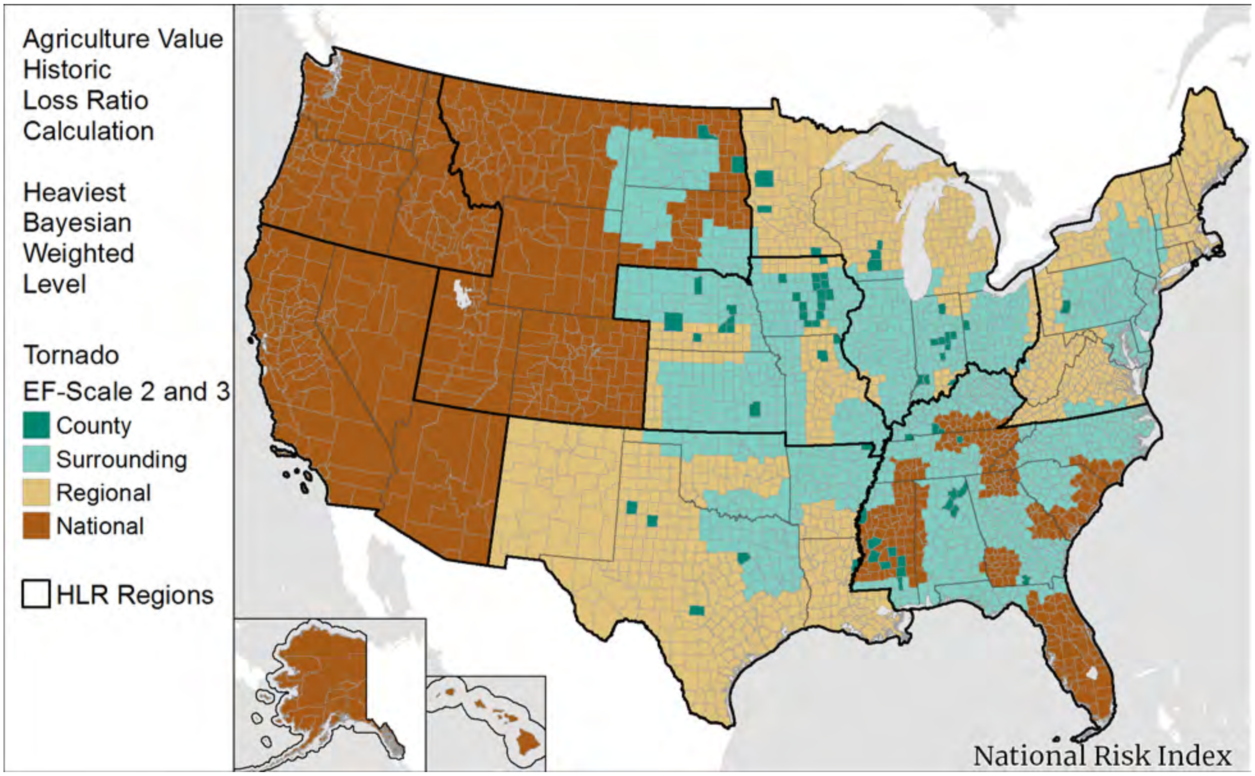

Figure 139: Tornado EF-Scale 2 and 3 Heaviest Bayesian Influence Level – Agriculture

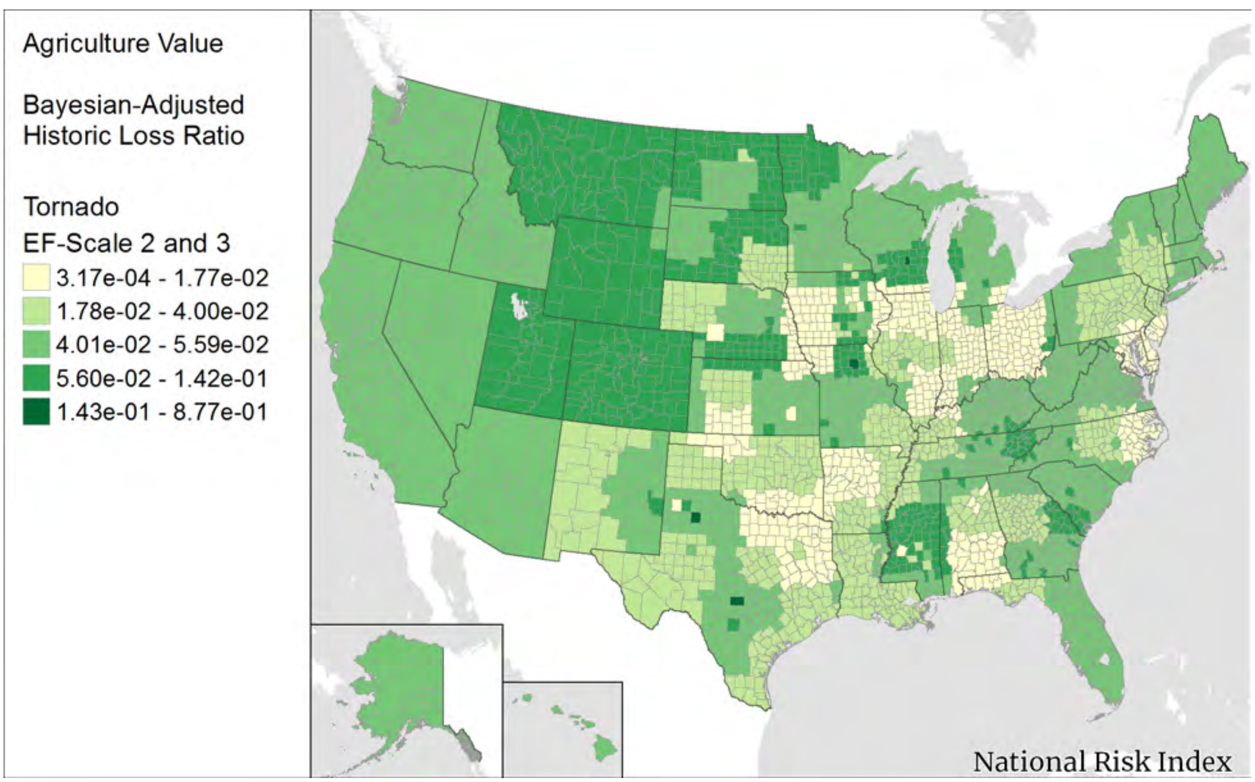

Figure 140: Tornado EF-Scale 2 and 3 Bayesian-Adjusted HLR – Agriculture

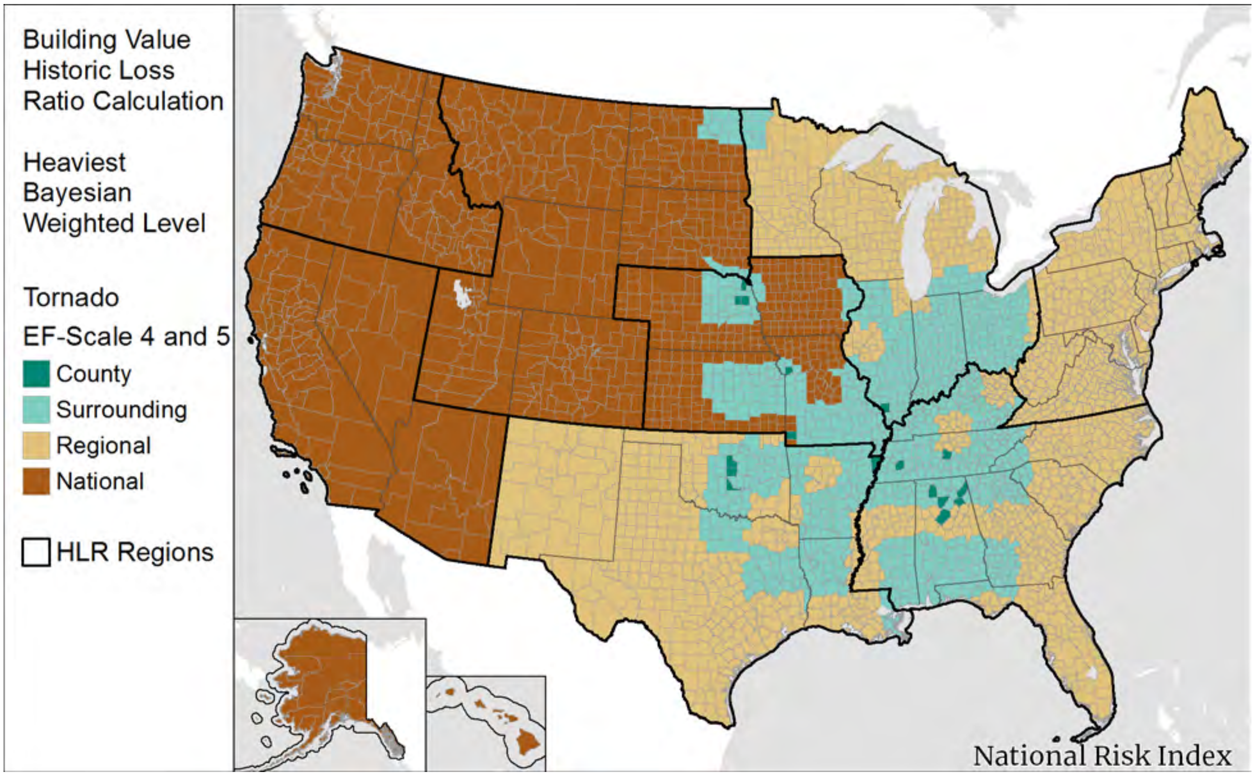

Figure 141: Tornado EF-Scale 4 and 5 Heaviest Bayesian Influence Level – Building Value

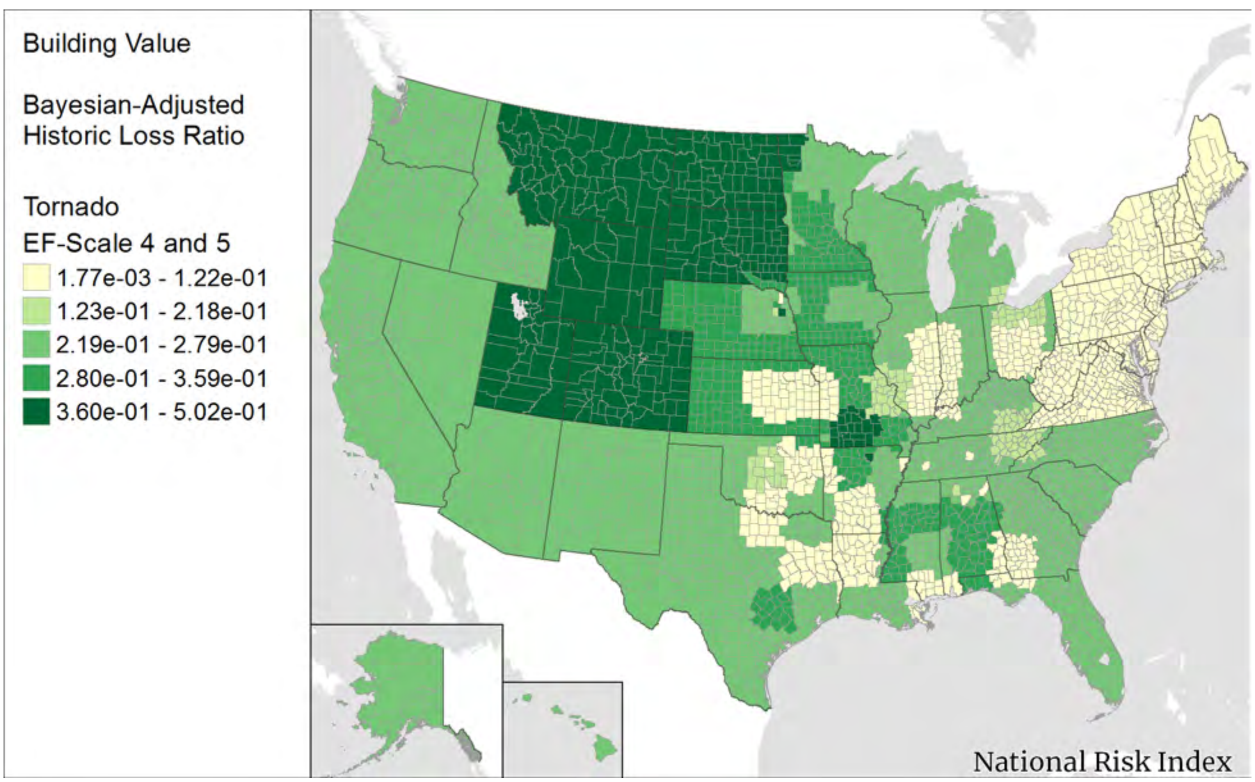

Figure 142: Tornado EF-Scale 4 and 5 Bayesian-Adjusted HLR – Building Value

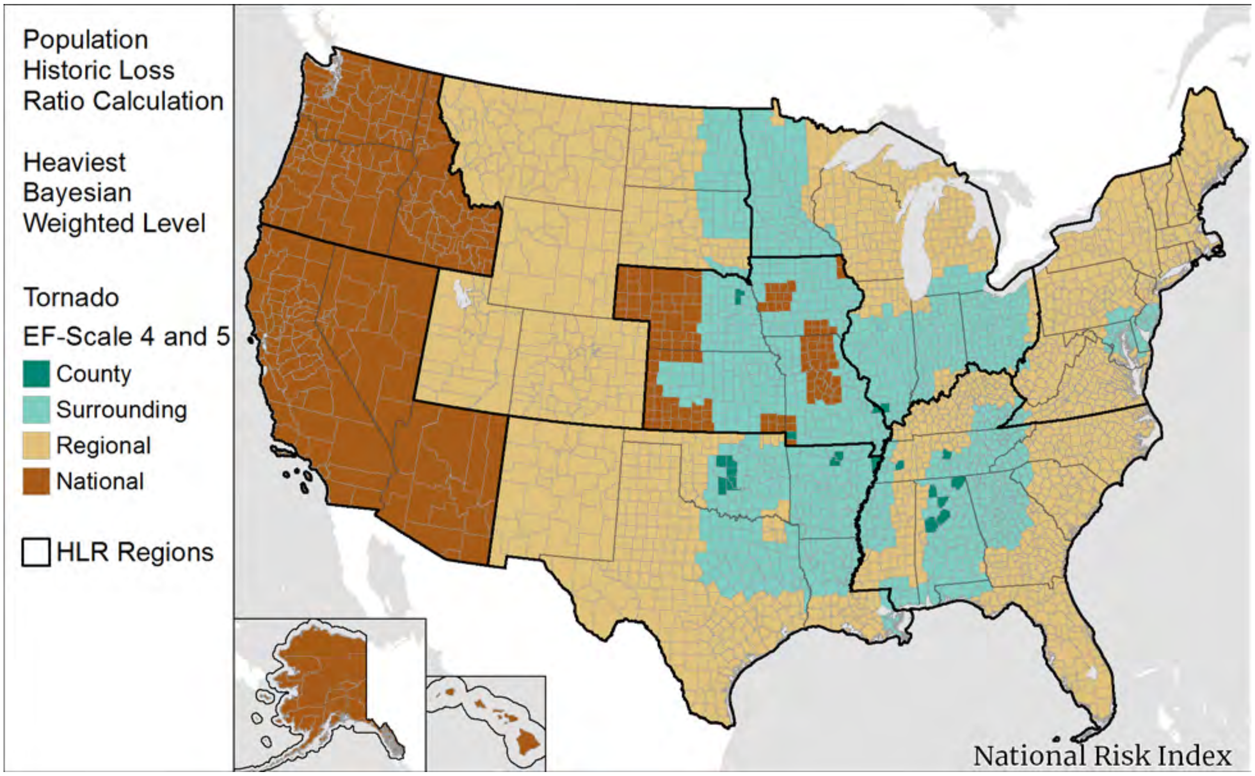

Figure 143: Tornado EF-Scale 4 and 5 Heaviest Bayesian Influence Level – Population

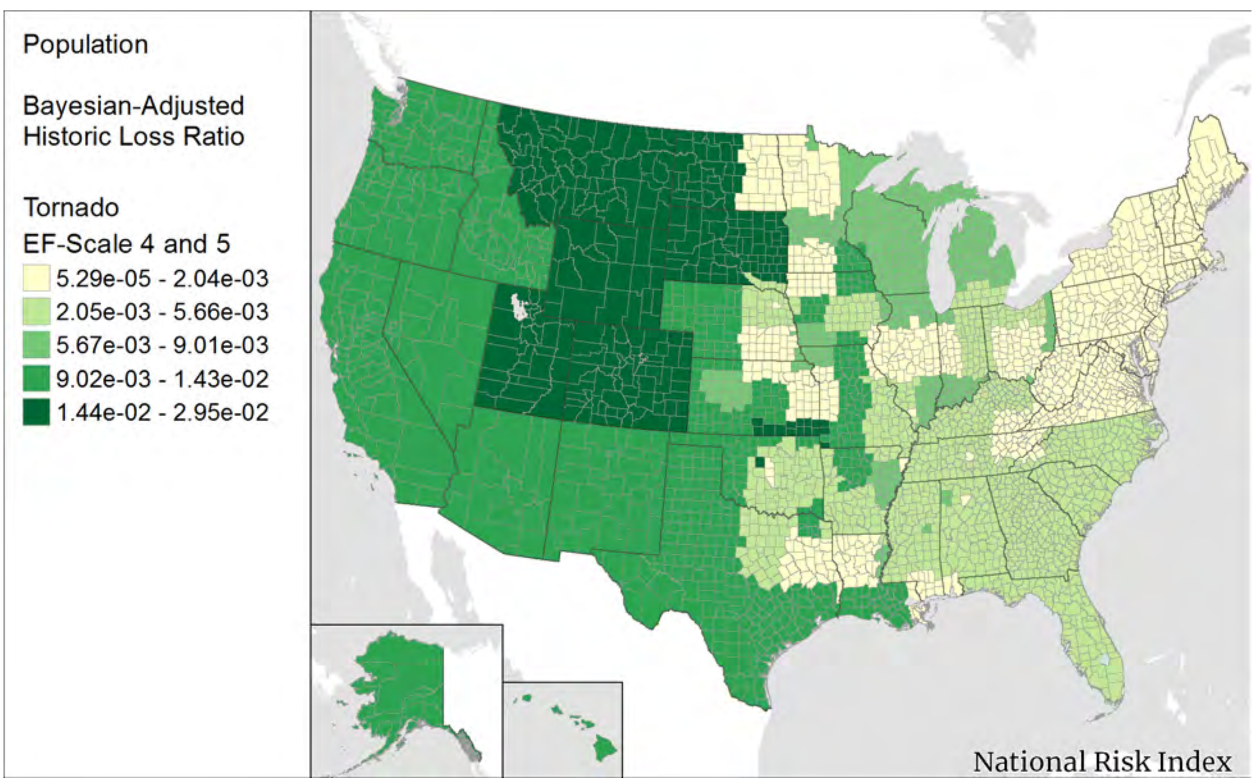

Figure 144: Tornado EF-Scale 4 and 5 Bayesian-Adjusted HLR – Population

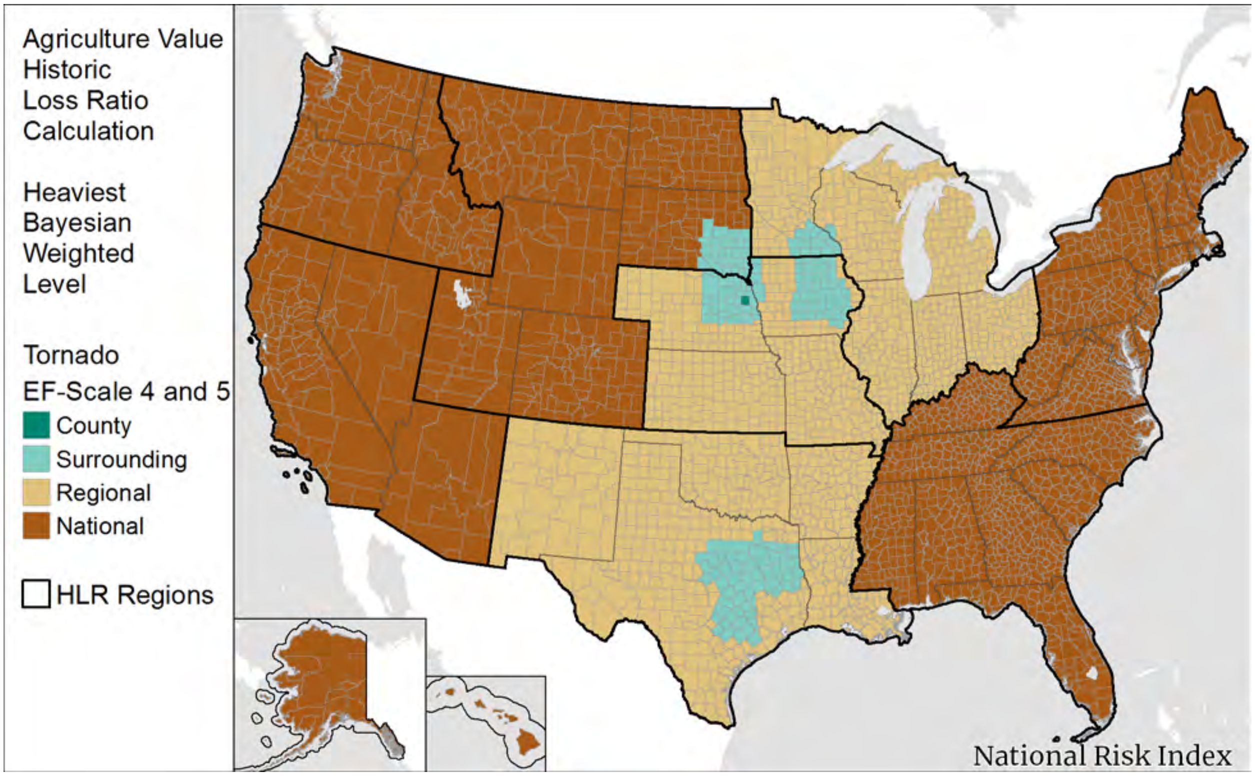

Figure 145: Tornado EF-Scale 4 and 5 Heaviest Bayesian Influence Level – Agriculture

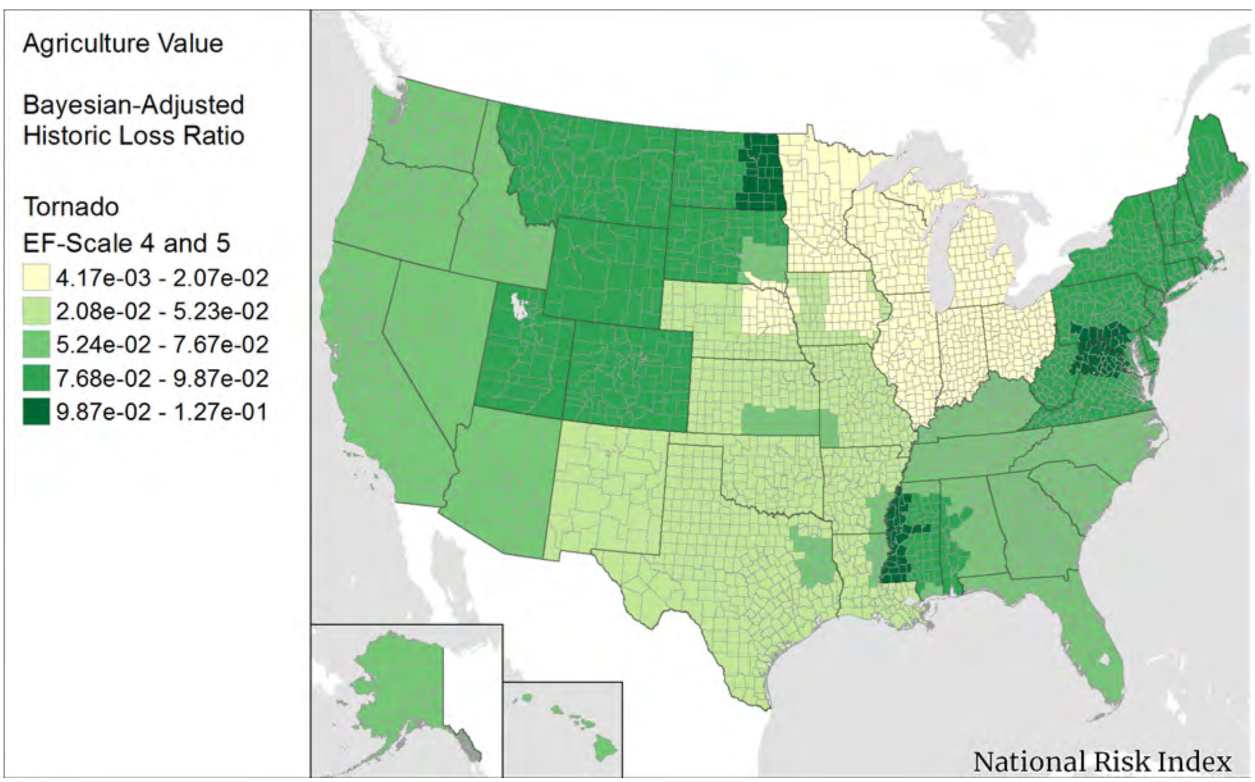

Figure 146: Tornado EF-Scale 4 and 5 Bayesian-Adjusted HLR – Agriculture

The resulting Bayesian-adjusted HLR by Tornado sub-type and consequence type is then inherited by the Census tracts within the parent county.

HLR values for each Tornado sub-type are multiplied by their respective sub-type annualized frequency and exposure to calculate the sub-type EAL. HLR values displayed in the application are a surrogate value calculated as the county EAL for a specific consequence type for all sub-types divided by the product of the summed Tornado sub-type annualized frequencies and the surrogate exposure, which is the total building value, population equivalence, or agriculture value of the county.

19.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated for each Tornado sub-type, the EAL can be computed at the Census tract and county level as in Equation 114.

Equation 114: Census Tract and County Expected Annual Loss to Tornado Sub-Type

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

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

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

$$EAL_{TRNDSub_{Co_{Bldg}}} = Exposure_{TRNDSub_{Co_{Bldg}}} \times Freq_{TRNDSub_{Co}} \times HLR_{TRNDSub_{Co_{Bldg}}}$$

$$EAL_{TRNDSub_{Co_{Pop}}} = Exposure_{TRNDSub_{Co_{Pop}}} \times Freq_{TRNDSub_{Co}} \times HLR_{TRNDSub_{Co_{Pop}}}$$

$$EAL_{TRNDSub_{Co_{Ag}}} = Exposure_{TRNDSub_{Co_{Ag}}} \times Freq_{TRNDSub_{Co}} \times HLR_{TRNDSub_{Co_{Ag}}}$$

where:

$EAL_{TRNDSub_{CT_{Bldg}}}$	is the building Expected Annual Loss due to Tornado sub-type occurrences for a specific Census tract (in dollars).
$Exposure_{TRNDSub_{CT_{Bldg}}}$	is the building value exposed to Tornado sub-type occurrences in the Census tract (in dollars).
$Freq_{TRNDSub_{CT}}$	is the Tornado sub-type annualized frequency calculated for the Census tract (occurrences per year).
$HLR_{TRNDSub_{CT_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Tornado sub-type for the Census tract.

$EAL_{TRNDSub_{CT_{Pop}}}$	is the population equivalence Expected Annual Loss due to Tornado sub-type occurrences for a specific Census tract (in dollars).
$Exposure_{TRNDSub_{CT_{Pop}}}$	is the population equivalence value exposed to Tornado sub-type occurrences in the Census tract (in dollars).
$HLR_{TRNDSub_{CT_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Tornado sub-type for the Census tract.
$EAL_{TRNDSub_{CT_{Ag}}}$	is the agriculture Expected Annual Loss due to Tornado sub-type occurrences for a specific Census tract (in dollars).
$Exposure_{TRNDSub_{CT_{Ag}}}$	is the agriculture value exposed to Tornado sub-type occurrences in the Census tract (in dollars).
$HLR_{TRNDSub_{CT_{Ag}}}$	is the Bayesian-adjusted agriculture Historic Loss Ratio for Tornado sub-type for the Census tract.
$EAL_{TRNDSub_{Co_{Bldg}}}$	is the building Expected Annual Loss due to Tornado sub-type occurrences for a specific county (in dollars).
$Exposure_{TRNDSub_{Co_{Bldg}}}$	is the building value exposed to Tornado sub-type occurrences in the county (in dollars).
$Freq_{TRNDSub_{Co}}$	is the Tornado sub-type annualized frequency calculated for the county (occurrences per year).
$HLR_{TRNDSub_{Co_{Bldg}}}$	is the Bayesian-adjusted building Historic Loss Ratio for Tornado sub-type for the county.
$EAL_{TRNDSub_{Co_{Pop}}}$	is the population equivalence Expected Annual Loss due to Tornado sub-type occurrences for a specific county (in dollars).
$Exposure_{TRNDSub_{Co_{Pop}}}$	is the population equivalence value exposed to Tornado sub-type events in the county (in dollars).
$HLR_{TRNDSub_{Co_{Pop}}}$	is the Bayesian-adjusted population Historic Loss Ratio for Tornado sub-type for the county.
$EAL_{TRNDSub_{Co_{Ag}}}$	is the agriculture Expected Annual Loss due to Tornado sub-type occurrences for a specific county (in dollars).
$Exposure_{TRNDSub_{Co_{Ag}}}$	is the agriculture value exposed to Tornado sub-type occurrences in the county (in dollars).

$HLR_{TRNDSub_{Co_{Ag}}}$	is the Bayesian-adjusted agriculture Historic Loss Ratio for Tornado sub-type for the county.

The total EAL values at the Census tract and county levels are the sums of the EAL values for each Tornado sub-type and consequence type as in Equation 115.

Equation 115: Census Tract and County Expected Annual Loss to Tornado

$$EAL_{TRND_{CT_{CnsqType}}} = EAL_{EF0\&1_{CT_{CnsqType}}} + EAL_{EF2\&3_{CT_{CnsqType}}} + EAL_{EF4\&5_{CT_{CnsqType}}}$$

$$EAL_{TRND_{Co_{CnsqType}}} = EAL_{EF0\&1_{Co_{CnsqType}}} + EAL_{EF2\&3_{Co_{CnsqType}}} + EAL_{EF4\&5_{Co_{CnsqType}}}$$

$$EAL_{TRND_{CT}} = EAL_{TRND_{CT_{Bldg}}} + EAL_{TRND_{CT_{Pop}}} + EAL_{TRND_{CT_{Ag}}}$$

$$EAL_{TRND_{Co}} = EAL_{TRND_{Co_{Bldg}}} + EAL_{TRND_{Co_{Pop}}} + EAL_{TRND_{Co_{Ag}}}$$

where:

$EAL_{TRND_{CT_{CnsqType}}}$	is the total Expected Annual Loss due to Tornado occurrences for a specific Census tract and consequence type (in dollars).
$EAL_{EF0\&1_{CT_{CnsqType}}}$	is the Expected Annual Loss due to EF-scale 0 and 1 Tornadoes for a specific Census tract and consequence type (in dollars).
$EAL_{EF2\&3_{CT_{CnsqType}}}$	is the Expected Annual Loss due to EF-scale 2 and 3 Tornadoes for a specific Census tract and consequence type (in dollars).
$EAL_{EF4\&5_{CT_{CnsqType}}}$	is the Expected Annual Loss due to EF-scale 4 and 5 Tornadoes for a specific Census tract and consequence type (in dollars).
$EAL_{TRND_{Co_{CnsqType}}}$	is the total Expected Annual Loss due to Tornado occurrences for a specific county and consequence type (in dollars).
$EAL_{EF0\&1_{Co_{CnsqType}}}$	is the Expected Annual Loss due to EF-scale 0 and 1 Tornadoes for a specific county and consequence type (in dollars).
$EAL_{EF2\&3_{Co_{CnsqType}}}$	is the Expected Annual Loss due to EF-scale 2 and 3 Tornadoes for a specific county and consequence type (in dollars).
$EAL_{EF4\&5_{Co_{CnsqType}}}$	is the Expected Annual Loss due to EF-scale 4 and 5 Tornadoes for a specific county and consequence type (in dollars).

$EAL_{TRND_{CT}}$ is the total Expected Annual Loss due to Tornado occurrences for a specific Census tract (in dollars).

$EAL_{TRND_{CT_{Bldg}}}$ is the building Expected Annual Loss due to Tornado occurrences for a specific Census tract (in dollars).

$EAL_{TRND_{CT_{Pop}}}$ is the population equivalence Expected Annual Loss due to Tornado occurrences for a specific Census tract (in dollars).

$EAL_{TRND_{CT_{Ag}}}$ is the agriculture Expected Annual Loss due to Tornado occurrences for specific Census tract (in dollars).

$EAL_{TRND_{Co}}$ is the total Expected Annual Loss due to Tornado occurrences for a specific county (in dollars).

$EAL_{TRND_{Co_{Bldg}}}$ is the building Expected Annual Loss due to Tornado occurrences for a specific county (in dollars).

$EAL_{TRND_{Co_{Pop}}}$ is the population equivalence Expected Annual Loss due to Tornado occurrences for a specific count (in dollars).

$EAL_{TRND_{Co_{Ag}}}$ is the agriculture Expected Annual Loss due to Tornado occurrences for a specific county (in dollars).

Figure 147 shows the total EAL (building value, population equivalence, and agriculture value combined) to Tornado occurrences.

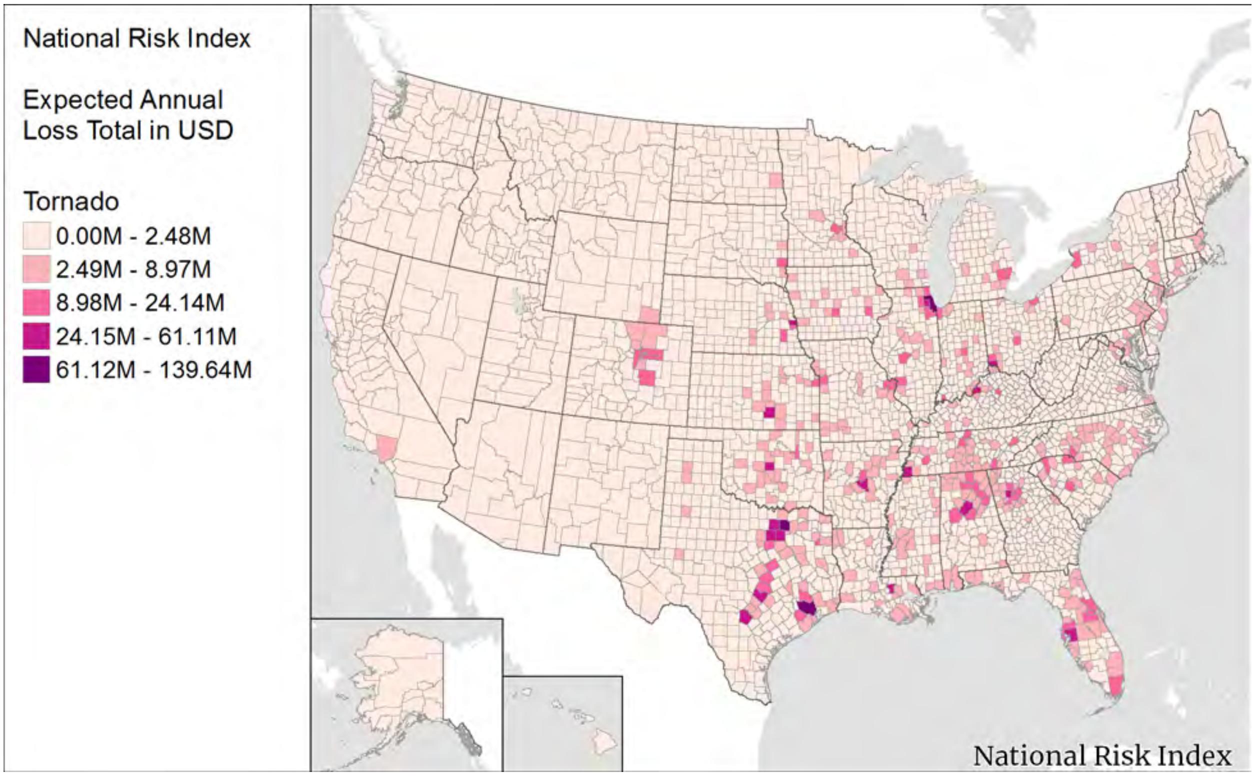

Figure 147: Total Expected Annual Loss by County to Tornado

With the Tornado total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 the 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[78]

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[79]

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[80]

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 modeled 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[81]

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

[78] 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.
[79] 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.
[80] 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.
[81] 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.

Susceptible Area Source: Washington State Department of Natural Resources, Tsunami Inundation Data[82]

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[83]

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 Occurrence Source: NOAA, National Centers for Environmental Information (formerly NGDC), Global Historical Tsunami Runup Data[84]

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 62).

Table 62: 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

[82] 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.
[83] Division of Geological & Geophysical Surveys, Alaska Department of Natural Resources. (2017). Tsunami inundations maps [online dataset]. Retrieved from http://dggs.alaska.gov/pubs/tsunami.
[84] 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 148) that will be used to calculate exposure at the Census block level.

Figure 148: Tsunami Inundation Zone Map

Tsunami runup points are buffered by 500 meters (see Figure 149). These buffers will be used to estimate annualized frequency at the Census tract level.

Figure 149: 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 150).

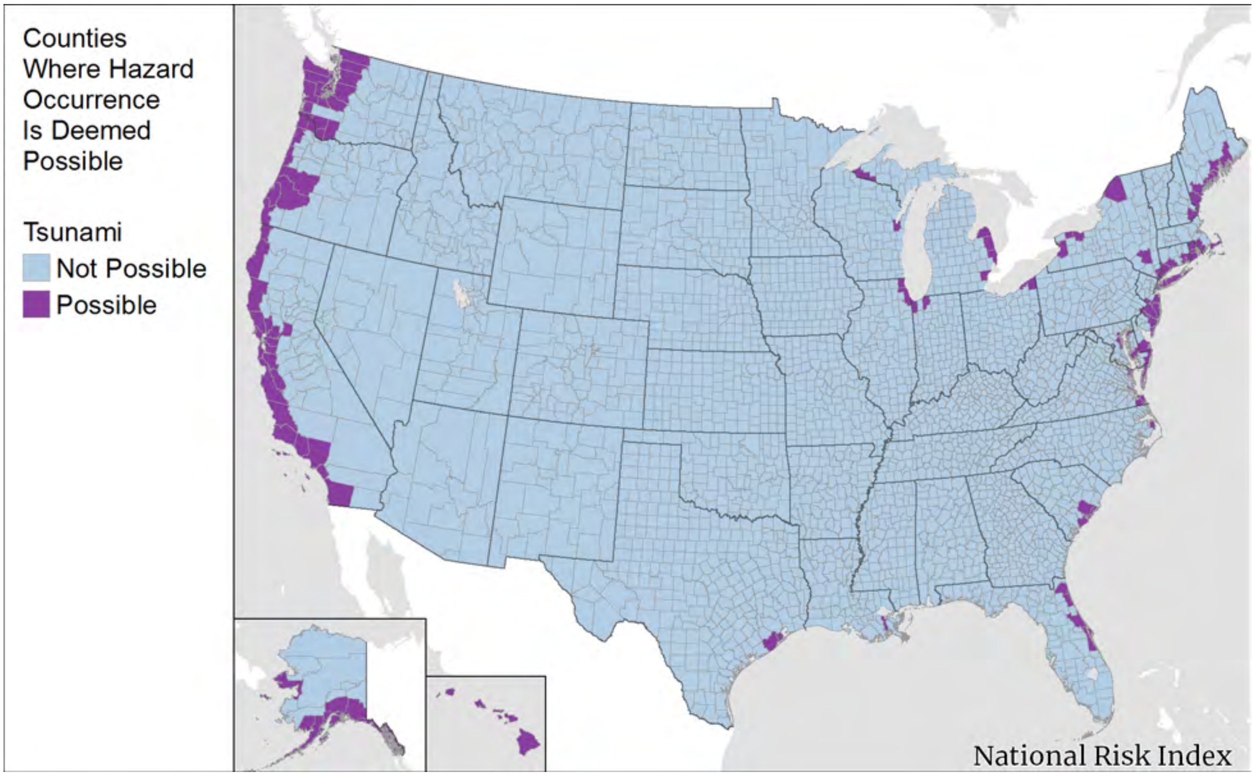

Figure 150: Map of Counties Deemed Possible for Tsunami Occurrence

20.4. Exposure

To identify areas of exposure, the Tsunami inundation polygons are intersected with the Census block polygons within the 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 Analytical Techniques). The resulting table contains the inundation polygon's unique identifier, Census block number, the intersected area, and the developed area of intersection (see Table 63). All area values are in square kilometers.

Table 63: 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 (see Equation 116). These Census block densities have been calculated by dividing the total exposure values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers). VSL was used to express population equivalence exposure in terms of dollars.

Equation 116: 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 equivalence 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 ($7.6M 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 building value exceeds the Hazus-recorded building value, then the Hazus-recorded building value is used as the building 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 Census 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 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 equivalence 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 equivalence exposed to Tsunami inundation for each Census block within the Census tract (in dollars).
$Exposure_{TSUN_{Co_{Pop}}}$	is the population equivalence 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 equivalence exposed to Tsunami inundation for each Census block within the county (in dollars).

20.5. Historic Occurrence Count

The historic occurrence count of Tsunami, in 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 Spatial Source Data) for which the buffered points intersect a Census tract. A historic occurrence 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. Annualized Frequency

The annualized frequency value represents the estimated number of recorded Tsunami occurrences, in 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 annualized frequency would imply, the annualized frequency is calculated at the Census tract level (see Equation 118) and inherited by the Census blocks it contains. This inherited Census block annualized frequency is used in the EAL calculations.

Annualized frequency calculations use the Tsunami runup-event polygons generated in Section 20.2 Spatial Processing 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 118: Census Tract Tsunami Annualized Frequency

$$Freq_{TSUN_{CT}} = \frac{EventCount_{TSUN_{CT}}}{PeriodRecord_{TSUN}}$$

where:

$Freq_{TSUN_{CT}}$	is the annualized frequency of Tsunami events determined for a specific Census tract (events per year).
$EventCount_{TSUN_{CT}}$	is the number of Tsunami runup-event polygons (with distinct originating events) 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 event count is 0, the Census tract is assigned the minimum annual Tsunami frequency. This minimum annual frequency is set at 0.004587, or once in the period of record (1 in 218 years).

20.6.2. ANNUALIZED FREQUENCY INHERITANCE AND AGGREGATION

The Census block inherits its annualized frequency value from the Census tract that contains it as in Equation 119.

Equation 119: Census Block Tsunami Annualized Frequency Inheritance

$$Freq_{TSUN_{CB}} = Freq_{TSUN_{CT}}$$

where:

$Freq_{TSUN_{CB}}$	is the Tsunami annualized frequency determined for a specific Census block (events per year).
$Freq_{TSUN_{CT}}$	is the annualized frequency of Tsunami runup events determined for a specific Census tract (events per year).

The application provides area-weighted average annualized frequency values at the county level. These values may not exactly match that of dividing the number of recorded Tsunami occurrences at the county level by the period of record. The annualized frequency values at the Census block level are rolled up to the county level using area-weighted aggregations as in Equation 120. Only Census blocks with a non-zero annualized frequency were included in the aggregation so that landlocked areas did not overly influence the annualized frequency values of the county.

Equation 120: County Area-Weighted Tsunami Annualized 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 area-weighted Tsunami annualized frequency calculated for a specific county.
$Freq_{TSUN_{CB}}$	is the non-zero Tsunami annualized 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 151 displays Tsunami annualized frequency at the county level.

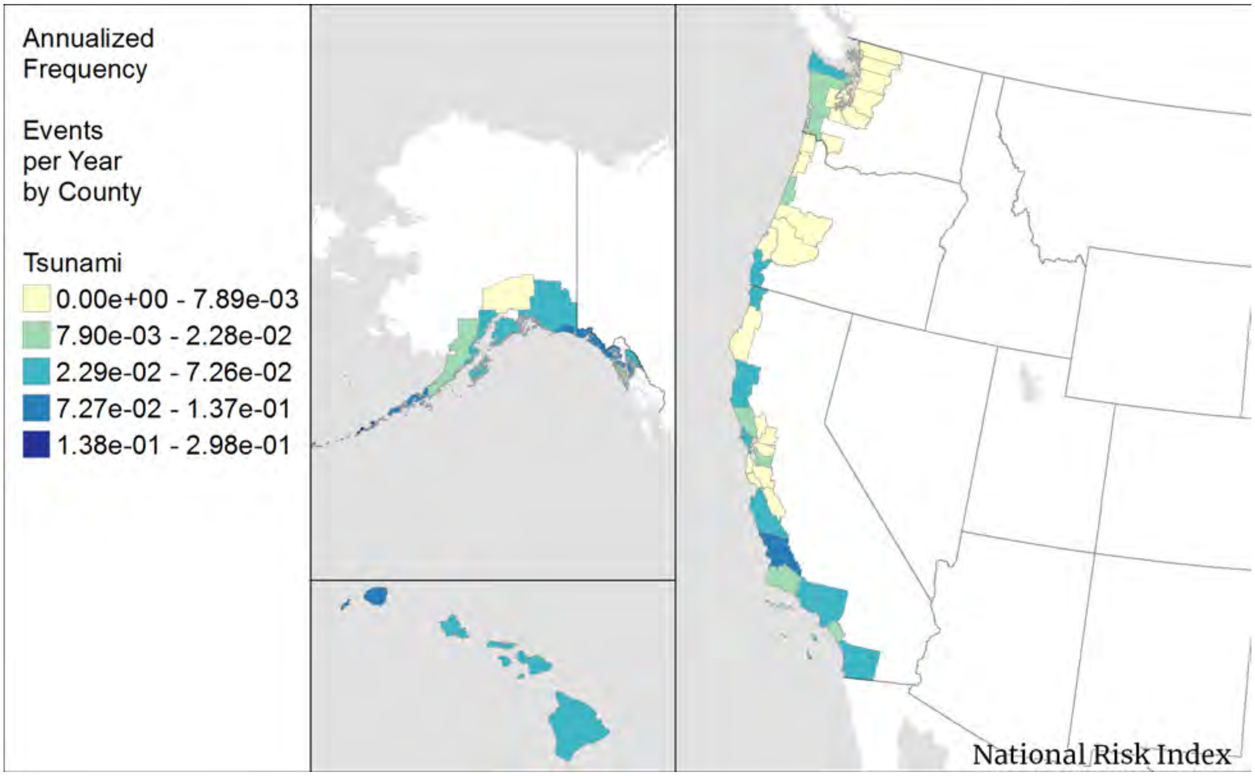

Figure 151: Tsunami Annualized Frequency by County

20.7. Historic Loss Ratio

The Tsunami HLR is the representative percentage of a location's hazard exposure 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 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Tsunami hazard type.

Loss data are provided by SHELDUS[85] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Two peril types are mapped to the hazard Tsunami (see Table 64). These native records are aggregated on a consecutive day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

Table 64: Tsunami Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Tsunami	0	0
Tsunami/Seiche	28	23

85 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 Exposure). 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 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 or impacted people).
$HLRExposure_{TSUN_{Co_{CnsqType}}}$	is the value (by consequence type) of the susceptible area estimated to have been exposed to the Tsunami event (in dollars or people).

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 (1996 to 2019). For Tsunami, the historic event count is extracted by using the intersection between the buffered Tsunami runup points (see Section 20.2 Spatial Processing) and the Census block polygons. This is a count of the distinct Tsunami originating events rather than the individual runup events. An annual rate is calculated as the event count divided by the period of record of 218.96 years, and this rate is multiplied by the SHELDUS period of record of 24 years to estimate a historic event-day count for the appropriate time range.

If the number of loss-causing Tsunami event records from SHELDUS is less than the scaled event count for the county, then a number of zero-loss records equal to the difference are 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 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

Figure 152 and Figure 154 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 Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Tsunami occurrences within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value, though its HLR may be influenced by other local, regional, or national occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing occurrences or have widely varying loss ratios get the most influence from regional- or national-level loss data. Figure 153 and Figure 155 represent the final, Bayesian-adjusted county-level HLR values for Tsunami.

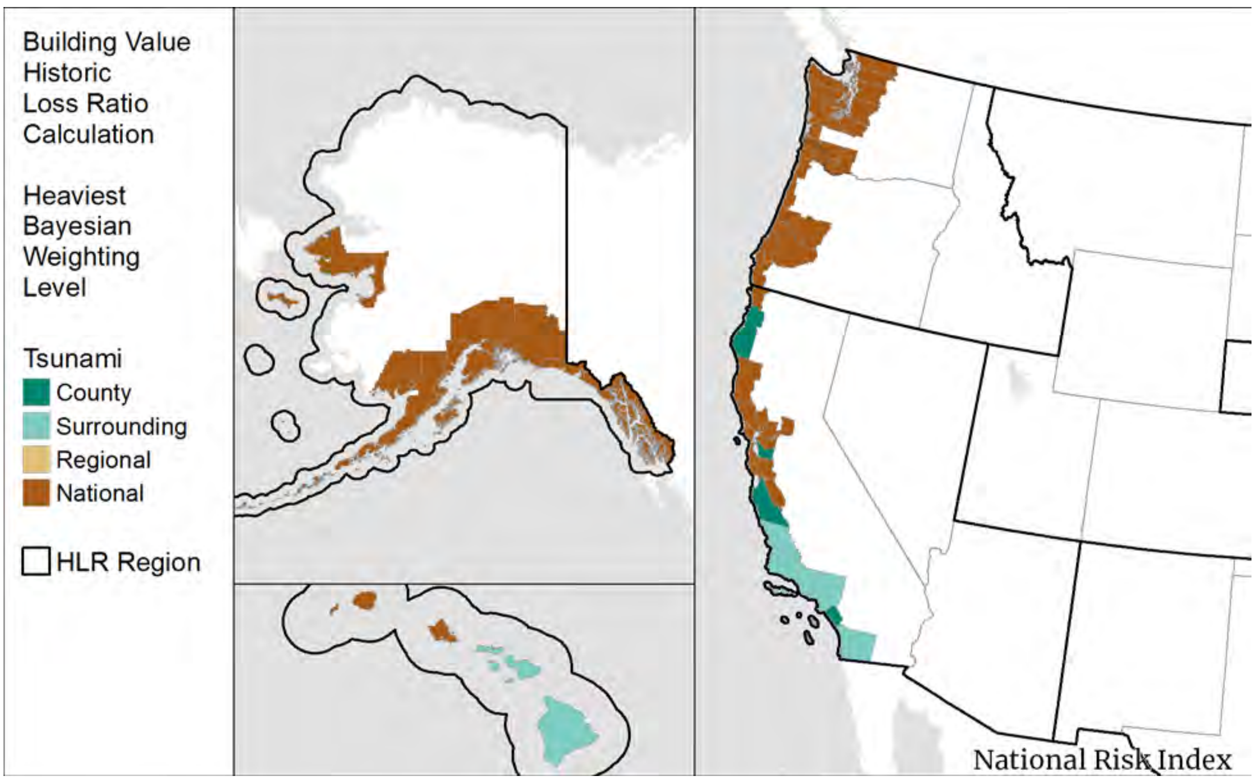

Figure 152: Tsunami Heaviest Bayesian Influence Level – Building Value

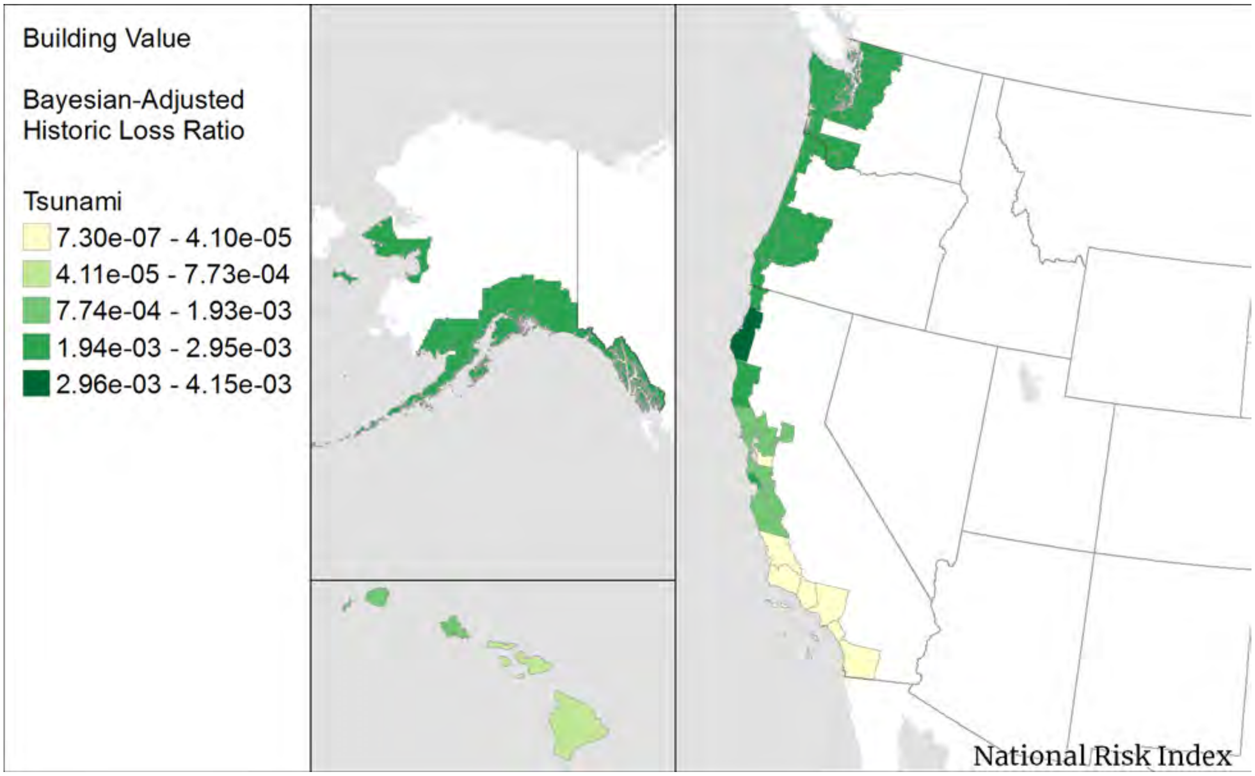

Figure 153: Tsunami Bayesian-Adjusted HLR – Building Value

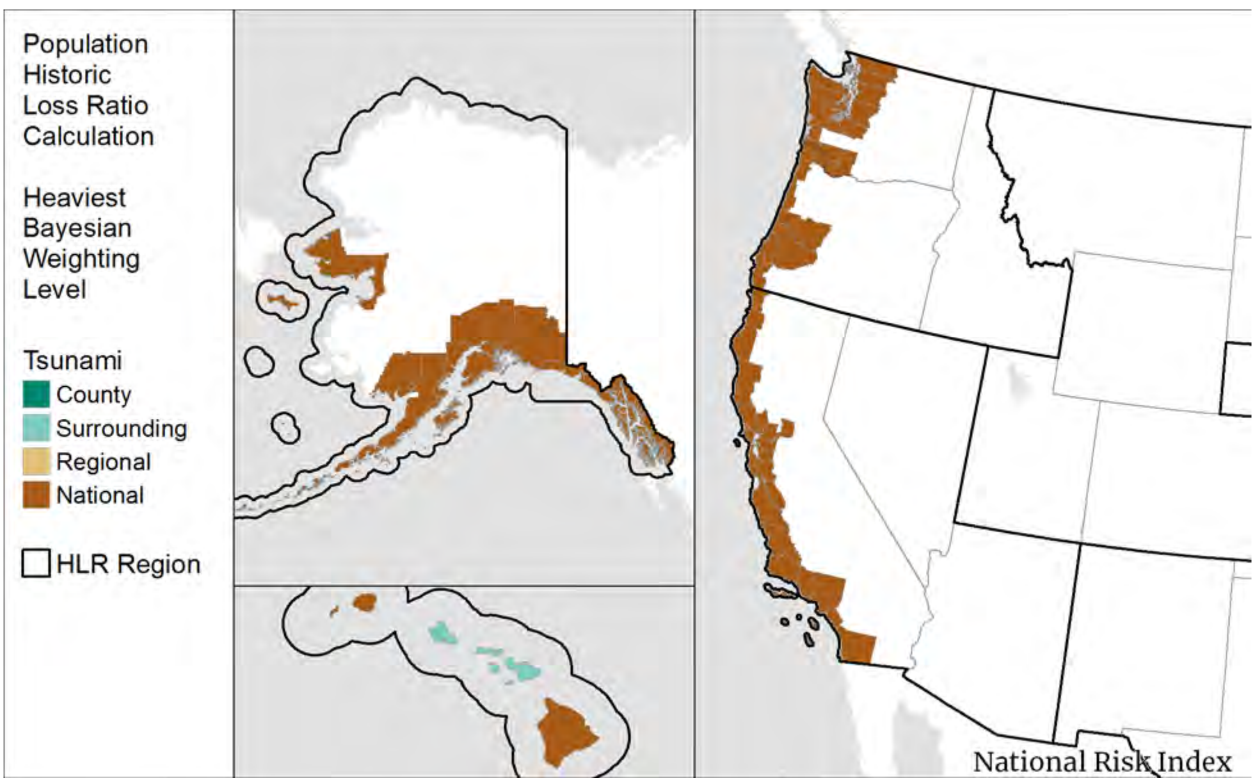

Figure 154: Tsunami Heaviest Bayesian Influence Level – Population

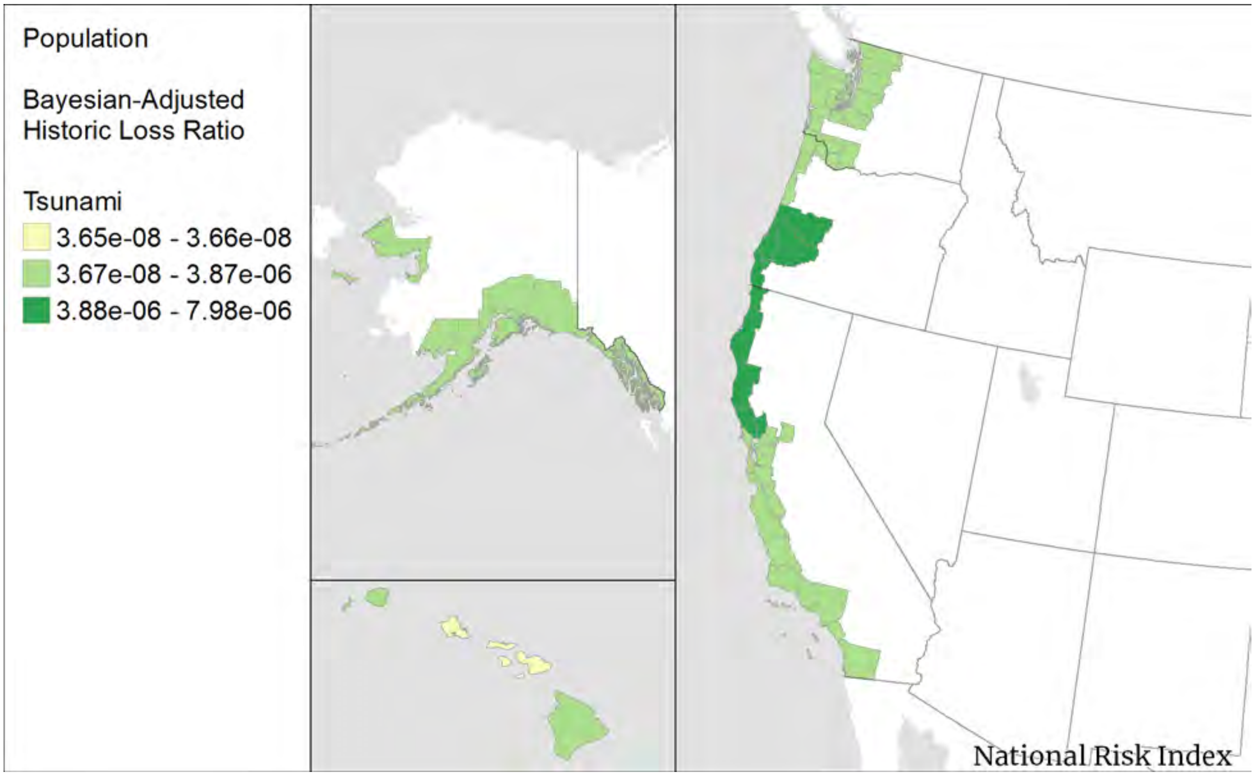

Figure 155: Tsunami Bayesian-Adjusted HLR – Population

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

20.8. Expected Annual Loss

Once exposure, annualized 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 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 building Expected Annual Loss due to Tsunami occurrences for a specific Census block (in dollars).
$Exposure_{TSUN_{CB_{Bldg}}}$	is the building value exposed to Tsunami occurrences in the Census block (in dollars).

$Freq_{TSUN_{CB}}$	is the Tsunami annualized 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 population equivalence Expected Annual Loss due to Tsunami occurrences for a specific Census block (in dollars).
$Exposure_{TSUN_{CB_{Pop}}}$	is the population equivalence value exposed to Tsunami occurrences 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 building and population equivalence EAL values of their Census block values as in Equation 123.

Equation 123: 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 building Expected Annual Loss due to Tsunami occurrences for all Census blocks in the Census tract (in dollars).
$\sum_{CB}^{CT} EAL_{TSUN_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Tsunami occurrences for all Census blocks in the Census tract (in dollars).
$EAL_{TSUN_{Co}}$	is the total Expected Annual Loss due to Tsunami occurrences for a specific county (in dollars).
$\sum_{CB}^{Co} EAL_{TSUN_{CB_{Bldg}}}$	is the summed building Expected Annual Loss due to Tsunami occurrences for all Census blocks in the county (in dollars).
$\sum_{CB}^{Co} EAL_{TSUN_{CB_{Pop}}}$	is the summed population equivalence Expected Annual Loss due to Tsunami occurrences for all Census blocks in the county (in dollars).

Figure 156 shows the total EAL (building value and population equivalence combined) to Tsunami occurrences.

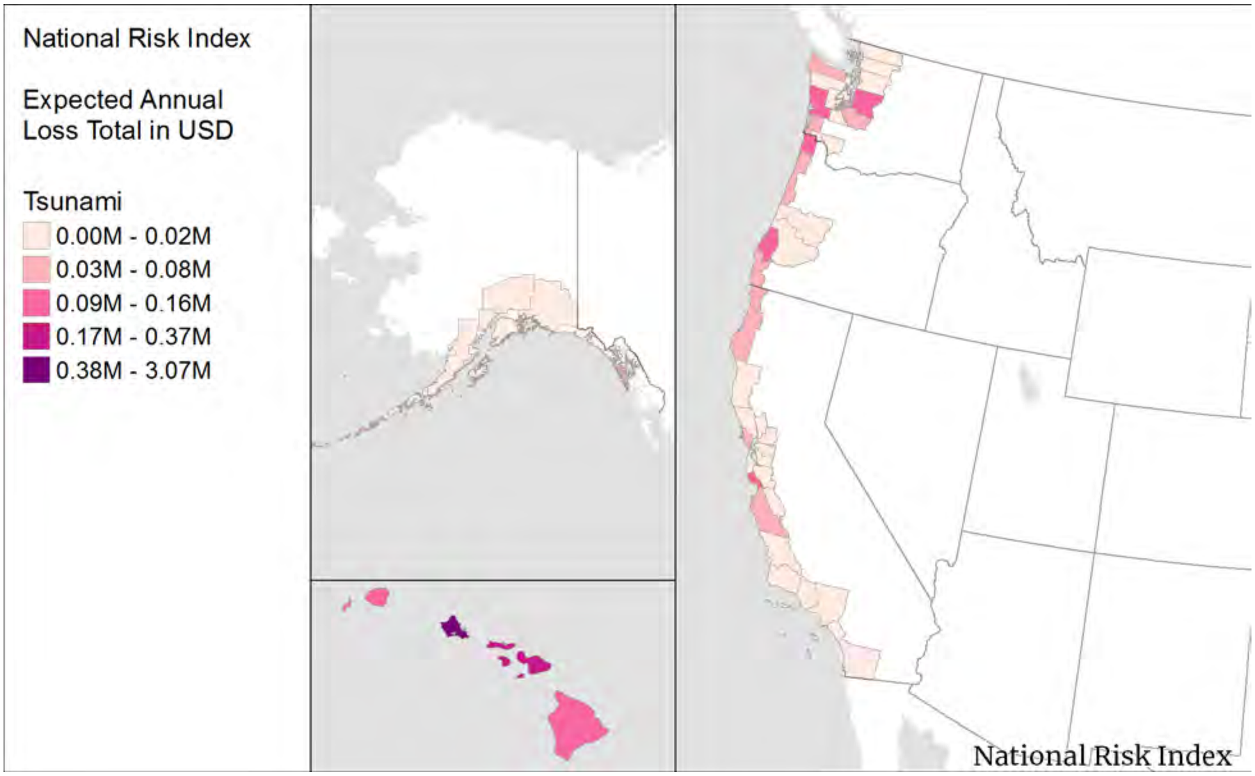

Figure 156: Total Expected Annual Loss by County to Tsunami

With the Tsunami total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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[86]

Historical Occurrence Source: Smithsonian Institution, Volcanoes of the World[87]

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 65 and Figure 157). 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 66).

Table 65: 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

[86] 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.
[87] 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.

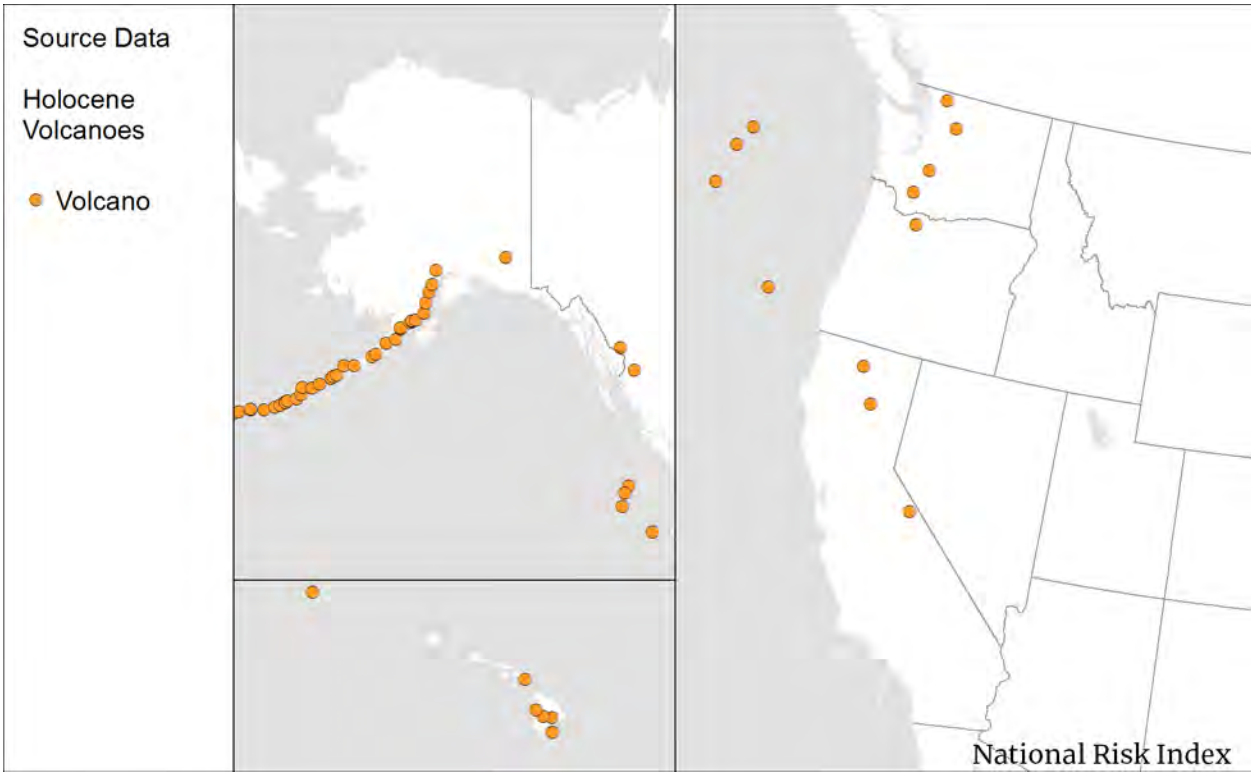

Figure 157: Map of Volcanoes

Table 66: 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 158). The 100-km buffer size was chosen as a worst-case scenario area of impact in case of eruption. The resulting volcano polygons are then used in calculating annualized frequency and exposure at the Census block level.

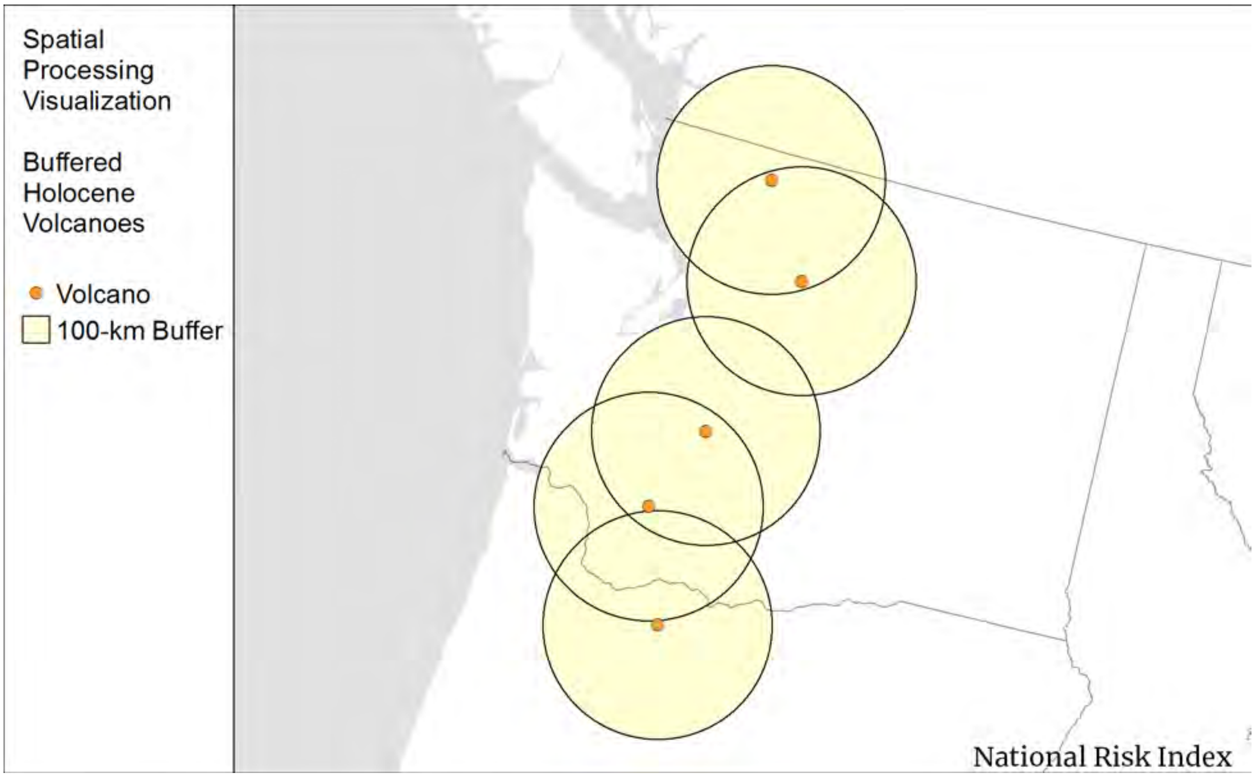

Figure 158: Buffered Volcanoes

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 159).

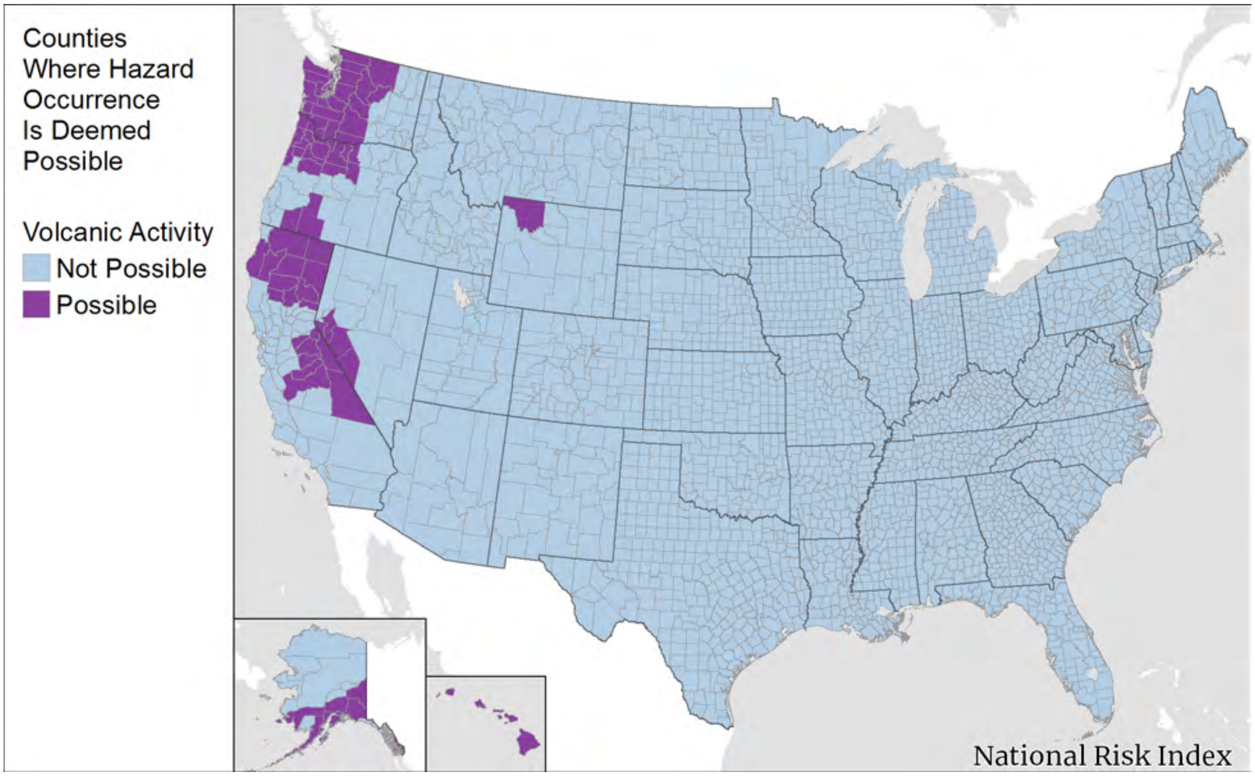

Figure 159: Map of Counties Deemed Possible for Volcanic Activity Occurrence

21.4. Exposure

To identify areas of exposure, the volcano polygons are intersected with the Census block polygons within the processing database. The resulting table contains the volcano's unique identifier, Census block number, and the intersected area in square kilometers (see Table 67).

Table 67: 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 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 density of the Census block to model the conservative-case concentration of exposure within the Census block (see Equation 124). These Census block densities have been calculated by dividing the total exposure values (as recorded in Hazus 4.2 SP1) by the developed land area (in square kilometers). The VSL was used to express population equivalence exposure in terms of dollars. Exposure is only computed for volcanoes designated as Holocene active in the GVM source data (H_active = 1).

Equation 124: 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 equivalence 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 ($7.6M 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 building value exceeds the Hazus-recorded building value, then the Hazus-recorded building value is used as the building 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 Census 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 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 equivalence 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 equivalence exposed to Volcanic Activity for each Census block within the Census tract (in dollars).
$Exposure_{VLCN_{Co_{Pop}}}$	is the population equivalence 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 equivalence exposed to Volcanic Activity for each Census block within the county (in dollars).

21.5. Volcano Count

The 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. Annualized Frequency

The annualized frequency of eruption or activity for volcanoes is exceptionally low (less than one eruption per 100 years for all counties except one) when compared to other types. An annualized 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 126. Annualized frequency is only computed for volcanoes that are designated as Holocene active in the GVM source data (H_active = 1).

Equation 126: Volcano Annualized 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 annualized 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 127, and the Census block-level value is used in the EAL calculations.

Annualized frequency calculations use the same intersection between volcano polygons and Census block polygons that was used to calculate exposure.

Equation 127: Census Block Area-Weighted Volcanic Activity Annualized Frequency

$$Freq_{VLCN_{CB}} = \frac{\sum_{VLCN}^{CB}\left(IntsctArea_{VLCN_{CB}} \times Freq_{VLCN}\right)}{Area_{CB}}$$

where:

$Freq_{VLCN_{CB}}$	is the area-weighted annualized 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 Volcanic Activity 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. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized frequency values at both the Census tract and county level. The annualized frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 128.

Equation 128: Census Tract and County Area-Weighted Volcanic Activity Annualized 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 area-weighted annualized 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 area-weighted annualized frequency of Volcanic Activity calculated for a specific county (occurrences 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 160 displays Volcanic Activity annualized frequency at the county level.

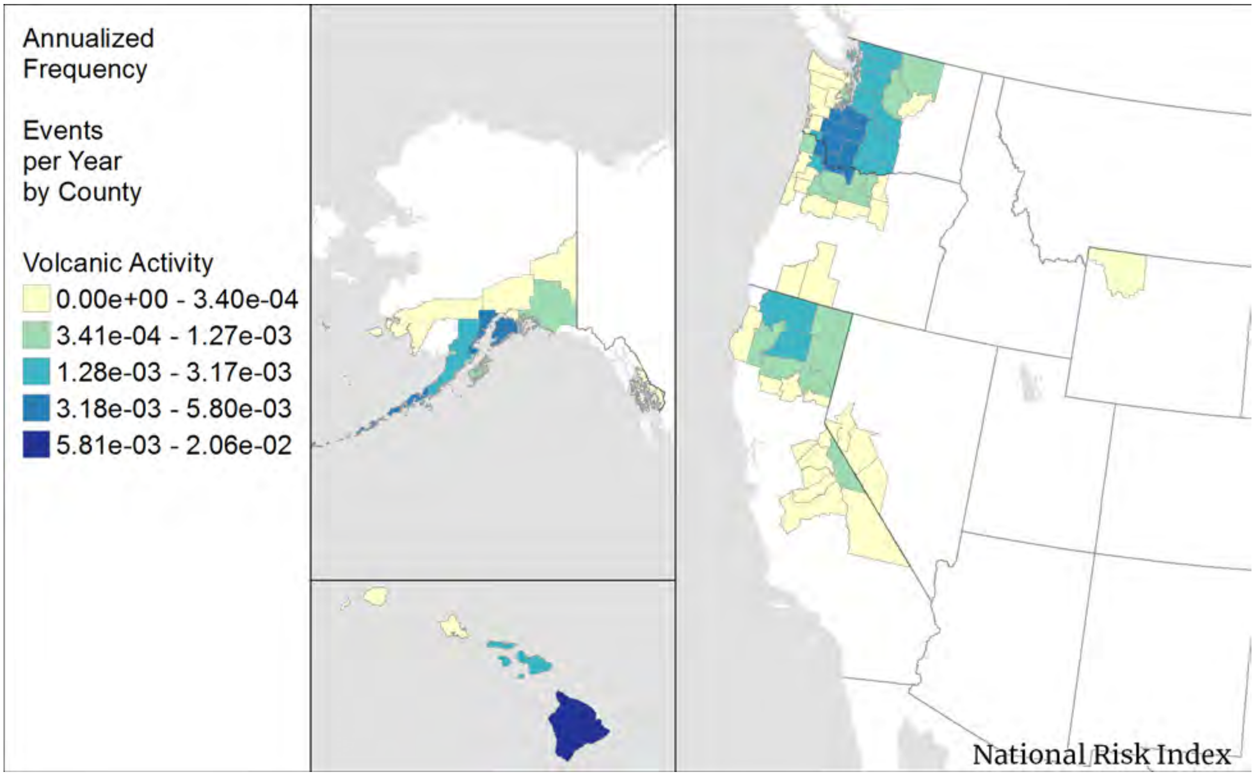

Figure 160: Volcanic Activity Annualized Frequency by County

21.7. Historic Loss Ratio

The Volcanic Activity HLR is the representative percentage of a location's hazard exposure that experiences loss due to a volcanic occurrence, or the average rate of loss associated with the volcanic occurrence. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Volcano Activity hazard type.

Loss data are provided by SHELDUS[88] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1960 to 2019 are included in the HLR calculation. Six peril types are mapped to the hazard Volcanic Activity (see Table 68). These native records are aggregated on a timeframe basis (see Section 5.4.4 Historic Loss Ratio Methodology).

[88] 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 68: Volcanic Activity Peril Types and Recorded Events from 1960-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Ashfall	28	17
Lahar	2	2
Lava Flow	1	1
Pyroclastic Flow	0	0
Vog	2	2
Volcano	9	9

The HLR exposure value for Volcanic Activity 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 129.

Equation 129: 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 or impacted people).

$HLRExposure_{VLCN_{Co_{CnsqType}}}$ is the value (by consequence type) of the susceptible area estimated to have been exposed to the volcanic event (in dollars or people).

A historic occurrence count is not computed for Volcanic Activity, so no zero-loss occurrences 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 161 and Figure 163 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 Bayesian-adjusted 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 Bayesian-adjusted HLR value, though its HLR may be influenced by other local or national occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing occurrences or have widely varying loss ratios get the most influence from national-level loss data. Figure 162 and Figure 164 represent the final, Bayesian-adjusted county-level HLR values for Volcanic Activity.

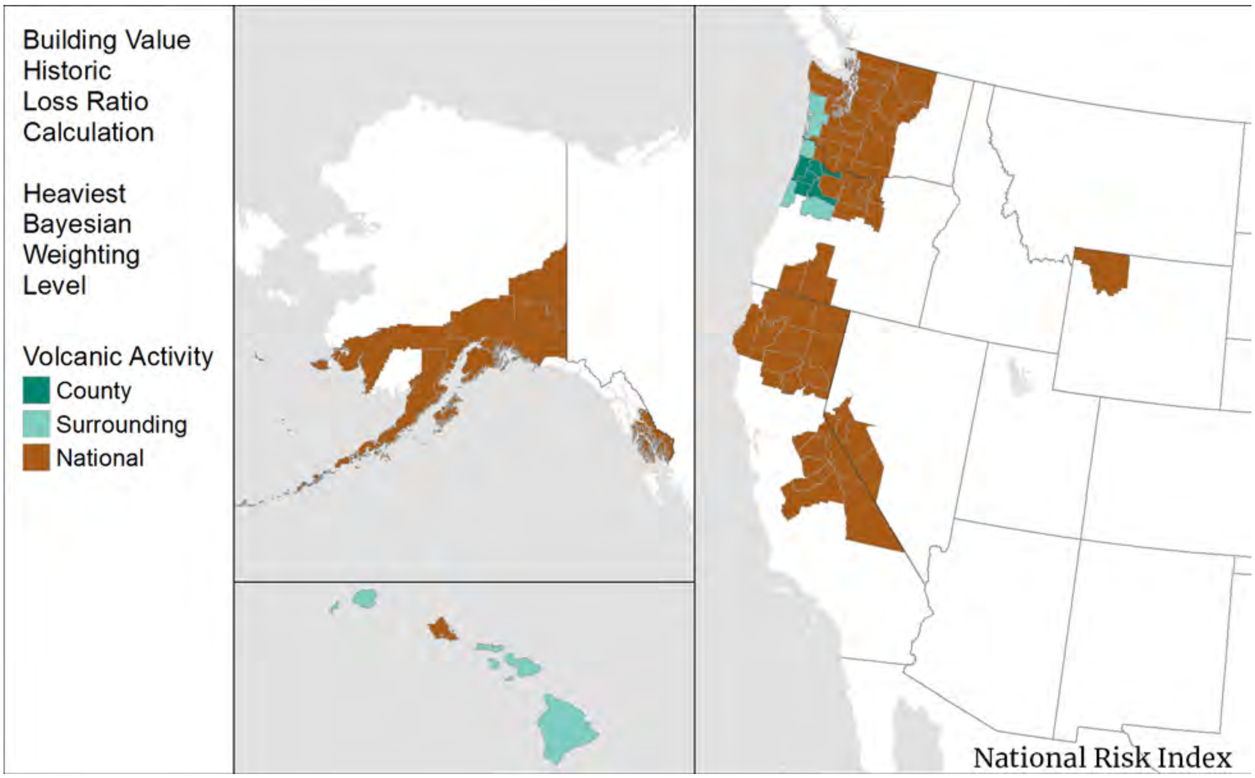

Figure 161: Volcanic Activity Heaviest Bayesian Influence Level – Building Value

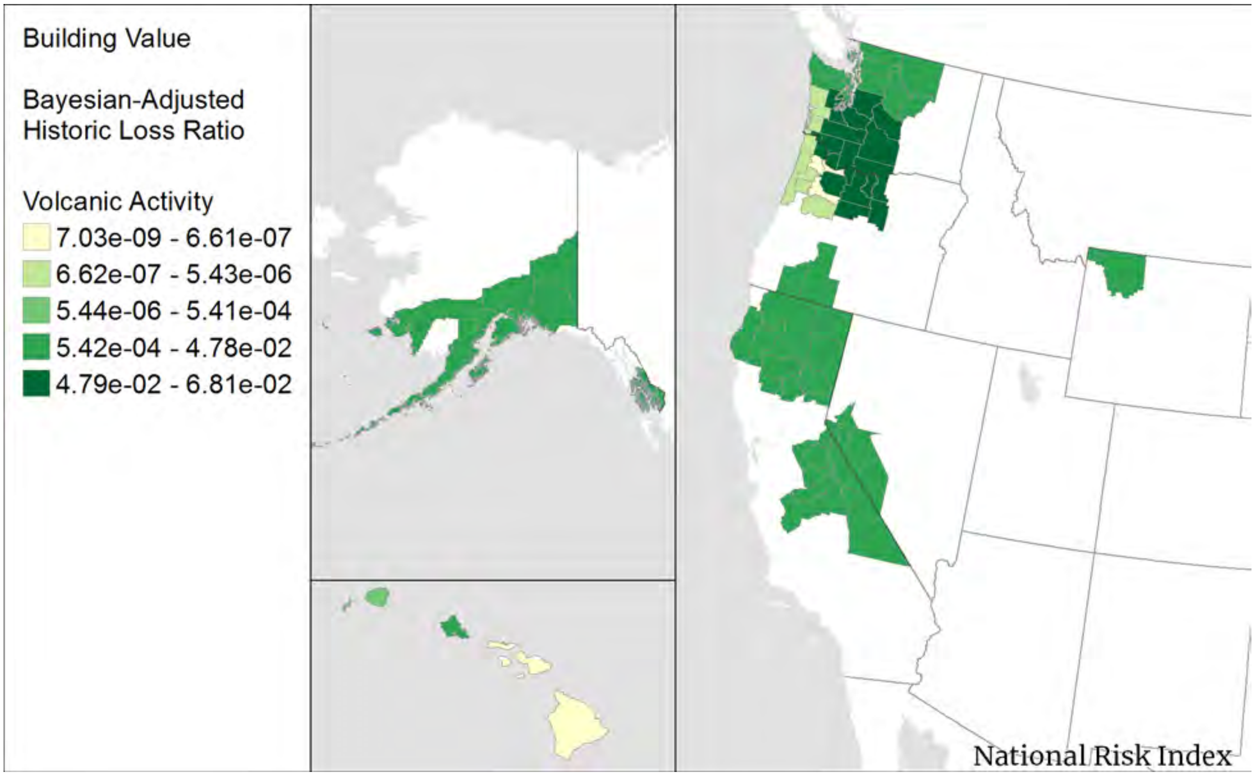

Figure 162: Volcanic Activity Bayesian-Adjusted HLR – Building Value

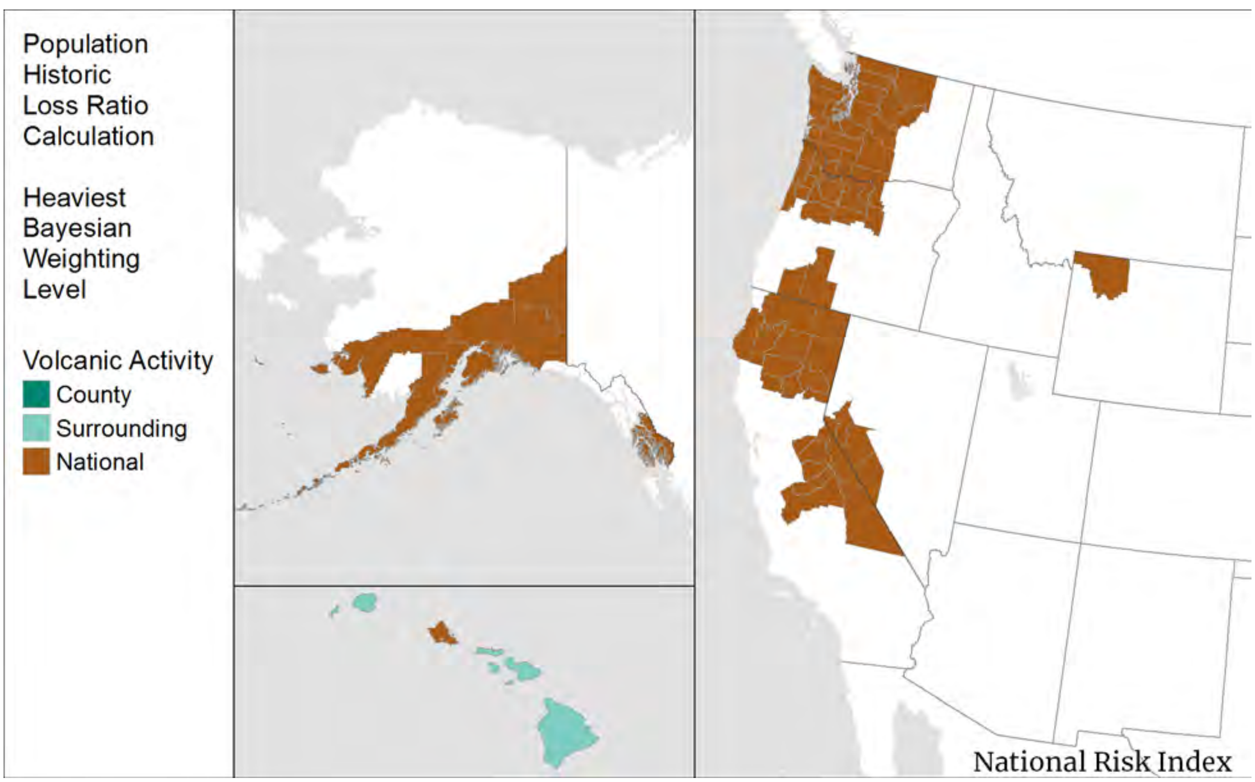

Figure 163: Volcanic Activity Heaviest Bayesian Influence Level – Population

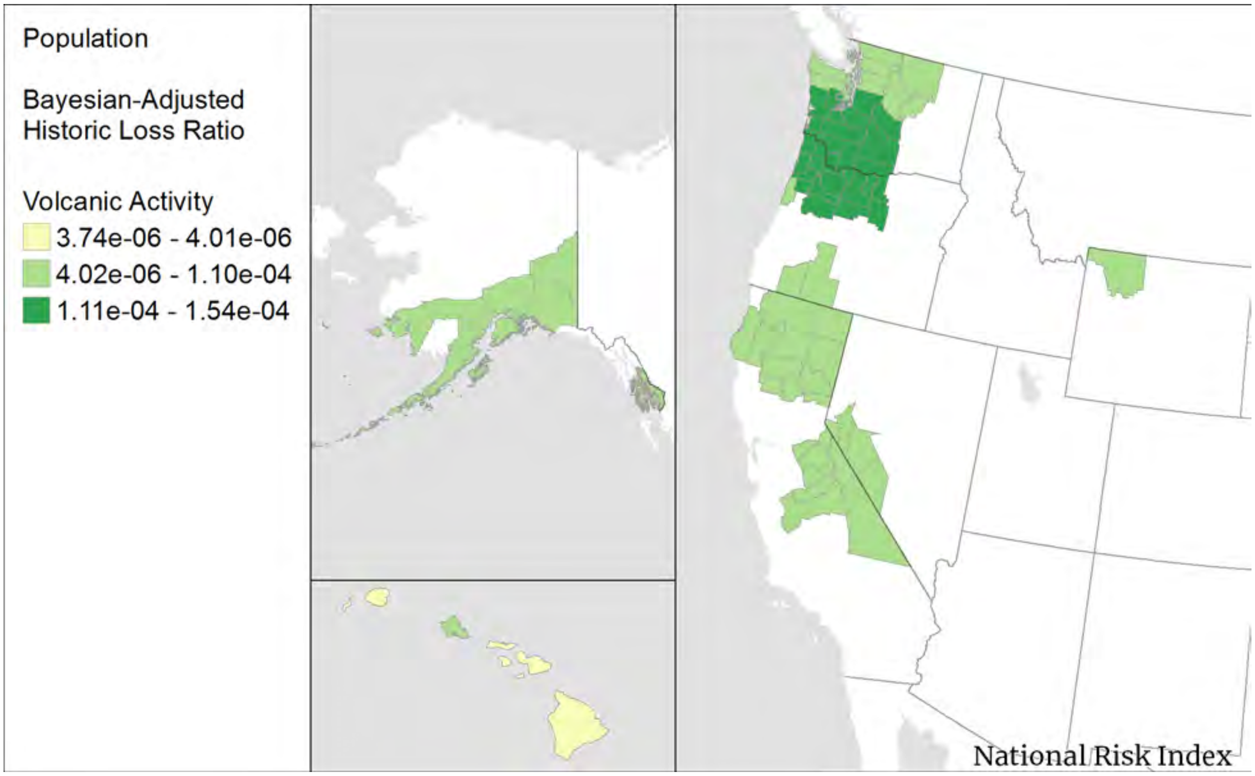

Figure 164: Volcanic Activity Bayesian-Adjusted HLR – Population

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

21.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 130. 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 130: 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 building Expected Annual Loss 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 Volcanic Activity annualized 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 population equivalence Expected Annual Loss due to Volcanic Activity for a specific Census block (in dollars).

$Exposure_{VLCN_{CB_{Pop}}}$ is the population equivalence 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 building and population equivalence EAL values at the Census block level as in Equation 131.

Equation 131: 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 building Expected Annual Loss due to Volcanic Activity for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{VLCN_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss 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 building Expected Annual Loss due to Volcanic Activity for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{VLCN\,CB_{Pop}}$ is the summed population equivalence Expected Annual Loss due to Volcanic Activity for all Census blocks in the county (in dollars).

Figure 165 shows the total EAL (population equivalence and building value combined) to Volcanic Activity.

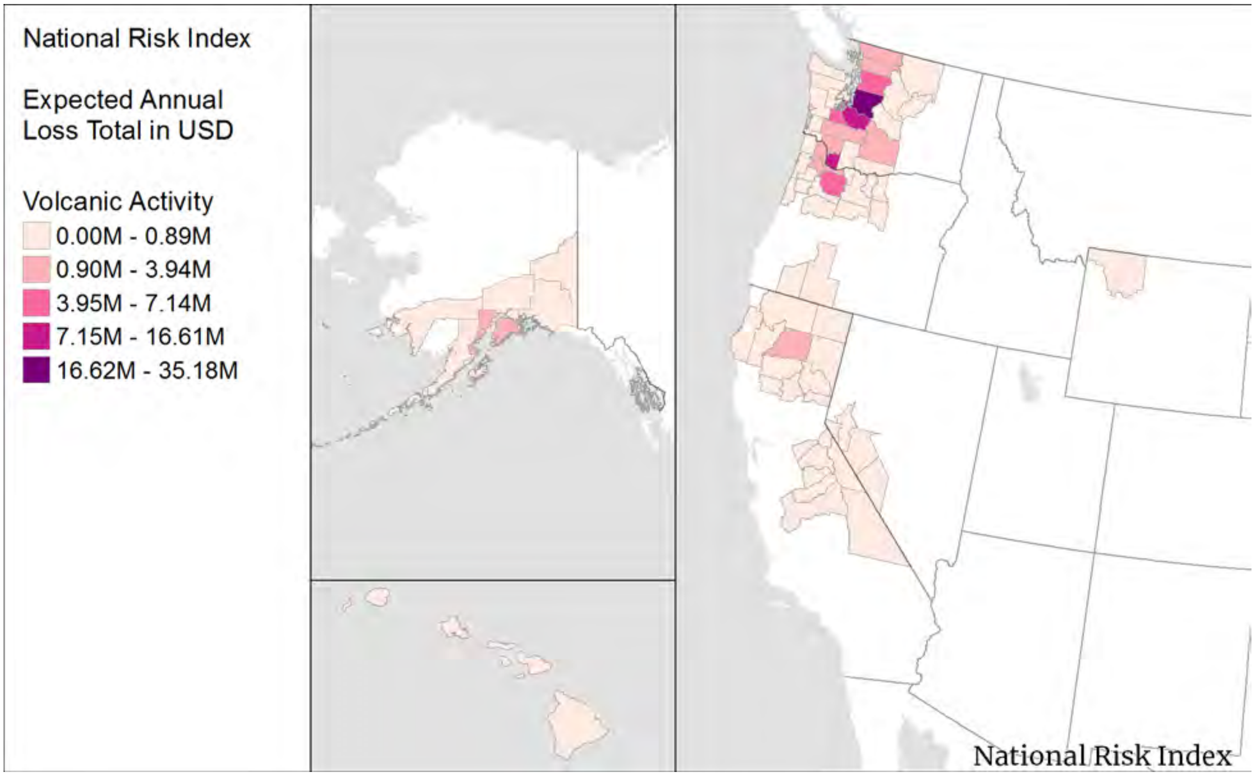

Figure 165: Total Expected Annual Loss by County to Volcano Activity

With the Volcanic Activity total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 Modeling and Susceptible Area Source: U.S. Department of Agriculture, Forest Service, FSim Burn Probability and Fire Intensity Level Data[89]

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 U.S. 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 166).

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, annualized frequency, and, therefore, EAL cannot be computed for these states.

[89] 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.

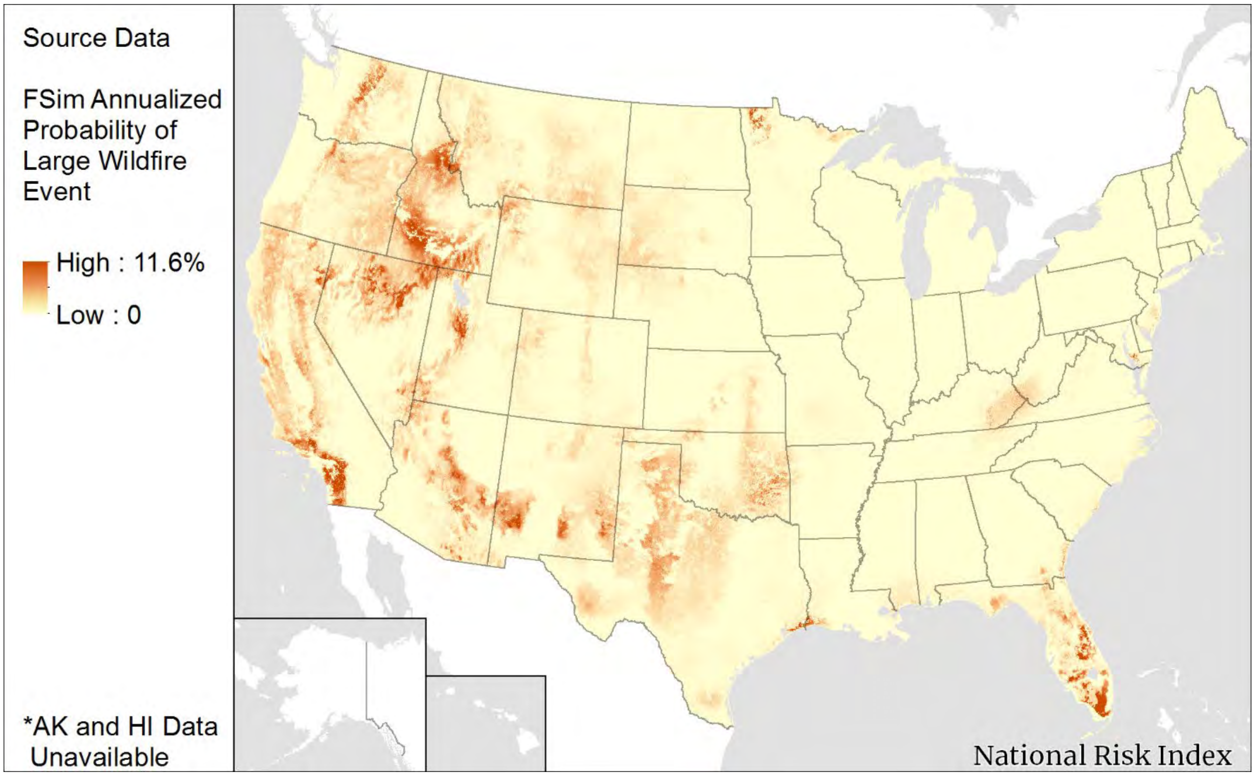

Figure 166: Burn Probability Raster

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 processing database. A polygon fishnet in 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 annualized frequency (see Table 69).

Table 69: 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 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 processing database. The resulting table contains the fishnet polygon's unique identifier, Census block number, and the intersected area in square kilometers (see Table 70).

Table 70: 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, the average population density, and the average agriculture value density of the Census block to model exposure within the Census block (see Equation 132). These average densities in the Census block 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). The VSL was used to express population equivalence exposure in terms of dollars.

Equation 132: Census Block Wildfire Exposure

$$Exposure_{WFIR_{CB_{Bldg}}} = \sum_{Fish}^{CB} IntsctArea_{WFIR_{Fish_{CB}}} \times AvgDen_{CB_{Bldg}}$$

$$Exposure_{WFIR_{CB_{Pop}}} = \left(\sum_{Fish}^{CB} IntsctArea_{WFIR_{Fish_{CB}}} \times AvgDen_{CB_{Pop}}\right) \times VSL$$

$$Exposure_{WFIR_{CB_{Ag}}} = \sum_{Fish}^{CB} IntsctArea_{WFIR_{Fish_{CB}}} \times AvgDen_{CB_{Ag}}$$

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 equivalence 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 ($7.6M per person).
$Exposure_{WFIR_{CB_{Ag}}}$	is the agriculture value exposed to Wildfire in a specific Census block (in dollars).
$AvgDen_{CB_{Ag}}$	is the average agriculture value density of the Census block (in dollars per square kilometer).

22.4.1. EXPOSURE AGGREGATION

To calculate exposure at the Census tract level, the exposure values for each Census block within the Census tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see Equation 133).

Equation 133: Census Tract and County Wildfire Exposure Aggregation

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

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

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

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

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

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

where:

$Exposure_{WFIR_{CT_{Bldg}}}$	is the building value exposed to Wildfire 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 exposed to Wildfire 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 equivalence value exposed to Wildfire in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{WFIR_{CB_{Pop}}}$	is the summed value of all population equivalence 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 equivalence value exposed to Wildfire in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{WFIR_{CB_{Pop}}}$	is the summed value of all population equivalence where the fire intensity level of 5 or 6 is greater than 0 for each Census block within the county (in dollars).
$Exposure_{WFIR_{CT_{Ag}}}$	is the agriculture value exposed to Wildfire in a specific Census tract (in dollars).
$\sum_{CB}^{CT} Exposure_{WFIR_{CB_{Ag}}}$	is the summed value of all agriculture where the fire intensity level of 5 or 6 is greater than 0 for each Census block within the Census tract (in dollars).
$Exposure_{WFIR_{Co_{Ag}}}$	is the agriculture value exposed to Wildfire in a specific county (in dollars).
$\sum_{CB}^{Co} Exposure_{WFIR_{CB_{Ag}}}$	is the summed value of all agriculture where the fire intensity level of 5 or 6 is greater than 0 for each Census block within the county (in dollars).

22.5. Annualized Frequency

The annualized 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 134), and the Census block-level value is used in the EAL calculations.

Annualized frequency calculations use the same intersection between Wildfire-probability fishnet polygons and Census block polygons that were used to calculate exposure.

Equation 134: Census Block Area-Weighted Wildfire Annualized 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 area-weighted annualized 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. ANNUALIZED FREQUENCY AGGREGATION

The annualized frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 135.

Equation 135: Census Tract and County Area-Weighted Wildfire Annualized 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 area-weighted Wildfire annualized frequency for a specific Census tract.
$Freq_{WFIR_{CB}}$	is the area-weighted annualized frequency of Wildfire probability determined for 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).
$Freq_{WFIR_{Co}}$	is the area-weighted Wildfire annualized 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 167 displays Wildfire annualized frequency at the county level.

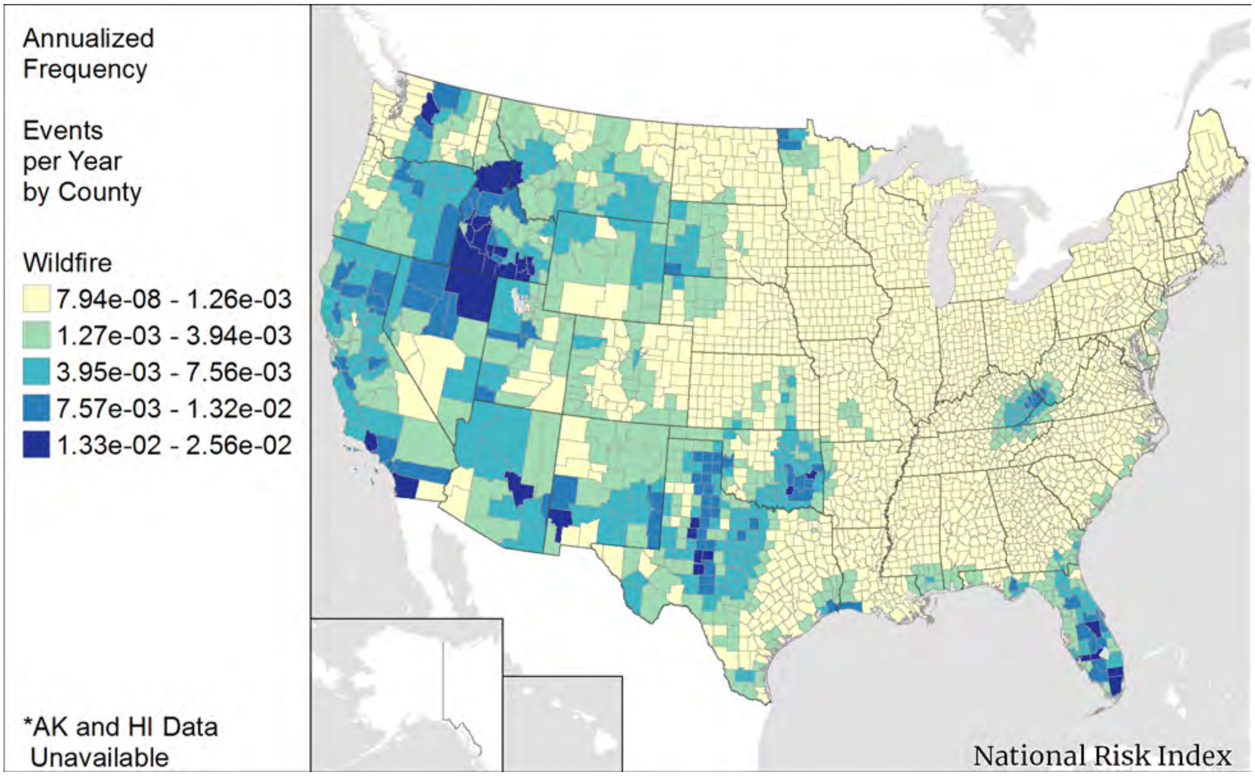

Figure 167: Wildfire Annualized Frequency by County

22.6. Historic Loss Ratio

The Wildfire HLR is the representative percentage of a location's hazard exposure that experiences loss due to a Wildfire occurrence, or the average rate of loss associated with a Wildfire occurrence. For a detailed description of the HLR calculation process, see Section 5.4 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Wildfire hazard type.

Loss data are provided by SHELDUS[90] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Five peril types are mapped to the hazard Wildfire (see Table 71). These native records are aggregated on a timeframe basis (see Section 5.4.4 Historic Loss Ratio Methodology).

Table 71: Wildfire Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Fire-Brush	0	0
Fire-Bush	0	0
Fire-Forest	150	144

90 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*
Fire-Grass	0	0
Wildfire	2,933	2,367

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 0.4. (Bayesian credibility is not utilized for building value HLR). Using this default value resulted in a nationwide building EAL to Wildfire that best approximated the average annual building loss reported in SHELDUS.

For population and agriculture, the HLR exposure values used in the LRB calculation are the population and agriculture value of the county's area that is most susceptible to Wildfire. This value is determined by summing the average population density or average agriculture value 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 136.

Equation 136: Loss Ratio per Basis Calculation for a Single Wildfire Event

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

where:

$LRB_{WFIR_{Co_{CnsqType}}}$	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 Wildfire event. Calculation is performed for population and agriculture.
$Loss_{WFIR_{Co_{CnsqType}}}$	is the loss (by consequence type) experienced from the Wildfire event documented to have occurred in the county (in dollars or impacted people).
$HLRExposure_{Co_{CnsqType}}$	is the value (by consequence type) of the susceptible area estimated to have been exposed to the Wildfire event (in dollars or people).

Wildfire frequency is based on a probabilistic model, so no zero-loss occurrences are inserted into the Loss Ratio table. After the population and agriculture 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 168 and Figure 170 display the largest weighting factor contributor in the Bayesian credibility calculation for the Wildfire population and agriculture value HLR of every county. This contributor is not necessarily the only geographic level contributing to the county's Bayesian-adjusted HLR. For example, a county for which the largest weighting factor contributor is the county-level data has experienced enough Wildfire occurrences within the county that its loss data are the dominant driver for its Bayesian-adjusted HLR value, though its HLR may be influenced by other local or national occurrences. The surrounding area's loss ratios have the greatest influence on the Bayesian-adjusted HLR of a county for which the largest weighting factor contributor is the surrounding-level data. Counties that have experienced few loss-causing occurrences or have widely varying loss ratios get the most influence from national-level loss data. Figure 169 and Figure 171 represent the final, Bayesian-adjusted county-level population and agriculture HLR values for Wildfire.

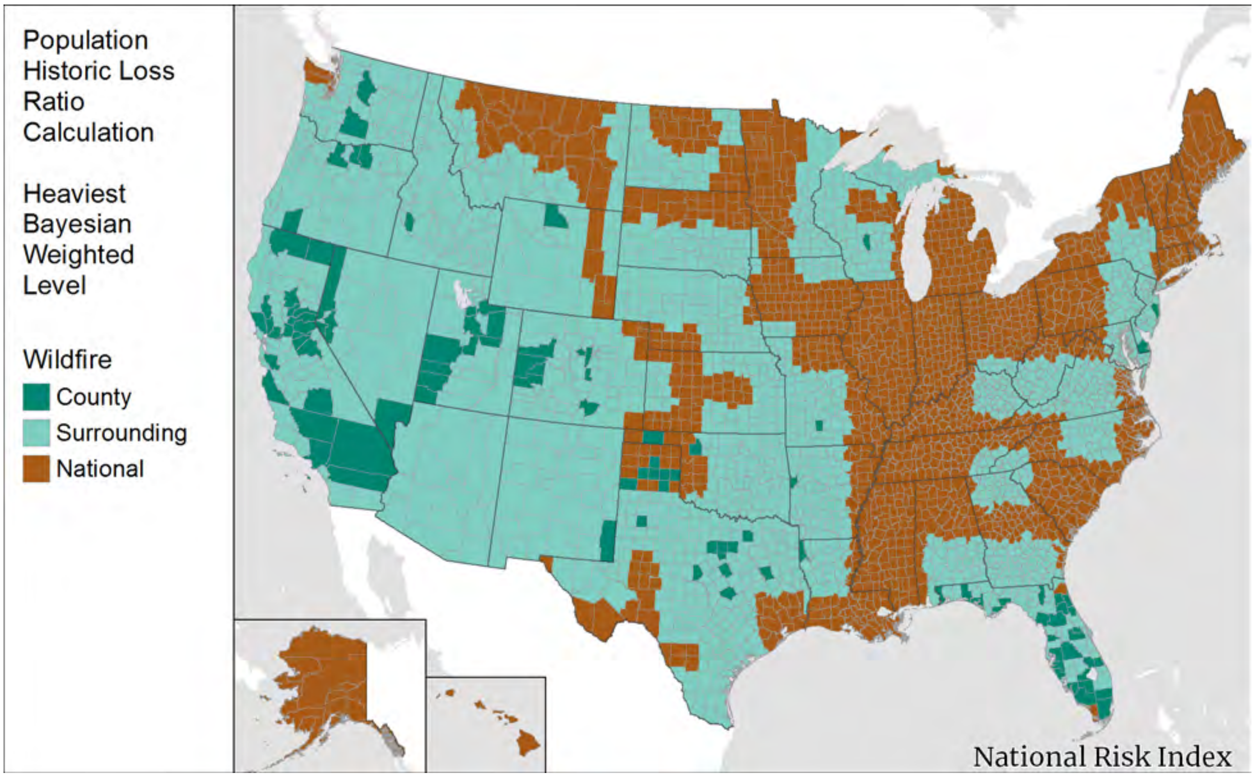

Figure 168: Wildfire Heaviest Bayesian Influence Level – Population

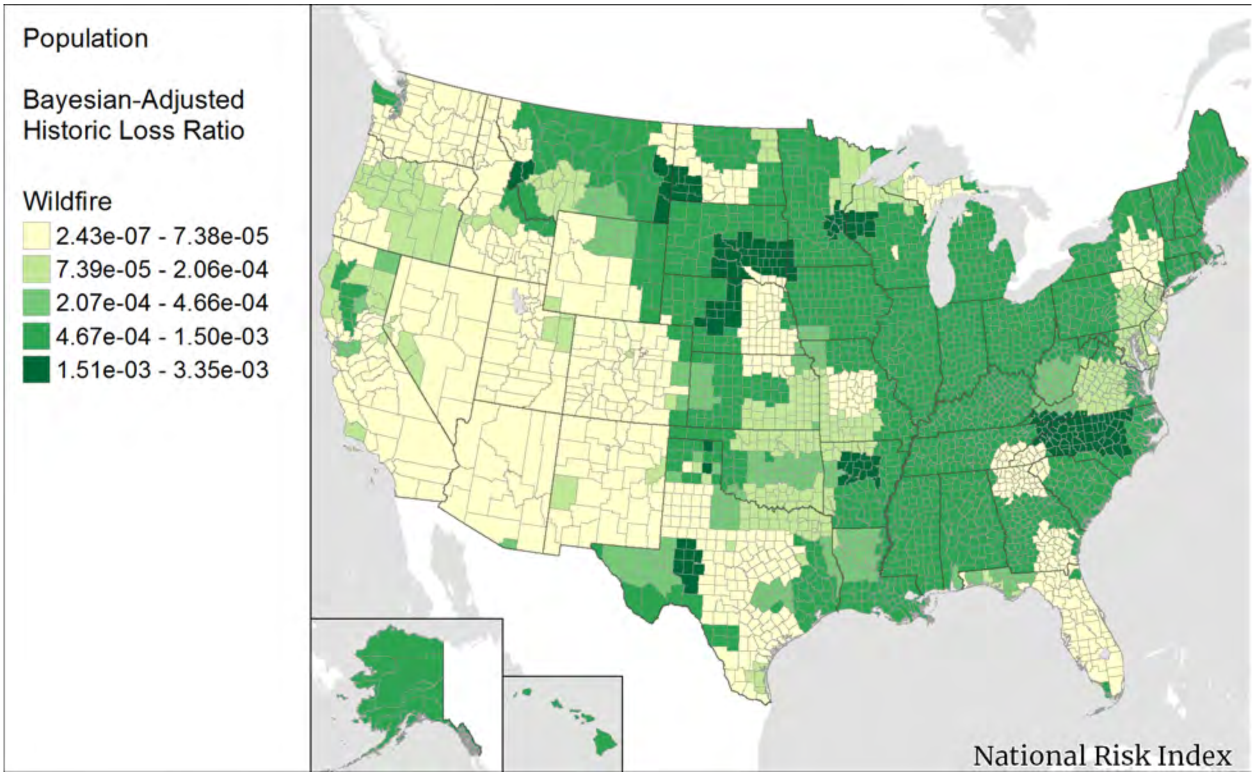

Figure 169: Wildfire Bayesian-Adjusted HLR – Population

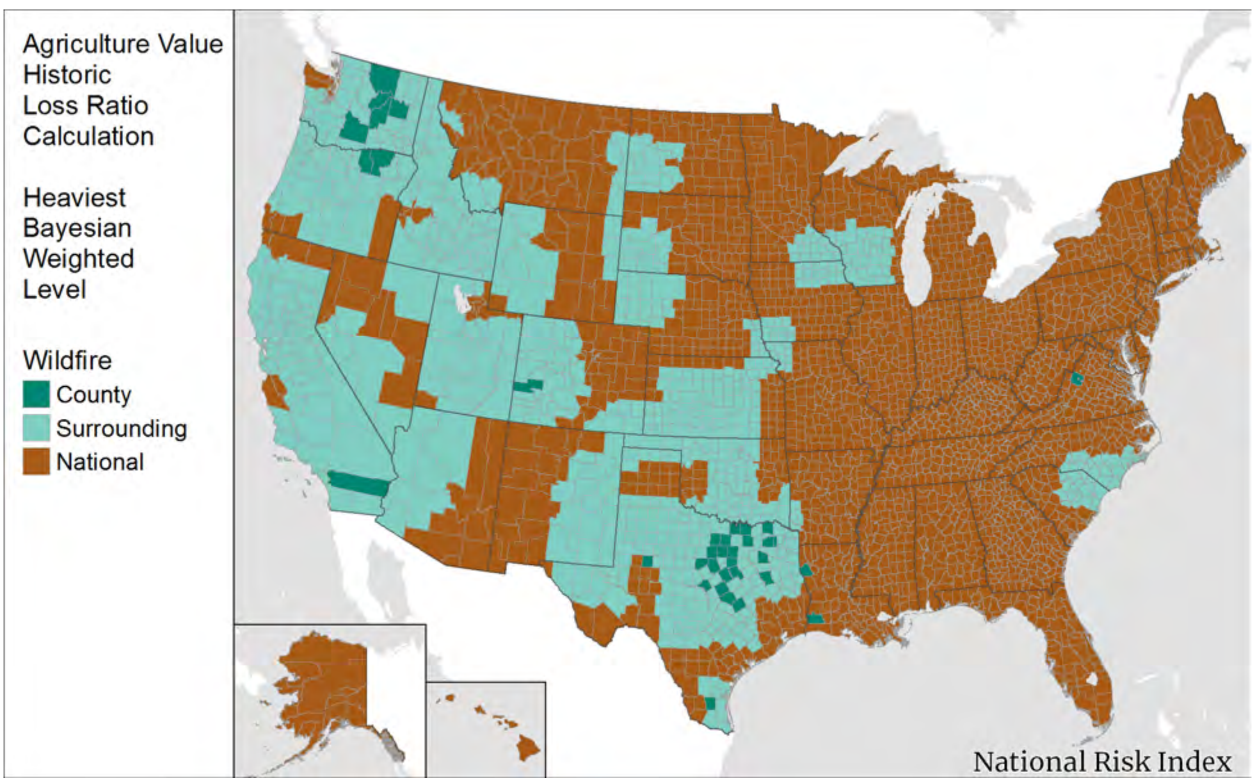

Figure 170: Wildfire Heaviest Bayesian Influence Level – Agriculture Value

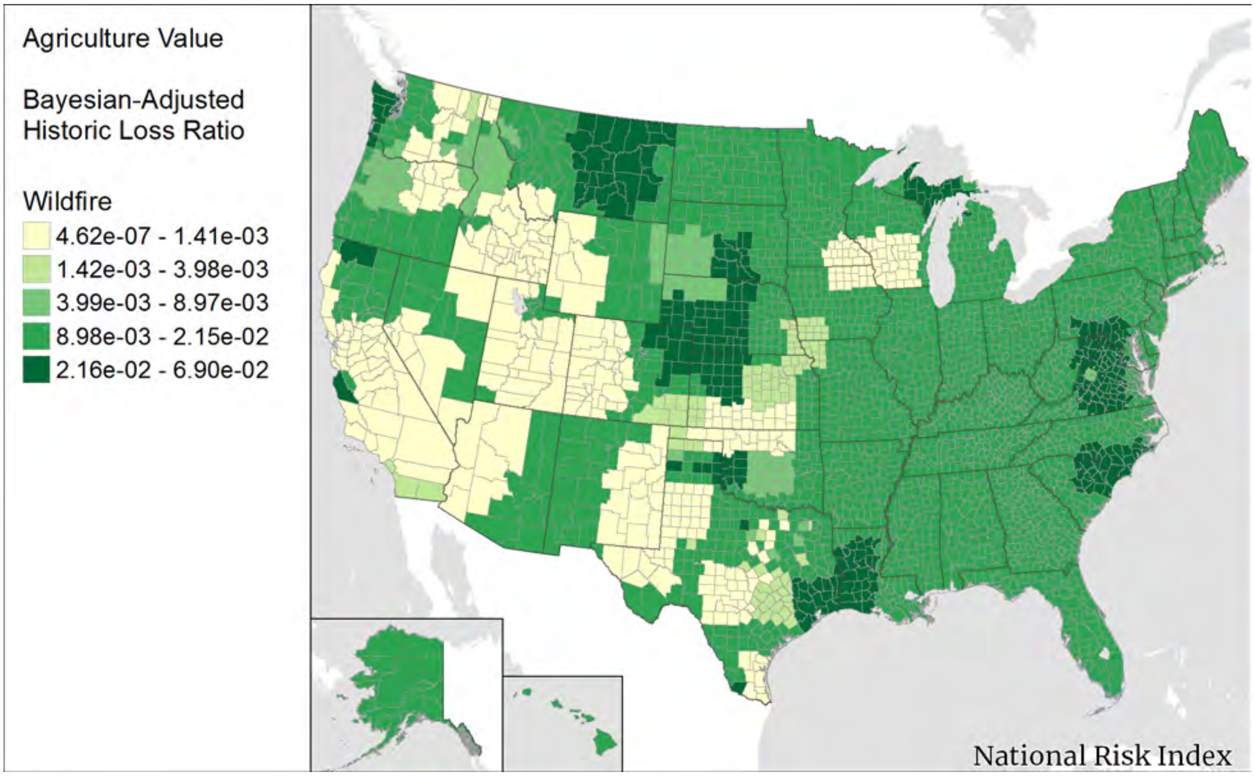

Figure 171: Wildfire Bayesian-Adjusted HLR – Agriculture Value

The resulting population Bayesian-adjusted HLR is then inherited by the Census blocks and Census tracts within the parent county.

22.7. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 137. 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 137: Census Block Expected Annual Loss to Wildfire

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

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

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

where:

$EAL_{WFIR_{CB_{Bldg}}}$	is the building Expected Annual Loss due to Wildfire occurrences 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 Wildfire annualized 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 population equivalence Expected Annual Loss due to Wildfire occurrences for a specific Census block (in dollars).
$Exposure_{WFIR_{CB_{Pop}}}$	is the population equivalence 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.
$EAL_{WFIR_{CB_{Ag}}}$	is the agriculture Expected Annual Loss due to Wildfire occurrences for a specific Census block (in dollars).
$Exposure_{WFIR_{CB_{Ag}}}$	is the agriculture value where the flame intensity level of 5 or 6 is greater than 0 in the Census block (in dollars).
$HLR_{WFIR_{CB_{Ag}}}$	is the Bayesian-adjusted agriculture 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 building, population equivalence, and agriculture EAL values at the Census block level as in Equation 138.

Equation 138: Census Tract and County Expected Annual Loss to Wildfire

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

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

where:

$EAL_{WFIR_{CT}}$	is the total Expected Annual Loss due to Wildfire occurrences for a specific Census tract (in dollars).

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

$\sum_{CB}^{CT} EAL_{WFIR_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Wildfire occurrences for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{WFIR_{CB_{Ag}}}$ is the summed agriculture Expected Annual Loss due to Wildfire occurrences for all Census blocks in the Census tract (in dollars).

$EAL_{WFIR_{Co}}$ is the total Expected Annual Loss due to Wildfire occurrences for a specific county (in dollars).

$\sum_{CB}^{Co} EAL_{WFIR_{CB_{Bldg}}}$ is the summed building Expected Annual Loss due to Wildfire occurrences for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{WFIR_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Wildfire occurrences for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{WFIR_{CB_{Ag}}}$ is the summed agriculture Expected Annual Loss due to Wildfire occurrences for all Census blocks in the county (in dollars).

Figure 172 shows the total EAL (building, population equivalence, and agriculture value combined) to Wildfire occurrences.

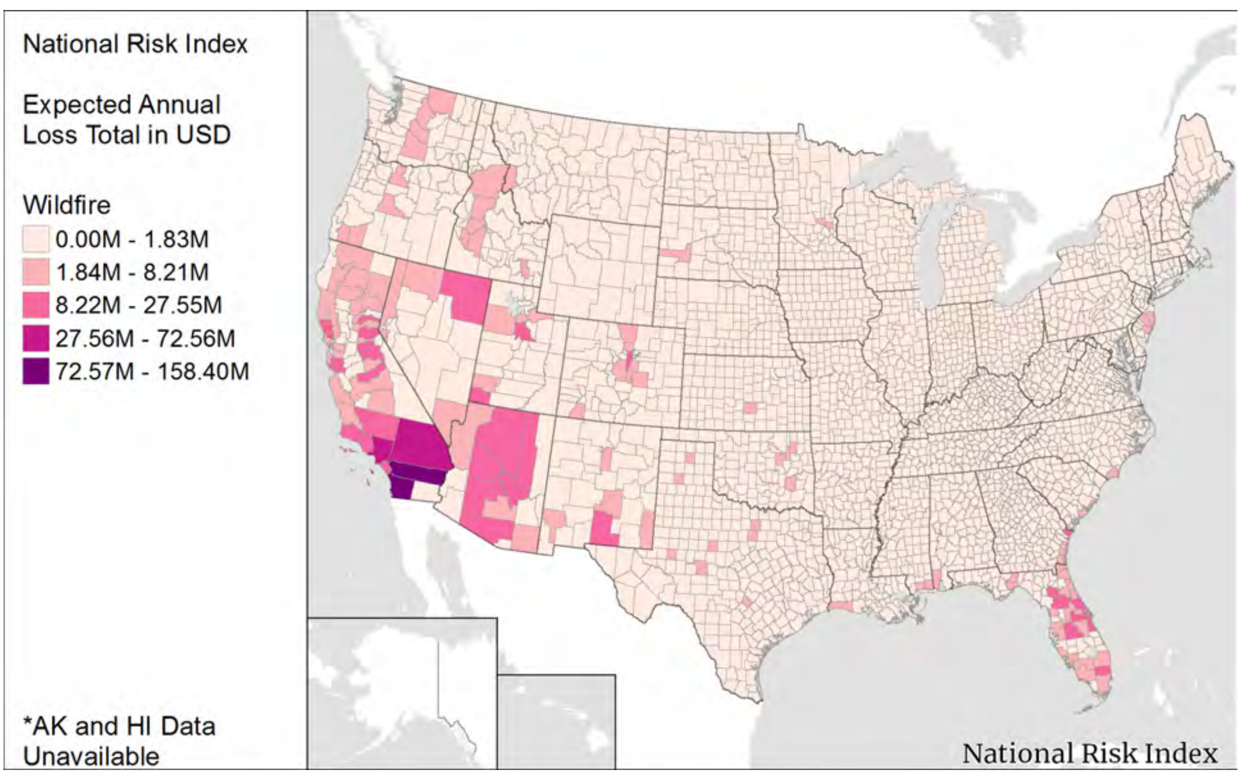

Figure 172: Total Expected Annual Loss by County to Wildfire

With the Wildfire total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 Occurrence Generating Source: National Weather Service, Winter Weather Alerts[91]

Historical Occurrence Compiling Source: Iowa State University, Iowa Environmental Mesonet[92]

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 annualized 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[93] 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.

Utilizing the Public Forecast Zone shapefile in conjunction with the Public Forecast Zone – County Correlation file,[94] a determination was made as to which Public Forecast Zones have single-county

[91] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *Active Alerts* [online dataset]. Retrieved from https://www.weather.gov/.
[92] Department of Agronomy, Iowa State University. (2018). *Iowa Environmental Mesonet* [online database]. Retrieved from https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml.
[93] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *NWS Public Forecast Zones* [online dataset]. Retrieved from https://www.weather.gov/gis/PublicZones.
[94] National Weather Service, National Oceanic and Atmospheric Administration. (2018). *Zone-County Correlation File* [online dataset]. Retrieved from https://www.weather.gov/gis/ZoneCounty.

coverage and which are either sub-county zones or made of portions of multiple counties. For perspective, the following approximate distributions 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.

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 many 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.

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 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. See Figure 173 for an example of the differences in the spatial resolution of weather alert boundaries.

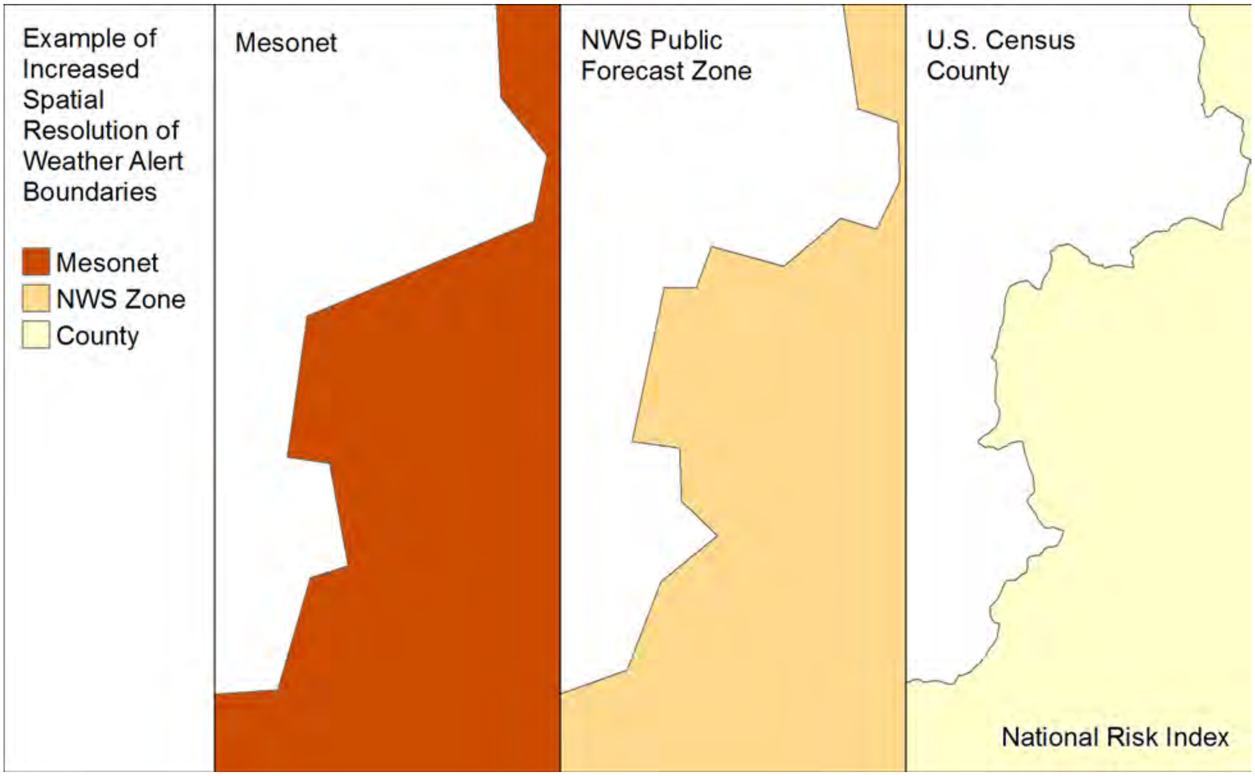

Figure 173: Three Boundary Definitions: Mesonet, Forecast Zone, and U.S. Census County

23.1.1. PERIOD OF RECORD

In the 1990s and early 2000s, the NWS's system of recording WWA made automated processing too difficult. So, in 2005, the 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 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 annualized 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 72 are considered NRI Winter Weather events (see Table 73).

Table 72: 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 73: Original Mesonet Winter Weather Records

WFO	*ISSUED*	*EXPIRED*	*PHENOM*	*SIG*	*NWS_UGC*	*AREA_KM2*
GJT	2/27/2017 1:00 PM	3/1/2017 3:39 AM	WS	W	COZ019	9720.85253906
PHI	3/14/2017 12:00 AM	3/14/2017 6:49 PM	BZ	W	NJZ001	1386.35180664
AFG	3/29/2008 8:00 PM	3/30/2008 12:17 PM	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. To illustrate this concept, the Winter Weather occurrences in Table 74 are expanded to create the Winter Weather event-day records in Table 75.

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.

Table 74: 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 PM	3/1/2017 3:39 AM	WS	W	COZ019	9707.610	Census County
45253	AJK	3/12/2017 11:50 PM	3/14/2017 2:00 AM	WS	W	AKZ022	4153.062	NWS Forecast Zone
45416	CYS	2/27/2017 9:00 PM	2/28/2017 10:02 AM	WS	W	WYZ112	2354.592	NWS Forecast Zone

Table 75: Sample Data from the Winter Weather Date Expansion Table

WinterStormDate ExpansionID	*WinterStormID*	*Issued*	*Expired*	*DateType*	*WinterStormHours*
35072	45437	2/27/2017 1:00 PM	2/28/2017 12:00 AM	Expanded Dates - Issued	11
35073	45437	2/28/2017 12:00 AM	3/1/2017 12:00 AM	Expanded Dates - New Dates	24
35058	45253	3/13/2017 12:00 AM	3/14/2017 12:00 AM	Expanded Dates - New Dates	24
35067	45416	2/28/2017 12:00 AM	2/28/2017 10:02 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 annualized frequency.

23.3. Determination of Possibility of Hazard Occurrence

Winter Weather can occur almost anywhere in the U.S. as the definition of a Winter Weather occurrence is locally defined by the area's weather forecast office. For example, a forecast office in Texas may define a Winter Weather occurrence 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 Spatial Processing) are intersected with the Census block polygons within the 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 76).

Table 76: 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-day polygons that intersected the Census block and dividing this sum by the number of intersecting event-day polygons. This is multiplied by the developed area building value density, the developed area population density, and the agriculture area value density of the Census block to model the conservative-case concentration of exposure within the Census block (see Equation 139). The densities of the Census block have been calculated by dividing the total exposure values (as recorded in Hazus 4.2 SP1) by the developed or agriculture land area (in square kilometers). The VSL was used to express population equivalence exposure in terms of dollars.

Equation 139: Census Block Winter Weather Exposure

$$Exposure_{WNTW_{CB_{Bldg}}} = \frac{\sum IntsctArea_{WNTW_{CB}}}{EventDayCount_{WNTW_{CB}}} \times DevAreaDen_{CB_{Bldg}}$$

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

$$Exposure_{WNTW_{CB_{AG}}} = \frac{\sum IntsctArea_{WNTW_{CB}}}{EventDayCount_{WNTW_{CB}}} \times AgValueDen_{CB}$$

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).
$EventDayCount_{WNTW_{CB}}$	is the total number of Winter Weather event-day polygons 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 equivalence 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 ($7.6M per person).
$Exposure_{WNTW_{CB_{Ag}}}$	is the agriculture value exposed to Winter Weather 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 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 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 building value exceeds the Hazus-recorded building value, then the Hazus-recorded building value is used as the building 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 Census tract are summed. To calculate exposure at the county level, the exposure values for each Census block within the county are summed (see Equation 140).

Equation 140: Census Tract and County Winter Weather Exposure Aggregation

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

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

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

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

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

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

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 equivalence 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 equivalence exposed to Winter Weather for each Census block within the Census tract (in dollars).
$Exposure_{WNTW_{Co_{Pop}}}$	is the population equivalence 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 equivalence exposed to Winter Weather for each Census block within the county (in dollars).

$Exposure_{WNTW_{CT_{Ag}}}$ is the agriculture value exposed to Winter Weather event-days in a specific Census tract (in dollars).

$\sum_{CB}^{CT} Exposure_{WNTW_{CB_{Ag}}}$ is the summed value of all agriculture areas exposed to Winter Weather for each Census block within the Census tract (in dollars).

$Exposure_{WNTW_{Co_{Ag}}}$ is the agriculture value exposed to Winter Weather event-days in a specific county (in dollars).

$\sum_{CB}^{Co} Exposure_{WNTW_{CB_{Ag}}}$ is the summed value of all agriculture areas exposed to Winter Weather for each Census block within the county (in dollars).

23.5. Historic Occurrence Count

The historic occurrence count of Winter Weather, in 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 Census 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 annualized 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. Annualized Frequency

The number of recorded Winter Weather occurrences, in event-days, each year over the period of record (12.14 years) is used to estimate the annualized frequency of Winter Weather events in an area. Because a Winter Weather event can last over several days or a single day, an event-day basis was used to estimate annualized frequency as this method better captures the variability in duration between occurrences. The annualized frequency is calculated at the Census block level using Equation 141, and the Census block-level value is used in the EAL calculations.

Annualized 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 141: Census Block Winter Weather Annualized Frequency

$$Freq_{WNTW_{CB}} = \frac{EventDayCount_{WNTW_{CB}}}{PeriodRecord_{WNTW}}$$

where:

$Freq_{WNTW_{CB}}$	is the annualized frequency of Winter Weather event-days determined for a specific Census block (event-days per year).
$EventDayCount_{WNTW_{CB}}$	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. ANNUALIZED FREQUENCY AGGREGATION

The application provides area-weighted average annualized 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 occurrences at the Census tract and county level by the period of record. The annualized frequency values at the Census block level are rolled up to the Census tract and county levels using area-weighted aggregations as in Equation 142.

Equation 142: Census Tract and County Area Weighted Winter Weather Annualized 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 area-weighted Winter Weather annualized frequency for a specific Census tract.
$Freq_{WNTW_{CB}}$	is the Winter Weather annualized 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 annualized 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 174 displays Winter Weather annualized frequency at the county level.

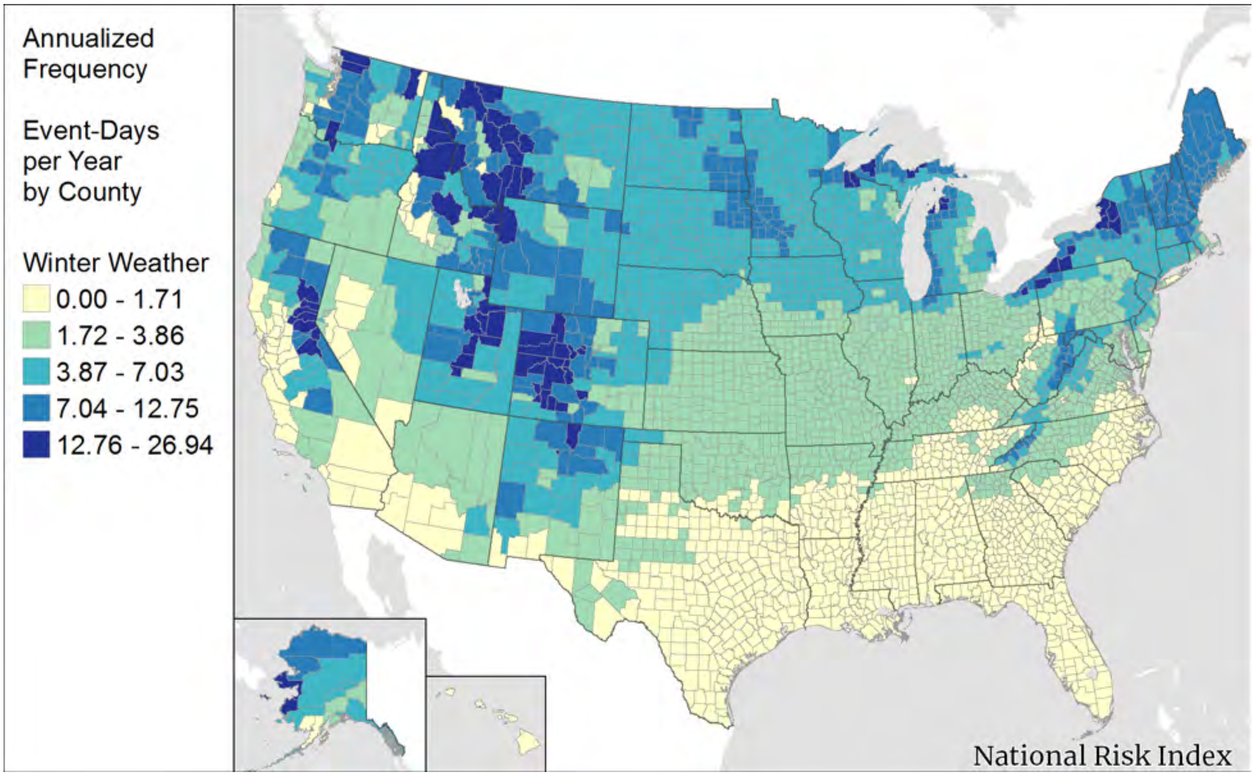

Figure 174: Winter Weather Annualized Frequency by County

23.7. Historic Loss Ratio

The Winter Weather HLR is the representative percentage of a location's hazard exposure 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 Natural Hazard Historic Loss Ratio. The HLR parameters described below are specific to the Winter Weather hazard type.

Loss data are provided by SHELDUS[95] at the county level, so this is the lowest level at which HLR can be calculated. SHELDUS events from 1996 to 2019 are included in the HLR calculation. Three peril types are mapped to the hazard Winter Weather (see Table 77). These native records are expanded on an event-day basis (to a maximum of 31 event-days) and aggregated on a single-event-per-day basis (see Section 5.4.4 Historic Loss Ratio Methodology).

95 For Winter Weather loss information, SHELDUS compiles data from the monthly Storm Data publication produced by NOAA's National Centers for Environmental Information.

Table 77: Winter Weather Peril Types and Recorded Events from 1996-2019

Peril Type in SHELDUS	*Total SHELDUS Loss Records*	*Total Records per Event Basis*
Blizzard	1,968	3,738
Storm-Winter	9,840	18,044
Winter Weather	3,346	4,048

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, or the total agriculture value of a county as recorded in Hazus 4.2 SP1. The LRB for each SHELDUS-documented event-day and each consequence type (building, population, and agriculture) is calculated using Equation 143.

Equation 143: 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, population, and agriculture).

$Loss_{WNTW_{Co_{CnsqType}}}$ is the loss (by consequence type) experienced from the Winter Weather event-day documented to have occurred in the county (in dollars or impacted people).

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

Winter Weather 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-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 (1996 to 2019). For Winter Weather, the historic event-day count is extracted using the intersection between the Winter Weather event-day polygons and the Census block polygons used to calculate exposure and annualized frequency (see Table 75). An annual rate is calculated as the event-day count divided by the period of record of 12.14 years, and this rate is multiplied by the SHELDUS period of record of 24 years to estimate a historic event-day count for the appropriate time range.

If the number of loss-causing Winter Weather event-day records from SHELDUS is less than the scaled event-day count for the county, then a number of zero-loss records equal to the difference are 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 1, 2, and 3 merged (see Section 5.4.4 Historic Loss Ratio Methodology).

Figure 175, Figure 177, and Figure 179 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 Bayesian-adjusted 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 Bayesian-adjusted 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 Bayesian-adjusted 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 176, Figure 178, and Figure 180 represent the final, Bayesian-adjusted county-level HLR values for Winter Weather.

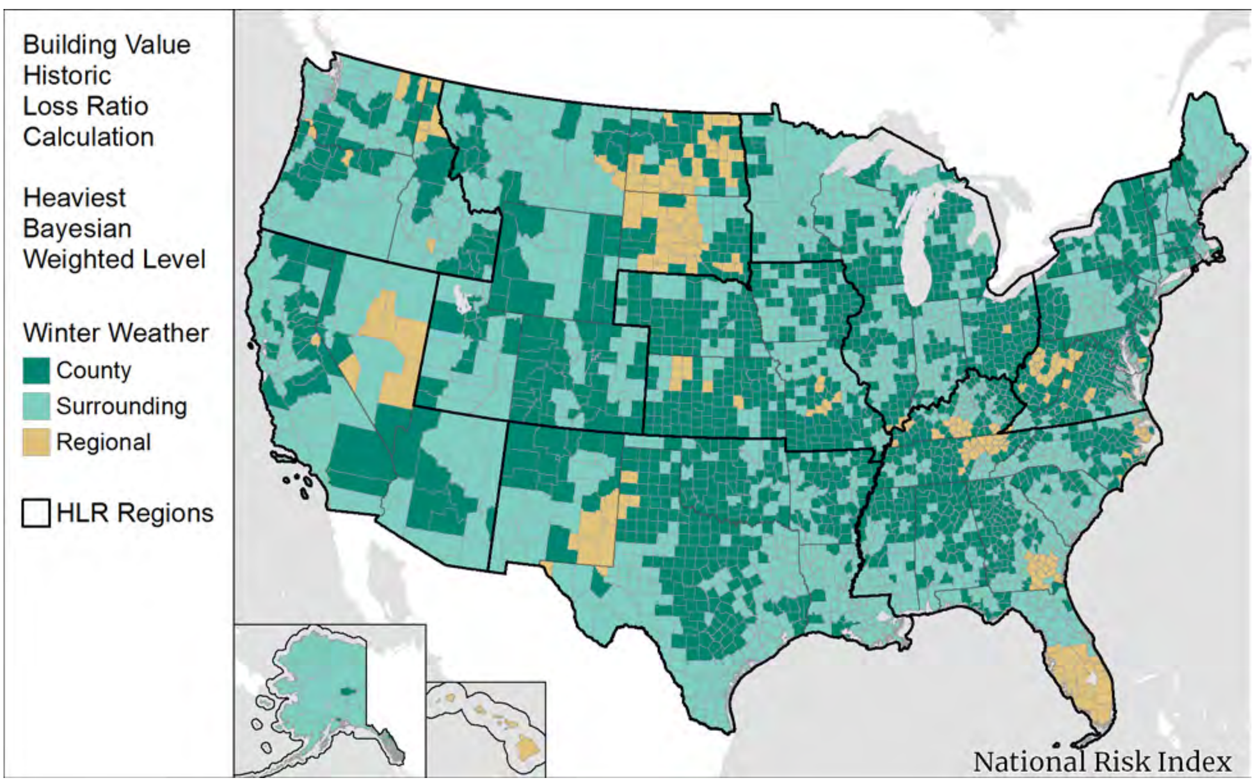

Figure 175: Winter Weather Heaviest Bayesian Influence Level – Building Value

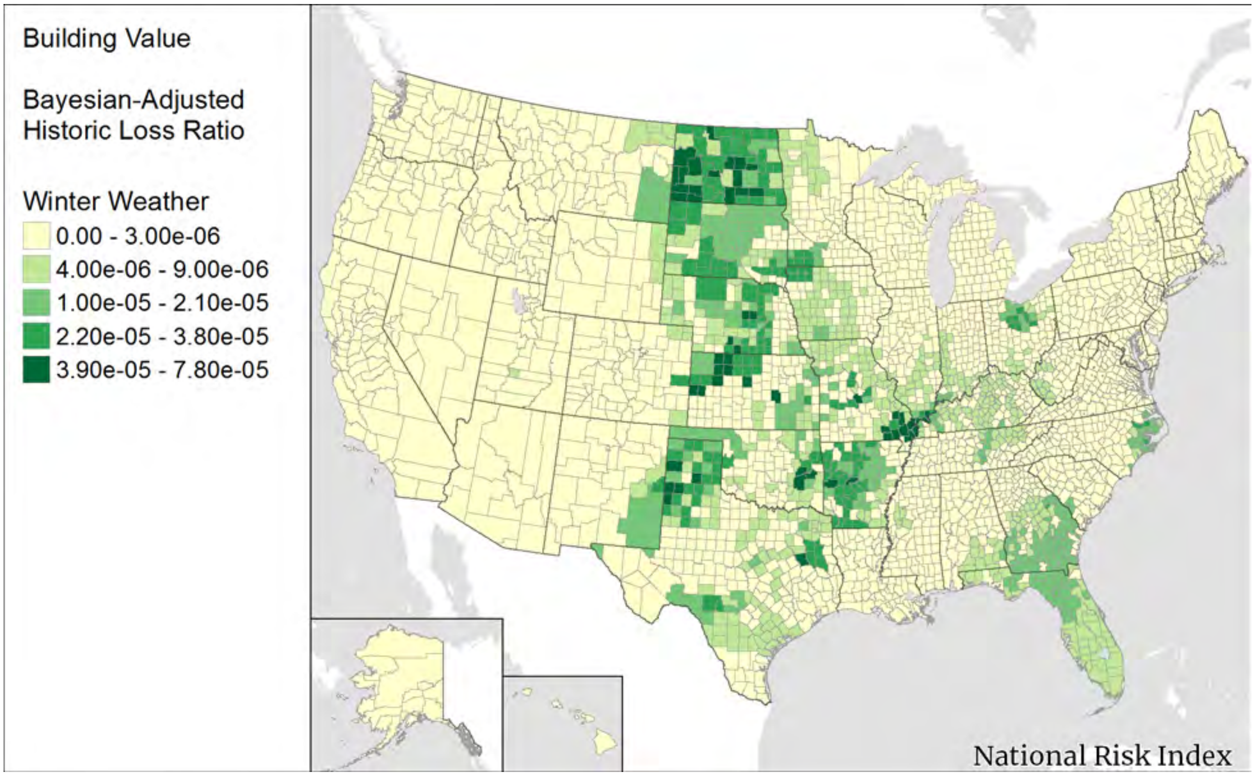

Figure 176: Winter Weather Bayesian-Adjusted HLR – Building Value

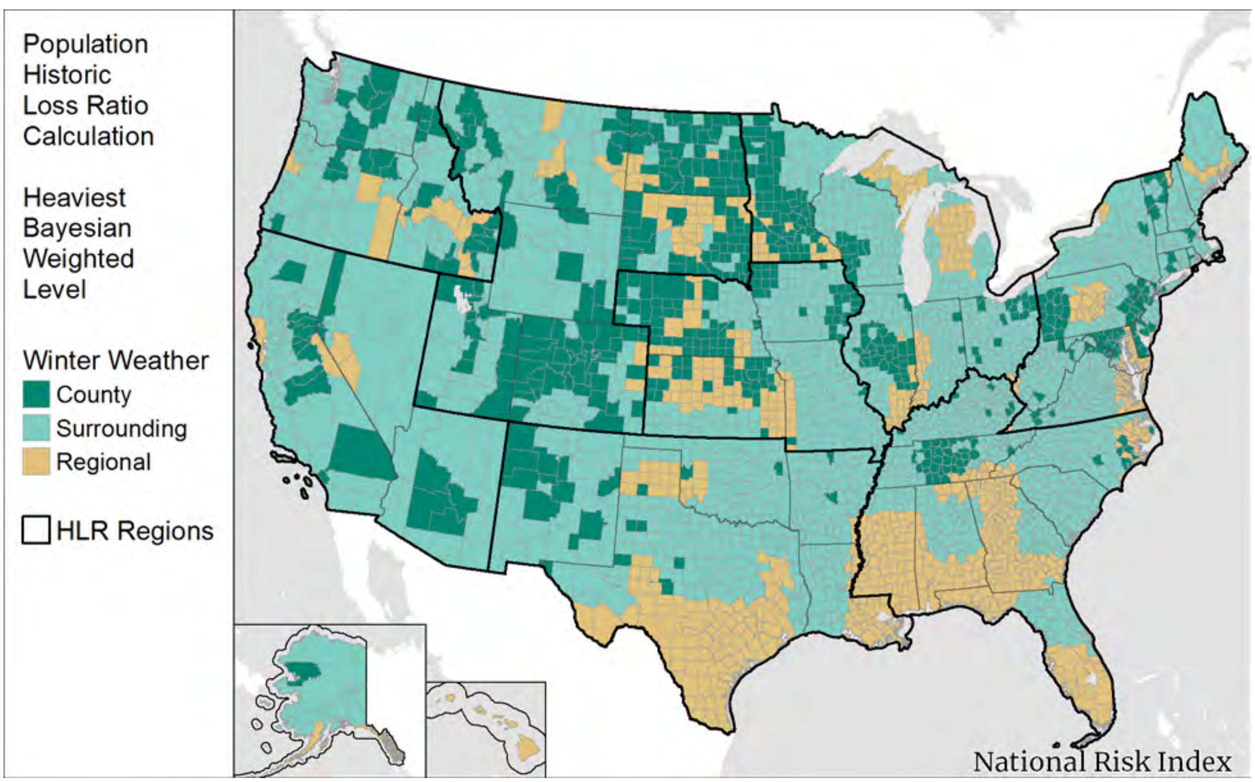

Figure 177: Winter Weather Heaviest Bayesian Influence Level – Population

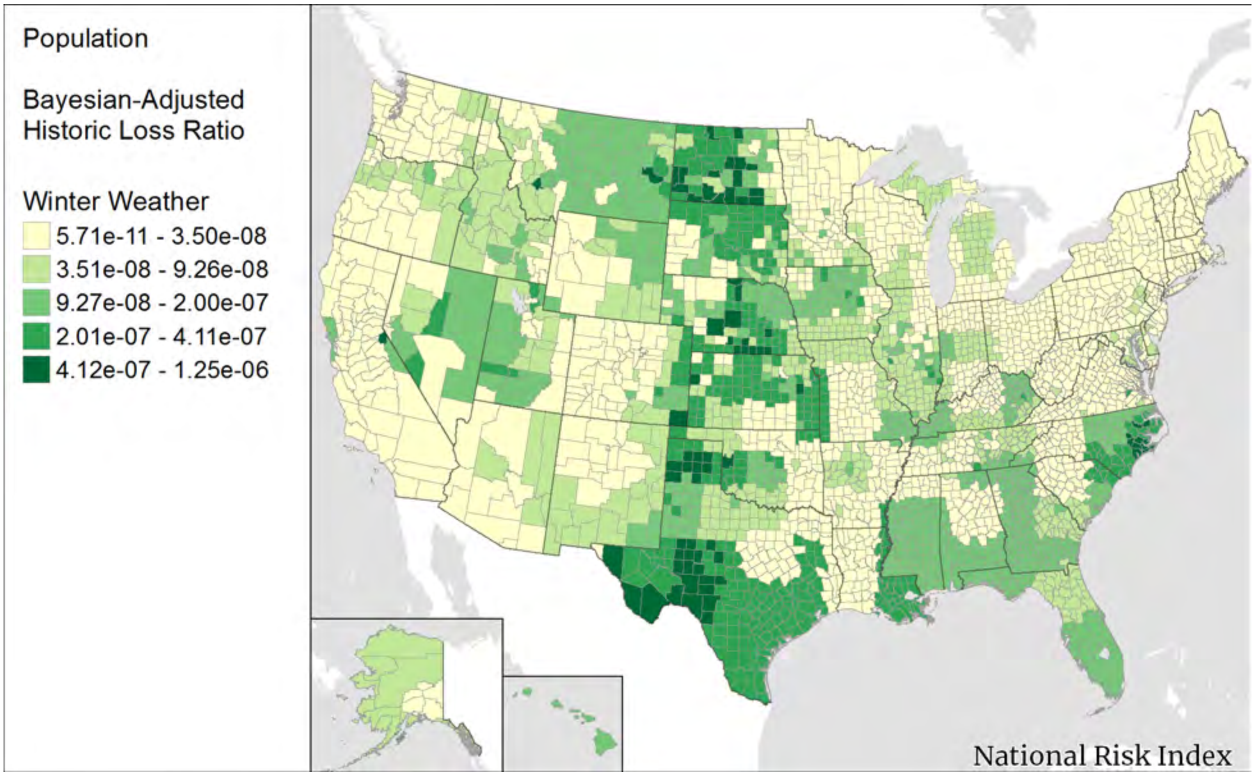

Figure 178: Winter Weather Bayesian-Adjusted HLR – Population

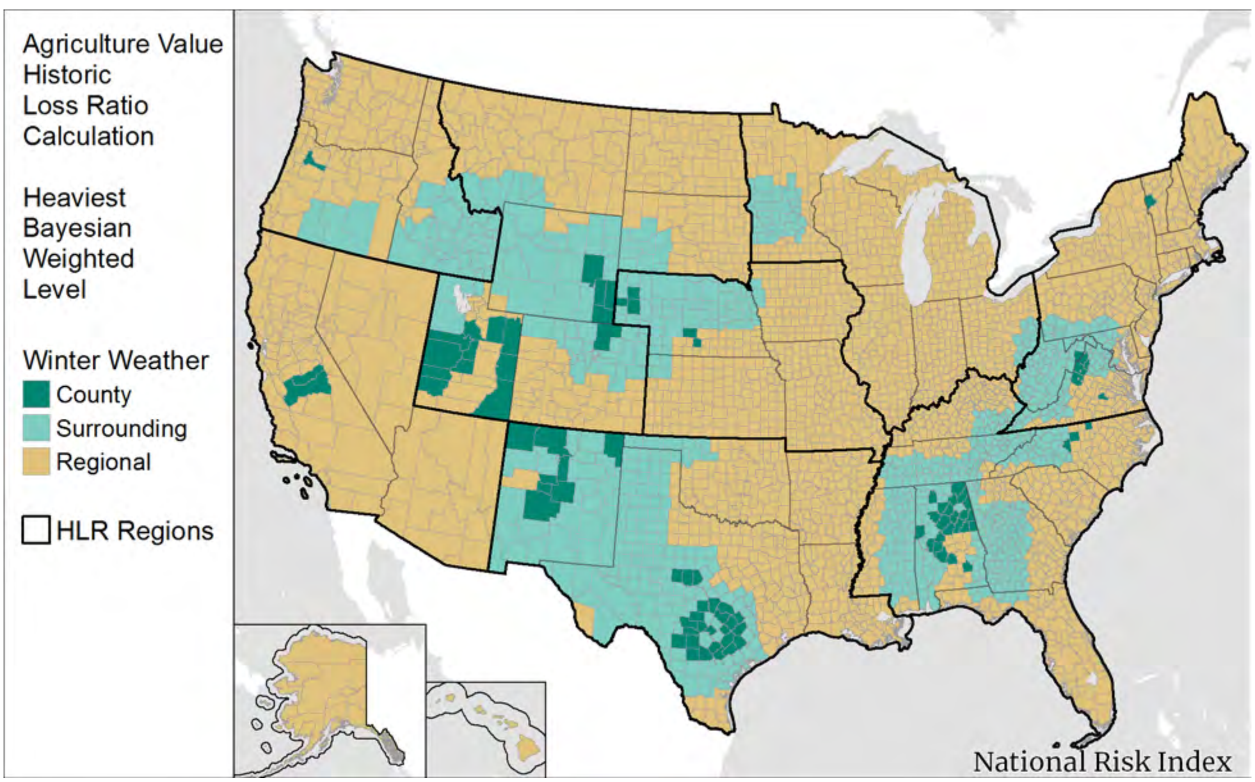

Figure 179: Winter Weather Heaviest Bayesian Influence Level – Agriculture Value

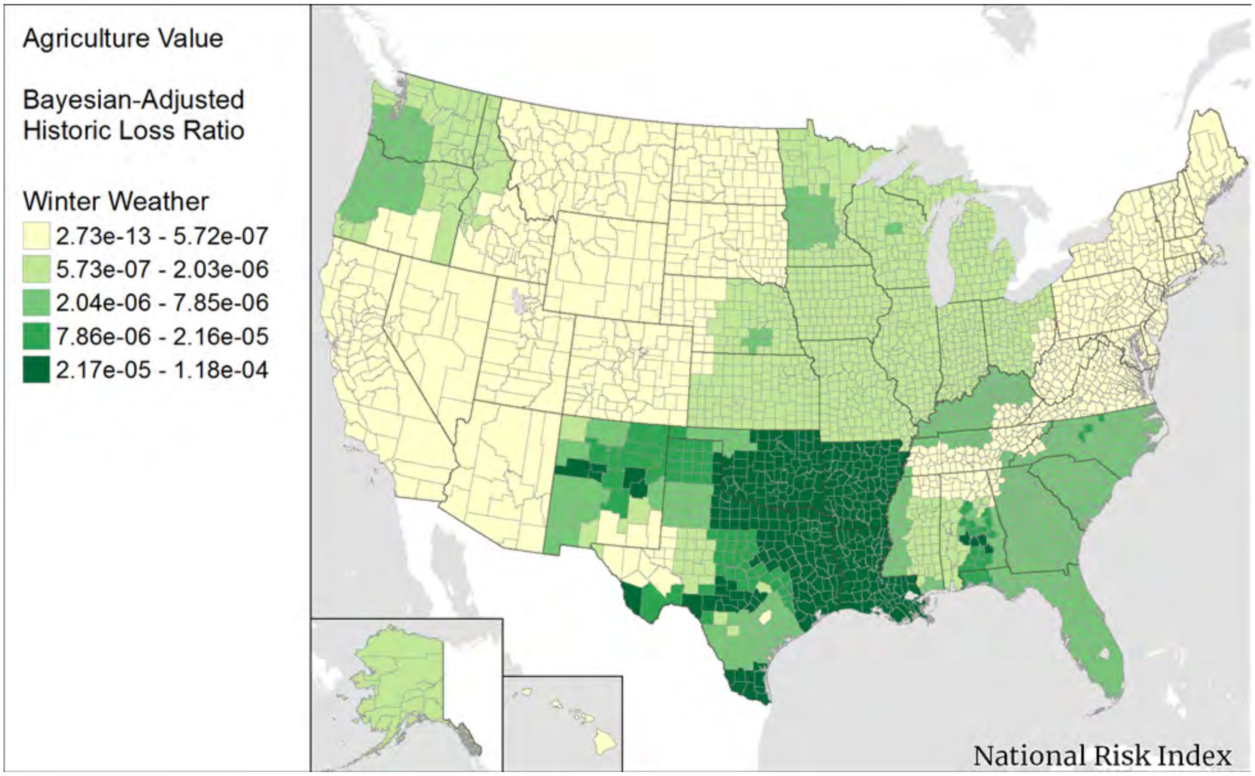

Figure 180: Winter Weather Bayesian-Adjusted HLR – Agriculture Value

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

23.8. Expected Annual Loss

Once exposure, annualized frequency, and HLR have been calculated, the EAL can be computed at the Census block level as in Equation 144. 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 144: Census Block Expected Annual Loss to Winter Weather

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

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

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

where:

$EAL_{WNTW_{CB_{Bldg}}}$ is the building Expected Annual Loss due to Winter Weather occurrences for a specific Census block (in dollars).

$Exposure_{WNTW_{CB_{Bldg}}}$ is the building value exposed to Winter Weather occurrences in the Census block (in dollars).

$Freq_{WNTW_{CB}}$ is the Winter Weather annualized 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 population equivalence Expected Annual Loss due to Winter Weather occurrences for a specific Census block (in dollars).

$Exposure_{WNTW_{CB_{Pop}}}$ is the population equivalence value exposed to Winter Weather occurrences 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.

$EAL_{WNTW_{CB_{Ag}}}$ is the agriculture Expected Annual Loss due to Winter Weather occurrences for a specific Census block (in dollars).

$Exposure_{WNTW_{CB_{Ag}}}$ is the agriculture value exposed to Winter Weather occurrences in the Census block (in dollars).

$HLR_{WNTW_{CB_{Ag}}}$ is the Bayesian-adjusted agriculture Historic Loss Ratio for Winter Weather for the Census block.

The total EAL values at the Census tract and county level are the sums of the aggregated building, population equivalence, and agriculture EAL values at the Census block level as in Equation 145.

Equation 145: Census Tract and County Expected Annual Loss to Winter Weather

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

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

where:

$EAL_{WNTW_{CT}}$ is the total Expected Annual Loss due to Winter Weather occurrences for a specific Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{WNTW_{CB_{Bldg}}}$ is the summed building Expected Annual Loss due to Winter Weather occurrences for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{WNTW_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Winter Weather occurrences for all Census blocks in the Census tract (in dollars).

$\sum_{CB}^{CT} EAL_{WNTW_{CB_{Ag}}}$ is the summed agriculture Expected Annual Loss to Winter Weather occurrence for all Census blocks in the Census tract (in dollars).

$EAL_{WNTW_{Co}}$ is the total Expected Annual Loss due to Winter Weather occurrences for a specific county (in dollars).

$\sum_{CB}^{Co} EAL_{WNTW_{CB_{Bldg}}}$ is the summed building Expected Annual Loss due to Winter Weather occurrences for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{WNTW_{CB_{Pop}}}$ is the summed population equivalence Expected Annual Loss due to Winter Weather occurrences for all Census blocks in the county (in dollars).

$\sum_{CB}^{Co} EAL_{WNTW_{CB_{Ag}}}$ is the summed agriculture Expected Annual Loss due to Winter Weather occurrences for all Census blocks in the county (in dollars).

Figure 181 shows the total EAL (building, population equivalence, and agriculture value combined) to Winter Weather occurrences.

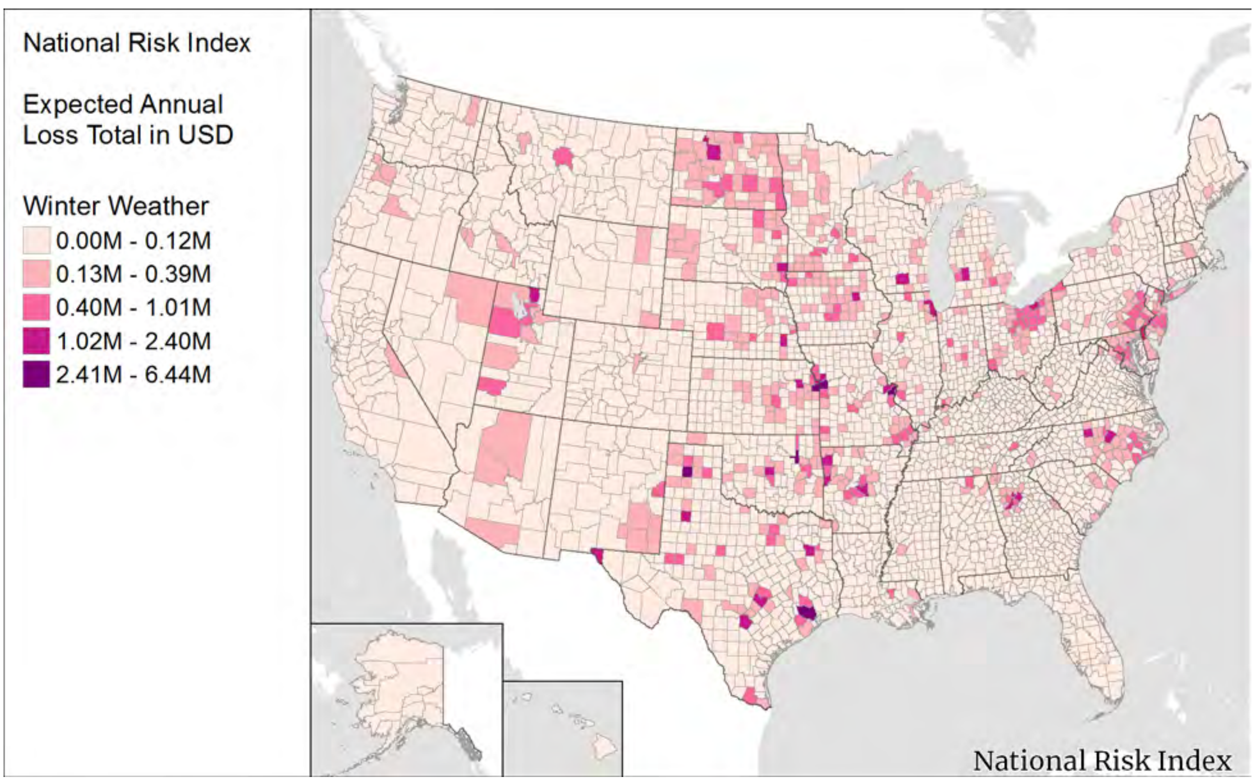

Figure 181: Total Expected Annual Loss by County to Winter Weather

With the Winter Weather total EAL value computed for each Census tract and county, the companion EAL score is computed (see Section 3.2 Scores and Ratings). The EAL score is a normalized value that describes the relative position of a specific Census tract or county in comparison to all communities at the same level. 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 National Risk Index 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. Through projects, education, and outreach, the CEMHS engages critical communities of practice, such as planning, community development, governance, defense, human welfare, and climate change adaptation.	Expected Annual Loss Expertise; Hazard Loss Ratio 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. Its services are designed to balance today's needs with tomorrow's obligations by fostering the wise use and conservation of energy, land, and mineral resources.	Tsunami Source Data
California Department of Conservation	The mission of the California Geological Survey is to provide scientific products and services about the state's geology, seismology, and mineral resources, including their related hazards that affect the health, safety, and business interests of the people of California.	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 crises, 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, and CDM Smith, Inc., as well as other companies who were not directly involved with the National Risk Index.	Natural Hazards; Determining Risk; Data and Methods; User Experience Research and Design; Software Development Expertise
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
Deloitte.	Deloitte Touche Tohmatsu Limited is a consulting company providing strategic, financial, operational, human capital, and IT services.	Data and Methods; Communication Expertise
FACTOR	FACTOR, Inc. 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 Expertise

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
U.S. DEPARTMENT OF HOMELAND SECURITY FEMA	The Federal Emergency Management Agency is a federal agency responsible for helping people before, during, and after disasters.	Natural Hazards Expertise; Coastal Flooding; Earthquake; Exposure and Riverine Flooding Source Data
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
IMAGINE WATER WORKS	Imagine Water Works is 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
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

Contributor	*Description*	*Expertise / Source Data*
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
NASA	The Cooperative Open Online Landslide Repository (COOLR), a project of the National Aeronautics and Space Administration's (NASA) Precipitation Measurement Missions, is a worldwide inventory of landslide events. COOLR currently includes NASA'S Global Landslide Catalog, Landslide Reporter Catalog, and collated landslide inventories from other institutions.	Landslide 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, National Science Foundation, and U.S. Geological Survey.	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
NOAA National Oceanic and Atmospheric Administration U.S. Department of Commerce	The National Centers for Environmental Information (NCEI) of the National Oceanic and Atmospheric Administration (NOAA) is responsible for preserving, monitoring, assessing, and providing public access to the nation's largest archive of climate and historical weather data and information. It provides over 25 petabytes of comprehensive atmospheric, coastal, oceanic, and geophysical data.	Lightning, Riverine Flooding, and Tsunami Source Data

Contributor	*Description*	*Expertise / Source Data*
	The mission of the National Hurricane Center of NOAA is to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts, and analyses of hazardous tropical weather and by increasing understanding of these hazards.	Coastal Flooding, Hurricane Source Data
	The mission of the National Weather Service (NWS) of the NOAA is to provide weather, water, and climate data, forecasts, and warnings for the protection of life and property and enhancement of the national economy.	Cold Wave, Heat Wave, Winter Weather Source Data
	The Office for Coastal Management of NOAA provides access to the science and environmental intelligence communities need to identify the best ways to address storm preparedness, erosion, development, habitat loss, sea level rise, public access, and threats to water quality.	Coastal Flooding Source Data
	The mission of the Storm Prediction Center of NOAA is to use innovative science and technology to deliver timely and accurate watch and forecast products/information dealing with tornadoes, severe thunderstorms, lightning, wildfires, and winter weather for the United States to protect lives and property.	Hail, Strong Wind, Tornado Source Data
	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
	New York Division of Homeland Security and Emergency Services (NY DHSES) provides leadership, coordination, and support for efforts to prevent, protect against, prepare for, respond to, and recover from terrorism and other man-made and natural disasters, threats, fires, and other emergencies.	How the Risk Index can Help Expertise
	Niyam IT is a consulting company crafting mission-critical technologies for emergency preparedness and response, natural resource management, law enforcement and justice, public health, and global citizen services.	Data and Methods; Tsunami Expertise

Contributor	*Description*	*Expertise / Source Data*
	Nodi Solutions is a consulting company that provides expertise on strategy, engineering, project and program management, emergency management, and strategic communications challenges. Nodi's team has experienced professionals across all parts of the enterprise for civil, defense, intel, and commercial organizations.	Natural Hazards Expertise
	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 Hazards Expertise
	Poland Consultants is a consulting practice that specializes in Earthquake engineering, disaster resilience, and related research and development.	Natural Hazards Expertise
	The RAND Corporation is a research organization that develops solutions to public policy challenges to help make communities throughout the world safer and more secure, healthier, and more prosperous.	Social Vulnerability; Data and Methods Expertise
	Resilience Action Partners is a joint venture involving Michael Baker International and Ogilvy Public Relations 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

Contributor	***Description***	***Expertise / Source Data***
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
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
AVAIL Albany Visualization And Informatics Labs	The mission of (Visualization and Informatics Lab) AVAIL at (State University of New York) SUNY Albany is to use the latest technology to solve modern transportation problems. Using a modern, web-based, and extensible visualization platform, AVAIL seeks to explore the interaction of current planning and research procedures through the use of visual analytics and informatics.	Data and Methods; Expected Annual Loss Expertise
STARR II Strategic Alliance for Risk Reduction	STARR II (Strategic Alliance for Risk Reduction) is a joint venture comprised of Atkins, Stantec, and Dewberry, leaders in Digital Flood Insurance Rate Map (DFIRM) mapping, risk assessment, risk communication, and mitigation planning.	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
The Polis Center	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 and Social Vulnerability Expertise
	The U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL) solves interdisciplinary, strategically important problems for the Corps of Engineers, Army, Department of Defense, and the nation. CRREL discovers, develops, and delivers advanced and applied science and engineering to complex environments, materials, and processes in all seasons and climates.	Ice Storm Source Data

Contributor	*Description*	*Expertise / Source Data*
	The U.S. Department of Agriculture (USDA) provides economic opportunity through innovation, helping rural America to thrive; to promote agriculture production; and to preserve our Nation's natural resources. The USDA Forest Service has been managing wildland fire on national forests and grasslands for more than 100 years. The agency works alongside state and local partners to protect people, communities, and resources across the entire shared landscape.	Wildfire Expertise
	The USDA's National Agricultural Statistics Service (NASS) conducts hundreds of surveys every year and prepares reports covering virtually every aspect of U.S. agriculture. Production and supplies of food and fiber, prices paid and received by farmers, farm labor and wages, farm finances, chemical use, and changes in the demographics of U.S. producers are only a few examples. NASS is committed to providing timely, accurate, and useful statistics in service to U.S. agriculture.	Exposure Source Data
	The U.S. Forest Service's Fire Modeling Institute's Missoula Fire Sciences Lab has a national charter to conduct fundamental and applied research relating to wildland fire processes, terrestrial and atmospheric effects of fire, and ecological adaptations to fire. It also develops associated tools and applications for scientists and managers.	Wildfire Source Data
	The U.S. Forest Service's National Avalanche Center (NAC) provides program guidance and support to Forest Service avalanche centers and military artillery programs, as well as field support and the transfer of information and technology.	Avalanche Source Data
	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

Contributor	*Description*	*Expertise / Source Data*
USGS science for a changing world	The USGS's Earthquake Hazards Program's role is to provide earth sciences information and products for earthquake loss reduction. The goals of the program are to improve earthquake hazard identification and risk assessment methods and their use, maintain and improve comprehensive earthquake monitoring in the United States, and improve the understanding of earthquake occurrences and their effects and consequences.	Data and Methods and Earthquake Expertise; Earthquake Source Data
USGS science for a changing world	The USGS's Landslide Hazards Program has the primary objective of reducing long-term losses from landslide hazards by improving our understanding of the causes of ground failure and suggesting mitigation strategies.	Earthquake and Landslide Source Data
UNDRR United Nations Office for Disaster Risk Reduction	The United Nations Office for Disaster Risk Reduction (UNDRR) 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
UCF	The University of Central Florida is a public research university located in Orlando, Florida.	Expected Annual Loss and Natural Hazards Expertise
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 Expertise
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

Contributor	*Description*	*Expertise / Source Data*
	The University of Michigan is a public research university located in Ann Arbor, Michigan.	Natural Hazards Expertise
	The University of Missouri is a public research university located in Columbia, Missouri.	Community Resilience Expertise; Social Vulnerability Expertise
	The National Drought Mitigation Center (NDMC) 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
	The University of North Carolina at Chapel Hill is a public research university located in Chapel Hill, North Carolina.	Community Resilience and Social Vulnerability Expertise
	The Hazards and Vulnerability Research Institute (HVRI) at the University of South Carolina is an interdisciplinary research and graduate/undergraduate training center focused on the development of theory, data, metrics, methods, applications, and spatial analytical models for understanding the field of hazard vulnerability science.	Community Resilience and Social Vulnerability Expertise and Source Data
	The Tsunami Research Center of the University of Southern California 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
	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 atmDospheres to improve our understanding of weather, climate, and atmospheric processes.	Natural Hazards Expertise

Contributor	Description	Expertise / Source Data
URBAN INSTITUTE	The Urban Institute is a nonprofit research organization that provides unbiased, authoritative insights to inform consequential choices about the well-being of people and places in the United States. 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
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
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

This document contains references and links to non-federal resources and organizations. This information is meant solely for informational purposes and is not intended to be an endorsement of any nonfederal entity by FEMA, U.S. Department of Homeland Security, or the U.S. government.

Appendix B – Hazard Data Characteristics Comparison

Table 78: Avalanche Hazard Characteristics

Hazard Type	Avalanche
Consequence Types	Population, Building
Annualized Frequency Data Source	SHELDUS
Annualized Frequency Period of Record	1960-2019
Hazard Occurrence Basis	Distinct events
Exposure Extent Data Source	Default exposure values
Exposure Type	Default exposure values
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Timeframe
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, National

Table 79: Coastal Flooding Hazard Characteristics

Hazard Type	Coastal Flooding
Consequence Types	Population, Building
Annualized 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
Annualized Frequency Period of Record	Not applicable; Annualized frequency modeled on each sub-type layer's annualized frequency and exposure area
Hazard Occurrence Basis	Distinct events
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 Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Consecutive day
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, Surrounding, Regional

Table 80: Cold Wave Hazard Characteristics

Hazard Type	Cold Wave
Consequence Types	Population, Building, Agriculture
Annualized Frequency Data Source	Iowa Environmental Mesonet
Annualized Frequency Period of Record	2005-2017
Hazard Occurrence Basis	Event-days
Exposure Extent Data Source	Iowa Environmental Mesonet
Exposure Type	Developed area density applied to area of the average hazard event
Historic Loss Ratio Data Source	NCEI Storm Events Database
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	Yes (maximum of 31 days)
Loss Aggregation	Single day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 81: Drought Hazard Characteristics

Hazard Type	Drought
Consequence Types	Agriculture
Annualized Frequency Data Source	U.S. Drought Monitor
Annualized Frequency Period of Record	2000-2017
Hazard Occurrence Basis	Event-days
Exposure Extent Data Source	U.S. Drought Monitor
Exposure Type	Agriculture value density applied to area of the average hazard event
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	Yes (maximum of 365 days)
Loss Aggregation	Single day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional

Table 82: Earthquake Hazard Characteristics

Hazard Type	Earthquake
Consequence Types	Population, Building
Annualized Frequency Data Source	USGS 100-Year Probability of Minor-Damage Earthquake Shaking
Annualized Frequency Period of Record	100-year probability
Hazard Occurrence Basis	Distinct events
Exposure Extent Data Source	P-366 Hazus Study
Exposure Type	Building value and population exposure from P-366 Hazus
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1960-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Timeframe
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, Surrounding, National

Table 83: Hail Hazard Characteristics

Hazard Type	Hail
Consequence Types	Population, Building, Agriculture
Annualized Frequency Data Source	NOAA, SPC Severe Weather Database
Annualized Frequency Period of Record	1986-2017
Hazard Occurrence Basis	Distinct events
Exposure Extent Data Source	Total county value
Exposure Type	Total building value, population, and agriculture value
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Single day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 84: Heat Wave Hazard Characteristics

Hazard Type	Heat Wave
Consequence Types	Population, Building, Agriculture
Annualized Frequency Data Source	Iowa Environmental Mesonet
Annualized Frequency Period of Record	2005-2017
Hazard Occurrence Basis	Event-days
Exposure Extent Data Source	Iowa Environmental Mesonet
Exposure Type	Developed area density applied to area of the average hazard event
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	Yes (maximum of 31 days)
Loss Aggregation	Single day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 85: Hurricane Hazard Characteristics

Hazard Type	Hurricane
Consequence Types	Population, Building, Agriculture
Annualized Frequency Data Source	NOAA, NHC HURDAT2 Best Track Data
Annualized Frequency Period of Record	Atlantic: 1851-2017; Pacific: 1949-2017
Hazard Occurrence Basis	Distinct events
Exposure Extent Data Source	NOAA HURDAT2 Best Track Data
Exposure Type	Developed area density applied to area of the average hazard event
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Consecutive day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional

Table 86: Ice Storm Hazard Characteristics

Hazard Type	Ice Storm
Consequence Types	Population, Building
Annualized Frequency Data Source	USACE, CRREL Damaging Ice Storm GIS
Annualized Frequency Period of Record	1946-2014
Hazard Occurrence Basis	Event-days
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 Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	Yes (maximum of 31 days)
Loss Aggregation	Single day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 87: Landslide Hazard Characteristics

Hazard Type	Landslide
Consequence Types	Population, Building
Annualized Frequency Data Source	NASA Cooperative Open Online Landslide Repository
Annualized Frequency Period of Record	2010-2019
Hazard Occurrence Basis	Distinct events
Exposure Extent Data Source	USGS Landslide Hazard Map
Exposure Type	Developed area density applied to Landslide susceptible areas
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	No
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 88: Lightning Hazard Characteristics

Hazard Type	Lightning
Consequence Types	Population, Building
Annualized Frequency Data Source	NOAA, NCEI Cloud-to-Ground Lightning Strikes
Annualized Frequency Period of Record	1991-2012
Hazard Occurrence Basis	Distinct events
Exposure Extent Data Source	Total county value
Exposure Type	Total building value and population
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Single day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, National

Table 89: Riverine Flooding Hazard Characteristics

Hazard Type	Riverine Flooding
Consequence Types	Population, Building, Agriculture
Annualized Frequency Data Source	NCEI Storm Events Database
Annualized Frequency Period of Record	1996-2019
Hazard Occurrence Basis	Event-days
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 Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	Yes (maximum of 31 days)
Loss Aggregation	Single day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, , Regional

Table 90: Strong Wind Hazard Characteristics

Hazard Type	Strong Wind
Consequence Types	Population, Building, Agriculture
Annualized Frequency Data Source	NOAA, SPC Severe Weather Database
Annualized Frequency Period of Record	1986-2017
Hazard Occurrence Basis	Distinct events
Exposure Extent Data Source	Total county value
Exposure Type	Total building value, population, and agriculture value
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Single day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 91: Tornado Hazard Characteristics

Hazard Type	Tornado
Consequence Types	Population, Building, Agriculture
Annualized Frequency Data Source	NOAA, SPC Severe Weather Database
Annualized Frequency Period of Record	1986-2019
Hazard Occurrence Basis	Distinct events
Exposure Extent Data Source	Average impact area per magnitude sub-type: • 0.8 km^2 for EF-Scale 0 and 1 • 13 km^2 for EF-Scale 2 and 3 • 79 km^2 for EF-Scale 4 and 5
Exposure Type	Average density applied to the average area of hazard impact per magnitude sub-type
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	No
Zero-Loss Record Padding	• Yes (for EF-Scale 0 and 1) • Yes (for EF-Scale 2 and 3) • No (for EF-Scale 4 and 5)
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 92: Tsunami Hazard Characteristics

Hazard Type	Tsunami
Consequence Types	Population, Building
Annualized Frequency Data Source	NOAA, NCEI Global Historical Tsunami Runup Data
Annualized Frequency Period of Record	1800-2018
Hazard Occurrence Basis	Distinct events
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 Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Consecutive day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional, National

Table 93: Volcanic Activity Hazard Characteristics

Hazard Type	Volcanic Activity
Consequence Types	Population, Building
Annualized Frequency Data Source	Smithsonian Institution Volcanoes of the World
Annualized Frequency Period of Record	9310 BCE-2018
Hazard Occurrence Basis	Distinct events
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 Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1960-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Timeframe
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, Surrounding, National

Table 94: Wildfire Hazard Characteristics

Hazard Type	Wildfire
Consequence Types	Population, Building, Agriculture
Annualized Frequency Data Source	USDA, Forest Service Fsim Burn Probability and Fire Intensity Level Data
Annualized Frequency Period of Record	Annualized probability
Hazard Occurrence Basis	Distinct events
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 Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	No
Loss Aggregation	Timeframe
Zero-Loss Record Padding	No
Bayesian Weighting Levels	County, Surrounding, National

Table 95: Winter Weather Hazard Characteristics

Hazard Type	Winter Weather
Consequence Types	Population, Building, Agriculture
Annualized Frequency Data Source	Iowa Environmental Mesonet
Annualized Frequency Period of Record	2005-2017
Hazard Occurrence Basis	Event-days
Exposure Extent Data Source	Iowa Environmental Mesonet
Exposure Type	Developed area density applied to area of the average hazard event
Historic Loss Ratio Data Source	SHELDUS
Historic Loss Ratio Period of Record	1996-2019
Loss Allocation Date Expansion	Yes (maximum of 31 days)
Loss Aggregation	Single day
Zero-Loss Record Padding	Yes
Bayesian Weighting Levels	County, Surrounding, Regional

Appendix C – Mesonet-NWS Weather Event Attribute Description

Table 96: 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 Occurrence Count

Table 97: Sample Historic Fishnet Hazard Event/Event-Day Count Data

Fishnet49kmID	*NumberHail Events*	*NumberHurricane Events*	*NumberIceStorm EventDays*	*NumberTornado Events: EF0&1*[96]	*NumberWind Events*
170	1	39	0	8	5
171	1	41	0	13	8
172	1	36	0	15	8

For widespread hazards that can occur anywhere within a county, a historic occurrence count (event or event-day) is performed at the level of a 49-by-49-km fishnet grid cell (see Table 97), which is then intersected with the Census block, Census tract, or county to estimate annualized frequency. If a Census block, Census tract, or county intersects multiple fishnet grid cells (see Figure 182), 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 occurrence event (or event-day) polygons. The hazard occurrence count for this Census block would be calculated according to Equation 146 and aggregated to the Census tract and county levels according to Equation 147.

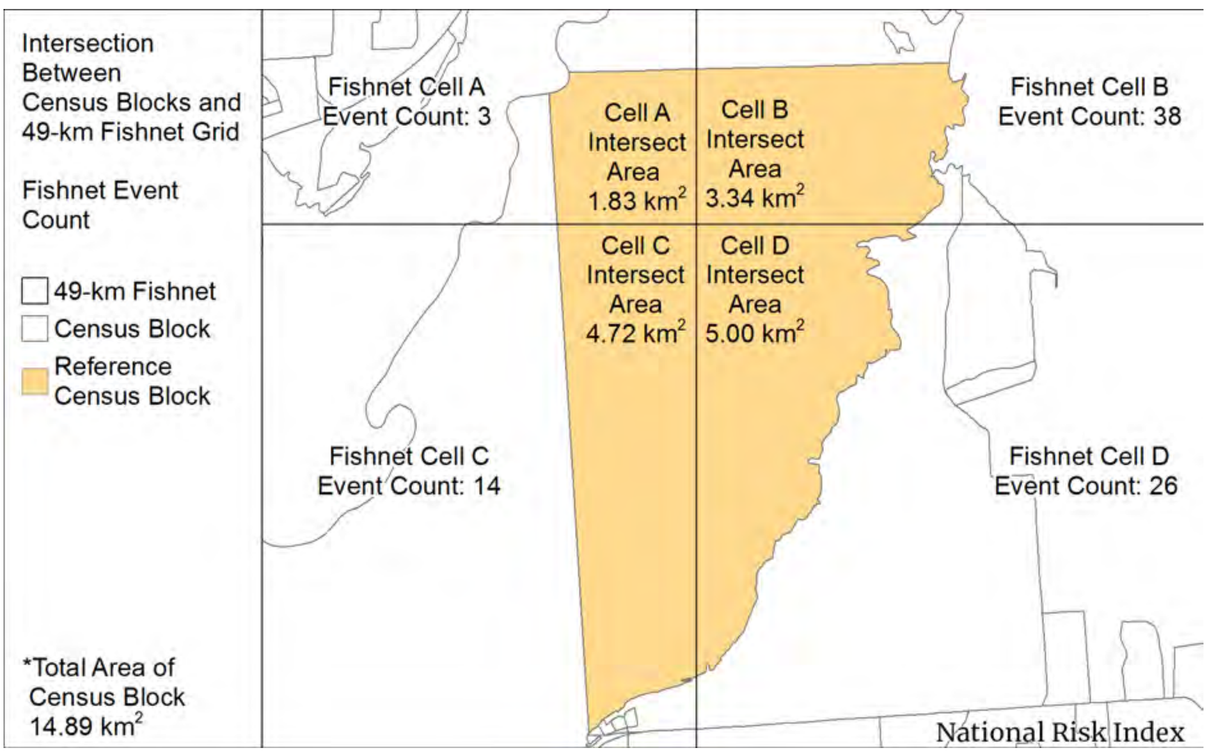

Figure 182: Intersection Between Census Blocks and 49-by-49 km Fishnet Grid

[96] Tornado event counts are actually performed for each EF-scale and follow a different methodology using the fishnet grid cell counts. See the Tornado frequency documentation for more information.

Equation 146: 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 occurrences (event or event-day) calculated for a specific Census block.
$EventCount_{Hazard_{Fish}}$	is the number of hazard occurrences (event or event-day) 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 147: 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 occurrences (event or event-day) 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 occurrences (event or event-day) 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 occurrences (event or event-day) 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).