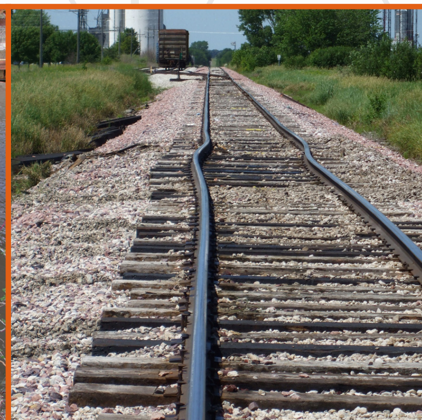
ILLINOIS ALL-HAZARDS TRANSPORTATION SYSTEM

Vulnerability Assessment

OCTOBER 2017





Illinois Department of Transportation

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Illinois All-Hazards Transportation System Vulnerability Assessment and Response Plan

FOREWARD

This document summarizes efforts undertaken as part of the Illinois All-Hazards Transportation System Vulnerability Assessment. The assessment generated four separate technical reports: Asset Classification Report, Hazard Classification Report, Vulnerability Report, and Action Plan. The full project report contains materials designated as Sensitive Security Information (SSI) by the Secretary of Transportation under 49 U.S.C. 44921. Pieces of the report containing SSI will not be made available to the public. The information contained in this summary report is intended to provide the public with insights to and results of the study.

ACKNOWLEDGEMENTS & APPRECIATION

This study covers a wide range of engineering and environmental technical disciplines and could not have been possible without the assistance of a large group of individuals. As part of this assessment, both a Stakeholders Group and a Technical Working Group were formed to assist in everything from finding data to developing statistical analysis methodologies. The groups included IDOT professionals from each of the nine districts, and representatives from nearly two dozen state and federal agencies. A special thanks to the U.S. Geological Survey, Federal Emergency Management Agency, and numerous IDOT staff members who patiently dealt with the repeated requests for information and generously contributed extra time to assist in this project. The intra- and interagency cooperation was instrumental in the process of developing the framework of the study. A sincere thanks to all those involved throughout the duration of the project.



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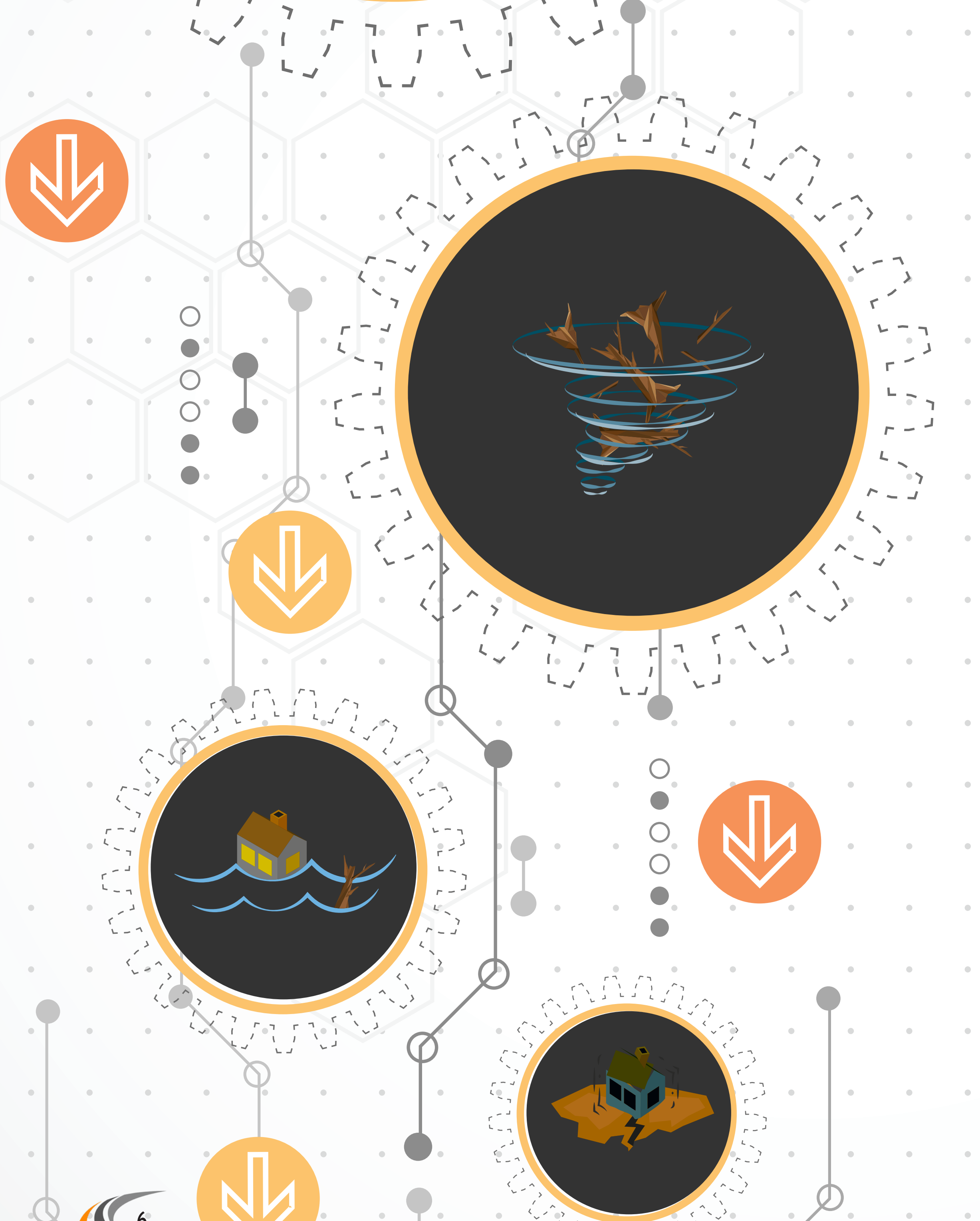


PART 1: INTRODUCTION

Vulnerability Assessments
Defining Transportation Assets
Refining Hazards & Risks
Resiliency

PART 1: INTRODUCTION

Vulnerability Assessments

The Illinois Department of Transportation (IDOT) last completed a transportation vulnerability assessment in 2003. This followed the tragic events of September 11, 2001, and like many studies developed by state and federal agencies at that time, the focus was on terrorist threats. The current vulnerability study was motivated by global events related to an increase in extreme weather events. In 2012 the Federal Highway Administration (FHWA) released The Climate Change and Extreme Weather Vulnerability Assessment Framework as a guidance document for state transportation departments in developing techniques to measure resiliency within the transportation network under changing weather conditions. In 2013, Hurricane Sandy alone resulted in the U.S. DOT releasing $3 billion in funds to strengthen resiliency to extreme weather events on top of the $5.7 billion allocated for recovery projects from the storm. The FHWA is looking to the states to evaluate their existing transportation infrastructure for preparedness to extreme weather events as well as how future projects can be designed with greater resiliency, where necessary.

States across the country have been developing pilot projects for FHWA since the release of the 2012 guidance. IDOT took a unique approach by developing a vulnerability assessment which evaluates risks as they exist now, and how they may exist in the future with a changing environment.

What is a vulnerability assessment? At its core, vulnerability is the potential susceptibility of something to damage. A vulnerability assessment seeks to answer the questions of “What is vulnerable?” and “How is it vulnerable?”. Every assessment becomes tailored to the specific thing being assessed and the limits set in the evaluation process. An epidemiologist, for example, studies the transmission of disease outbreaks, but each study must narrow the scope to clearly identify what should be considered at risk (only humans or humans and other animals, only children or children and adults, etc.), and what they are specifically at risk from (which viral and/or bacterial infections). A clearly defined scope is paramount to receiving full value from any assessment.

Risk. Threat. Source. Hazard. Vulnerability. Terminology is important, and must be kept in context with the use in each assessment. After all, one landscaper may call a short woody plant a shrub, while another a might call it a tree. If an assessment doesn’t define what a shrub or tree is, then it may be difficult to determine if differences between them are important. Some assessments may use terms like risk and vulnerability interchangeably, while others use the same terms to distinguish two different concepts. Clarity of the process requires clarity of the terminology.

PART 1: INTRODUCTION

In Illinois, businesses, residents, and visitors have access to one of the largest and most effective multi-modal transportation systems in the nation. This includes roads, railways, airways, waterways, canals, and terminals such as airports, railway stations, bus stations, warehouses, and intermodal facilities. Illinois' centralized geographic location, as well as the diversity of available transportation options, places the Illinois transportation system in an essential role in the nation's ability to move goods and people.

DEFINING TRANSPORTATION ASSETS

One may assume that an IDOT vulnerability assessment would focus mainly on roadways and bridges, as these are the pieces of infrastructure most associated with the agency. However, IDOT is an intermodal agency that also provides regulatory oversight, technical support, and/or operational support to air, rail, and bus services in the state. IDOT also oversees the supporting operations and maintenance infrastructure that the transportation system could not function without (snowplows, weigh stations, drainage pumps, etc.).

The initial phase of this study focused on defining the limitations of what assets would be included. Whether road, rail, or otherwise, the compilation of assets needed to be sorted and categorized. For reference, there are approximately 150,000 miles of roadway and more than 35,000 bridge and drainage structures tracked by IDOT. Although IDOT has a certain level of oversight on local routes, responsibilities for maintaining the various highways are divided between state and local road jurisdictions. With respect to rail, IDOT supports Amtrak routes to provide passenger rail services in Illinois, but does not own the railroad tracks the passenger trains operate on. Instead, private freight companies enter into cooperative service agreements to share rights to the tracks, and IDOT and the Federal Railroad Administration (FRA) agree to pay for upgrades and/or certain portions of the maintenance to keep the line in order. Decisions on what assets should be included or excluded from the study centered around IDOT's role in operation and maintenance, and their contribution to regional and/or national public transportation.

The Asset Classification Report evaluated the transportation resources throughout the state and consolidated them into four broad categories:

Transportation Corridors

Bridge Infrastructure

Operations

Transportation Hubs

TRANSPORTATION CORRIDORS

Corridors capture the physical footprint of a roadway or railway route in its entirety within Illinois. Corridors represent the line connecting Point A to Point B.

BRIDGE INFRASTRUCTURE

Bridge Infrastructure represents the pieces of a corridor which cross over or under something. This includes not just bridges, but also culverts and tunnels.

OPERATIONS

Operations captures the parts of the supporting infrastructure of the corridors. Operations represents the pieces seen and unseen by the public, and includes both amenities (e.g. rest areas) and necessities (e.g. salt storage).

TRANSPORTATION HUBS

Transportation Hubs capture the infrastructure used as a primary designated transfer point between intermodal services. Hubs include stations and ports, and represent facilities where the type of transportation services changes (i.e. take a cab to the airport to get on an airplane).*

*This category was defined in the Asset Classification Report as part of classifying all transportation components; however, this group of assets was excluded from the study.

This study includes more than 14,000 miles of roadways, nearly 14,500 bridges, 55 daily rail routes, and 400+ operations locations.

PART 1: INTRODUCTION

REFINING HAZARDS & RISKS

A hazard can be defined generically as a source of danger or risk. The terms risk and hazard can often be interchanged, but this vulnerability assessment distinguishes these terms such that a 'hazard' represents a source event while the 'risk' is the associated negative outcome. For example, flooding would be a hazard while the risk could be structural damage. This subtle difference was instituted to keep apples with apples when discussing risk across asset types. Evaluating how flooding can damage a bridge, road, or building is different. The flooding is consistent as a hazard, but the types of risk can vary between asset categories (for example, a flooded road can shut down part of the transportation network, but a flooded maintenance building may not affect the transportation network).

The title of 'All-Hazards' identifies the intent of the study to be as inclusive as possible when considering the types of hazards transportation assets may be exposed to. A Hazard Classification Report was developed to identify the myriad of hazards assets could be exposed to, then narrowed down the list to those hazards considered to warrant more detailed evaluation. The first major step was to divide the hazards into two principle classifications: Manmade and Natural.

Manmade hazards are those types of events caused by people; natural hazards are those types associated with severe weather and geologically related events. Potential hazards were reviewed for their relevance to transportation assets and for the geographic area (Illinois) to determine applicability to the vulnerability assessment. The study narrowed the hazards to nine primary categories (shown right).

MANMADE HAZARDS

Chemical/Biological/Radiological/Nuclear (CBRN) Incidents

Explosives

Small Arms Attack

Electro-magnetic Pulse

Cyber-attack

NATURAL HAZARDS

Precipitation (Flooding, Snow, & Ice)

Temperature (Freeze/Thaw Cycling & Extreme Heat and Cold)

Wind (Tornado and Straight-Line Winds)

Geologic (Landslide, Earthquake, Subsidence, & Sinkholes)

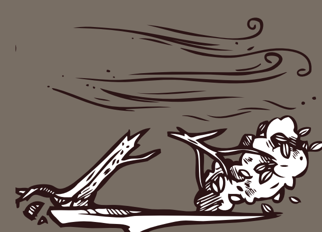
RESILIENCY

Resiliency within a transportation system is expressed by its ability to both handle stresses and quickly recover when those stresses result in damage. Resiliency doesn't necessarily mean all parts are impervious to damage, rather it is the combination of resistance, redundancy, and response plans. The purpose of a vulnerability study is to identify risk to assets from a defined hazard (or set of hazards) in order to be aware of weaknesses in the system exist that impact its resilience. Without understanding the how, what, when, where, and why, there is no way to be prepared for or offset that risk. The FHWA used the term 'adaptive capacity' in their 2012 framework to describe the ability for infrastructure to be resistant to the hazards associated with climate change, and for services to be restored quickly in the event of a negative impact from a hazard. Adaptive capacity becomes a measurement of resiliency; the use of the word 'adaptive' implies a change in the risk. This study seeks to first measure the vulnerability of assets to existing hazards, then identify the means to measure any change in risk from those hazards as a result of climate change. The goal is to clearly understand 1) the here-and-now, 2) what the potential future scenario could be, and 3) how that interaction impacts vulnerability. If those three parts are defined, a measurement of resiliency can be provided for both existing and projected future conditions.

GLOBAL WARMING, CLIMATE CHANGE, EXTREME WEATHER...

The old saying goes, 'Being a weatherman is the best job to have- it's the only one where you get to be wrong more than half the time and keep your job.' Although the phrase is always good for a chuckle, it couldn't be farther from the truth. Weather forecasting has become extremely accurate and critical for emergency managers when making decisions on mobilizing resources during extreme weather events. Scientific measuring tools and forecast modeling have become incredibly sophisticated in their predictive capabilities. The American Global Forecasting System (GFS) and the European Center for Medium-Range Weather Forecast (ECMWF) are two of the most powerful models in the world and regularly compete with each other. They are not always 100% accurate, but one of them typically captures the most significant events, such as when the ECMWF predicted the left hook of Hurricane Sandy. Models such as these provide the opportunity to see future dangers and plan accordingly. Climate models follow suit with weather models and provide the same opportunity for understanding future dangers, but on a much larger timeline.

Most natural hazards are caused by weather. This all-hazards assessment incorporates a climate change scenario to evaluate potential changes over time to risks posed by various natural hazards given the current understanding of weather on the planet. Weather is an extremely complex subject for which scientists can spend their entire careers learning about. The typical person may hear the occasional news report or see graphs depicting rises in global temperatures, but it can be difficult to connect melting glaciers in remote areas with weather events that can affect people in Oregon, Virginia, or Illinois. A later chapter in this report, Climate & Weather, provides a brief discussion on what causes our weather, and how changes to things like ocean temperatures can result in changes to weather patterns.



PART 2: STUDY COMPONENTS

Assets Considered
Hazards Considered

ASSETS CONSIDERED

The purpose of the vulnerability study was to conduct a statewide evaluation of transportation assets. Illinois is not a small state. Illinois has a lot of transportation assets. The sheer volume of resources prevents an individualistic approach to asset evaluation. To manage the information, the selection of assets was required to be contained within a database format where it could be sorted, grouped, and processed. IDOT maintains numerous independent databases from which asset data were drawn. Additional data relevant to hazards were pulled from other state and federal agencies for incorporation into a single master asset database. Within this mountain of data, the study had to clearly define the limitations of what was being evaluated in the final assessment.

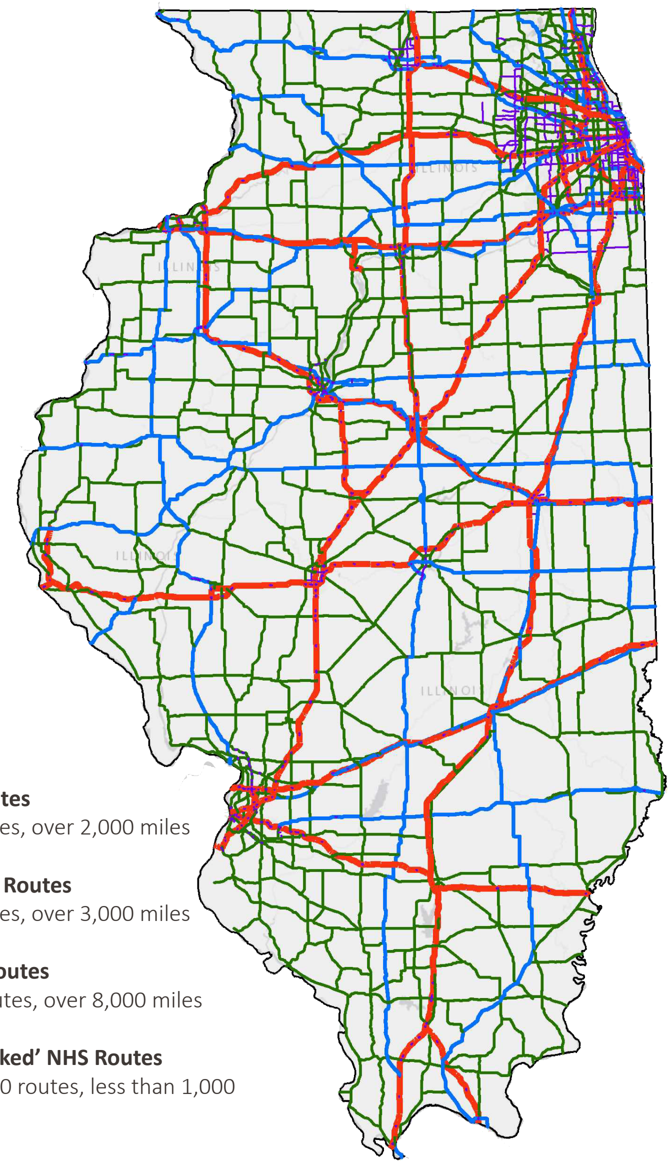
The McCluggage Bridge carries U.S. Route 150 over Upper Peoria Lake on the Illinois River. This is just one of the thousands of assets analyzed as part of this vulnerability study.

TRANSPORTATION CORRIDORS

The total sphere of the defined corridors in Illinois would include all road and rail routes. This was the starting point for consideration; from here the representative routes were selected for evaluation.

ROADWAY CORRIDORS

Roadway Corridors were reduced to those primarily maintained by IDOT and designated as state or federal routes, or as part of the National Highway System (NHS). A designated route includes named routes such as Interstate 55, Illinois Route 1, and U.S. Route 30. County highways and local municipal roads were not included unless they are part of the NHS. The NHS designation includes all federal routes and some state routes, and also includes local road segments which are considered vital to the nation's economy, defense, and/or mobility. NHS segments on local roads often only cover a short distance, but connect airports, train stations, or other important components within the transportation network. These selected routes are all instrumental for statewide planning by IDOT.



Interstates
23 Routes, over 2,000 miles

Federal Routes
26 Routes, over 3,000 miles

State Routes
155 Routes, over 8,000 miles

'Unmarked' NHS Routes
over 300 routes, less than 1,000 miles *

*Unmarked routes are generally locally named streets without state or federal route designations.

RAIL CORRIDORS

Rail Corridors were reduced to those routes providing passenger rail service. Amtrak operates 14 service routes in or through Illinois; however, most of these share track space with other routes. For example, the Lincoln Service is a state route connecting St. Louis to Chicago; the Texas Eagle is a national route connecting Chicago to San Antonio [Texas]. Within Illinois, both service routes operate on the same line of tracks. All service routes converge at Union Station in Chicago like spokes on a bicycle wheel. Freight rail is an important economic driver in Illinois, but managing passenger rail service routes is an integral part of IDOT's responsibilities.

California Zephyr
2 trains per day

Capitol Limited
2 trains per day

Cardinal
1 train per day

City of New Orleans
2 trains per day

Empire Builder
2 trains per day

Lake Shore Limited
1 train per day

Southwest Chief
2 trains per day

Texas Eagle
2 trains per day

Hoosier State
1 train per day

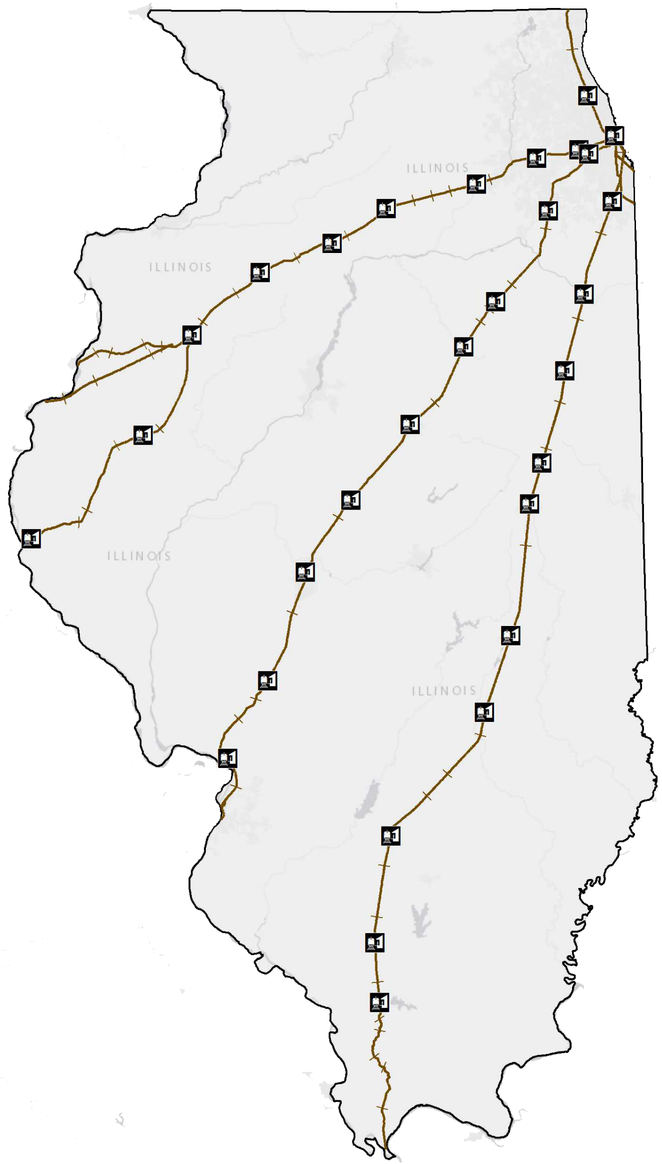
Lincoln Service
8 trains per day

Illini & Saluki Service
4 trains per day

Carl Sandburg & Illinois Zephyr Service
4 trains per day

Hiawatha
14 trains per day

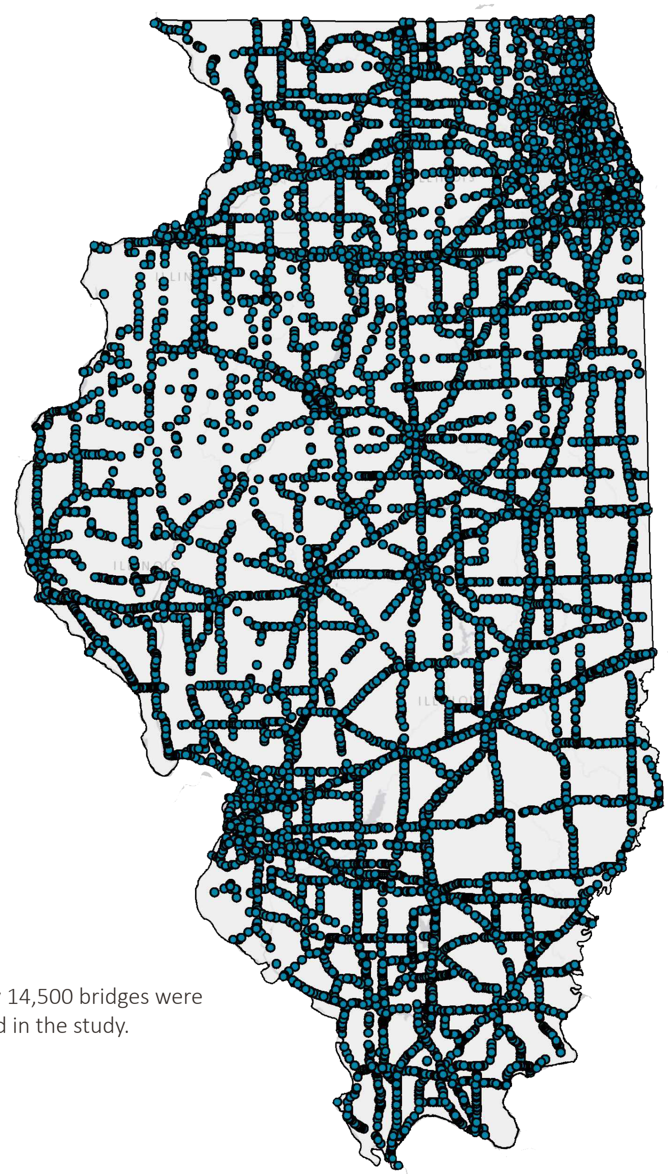
Michigan Service
10 trains per day



BRIDGE INFRASTRUCTURE

The evaluation of bridges was limited to those associated with the selected road and rail corridors. This asset category includes all structures which pass over or under the corridor, not just the structure carrying traffic on the designated routes. Railroad bridges which are not on state owned property (roadway right-of-way) are not captured in the IDOT database.

The railroad bridges presented a limitation for the study. IDOT is responsible for gathering information on all bridge structures within its right-of-way. Any combination of a roadway bridge over a railroad, or a railroad bridge over a roadway will result in the information about the bridge being captured in the statewide database. Any railroad bridge over another railroad or over water that doesn't fall on state owned property is only tracked by the railroad owner. Information maintained by the railroads is not publicly available, and likely not documented in a similar format to IDOT standards (meaning it's not necessarily directly compatible with the evaluation criteria). Hence, the bridges carried forward for evaluation capture all the structures associated with the roadways, but do not capture all the structures associated with the railroads.



Roughly 14,500 bridges were included in the study.

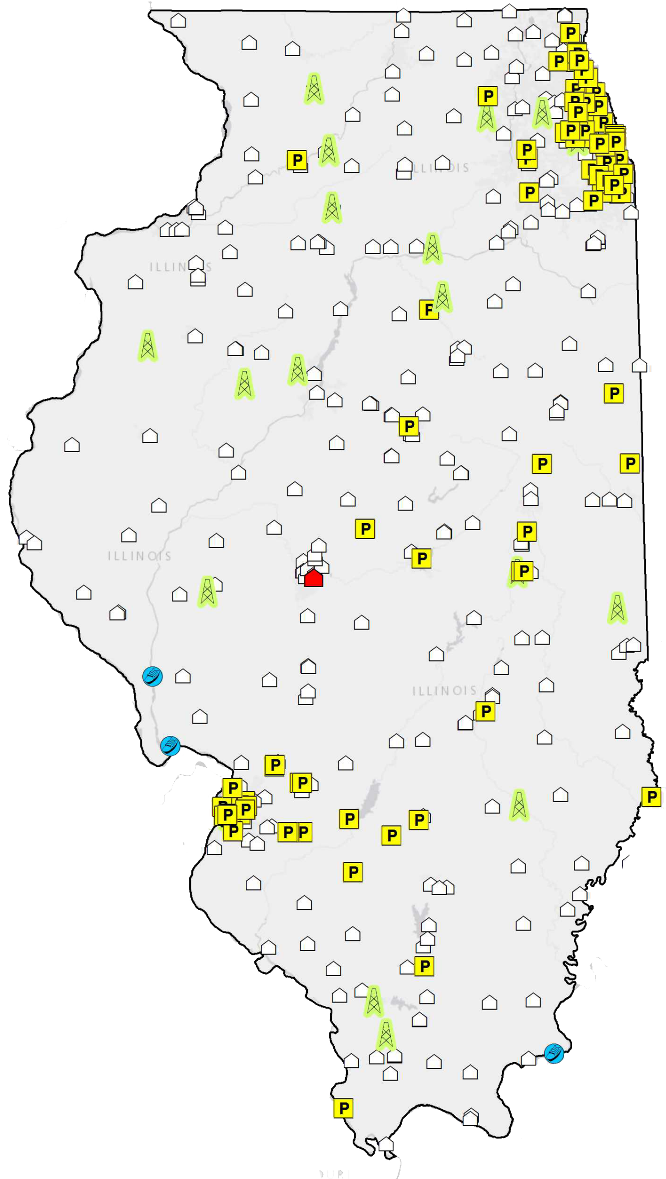
OPERATIONS

Supporting transportation infrastructure was consolidated to approximately 400 IDOT owned and managed facilities.

These included:

- Rest Areas
- Weigh Stations
- Communication Towers
- Ferries
- Pump Houses
- Maintenance Yards
- Headquarter Buildings
- Storage Facilities
- Salt Domes

Facilities are represented on the adjacent map as single locations, though a given location may have multiple operations. For example, the location of the District 8 headquarters is not only a regional headquarters building, but also includes a pump house and communication tower on the property. The 400+ locations were reviewed for each operational contribution to the transportation system.



HAZARDS CONSIDERED

The manmade and natural hazards considered appropriate to carry forward were introduced in Part 1. No further detailed information regarding manmade hazards will be discussed under this section due to security considerations.

How the study narrowed down the hazard types was an important part of evaluating risk. A clear distinction was made between the transportation system and the participants in the system. Snow covered roads can create dangerous driving conditions which can increase the potential for both fender benders and fatal accidents; however, this vulnerability study does not consider the impacts of the hazards to individual drivers on the road. Instead, the study focuses on how a hazard can impact asset infrastructure such that the system is impaired, e.g. how is a bridge at risk from snow, not how is the car driving on the bridge at risk from the snow.

Different states around the country are exposed to different environmental stressors, and each state may be impacted differently by climate change. Illinois was evaluated based on environmental hazards that could occur within the state, how each of those hazards can impact the transportation system, and which of those hazards are potentially influenced by climate change. The initial review of potential natural hazards included: sea-level rise, storm surges, volcanic activity, avalanches, fog, wildfires, and drought. Each of these was considered inappropriate to carry forward due to its low likelihood of occurring in the state, or its unlikelihood of impacting infrastructure. The natural hazards carried forward for further evaluation were grouped into four major categories: Precipitation, Temperature, Wind, and Geologic. Each category contained the types of hazards which could be generated from a similar source.

The definition of a hazard 'source' was flexible within the interpretation for preparation of categories. A thunderstorm could be the source of a tornado and heavy rains, but this study categorized source such that these two hazards were separated by form into precipitation and wind categories. Each of these hazard types was evaluated independently for how it could impact assets.

INCLUDED NATURAL HAZARDS

Precipitation (Flooding, Snow, & Ice)
Flooding can produce significant destruction of infrastructure. Flooding can be generally divided between flash floods and non-flash floods, based on the speed at which the event occurs. Flash flooding typically occurs higher up in a watershed and develops within six hours of a storm; non-flash flooding occurs lower in the watershed and develops after six hours of a storm. Flash floods are the more violent of the two as the runoff from surrounding land happens so fast it overwhelms the drainageways and drainage systems because the water cannot move downstream fast enough to stay in the channel. Flash floods have swift moving water which quickly picks up debris and generates strong scour forces.

One of the strong drivers of severe weather in the Midwest is the interaction between the warm moist air moving northeast from the Gulf of Mexico colliding with the cooler air driven south from northern Canada. With the potential for increased moisture in the future under current climate change conditions, severe storms are projected to have the capacity to produce heavier rainfalls in Illinois.

Extreme winter events include blizzards and ice storms. Neither of these, nor typical snow or ice accumulation by itself tend to cause significant damage to the transportation infrastructure itself. Snow and ice can cause poor driving conditions which can cause accidents; however, accidents are a normal part of the network operation were not included within the assessment as a hazard. Snow and ice do result in a cumulative maintenance impact to infrastructure from the wear and tear from de-icing chemicals and plowing. The form that precipitation is likely to take (snow, ice, rain) is difficult to predict. The overall warming trend will result in fewer days below freezing in Illinois. Precipitation during the winter period is anticipated to increase over the next several decades; the resulting form of precipitation will likely be highly variable year to year.

Major flood events can create washouts behind bridge structures, potentially compromising the integrity of the bridge.

Precipitation in the form of rain, snow, or ice can create a cumulative maintenance impact to Illinois infrastructure as seen in the images above.

Temperature (Freeze-Thaw / Heat & Cold)

Freezing water expands in volume by ~10% which allows liquid to break solid rock. Water freezing within the pores and linings of concrete and asphalt can cause deterioration, and repetitive cycling between liquid and ice states accelerates the process. Roadways are further damaged by the rising and sinking of the subsoils under the road surface during these events. Uneven freezing and thawing of roadway subsoils can lead to the formation of ruts in the road surface. Currently, every county in Illinois experiences some freeze-thaw cycles each year, though the number of days varies across the state and from year to year. The total annual number of days below freezing is projected to decrease in the future, but this warming could actually result in an increase of freeze-thaw cycles in certain parts of the state where temperatures may hover above freezing during the day and dip below overnight more often.

The terms "extreme heat" or "extreme cold" are relative to the starting reference point. Extreme heat in Antarctica vs. Florida mean different things in context, but extreme in the context of Illinois refers to temperatures where infrastructure is stressed. Transportation infrastructure is generally less susceptible to damage by cold than by heat. Plastics and steel tend to become brittle under extreme cold; however, temperatures required to cause structural issues are far below anything which would be experienced in the state. Extreme heat for Illinois is defined by the number of days where temperatures average in or above the nineties (degrees Fahrenheit). 95°F is typically used as a representative value for estimating annual counts. At these temperatures, the potential for heat buckling in road surfaces and rail lines increases. The average number of days above 95 varies from 10 days around Chicago to 30 around Cairo; these averages may potentially increase by a factor of two over the coming 70-80 years. Chicago, for example, could experience nearly three weeks each summer above 95 degrees by 2100.

Wind (Tornados & Straight-line Winds)

Illinois ranks fifth in the United States for the most tornadoes per square mile. The Federal Emergency Management Agency (FEMA) considers tornadoes to be nature's most violent storms, with whirling winds potentially exceeding 300 miles per hour (mph), and generating damage paths in excess of one mile wide and 50 miles long. Most tornadoes in Illinois have winds ranging from 110-167mph, strong enough to cause severe damage to most transportation assets. Straight-line winds (also called a Derecho or a downburst) can occur in association with extreme thunderstorms and can produce wind gusts in excess of 130mph. Climate models for the Midwest generally do not project locations for, or an average number of, these extreme events. Climate models generally seek to predict the overall conditions which may be present for the potential for their formations. The higher variability in the jet streams and the increased energy/moisture in the atmosphere from Gulf waters during certain seasonal periods provide the potential for an increase in these events in the future.

The average number of tornadoes in Illinois over the last century each year is approximately 60; however, anomalies do occur such as no recorded events in 1919 or double of the number of average events in 2006 when 124 were recorded. Climate change may cause an increase in the average number per year over the coming decades.

Geologic (Earthquakes, Landslides, Sinkholes, & Subsidence)

Illinois is at risk from two major seismic zones, the Wabash Valley Seismic Zone (WVSZ) and the New Madrid Seismic Zone (NMSZ). The Wabash Valley Zone is located between southeastern Illinois and southwestern Indiana. The NMSZ is located in the Central Mississippi Valley and includes portions of Alabama, Arkansas, Illinois, Indiana, Kentucky, Missouri, Mississippi, and Tennessee. During any 50-year time span, there is a 25 to 40 percent chance of a magnitude 6.0 or greater earthquake in this seismic zone. Since 1974, the year network monitoring of seismic activity began, more than 3,000 earthquakes have been recorded in the NMSZ. Fortunately, none of these earthquakes has exceeded a magnitude of 5.0, and most occurred without our noticing. The largest earthquake in recent years occurred in the WVSZ. This earthquake registered a magnitude of 5.4 and occurred in Mt. Carmel, Illinois on April 18th, 2008. The review of literature does not suggest that seismic zones which could affect Illinois would be influenced by the potential triggers that could be associated with climate change.

Landslides can be triggered by water, earthquakes, and volcanic activity, but intense rainfall or snowmelt are the primary causes. They often happen simultaneously with flooding and can be more easily triggered after a fire has removed the vegetation from a slope. According to an inventory of landslides in Illinois conducted by the Illinois State Geologic Survey (ISGS), at least $8 million in damages from landslides have been documented since 1928. The compiled data show that most landslides in the state have been induced by construction activities and that most occur along the Illinois and the Mississippi Rivers. Intense rainfall over a short period of time has been correlated with an increased probability of landslides. The projections for Illinois to see an increase of intense precipitation events increases the potential for landslide occurrences in the future, but there is currently no method to predict this.

Sinkholes can be generally defined as a cavity in the ground caused by water erosion or mine subsidence. Sometimes the ground slowly subsides, other times it collapses instantaneously. Sinkholes naturally form in certain types of rock formations where the underlying rock can be dissolved by groundwater. Areas where these conditions occur and sinkholes are prevalent are referred to as karst terrain. Sinkholes in Illinois are prevalent within Monroe, Randolph and St. Clair Counties. This area is often called the Illinois Sinkhole Plain, with an estimated 10,000 sinkhole features. Natural Sinkhole formation in Illinois generally is not directly linked to climate change. Mine subsidence is a common occurrence in Illinois given the state's mining history. Although mines are manmade, they are included within the study under natural hazards, and not projected to change regarding climate. 'Unnatural' sinkholes have become more common in urban areas. These are often associated with underground utilities where subsoil may settle or be washed away, and are generally independent of any climate change issues.

EXCLUDED NATURAL HAZARDS

Drought & Wildfires

Climate change is expected to cause the transition of compressed rain events during the year, with hotter, dryer summers and warmer, wetter winters. Additionally, variability in weather will likely increase causing seasonal droughts to become more severe. Wildfires are typically associated with drought; thus, the first response could be to anticipate them as a developing problem. While droughts can cause localized wildfires in Illinois (now and under climate change scenarios), neither the landscape nor the severity of the droughts are anticipated to support the type of conditions where wildfire can threaten transportation infrastructure.

Volcanos, Fog, & Avalanches

Illinois does not contain any mountain ranges which have geologically active volcanic activity or the elevations to support the formation of avalanches. Localized dense fog is not an uncommon occurrence in the mornings during spring or fall, but fog would not occur at levels warranting consideration within the vulnerability assessment in Illinois now nor under any projected climate change scenarios.

Sea-level Rise & Storm Surges

Sea-level rise is a major concern regarding climate change, and the Lake Michigan coastline does make Illinois a coastal state. The Great Lakes are considered inland seas and collectively comprise the largest body of freshwater on the planet. Current melting glaciers and polar ice caps are resulting in a slow and steady rise in ocean waters. Storm surges occur when the winds from large storms push surface waters closer to the shoreline causing inland flooding. As ocean levels rise, storm surges such as those associated with Hurricane Sandy can overwhelm coastal flood protection measures. Unlike oceanic coastal cities, the levels of water in the Great Lakes are not influenced by a rise in the oceans; however, they are influenced by the weather patterns. Climate research indicates the likelihood of greater fluctuations in the lake levels because of climate shifts, but they are not anticipated to generate additional flooding along the coastline of Lake Michigan.

"While droughts can cause localized wildfires in Illinois (now or under climate change scenarios), neither the landscape nor the severity of the droughts are anticipated to support the type of conditions where wildfire can threaten transportation infrastructure."

PART 3: MEASURING VULNERABILITY

Developed Methodology
Impacts to Illinois Transportation Resources

PART 3: MEASURING VULNERABILITY

DEVELOPED METHODOLOGY

Vulnerability, within this study, is not simply a measurement of risk to each separate asset, but the measurement of risk to the system. To further complicate things, this study also needed to meet two separate goals simultaneously: measure vulnerabilities to traditional hazards, and measure vulnerabilities to hazards under projected future conditions related to projected climate change. To accomplish this task measurements were produced for both the baseline conditions and conditions for those hazards which are susceptible to change under potential future climate change conditions. The resulting comparisons between the baseline and future risk scenarios represent the system's resiliency to climate change. The storm surge from Hurricane Sandy, for example, flooded multiple underground subway tubes in the Boston-New York City metro area. The flooding resulted in part because the system was not anticipated to experience that level of storm surge. Comparing the risk between what infrastructure was designed for and what it may be exposed to can identify a foreseeable lack of preparedness.

The framework of this assessment established vulnerability through measuring the interaction of how:

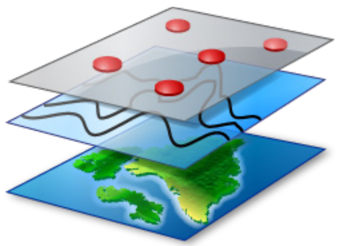
(1) ***Critical*** an asset is to the transportation network;
(2) ***Exposed*** an asset would be to a defined hazard; and
(3) ***Sensitive*** an asset is to each hazard.

Combining the measurements of criticality, exposure, and sensitivity generate a Vulnerability Index (VI). The VI score considers the interplay of the components such that an asset may be highly sensitive to a given hazard, but have a low VI because it is not considered critical. Conversely, an asset may be highly critical but have the same or lower VI than less critical assets because it is either not exposed or not sensitive to the selected range of hazards. The multilevel modeling produces independent scoring for criticality, risk (exposure and sensitivity), and vulnerability which allows project planners to parse out the separate components and have the opportunity to review by county, district, region, or state which asset resources are the most critical or the most at risk independent of the overall level of vulnerability.

Measurements of criticality (and, by extension, vulnerability) are protected information. The overall methodology will be presented for criticality and vulnerability, but in the interest of security, scoring details will limited to the risks associated with natural hazards.

Peak vulnerability exists within the area overlapped by all three components

PART 3: MEASURING VULNERABILITY



The assessment included a synthesis of multiple studies and differing methodologies to produce a framework which contains enough flexibility to manage the volume of assets, their associated data, and assessment needs. The methodology created independent evaluations which provide the ability to glean information pertinent to different aspects of criticality and risk. Limitations of resources and data availability prevented a full assessment of all assets, but the study established a foundation for future iterations.

Criticality, risk, and vulnerability were measured by generating independent evaluation models within a spreadsheet format which could interact with the master database containing all the information for the assets and the associated hazards. The master database was paired with a geodatabase which placed all the assets within a geographical mapping environment*. Five separate products were prepared using the data:

- **Criticality Index Classification**
- **Risk Analysis Classification** [for manmade hazards]
- **Risk Analysis Classification** [for existing natural hazards]
- **Risk Analysis Classification** [for predicted climate change hazards]
- **Vulnerability Index Classification**

**For those readers unsure what a geographical environment is, think of Google Earth or any other online mapping tool. The geodatabase takes the raw information about something such as a section of road being 2 lanes, concrete, and constructed in 1998, and associates that information with a point, line, or polygon on a map.*

CRITICALITY

CRITICALITY, as used in this study, indicates the importance of transportation assets within their assigned asset category relative to other assets in the same asset category. Although the criticality scores are not directly comparable between asset categories, they do influence each other; i.e. the score of a road corridor segment is not directly comparable to a bridge structure, but the presence of a bridge within a road corridor can influence the sensitivity of the corridor.

RISK

RISK, as used in this study, is the net effect of the measured probability of being exposed to a hazard and the sensitivity of the asset to the hazard. Exposure is the likelihood of an asset to encounter a given hazard without consideration of the impact the hazard could have; sensitivity measures the effect a hazard would have on an asset without consideration of whether or not it could be exposed. Evaluating both probability and sensitivity separately provide predictability when the context changes. In a gross simplification, two bridges constructed identically are at equal risk from earthquakes when located in the same seismic zone while not at equal risk when located in different seismic zones. In this example, by measuring factors which make bridges susceptible to earthquakes independent of exposure then allows adjustments to risk should it be determined the seismic conditions change in the future.

CRITICALITY CLASSIFICATION

Criticality, as defined in the study, is completely independent of the risks associated with hazards; therefore, criticality only indicates which transportation assets are of the greatest importance within their asset category. Determination of criticality contains a high degree of complexity as the process can easily overlook local and/or regional importance. For example, Average Annual Daily Traffic (AADT) is a key marker for roadways in considering criticality; the more cars on the road, generally the more important the road is. However, if volume becomes the only, or the most heavily weighted variable, then critical roads would only occur within the densest urban areas. Criticality must balance items such as volume, connectivity, and function.

Determination of criticality for this study was adapted from the approach developed as part of the U.S. Department of Transportation's (USDOT) Gulf Coast Study (FHWA-HEP-11-029). The study evaluated assets based on different performance values from different perspectives. Rating critical infrastructure considered the interaction of defined variables separated into three groupings of importance: (1) general operation/ use/function; (2) socioeconomic impact; and (3) ability to affect health and safety. Following review of numerous other methodologies, this was determined the most appropriate for adaptation to the Illinois study.

The adaptation maintained of the three overall groupings, but tailored these to the study on a global level and for each asset category. The three groupings are intended to evaluate an asset from different aspects, but special attention was given to preventing 'double dipping'. The same variable was not allowed to be evaluated twice by being in more than one group.

Variables could be similar between groups to strengthen a position, but not identical. For example, a section of railroad could be evaluated for how many passenger rail trains ran per day and separately by how many freight trains, but not twice for the total number of trains. In this situation, how many passenger rail vs. freight rail trains may be carried per day provides two discreet pieces of information about the railroad even though they both add up to the total amount of trains per day. Depending on whether the number of passenger or freight rail trains is more important, an answer can be weighted in the evaluation.

ADAPTATION OF IMPORTANCE GROUPS FOR ILLINOIS

(1) Operational

The immediate impact the infrastructure asset has on the function of the transportation system relative to other parts of the network if lost. Assets such as a bridge or pump house are considered as a whole, while roadways and rail lines are considered as segments of the whole. These variables are intended to measure redundancy or impedances in the system.

(2) Socioeconomic

The ability of the infrastructure asset to affect the local, regional, or national economy through movement of goods and services, access to employment centers, and the social characteristics of the local community relative to other parts of the network. These variables measure contributions to community function.

(3) Health and Safety

The potential role infrastructure asset play during emergency or hazardous situations relative to other parts of the network. These variables measure secondary value.

Queries are questions asked of the data in a formula once information has been properly formatted in a database (e.g. how much traffic does the road carry, how many lanes does it have, what seismic zone is it located in, etc.). Variables are the information available for use in the database (i.e. is there information about traffic volume?). The availability of useful information is critical to develop a system to measure vulnerability. Once the data were sorted and a variable list was completed, it was necessary to decide how much value [weight] to assign to each variable. The weighting process was not predetermined, but a couple of general rules of thumbs were followed:

» None of the three groups should carry more than 50 percent of the weighting,
» The Operational group should have a greater weight than Socioeconomic and Health & Safety in each case

Selection of variables to associate with the Operational, Socioeconomic, and Health and Safety groups was limited to the available geospatial data identified during the development of the Asset Classification and Hazard Classification technical reports. Direct and indirect information was considered while developing the evaluation criteria. An example of an indirect variable is a buffer zone created around a medical facility. There was no way to directly determine whether or not a roadway provides a primary access route to a hospital without manually evaluating each roadway throughout the state, but it can be assumed if the roadway is within a certain distance of the facility it could become a primary access route during an emergency which would increase its importance. A GIS program can query all medical facilities within the state and generate a buffer area which can be linked to any roadway segment. Thus, the information is collected without individual reviews. Although direct and indirect measurements can be important, variables of direct measurements were typically assigned greater weight. Variable selection and weighting were coordinated with the members of the technical working group.

PROCESSING INFORMATION

IDOT stores bridges and operations facilities as points on a map. These are discreet places which can be easily evaluated. Road and rail segments are stored as lines which break depending on the beginning and end points of previous construction projects, or where something about the road/rail changes (e.g. a road segment transitions from having a 10ft shoulder to an 8ft shoulder). Because of this, the length of the road and rail segments can range from less than 10ft to greater than a mile. Logical termini are necessary to evaluate a section of road or rail (i.e. what value does a randomly located 6ft section of road have to the system?). So, a set of rules was created to join segments in the geodatabase such that the section evaluated connected pieces of the transportation system. Roadway segments were joined such that they broke at intersections or interchanges (this associated criticality and risk in context to a reasonable Point A and Point B rather than random termini). Railroad segments were joined such that they broke at stations and where service lines joined or split.

RISK CLASSIFICATION

A methodology to evaluate risk was developed specifically for this project from a mixture of novel concepts and concepts gleaned from review of numerous national hazard assessments, including FHWA climate change adaptation pilot studies. As an all-hazards assessment, the primary focus of risk is the identification of threats which can produce immediate and permanent harm to infrastructure. As a climate adaptation study, a primary purpose is to identify what differences exist between the risks from natural hazards now versus an estimated projected climate. This study sought to create a methodology which could serve both focal points. To accommodate these considerations, the evaluation of natural hazards was subdivided into three parts.

» Existing Natural Hazards Risk Analysis
» Future Natural Hazards Risk Analysis
» Maintenance Analysis

The natural hazards were selected based on their potential to cause damage and/or impact the overall operations. Snow, for example, by itself does not directly harm a roadway surface, but the supporting infrastructure (e.g. snow plows and salt) should be part of the system where snow occurs with regularity. Without supporting infrastructure, an 8 or 10inch snowfall could shut down access to assets for an extended time, whereas with supporting infrastructure the asset remains in service. Further, the supporting infrastructure could indirectly result in the degradation of an asset (e.g. salt application on bridges affecting how quickly rust develops on metal surfaces). If a projected climate scenario changes the frequency and intensity of a natural hazard, it should be determined whether the hazard poses an increased or decreased threat, and whether a change in the supporting infrastructure may be required.

Each natural hazard was separated into a ‘damage event’ or ‘cumulative event’ category based on the whether the primary threat produced was an immediate loss of the asset or produced certain maintenance requirements and/or additional supporting infrastructure. A damage event describes a single event with the potential to cause a catastrophic loss of the asset type. A cumulative event describes those events which degrade the asset over time and trigger specific maintenance activities, but are considered a normal part of the operation for the asset type. The cumulative events would not typically be considered in a vulnerability assessment as they are already accounted for in the normal operation and maintenance plans of a transportation agency; they are considered within this study to determine if a climate change scenario would potentially alter operation and maintenance needs.

Natural Hazard Type	Damage Event	Cumulative Event
Precipitation- Flooding	Bridges/Corridors/Operations	
Precipitation- Snow		Bridges/Corridors/Operations
Precipitation- Ice		Bridges/Corridors/Operations
Temperature- Freeze/Thaw		Bridges/Corridors/Operations
Temperature- Extreme Heat		Bridges/Corridors/Operations
Temperature- Extreme Cold		Bridges/Corridors/Operations
Wind- Tornadoes/Straight Line	Bridges/Corridors/Operations	
Geology- Landslide	Corridors/Operations/Bridges*	
Geology- Earthquake	Bridges/Corridors/Operations	
Geology- Sinkholes/Subsidence	Bridges/Corridors/Operations	

*Landslides as they apply to bridges in this study were not calculated during the risk analysis. In Illinois, the type of landslide which would cause significant damage to the structure would be associated with a flooding event. To prevent “double-counting” in the risk analysis, landslides’ effects on bridges was factored in the risk under flooding.

PART 3: MEASURING VULNERABILITY

EXPOSURE
X SENSITIVITY
RISK

The hazards were secondarily evaluated as to whether the projected climate change scenario could change the level of risk, which could in turn impact overall vulnerability. The key point of this portion of the evaluation was not to find if the scenario resulted in a change in weather events, but whether those changes could be measurably determined to alter the level of risk. For example, the prediction that Illinois could receive either an additional 4 inches, or 4 fewer inches of snow on average per winter would not alter the risk posed to the transportation system because supporting infrastructure is present to handle the cumulative events. However, predicting an increase or decrease in earthquake magnitudes across Illinois would alter the risk posed because infrastructure may or may not be built to handle the change.

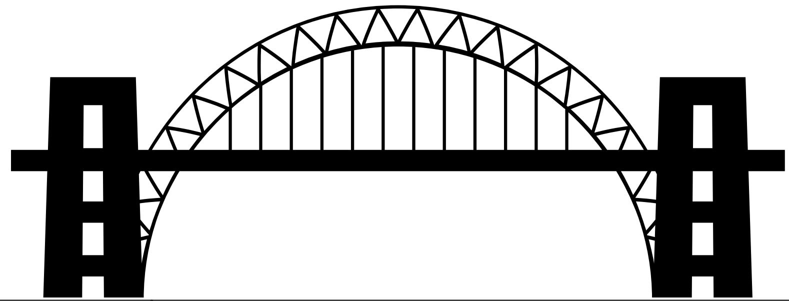
Criticality Index values were generated for each individual asset included in the study. The difference between the risk analysis and the maintenance analysis is with regard to evaluating an individual asset or a portion of the system. The risk analysis progresses each individual asset forward to generate a Risk Analysis Index value based on the hazards which could produce a damage event. The maintenance analysis progresses a self-contained discussion of those hazards which have the potential to influence changes to design standards, maintenance requirements, or life cycle costs of asset categories but do not pose an imminent threat to any specific asset.

Risk is the combination of exposure and sensitivity. The process for evaluating risk begins similar to criticality by developing and selecting information about an asset in relation to the hazard. Unlike criticality, where the final classification of an individual asset is derived on the importance of the asset relative to other assets within the transportation network, classification of risk for an individual asset is derived only from the relativity of the hazards (i.e. criticality = asset compared to other assets; risk = asset compared to hazard). Classification of risk is based on the combinations of exposure and sensitivity. For this study, variables were established to determine if an asset had a low or high probability of exposure to the hazards, and if it had a low or high sensitivity to the hazards. These produced the following four classifications:

Low Risk	Low Sensitivity/Low Exposure
Medium-Low Risk	High Sensitivity/Low Exposure
Medium-High Risk	Low Sensitivity/High Exposure
High Risk	High Sensitivity/High Exposure

Only hazards with the potential for a 'damage event' were carried forward in the risk analysis. The risk analysis evaluated each asset against all hazards simultaneously. An asset is at 'high risk' if it is considered sensitive and exposed to any single hazard. Level of Exposure will always be specific to each hazard type; however, sensitivity factors may be shared between hazards (e.g. an exposed bridge piling foundation may indicate susceptibility to damage from both flooding and earthquake events). It should be noted that the likelihood and/or frequency of a damage event was not considered in the assessment, only that it could occur (i.e. risk was assigned regardless of whether there was a 10% or 90% chance).

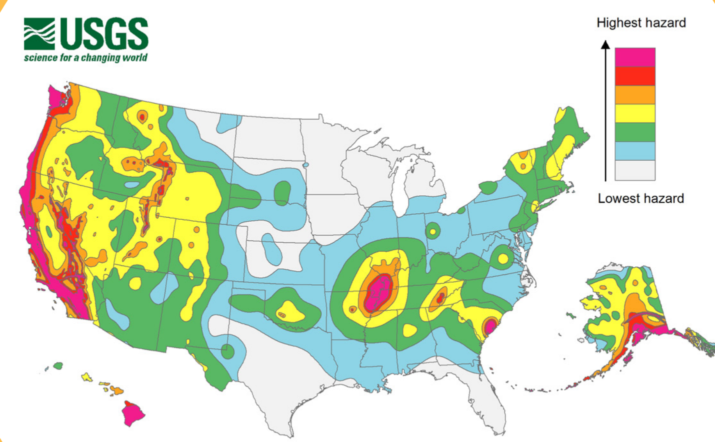
The variables used to measure sensitivity and exposure are important for maintaining consistency in the process between capturing the existing risks and how future changes can predict whether those risks increase or decrease. The four combinations of sensitivity and exposure provide flexibility to recalibrate risks if the asset becomes more sensitive to hazards, or more exposed. A simplified example of risk categories for a bridge are shown here.



Low Risk	Designed to handle an earthquake of 7.0 magnitude, in a zone not anticipated to have an earthquake larger than 2.0
Medium-Low Risk	No specific seismic design considerations, in a zone not anticipated to have an earthquake larger than 2.0 magnitude
Medium-High Risk	Designed to handle an earthquake of 7.0 magnitude, in a zone anticipated to have earthquakes of 7.0
High Risk	No specific seismic design considerations, in a zone anticipated to have an earthquake of 7.0 magnitude

This example isolates a bridge asset paired with a seismic hazard. Risk categories/combinations identify potential exposure to earthquakes and whether the infrastructure can withstand an earthquake. The full model simultaneously evaluates all hazards to produce the risk classification, but still captures each independently so the reviewer can identify which hazard(s) trigger an elevated risk factor if present (i.e. could it be flooding or earthquakes that caused an increase).

PART 3: MEASURING VULNERABILITY



HOW TO MEASURE EXPOSURE

Earthquakes: What seismic zone is the asset located in? Distinct zones have been designated in Illinois based on the underlying soil types and the distance from primary fault lines.

Sinkholes: Is the asset located within a karst area?

Landslides: Is the asset located within a low, medium, or high landslide incidence zone? The U.S. Geological Survey (USGS) has developed maps in Illinois identifying areas of potential landslides based on past records.

Subsidence: Has the asset been constructed over an area with known mines? The Illinois State Geological Survey (ISGS) maintains maps of active and closed underground mining operations within the state.

High Winds: Are you in Illinois? Tornadoes and straight-line winds can occur anywhere in the state. Any asset located above ground has the potential to be exposed.

Flooding: What hydraulic studies have been performed? Flooding occurs in many forms and under various conditions. Flood information may come from floodplain mapping, asset specific modeling, or historical records.

HOW TO MEASURE SENSITIVITY

Sensitivity can be indicated by either the type or condition of an asset.

By type: Buildings can be destroyed by high winds while roadways and most types of bridges remain unaffected during the storm besides collecting debris.

By condition: Bridge condition assessments are completed on a rotational basis by IDOT to identify potential issues such as fractures in structural components or scouring of the approaching roadway embankment. A combination of characteristics of type and condition was developed for the asset groups to indicate a measurement of sensitivity.

IDOT routinely completes bridge condition checks to identify potential problems.

WHICH NATURAL HAZARDS ARE AFFECTED BY CLIMATE CHANGE? HOW DOES THIS IMPACT RISK?

Damage Events

☐ Flooding
☐ High Winds
☐ Earthquakes
☐ Landslides
☐ Sinkholes
☐ Subsidence

Cumulative Events

☐ Snow & Ice Accumulation
☐ Freeze/Thaw Cycling
☐ Extreme Temperatures (Cold)
☐ Extreme Temperatures (Heat)

UNAFFECTED BY CLIMATE CHANGE (IN ILLINOIS)

Earthquakes: Glaciers weigh a lot, so much so that they tend to deform the Earth's crust. When they advance, the land underneath is squished. When they retreat, the land begins to slowly rise again like a memory foam pillow. The rising of the crust is referred to as either glacial or isostatic rebound. Lands today are still rebounding from the last ice age, which in combination with tectonic forces directly influences how areas around the world are experiencing sea level rise. The southern coast of Alaska, for example, is rising faster than sea level is rising. While the worldwide retreat of glaciers does have an impact on crustal plates, there is no evidence to suggest significant change in seismic activity from the fault lines in and near Illinois would occur over the course of the next century.

Sinkholes & Subsidence: Sinkhole formation in Illinois occurs from the dissolution of carbonate rock (limestone) by water moving through bedrock. Some human activities can cause groundwater levels to repetitively drop then recharge (such as heavy groundwater pumping for irrigation of croplands) are known to influence sinkhole formation. As noted in the general climate discussion, the intensity of summer droughts over the coming decades is projected to increase. This could prompt greater use of agricultural irrigation, but sinkhole formation is a long process. If an increase in groundwater pumping did occur over time, change in the rate of sinkhole formation would be highly localized and difficult to detect potential impacts to infrastructure.

Landslides: Climate change has been demonstrated to influence the threat of landslides under various conditions. In Alaska, the permafrost has been increasingly thawing, which has created unstable slopes within mountain passes. Recent increases in rainfall intensity in western Oregon and Washington has produced destructive landslides. In 2009, twenty-three counties in Washington were designated as federal disaster areas due to landslides triggered by heavy rains. This hazard can be influenced by climate change, but the conditions in Illinois are not such that they compare to these other areas.

CLIMATE CHANGE AFFECTS THE HAZARD…. BUT NOT THE RISK

Snow & Ice: On average, winters will become shorter with most years producing extended fall and spring periods, with the most dramatic effects likely in Northern Illinois. Using the phrase 'on average' again, winters will become warmer, but the result may be better described as weather becoming less predictable year to year. Recent history provides some examples of what may be expected to become the new normal. The winter of 2014-2015 produced one the coldest and heaviest snowfall totals recorded across the state. The following winter (2015-2016) produced well above average temperatures and although the total amount of precipitation received was in the normal range, it featured very little snowfall; the winter was the fourth warmest on record for Rockford, which also received less than half the normal amount of snow. The variability in weather over the winter periods will mean the existing infrastructure IDOT uses to keep roadways free of ice and snow will continue to be required, despite a predicted 'on average' rise in temperature.

Extreme Temperatures (Cold): As described under snow and ice, winters will generally become shorter and warmer in the coming decades, but variability will remain to periodically produce extremely cold winters. Weather patterns influenced by the Arctic and North Atlantic Oscillations will periodically result in the plunging of arctic air mass over the Midwest. The anticipation of having generally warmer winters reduces the total number of days of extreme cold; however, the risk remains unchanged as the supporting infrastructure will continue to be required.

Wind: The intensity and frequency of severe thunderstorms are anticipated to increase in Illinois over the coming decades. The Fujita scale of F0-F5 is used to designate the estimated wind speed of these events with F0 being the slowest (less than 75mph) and F5 being the most intense (in excess of 300mph). Any event equaling an F2 or higher has the potential to destroy buildings. Because the methodology used does not consider the frequency, only whether the damage event can occur, and the existing intensity already produces damage events, an increase in frequency or intensity does not change the level of the hazard.

Predicting winters in Illinois is a challenge under the current conditions, but predicting them under climate change scenarios may be best summarized as a collective shoulder shrug. Winters will trend warmer, but some winters may be dominated by events of freezing rain, others by snow, and others still by rainfall. It may be hard to define what an average winter will bring.

AFFECTED BY CLIMATE CHANGE AND POTENTIALLY CHANGE THE RISK

Flooding: Flash floods occur because of high rainfall intensity; i.e. a lot of rain in a short amount of time. Non-flash flooding (also known as riverine flooding), occurs because of the pure volume of rain over a large area. An important distinction between them is flash floods are localized while riverine floods are regional. Five inches of rain falling over the course of a couple hours isolated over the Quad Cities will cause creeks to overflow their banks. In this case, municipal storm sewers would not drain fast enough and basements and streets would consequently flood, but the level of the Mississippi will not rise. Now imagine five inches of rainfall spread across Iowa, Wisconsin, and Illinois. This would create so much runoff that the Mississippi River would respond. Climate change has increased ocean temperatures which generates more moisture in the atmosphere. The additional moisture creates the situations for storms to produce heavier rainfall events anywhere they develop….including over Illinois.

"Increased flooding events can cause greater damage within a single storm; increased summer temperatures can create an increase in maintenance problems."

Freeze/Thaw: With extreme variability anticipated to become the new normal winter weather in Illinois, not every year will produce more freeze/thaw cycles across the state. However, it is likely that the warming winter trend mixed with the variability will produce more cycles on average. The rate of asphalt deterioration and extent of pothole formations are affected by the number of these cycles. More cycling can cause an increase in problems associated with pavement rutting and potholes, which can impact overall life cycle costs and annual operational maintenance.

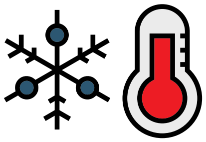
Extreme Temperatures (Heat): Days at or above 95^{o}F is a general benchmark used to estimate both design specifications and anticipated maintenance related to heat buckling issues (for both roadways and railroad tracks). Depending on localized conditions of rail steel, or roadway pavement, buckling can occur at higher or lower temperatures, but 95^{o}F provides a frame of reference. The change over time regarding increases in summer temperatures can include higher peak temperatures (i.e. record setting temperatures), but the more meaningful number for transportation infrastructure in Illinois will be both the total number and greatest consecutive number of days in the nineties. As with freeze/thaw cycling, the increase in the number of days above 95^{o}F negatively impacts life cycle costs and annual operational maintenance needs.

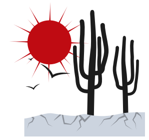
HAZARDS WITH THE POTENTIAL TO BE IMPACTED BY CLIMATE CHANGE

☑	Flooding
☑	High Winds
☒	Earthquakes
☑	Landslides
☒	Sinkholes
☒	Subsidence
☑	Snow & Ice Accumulation
☑	Freeze/Thaw Cycling
☑	Extreme Temperatures (Cold)
☑	Extreme Temperatures (Heat)

HAZARDS WITH THE POTENTIAL FOR THE CHANGE TO AFFECT MEASURED RISK

☑	Flooding
☒	High Winds
☒	Earthquakes
☒	Landslides
☒	Sinkholes
☒	Subsidence
☒	Snow & Ice Accumulation
☑	Freeze/Thaw Cycling
☒	Extreme Temperatures (Cold)
☑	Extreme Temperatures (Heat)





Based on our vulnerability assessment, the hazards which have the potential to be impacted by climate change and could affect measured risk are Flooding, Freeze/Thaw Cycling, and Extreme Heat.

HOW ARE THE POTENTIAL CHANGES TO RISKS MEASURED?

Anticipated changes to cumulative hazards of Freeze/Thaw and Heat will occur gradually over time. The changes in risk are not represented by single events which can cause system failures, rather subtle events resulting in more maintenance activities. Addressing these impacts requires proactive planning to develop future design specifications which may not be necessary to implement for several years (until a trigger point in average or peak temperatures is reached). For example, asphalt resurfacing is typically necessary every seven years on highways. As temperatures rise, the asphalt formulations used in current design specifications may need adjusted to maintain the normal design life cycle. Separately, as winter soil moisture levels increase, both heat buckling in the summer and frost heaving in the spring can be exacerbated. Frost heaving generates conditions for pothole formation and pavement rutting. Design specifications to improve drainage and moisture control within the sub-soils and base layers may need to be modified. These hazards do not need to be directly measured on an individual asset basis within this study, but do need to be monitored for determining appropriate times to implement new standards.

Changes to risk from catastrophic floods are already underway; flood intensities have increased over the past several decades and will continue to increase in the coming decades. Risk from flooding is not ubiquitous to the assets like a cumulative impact, but specific to each asset. Risk cannot be evaluated on the basis of whether or not the asset crosses a waterway, rather on the characteristics of the waterway. Two equally important variables must be predicted before estimating any change in the risk from flooding: 1) What might the new rainfall intensity be? and 2) How may the new rainfall intensity affect the flood elevations of a given waterway?

Predicting the change in rainfall intensity

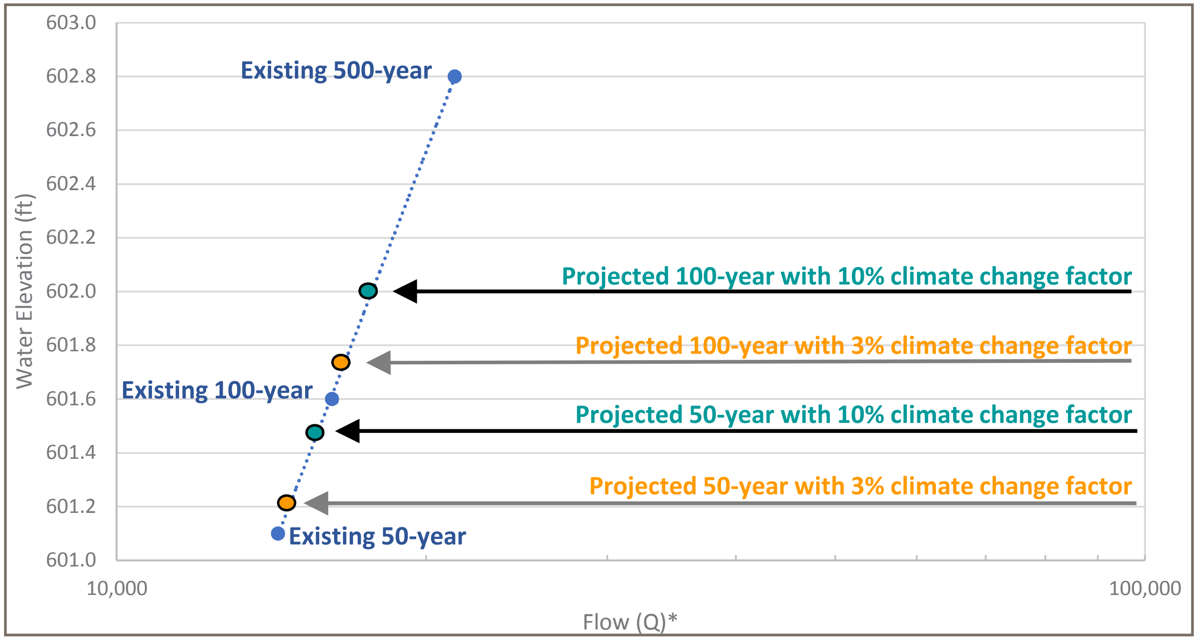
Weather events are localized and sensitive to slight changes; what separates a EF3 from an EF4 tornado, or an ice storm from a snowstorm can be very minor and very specific to the location or the time of day the storm forms. Global climate models use historical weather information to predict trends in major circulation patterns. Climate change predictions are made by adjusting inputs in the models which produce outputs of annual or seasonal conditions over grid blocks generally representing hundreds of square miles. For rainfall, the trends generate estimates (with a defined degree of confidence) on how much precipitation will occur in a grid block over a three-month period, but this does not directly predict how large storms will be within that timeframe.

In addition to determining how to translate a seasonal estimate into a peak storm event, an underlying question remains about what future to align the estimate with. Greenhouse gas emissions are the primary driver of climate change. How much carbon will be in the atmosphere in the year 2050, 2080, or 2100? This answer is partially dependent on the carbon policy decisions of different nations all over the globe.

Rather than picking a single future scenario, two futures were estimated using a ‘high’ and ‘low’ emissions forecast developed by the Intergovernmental Panel on Climate Change’s (IPCC). These different scenarios predict Illinois to experience an increase of annual precipitation between the range of 3-9%. Although an annual increase in precipitation does not necessarily correspond to the same increase in peak storm events, the study team deemed it appropriate to establish an adjustment factor of 3% and 10% increase to be applied to peak storm flows.

Predicting the change to flood elevations

A hydraulic study is completed for each highway or railway drainage structure as part of the structure design. A hydraulic study calculates the flow of water in cubic feet per second, represented as 'Q' for 10-/50-/100-/500-year storm events (flow is a product of rainfall intensity and watershed characteristics: a drainage in a deep, steep valley produces more flow than a wide, flat prairie with the same amount of rain). These different flows are used to calculate the elevation of the water in the stream/river during each event. Depending on the type of route (interstate, county highway, urban street), and the anticipated lifespan of the drainage structure, the structure is designed to pass either the 50-year or the 100-year flow.



**Part of the mathematical process converts the flow data into a logarithmic scale, the x-axis represents the flow under the structure*

Existing IDOT hydraulic studies for Illinois bridge structures serve as the basis for estimating the difference in water elevations under climate change.

Event Interval	Flow (Q)	Water Elevation (ft)
50-year	14,345	601.0
100-year	16,190	601.6
500-year	21,320	602.8

Existing hydraulic studies provided the means to estimate water elevations under the climate change scenario. A slope regression analysis was generated from the original hydraulic calculations. This analysis predicts new water level elevations if the flows were modified, as long as the flow does not exceed the 'Q' of the 500-year interval. For this study, the 3% and 10% climate adjustment factors were applied to the historical 50- and 100-year flows to project new flood elevations. This strategy did not attempt to determine the worst possible flooding event, rather it sought to determine what a reasonable adjustment to a design criterion would produce when applied to existing infrastructure. What does a flood look like in a 100-year storm if a 100-year storm is increased by 3 or 10% from the current standard?

CONCLUSION

The methodology developed for the study generated an independent evaluation of IDOT's assets for criticality, risks, and vulnerability at existing conditions. Further, the study evaluated how climate change may impact risk. Symmetry was maintained in the evaluation process for criticality, risk, and vulnerability such that each step classified the assets into one of four levels, with Level/Class 1 being of the lowest and Level/Class 4 being of the highest degree of criticality/risk/vulnerability. While detailed information cannot be provided for security reasons, the findings of the study for the different assets can be generalized. Of the four classifications, assets within Levels 3 and 4 represent those where consideration of mitigating measures may be warranted to increase the resiliency of the transportation system. These tables summarize the results of the study for the risk and vulnerability classifications of the existing conditions. The climate change adjustments for flooding were calculated separately.

ASSET RISK SUMMARY

Transportation Category	Class 1 and Class 2 (%)	Class 3 and Class 4 (%)
Bridges	88.3	11.7
Road Corridors	71.8	28.2
Rail Corridors	90.6	9.4
Operations	56.7	43.3

This summary table represents the percentage of assets within the different transportation categories identified to fall within the upper and lower levels of risk classification. These percentages represent infrastructure potentially directly exposed and sensitive to one or more of the various event hazards.

VULNERABILITY SUMMARY

Transportation Category	Class 1 and Class 2 (%)	Class 3 and Class 4 (%)
Bridges	98.4	1.6
Road Corridors	96.6	3.4
Rail Corridors	96.0	4.0
Operations	90.5	9.5

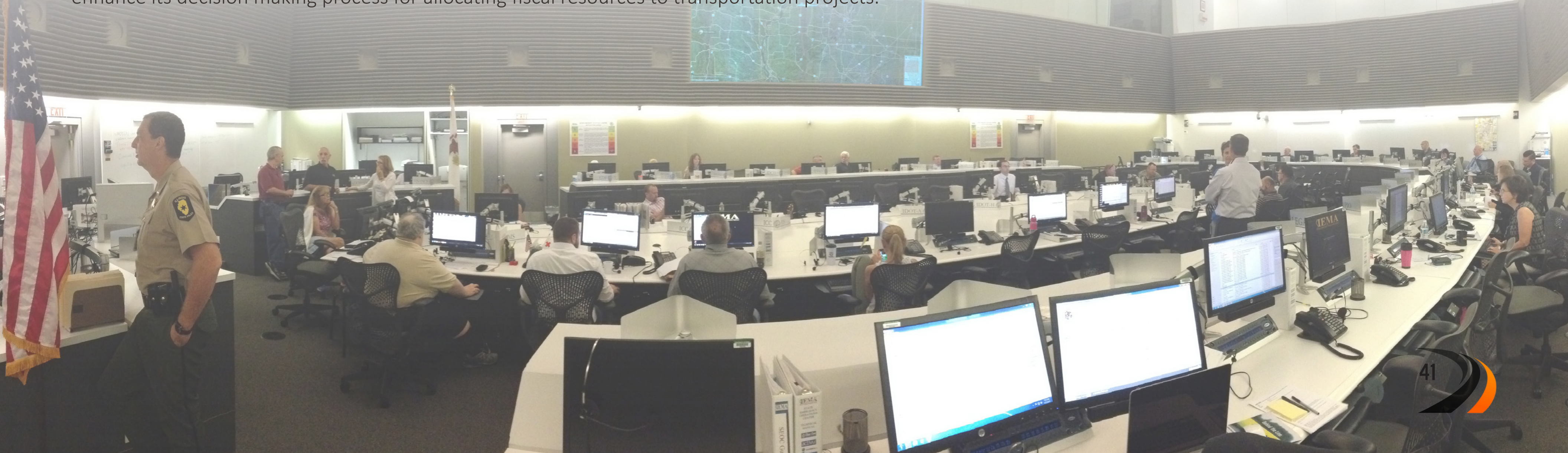
This summary table represents the percentage of assets within the different transportation categories identified to within the upper and lower levels of vulnerability classification. These percentages represent consideration of both the importance of and risk to the assets to highlight those which should be given priority as part of the transportation planning process.

IDOT coordinates with numerous transportation and emergency response agencies, including the Illinois Emergency Management Agency (IEMA), Illinois State Police (ISP), Federal Emergency Management Agency (FEMA), Illinois State Toll Highway Authority (ISTHA), Office of the State Fire Marshal, and municipalities across the state. As partners, IDOT and these agencies develop emergency response plans to a wide variety of potential scenarios. The development of this All-Hazards Vulnerability Assessment provides crucial information for planning efforts to identify potential issues with key pieces of infrastructure in relation to various conditions. If an earthquake strikes southern Illinois, which bridges and which routes may be impacted? If there is a flood event occurring over a multi-county area, which corridors may be temporarily impassable? Each of the risks evaluated has the potential to impact the transportation system, and impacts can be compounded if multiple emergencies occur simultaneously. Offsetting risk and establishing contingencies is not possible without understanding the vulnerabilities in the system.

Illinois Department of Transportation

Illinois All-Hazards Transportation System Vulnerability Assessment and Response Plan

Although previous studies have been performed on a localized basis throughout the state, this is the first study to provide a comprehensive assessment of the statewide resources managed by IDOT. The methodology establishes a foundation for future studies to adjust and improve the evaluation process as more data become available over time. Transportation planning in Illinois occurs at the local, regional, and statewide level. The division of the assessment into the different indices allows planners on each level the opportunity to have additional information on their transportation resources to assist in prioritization and/or mitigation. Even in a non-critical corridor, it may be justified to retrofit a bridge to increase the resiliency against earthquakes. A critical corridor may not have a flooding issue currently, but flooding problems could be projected under a climate change scenario; the corridor may justify a future improvement project to incorporate higher flood elevation design criteria as a contingency. The information associated with these different aspects is now available to planners and provides the state the ability to further enhance its decision making process for allocating fiscal resources to transportation projects.



PART 4: CLIMATE & WEATHER

When Weather Becomes Climate
Driving Forces of Weather
Climate Change

WHEN WEATHER BECOMES CLIMATE

Why isn't it called weather change?

The earth is not a static place. Over geologic timeframes the oceans have risen and fallen as ice ages have come and gone. The continental plates shift around the surface of the planet like a rough game of shuffleboard. As the continents move they can cause changes in the ocean currents and create mountain chains which reach into the sky to impact how the wind blows. Solar flares, volcanic activity, salinity of the ocean.... the list can go on, but all these variables intermingle with each other to generate the climate that exists on earth at a given point in time.

A meteorologist, oddly enough, doesn't study meteors. We do, however, rely on them to know whether to take an umbrella, if it's OK to wear shorts, or whether we are going to need to put on a sweater before heading out the door. A meteorologist tells us what to expect about the weather outside Sunday through Saturday. In contrast, a climatologist doesn't predict the weather per se. They won't tell us what the chance of rain on a Tuesday in 50 years will be. A climatologist seeks to predict what the overall conditions of an area should be based on the available data. While a person may study to be both things, meteorology and climatology are distinct. In the process of discussing climate change, the subtle separation of weather from climate is important to note.

A flash flood on July 15, 2017 resulted in the death of nearly ten members of a family near Payson, Arizona. At the time of the incident the southwestern U.S. was experiencing a drought in a period where temperatures were sustained above 100 degrees Fahrenheit (F) for weeks. The flood was caused by a pop-up thunderstorm which developed miles from the swimming hole the family was enjoying that afternoon. This tragedy occurred due to an event of weather, not an event of climate.

Historic and archaeological records can describe two separate cultures which flourished for centuries in the period roughly before 1300 (A.D.): the Anasazi and Vikings. The Anasazi were located in the southwest U.S. and were able to subsist on sustainable agricultural practices on the mesas. The Vikings developed a dominant seafaring society across the northern Atlantic Ocean extending from Norway to Newfoundland. Around 1300, cooler conditions began to set in globally. This caused glaciers to expand, sea ice to thicken, growing seasons to shorten, and changes in weather patterns which caused droughts in some areas and floods in others. Rains already scarce became even less frequent in the southwest, crippling the crop production of the Anasazi and forcing them to abandon their homelands. Harsher winters and increased sea ice crippled both agriculture and ability for safe ship passage across the Viking's territory, forcing them to abandon settlements and dissipate into other cultures. These two civilizations disappeared within a short timeframe as a result of a shift in climate, the cumulative effect of weather, not due to any specific event of weather.

PART 4: CLIMATE & WEATHER

Weather
The state of the atmosphere with respect to temperature, wind speed, precipitation, etc. at a given location.

Climate
The description of the prevailing (expected) types of weather conditions for a given location.

The key difference between weather and climate is time scale and the act of the personal physical experience. Weather is the specific events that occur: a tornado that devastates a community, timely rains that produce a bumper crop, or a perfect warm sunny day on the beach. Climate uses all the known information from the past to describe (or predict) the relative conditions a person might anticipate encountering if they were able to travel through time and space. Climate seeks to project average seasonal or annual measures of temperature, precipitation, etc.; projection of weather is focused on the here and now such to say there will be a high of 56 degrees with a 20% chance of rain in the afternoon. Weather changes daily, but it takes years to identify changes in climate.

DRIVING FORCES OF WEATHER

Scotland is situated at roughly the same latitude as Juneau, Alaska?
The fundamentals we learned in grade school of the earth as a spinning ball with its axis tilted relative to the sun formed our first understanding of what causes the seasons and why the north and south poles are covered in ice. Following this lead, the inclination of climate typically follows that the closer a person gets to the poles the colder the ambient temperature will become, and conversely, hotter as the equator is approached. Yet consider that London, England is farther north than Montreal, Canada. England is known for mild winters while Montreal is nicknamed the 'underground city' for the harsh winters. Prior to diving into the topic of how climate change may be experienced in Illinois, a brief detour into the forces that drive the weather patterns is appropriate.

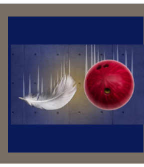
WHAT DRIVES WEATHER?

01 GRAVITY
02 DENSITY
03 SPEED
04 INERTIA
05 TEMPERATURE
06 PRESSURE

01 GRAVITY

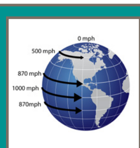
The earth is spinning at approximately 1,000 miles per hour (mph) at the equator, but the centrifugal force doesn't throw everything off the face of the planet because the gravity from the mass of the earth pulls everything toward the center. Gravity pulls on molecules and atoms the same way it pulls on apples and elephants, if not, all the gases would have blown away leaving a barren and rocky surface long ago. Gravity is constant and indirectly inputs some of the energy into the system as gases interact with one another being pulled toward the surface.

02 DENSITY



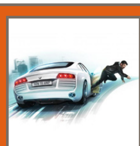
As demonstrated by the famous experiment of a feather and cannonball in a vacuum, gravity will pull both objects at the same speed when there is no resistance. However, the atmosphere is not a vacuum, thus the cannonball always wins. The natural properties of gases cause them to act like strangers on a subway and actively spread out from each other. Gravity pulls down, the gases push back on each other as they get closer together. Like the cannonball cuts through the air faster than the feather, denser gases cut through the lighter ones to get closer to the surface. These interactions help form the layers of the atmosphere.

03 SPEED



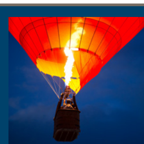
Cape Canaveral, Florida and Houston, Texas are used as primary launching sites for sending rockets into space not because the scientists and engineers appreciated beautiful beaches and longhorn cattle, but because they are the two southernmost states in the U.S. (i.e. closest to the equator). Due to the shape of the planet, this provides the rockets at these locations with extra starting speed compared to northern states. The farther away from the axis, the faster an object on the planet surface is moving. While the rotation at the equator is ~1,000 mph, Houston and Cape Canaveral are moving roughly 100 mph slower, but a person standing near the north or south pole is moving at less than 1 mph.

04 INERTIA



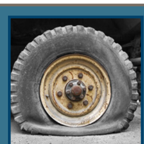
While we don't feel it, the speed of the earth's rotation is captured in us. When we jump straight up we come down in the same spot because the earth and us, in that spot, are moving at the same speed. However, jumping out of a moving vehicle a person arcs forward and outward with the extra inertia of the vehicle, and the ground will let them know the two are moving at very different speeds. The difference in speeds between the equator and poles causes an inertial shift (also referred to as deflection). This causes ocean currents and prevailing winds to spin clockwise in the northern hemisphere and counter-clockwise in the southern.

05 TEMPERATURE



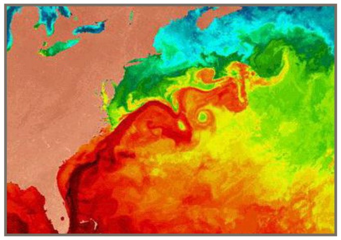
Molecular atoms, like a lazy college roommate, always seek to find a low energy state. Atoms convert excess energy into heat energy which then is radiated outward allowing them to reduce their energy state. The hot sand underfoot on the beach can be thought of as the grains of sand trying to cool themselves off. Applying energy does two significant things: it causes objects to radiate heat and can alter density. Two of the same air molecules at different temperatures have different densities and will act like oil and water with the warmer (less dense) rising above. This is the basic principle that allows hot air balloons to float in the sky, and why they must intermittently heat the air inside the balloon.

06 PRESSURE



Air pressure is the force exerted on us by the sum of the air molecules surrounding us. Because colder air molecules are denser, they occupy less space requiring more molecules in the same space to equal the same pressure. When a car tire which was filled with air at 80^{o}F cools to 15 degrees the air will shrink, but will expand again once the temperature is raised. The tire does not lose air as the temperature cools, but still loses pressure. The take away point for pressure is that high pressure exerts force outward, low pressure is a negative pressure pulling things inward.

Referring back to these six fundamental components can be helpful when thinking about what drives the forces of nature to produce weather patterns. Everything from the formation of a hurricane to the melting of polar ice caps can be broken down and traced back to these concepts. The interaction of these forces drives the events that create weather by controlling the ocean currents, establishing the primary convection cells, forming the jet streams, and localizing pressure cells.

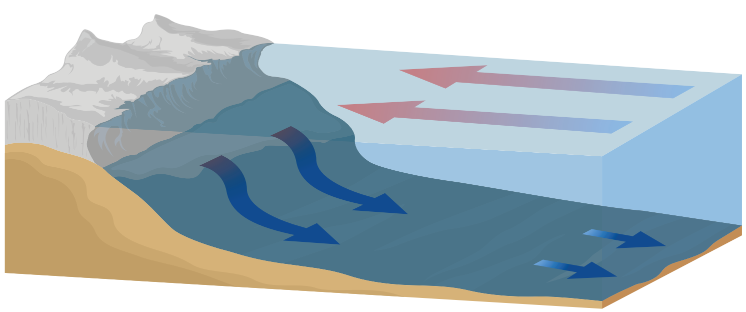


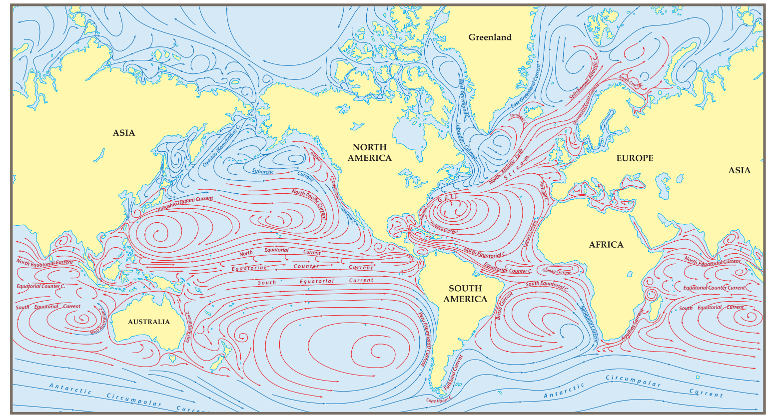
Land and water retain and radiate heat differently. Land will heat up extremely quickly and just as quickly shed heat once the sun has set. This is the reason why a desert may be well over 100°F during the day and drop below 50°F overnight. Water is the opposite, with temperatures in large bodies of water tending to change substantially only seasonally and not daily. For being so far north, the United Kingdom has a relatively warm temperate climate due to the warm ocean waters surrounding it. This is supported by the warm Atlantic Gulf current flowing off the eastern side of the United States.

Ocean Circulation

Three-quarters of the earth is covered in water, which means the bulk of the energy of the sun hitting the planet is being absorbed by the oceans. The major ocean currents soak up that heat and distribute it around the globe. The heat in the oceans helps mediate daily and seasonal temperature swings around the globe. The rotation of the earth causes the major ocean currents to spin clockwise in the northern hemisphere and counter-clockwise in the southern. The warm equatorial waters are carried towards the poles, but the ocean currents are not two dimensional.

Dominant currents move both horizontally and vertically through parts of their cycles. Sea ice is predominately fresh water. This may not seem significant but the way salt water forms freshwater ice plays a big role in ocean currents. Salt lowers the freezing point of water (which is why it is applied to the roads during the winter). As ocean water cools to the point where it begins to form ice, the salt does not freeze with the water. The salinity (concentration of salt in the water) increases under the ice as it forms because of the salt being separated from the water contained in the ice. The higher salinity makes this layer of water denser and colder than even the water at the bottom of the ocean, triggering a downward current as it sinks.



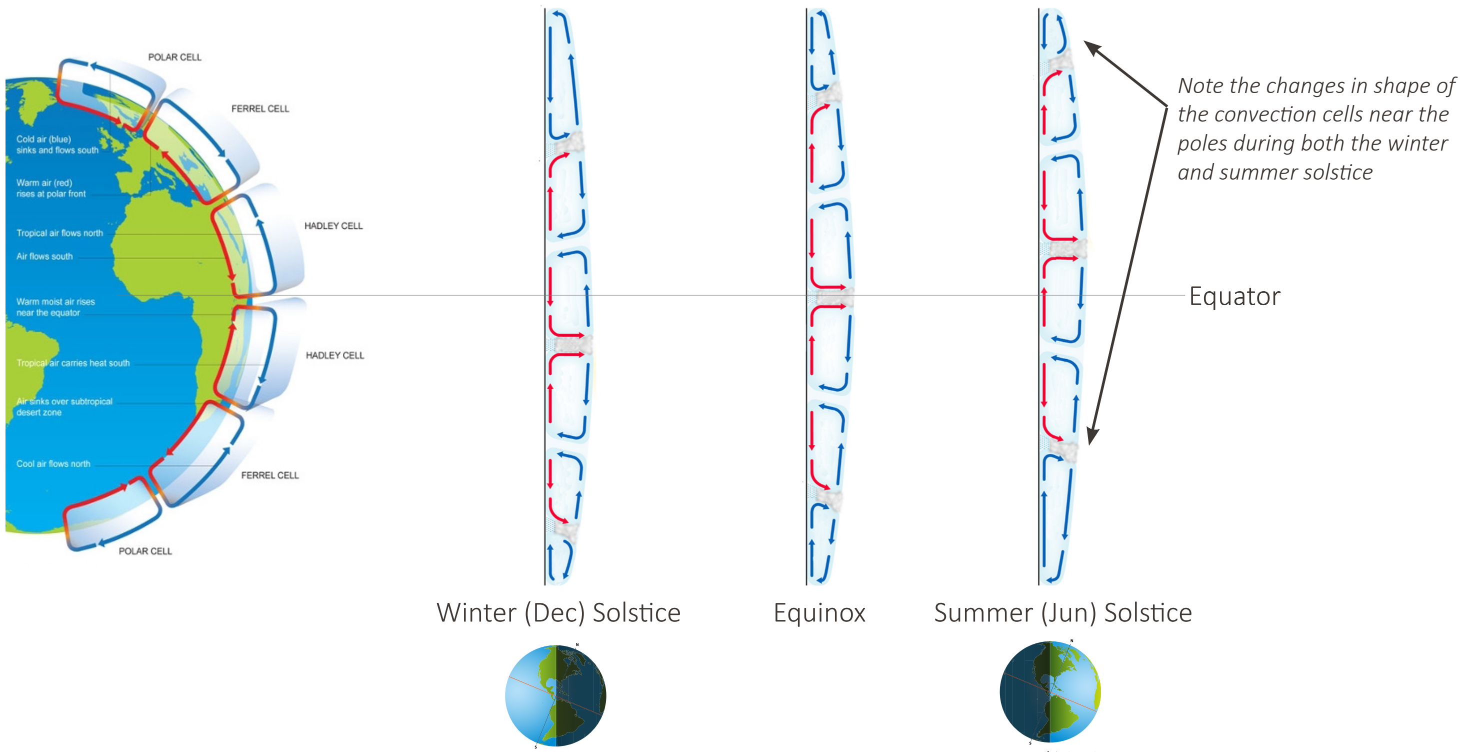


The oceans are all connected through these complex interactions of heat and density transfers, and the ability of the ocean to absorb and redistribute heat around the globe plays a significant role in weather patterns. The ocean currents are not 100% consistent in their movements, and cyclical events – a slowing of the current here, a larger than normal raise in surface water temperatures there – can trigger weather events referred to as oscillations. One oscillation farmers in Illinois pay particular attention to is the El Nino-Southern Oscillation (ENSO) which produce El Nino and La Nina years. These drive drought years and flood years in the Midwest and are impacted by sub-surface ocean temperatures in the Pacific. A minor change in temperature from stronger or weaker ocean currents can change atmospheric circulation for a year or more. Oscillations are part of global variability patterns; climate change looks beyond these normal patterns.

Convection Cells

The difference between a regular oven and a convection oven is the circulation of the warm air. In a regular oven, the hottest air rises to the top and sits statically; a convection oven uses a fan inside the oven to circulate the air around to keep an even temperature everywhere inside. The earth doesn't have a fan, but the heat radiating off the planet's surface generates a pattern of air circulation which distributes mass volumes of air around the globe. A planetary fan is not necessary for circulation as the rising air slowly cools higher up in the atmosphere causing it to fall back toward the surface. Although warm air can rise locally anywhere on earth, an overall system forms from major zones of rising air occurring near the Antarctic and Arctic Circles and at the Equator, and falling air near the mid-latitudes. These establish three separate convection cells in the northern and southern hemispheres.

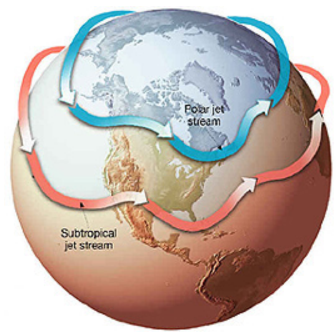
The tilt of the earth on its axis relative to the sun is what causes our seasons and the updraft of the polar air near the Arctic and Antarctic Circles. The tilt also triggers the cells to change in size throughout the year as they slide north and south as the angle of the sunlight hitting the earth changes. The image presented below captures an idyllic representation of the convection cells rising and falling consistently, though in reality the air currents are constantly fluctuating in strength, size, and speed as they interact.



Location, location, location is the key phrase in real estate. A globe and marker is all that is needed to see how these convection cells impact climate. The air in the upward circulation near the poles and the equator carries a significant amount of moisture which is released as rain and snow when initially cooled. By the time the circulation of these two cells converge over the mid-latitude zone they have released nearly all the original moisture meaning as the air falls toward the ground it is 'moisture hungry'. Tropical rain forests all occur within the updraft areas between the Tropic of Cancer and Capricorn (which mark the latitudes where the sun consistently shines for 12 hours each day year-round). Conversely, most of the world's desert environments occur where the downdraft of the convection cells meets near the mid-latitudes.

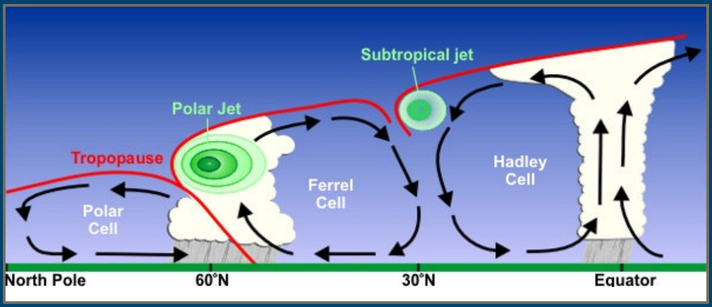
Jet Streams

Jet streams are thin bands of fast moving air which occur high in the atmosphere at the boundaries of the convection cells. The streams would not occur if not for the cells, but they function independently from them. While the correlation is not one for one, use this analogy for a visualization tool: Imagine when rain water droplets hit the ground they follow the landscape to the lowest points where the droplets consolidate into rivers. The jet streams are akin to a lot of individual air molecules getting together to form a river of wind in the sky.



The streams form due to the combination of the earth's rotation and temperature/pressure differentials which develop at the boundaries of the cells. They always flow easterly due to the direction of rotation and can reach speeds in excess of 200mph. The locations of the jets streams provide clues to where the boundaries of the convection cells are and help meteorologists predict how major weather patterns may develop as they shift from north to south. Part of what we experience in seasonality is an expression of where the boundaries of the cells fall. As winter approaches, the polar jet stream slips south, bringing colder temperatures to Illinois. As summer approaches, the polar jet stream slides north, bringing warmer temperatures.

The complex movements of the air circulation make it tricky to capture the exact motion in a two-dimensional image, let alone the degree of twisting and turning going on as the convection cells squish and squeeze each other. For a secondary visualization tool, imagine the jet streams flowing eastward across the globe as an amusement park ride. On this ride, giant sized kids are sliding along on rafts next to each other inside two very flexible slip-n-slide tubes (with the tubes representing the jet streams). The slip and sliders get thrown left and right while the convection cells are constantly being distorted. The momentum of the kids can push on the cells as it forces them to turn, the jet streams affects where the boundary of the cells are while also having to follow them. It is a bumpy ride and the kids sometimes end up bumping into each other, but the slide keeps on going.

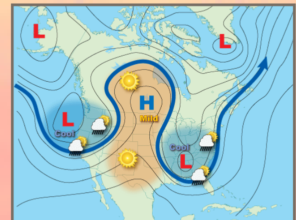


Recalling the deflection described during the discussion about inertia, objects in motion on the Earth's surface cannot move in a straight line when changing latitudes because of difference in the relative speeds. The deflection causes movement in the northern hemisphere to shift to the right, while the southern hemisphere shifts left, but the shift is always relative to the direction moved. Because the flow of air at the top and bottom of a cell is moving in opposite directions north and south (one toward the equator, one toward the poles), they are also moving in opposite directions east and west. They both shift right, thus the flow heading towards the equator will have predominantly westerly wind while the flow towards the poles will have a predominantly easterly wind. This creates a swirling corkscrew motion within each convection cell, with the adjacent cell having the opposite corkscrew rotation.

Rather than moving in a two-dimensional pattern, the winds move three dimensionally in a motion more closely aligned with a corkscrew swirl of a roller coaster as they traverse the globe.

Pressure Cells

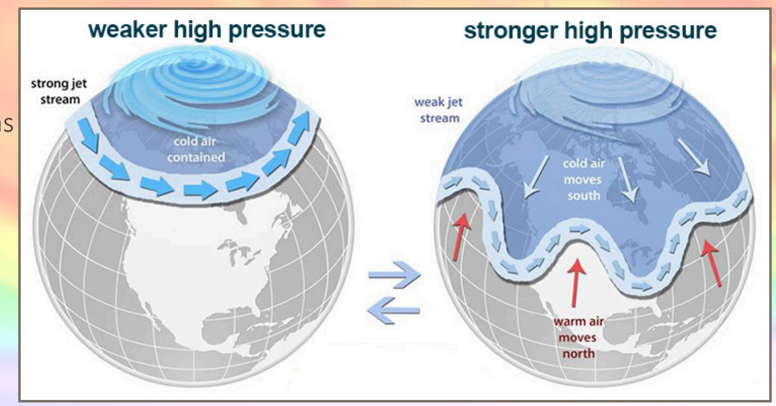
If the planet was perfectly symmetrical it is possible the ocean currents, convection cells, and jet streams would not vary and weather would be 100% predictable. This is not the world we live in. Low pressure cells form when air is heated and rising, high pressure cells form when air is falling. The description of the convection cells provides a backdrop for the overarching momentum of global circulation, but the convection cells are constantly distorted and disrupted by isolated low- and high-pressure cells.

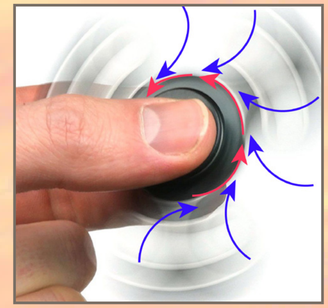


Isolated pressure cells develop within the larger convection cells acting to strengthen or destabilize the boundaries, and act as the main drivers of localized weather events. The convection cells determine the framework for what kind of weather is possible, but the development of a tornado or severe thunderstorm is dependent on the conditions of the local pressure cells which causes them to be the main points of discussion on the evening weather report. The 'H' and 'L' on the weather maps indicate the center area of the various pressure cells.

Energy tends to stay in balance; a strong low-pressure cell in one location can correlate with a strong high-pressure cell elsewhere. A strong or weak cell further correlates with differential gradients. Thinking about a hot air balloon, air heated to 100^{o}F inside the balloon to will cause it to rise differently if the ambient air temperature is 50^{o} vs 90^{o}. The greater the difference in temperatures, the faster the air will rise. Extreme low-pressure cells generate hurricanes, tornadoes, derechos, and severe thunderstorms from massive differences in temperatures and pressures.

Highly localized pressure cells are associated with severe weather events (tornadoes, hurricanes, etc.), but broader persistent pressure cells can impact seasonal patterns. Atmospheric oscillations similar to oceanic oscillations (like El Nino) can occur as a result of slightly different mechanisms. Atmospheric oscillations such as the Arctic Oscillation and North Atlantic Oscillation can amplify or limit the strength of the high pressure 'cap' that naturally sits on top of the north pole. The stronger the high-pressure zone, the harder the cell pushes away from the poles. Under higher than normal pressure conditions, bubbles or bulges can develop and plunge frigid polar air farther south than usual during the winter months (snowfall in Texas). Under lower than normal pressure conditions, tropical winds push warmer air farther north than usual during the winter months.





As an ancillary note, hurricanes and tornadoes spin the opposite direction of their respective hemispherical shift. Thus, in the northern hemisphere a hurricane spins counter-clockwise. To visualize why this occurs imagine the funnel cloud as fidget spinner; the center of the spinner represents the point of low pressure. As air rushes towards the center it shifts right, the faster the low-pressure cell pulls the air towards it the harder the shift to the right as it approaches the center. This generates the motion of air at the edges of the funnel cloud shifting to the right causing the air inside the funnel to spin left/ counterclockwise, the same as pushing the fidget spinner to the right causes it to spin left/counterclockwise.

Extreme weather events are becoming more extreme due to climate change.

CLIMATE CHANGE

Climate change is a natural phenomenon. The history of the earth is rich with evidence of the times when glaciers advanced and retreated across the hemisphere. The current time stamp places us within an interglacial period, with the last ice age fading roughly 10,000 years ago. Although humans as a species have been around longer, nearly the whole of human civilization is held in this short window of time. Having the wealth of knowledge gained by scientists over the past several hundred years provides a sense for the delicate balance that exists with the mechanics which impact the climate. The unique nature of our current existence is that we for the first time in our history have begun to understand our own involvement in those mechanics through our emissions of greenhouse gases since the industrial revolution.

Detailed recording of weather events, in context, has only been around since the 20th century. Scientists have been able to reconstruct climate data from around the world using numerous different methodologies (e.g. studying growth rings of trees or historic harvest records), but having exact daily measurements of precipitation, temperature, air pressure, humidity, etc. across the developed world has only been possible for the last century. Certain climate terminology has become engrained as part of modern infrastructure design. Buildings, roads, bridges, etc. are evaluated for their adaptation for, or resiliency to, specific projected weather events. To develop appropriate standards, engineers must estimate specific conditions the infrastructure will be exposed to. These standards are always based on the best available data; however, these standards can become restricted by the snapshot in time when the underlying estimations were made.

Most levees, bridges, and culverts are designed to meet event scenarios classified as either a 50-year, 100-year, or 500-year event. This nomenclature means there is an expectation that the infrastructure will only encounter that size of an event once in the defined timeframe. Thus a 50-year event should only occur on average once every 50 years while a 500-year event only once every 500 years. These estimates are based on probabilities from the historic records, and probabilities allow for the potential to observe the occurrence of multiple peak events within a given period. However, while weather is naturally variable, when the trend continues it is likely the projection is no longer accurate. In other words, over the course of 200 years there should be times when 10-year events occur more than once in the same year, but also not recorded for a 20-year span. Over time these events should occur on average once every 10 years. With climate change, understanding how to predict what a 10-year or 500-year event becomes problematic. This is one of the fundamental threats climate change poses to infrastructure. When levees, roads, and bridges no longer meet their intended standards, they could fail to withstand extreme weather events.

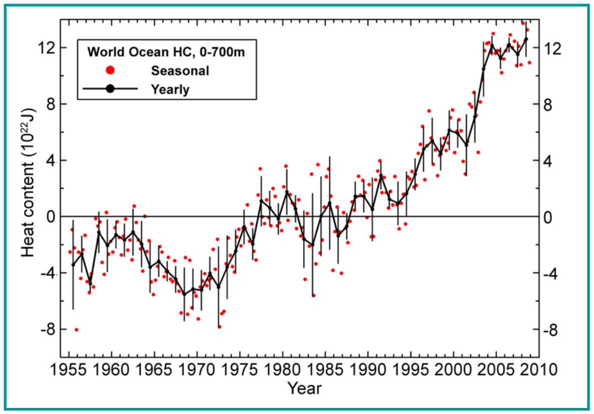
"WHAT DOES IT MATTER IF THE AVERAGE GLOBAL TEMPERATURE RISES?"

'Weather anomaly' is the term for the events which fall outside what is considered the normal range. The 50-, 100-, or 500-year events are predicted anomalies engineers and planners rely on for designing infrastructure. These predictions are not linear, meaning the difference between 50-year and 100-year rainfall events could be 2 or 20inches depending on climatic conditions. Climate change not only disrupts the frequency, but also the intensity. Most bridges are designed to handle the 100-year event. The question is not whether the bridge should be built to the 500-year event, rather the question is "what does the accurate 100-year event look like?". With extreme weather events becoming more extreme, identifying the appropriate design standards is a critical part of building infrastructure with resiliency. When the design standards become outdated, a levee which was once considered 'overbuilt', may no longer be tall enough to protect a community from flooding.

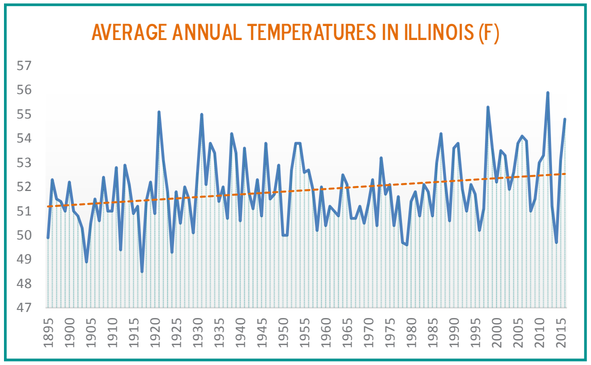
The phrase "climate change" evolved from the initial term global warming. The original term is accurate to the overall trend, but does not capture the impact of the situation quite the same as climate change. Global warming may give the impression there is only a simple trend that summers will get longer, and winters will get shorter. Climate change better describes the overall impact, as the change is not spread equally across the globe. Some areas will be impacted more than others.

The initial heat trapped in the lower atmosphere from the elevated greenhouse effect from human impacts has been getting stored disproportionately in the oceans compared to ambient air temperatures. The National Oceanic and Atmospheric Administration (NOAA) identified in their 2015 State of the Climate report that the oceans account for over 90% of the warming in the climate system. Studies conducted by NASA's Jet Propulsion Laboratory (JPL) from 2003-2012 identified a substantial amount of the warming occurred in the oceans at depths between 300-1,000ft below the surface of the sea. Due to the role the oceans play in the various cycles controlling climate, storing heat in the ocean is akin to charging a taser battery (the more juice in the battery the greater and/or longer the resulting jolt).

Heat in water is a form of stored energy. Heat drives the hydrologic cycle through the transfer of energy between ice, liquid water, and water vapor. Ice is the lowest energy state of water (consider it a 'no energy' state for this discussion), and vapor is the highest energy state. The warmer the oceans and ambient air temperatures, the more water enters the atmosphere as vapor. More energy, more water, bigger storms, bigger anomalies.



Global Ocean Temperatures Rise: *Heat captured in the oceans has been rising faster than the global air temperatures over the past several decades.*

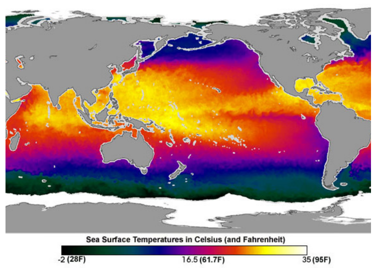


Illinois Air Temperatures Rise: *Average annual temperatures in Illinois are trending steadily upward over the course of the last 120 years.*

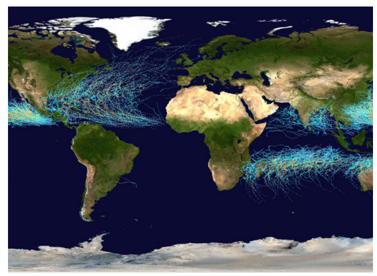
THOUGHT EXPERIMENT: ILLINOIS IS NOT A MARINE COASTAL STATE... DOES IT MATTER WHETHER HURRICANES GET STRONGER OR MORE REGULAR?

Yes. Hurricanes cannot survive as hurricanes very long after making landfall, but they do not simply disappear.

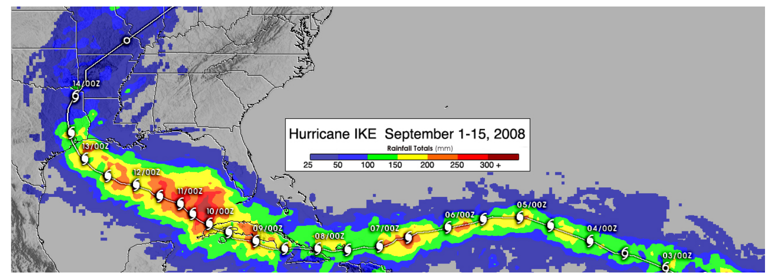
OCEAN TEMPS + HURRICANES → POTENTIAL FOR SEVERE WEATHER IN ILLINOIS



Ocean currents rotate clockwise in the northern hemisphere and counter-clockwise in the southern hemisphere
meaning
the surface waters will naturally rise in temperature from east to west along the equator
meaning
the warmest waters should occur off the eastern coasts of the continents



Tropical depressions and hurricanes are massive low-pressure cells which require warm waters to form
meaning
they should generally occur consistently the location of the warmest waters, and not be associated with cold waters
secondarily meaning
the warmer the water, the greater potential to 'feed' the low-pressure cell and create bigger storms



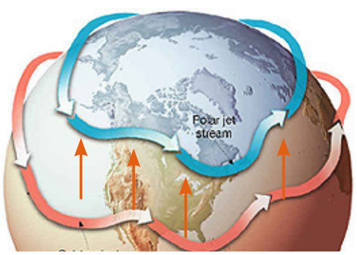
Once a hurricane makes landfall, it can no longer draw heat from the ocean, causing the low-pressure cell to diminish in strength as the storm continues to track north-northeast. The remnants of a hurricane still carry a vast amount of moisture. A storm that hits the coast in Texas, Mississippi, Louisiana could spawn severe storms as far north as Canada. Historical data indicate prior to the turn of the century a tropical system would pass through Illinois roughly every 26 years. Not only have the intervals been getting closer together, but in the summer of 2005 alone, four systems moved through Illinois (Arlene, Dennis, Katrina, and Rita). Bigger, or just more, hurricanes can mean greater potential for flooding in Illinois.

Any time a tropical system makes landfall they have the potential to generate severe weather, including heavy rainfall. An event in 2008 (remnants of Hurricane Ike) dropped five inches of rain across large parts of Illinois causing widespread flooding as it moved northward. These types of systems have a high potential to trigger both flash floods and riverine floods as they deposit so much rain over a broad area.

THOUGHT EXPERIMENT: DOES THE WARMING TREND MEAN PLACES WILL JUST HAVE SHORTER WINTERS?

No. Warming global temperatures do not treat all places equally, or limit the impacts to one season.

WARMING EQUATORIAL WATERS + WARMING POLAR WATERS → IMPACTS IN SEASONAL TEMPERATURES



Increased ocean temperatures at the equator allow for a stronger/ higher convection current

meaning

it is similar to warming the air in a car tire, the entire convection cell becomes warmer and pushes outward

meaning

a primary reason winters can get warmer is because the equatorial cell expands toward the poles pushing against the polar convection cell

Ocean currents will circulate warmer equatorial waters to the polar region such that less ice can form over the winter periods

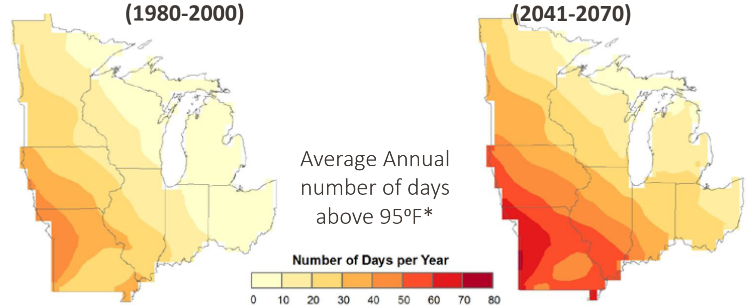
meaning

an increase in atmospheric moisture at higher latitudes

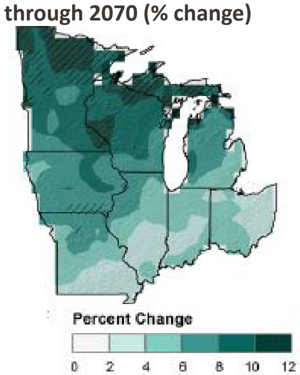
meaning

wetter winters at higher latitudes

Actual Average Temperatures (1980-2000) | **Projected Average Temperatures (2041-2070)**



Projected Increase in Precipitation through 2070 (% change)



The jet stream represents a general demarcation zone between the convection cells, with warmer air on one side and cooler air on the other. Any change in the convection cells is reflected in the position and strength of the jet streams. An expansion of the equatorial cell correlates to a northern migration of the jet stream at the mid-latitudes. If the subtropical jet stream shifts toward the poles, the temperatures shift with it. As the migration occurs, places progressively begin to resemble the normal seasonal temperatures of the areas closer to the tropics. Illinois over time, for example, may experience seasonal temperatures on par with those currently in Tennessee, Oklahoma, or Texas.

A change in seasonal temperatures at a particular location does not directly equate to the impact of the annual precipitation. The addition of moisture and energy into the overall weather system means on a global scale more precipitation will fall, but how it is distributed may vary differently than temperature distribution.

**From the North American Regional Climate Change Assessment Program (NARCCAP) for the 2041-2070 high (A2) emissions projections conducted in 2012*

Drought is associated with high pressure (air pushing down from the upper atmosphere sucking up all the moisture), and precipitation with low pressure (air rising and cooling providing the potential to have that released as precipitation). Not all low-pressure cells are created equal. A low-pressure cell developing over the desert is not able to contribute a lot of moisture to the atmosphere, one over an ocean can contribute plenty.

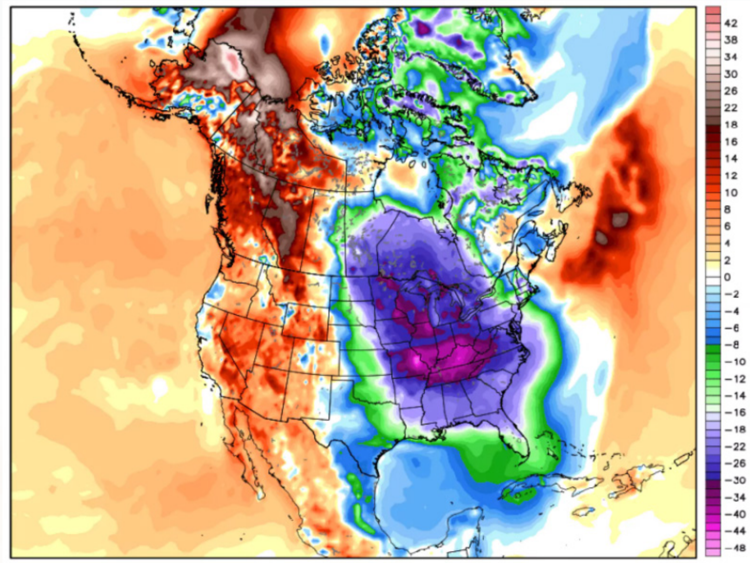
MORE RAIN… AND MORE DROUGHT?

Globally climate change is anticipated to increase precipitation. Fresh water is a precious commodity; however, the issue is the potential change in distribution of precipitation as a result. Weather patterns are dynamically linked such that a subtle change in one area can have major changes to another. More overall heat/energy in the system has the potential to do funny things. Strong winds develop from strong temperature/pressure gradients. Currently the polar regions (and especially the north pole) are warming disproportionately to the tropics. During the summer months in the northern hemisphere, the temperature gradient between the polar updraft and the equatorial updraft may be diminished. The effect could be to reduce the speed of the sub-tropical jet stream which increases the likelihood for weather patterns to stall out for an extended period: heat waves could hang out for weeks over the Midwest, or conversely storms could track slower causing more frequent flooding in certain areas of the country. Even locations within the Midwest may experience the effects differently. Arkansas is projected to receive less annual rainfall while Illinois more.

The Arctic Circle remains in constant darkness during the winter months, and although the ice sheets may be thinner from warming oceans, the seas at the north pole will still freeze over in this period of darkness. Warmer ocean waters at the edge of the Arctic Circle have the potential to generate stronger low-pressure updrafts which in turn can result in a stronger high-pressure zone directly over the north pole. This pent-up pressure can trigger episodes where the jet stream bulges out creating an Arctic blast over mid-latitude regions. These pressure zone events can occur with or without climate change, but the temperature changes install greater instability of what is currently considered normal weather. While average winter temperatures in Illinois may increase, these Arctic blasts may occur more often then they currently do. Consider the weather experience from the winter of 2014-2015 where a series of these events caused temperatures in Atlanta to fall into the teens in January and New York was hit with repeated heavy snow storms through the winter and even had temperatures near zero for several days in early April.

All the little idiosyncrasies which create weather on Earth interact in peculiar ways. Warmer waters at the equator start a Rube Goldberg effect causing ice sheets in Greenland to melt. As we approach the next century in Illinois, summers are projected to get hotter and drier, while winters get warmer and wetter. Annual rainfall totals are projected to increase slightly; however, the entire distribution is anticipated to shift with rain falling in more isolated seasonal periods. This creates the odd result of an increase in drought periods and increased flooding events. The amount of rainfall associated with the currently calculated 5-, 10-, 50-year, etc. storm events will necessarily need to be recalculated to account for higher events. Climate models do not predict more rainfall everywhere, but they do predict a net increase globally. These models identify the simultaneous creation of the conditions for increased drought and flooding depending on what time of year and location on the planet.

Climate is an extremely complex topic and the breakdown provided is an attempt to simplify some of the more basic components into digestible bits such to facilitate discussion of what climate change means globally and to Illinois. Each year our understanding of weather phenomenon improves, including our own role in shaping planetary climactic processes. A methodology was developed using these principles to apply climate change adjustment factors for consideration of threats to Illinois transportation assets in the future. The factors applied are not values set in stone, rather they reflect reasonable potential outcomes should the current trends continue.



In February of 2015, an instability in the polar jet stream caused a blast of polar air to escape as far south as Florida. This cold air did not blanket the entire northern hemisphere, rather created a pocket of air temperatures around 30 degrees below average in the Midwest while creating a pocket of air temperatures 30 degrees above average in Alaska!

PART 5:
LOOKING FORWARD

PART 5: LOOKING FORWARD

The update to the All-Hazards Transportation Vulnerability Assessment is not complete. This study developed a methodology for IDOT to incorporate evaluation factors for vulnerabilities to both manmade and natural hazards, and to consider how changes to risks from natural hazards which may be affected over time by climate change. The effort was focused on building a framework which maintained the flexibility to be tweaked for improvement without having to be reconstructed as more data become available. A limiting factor for this study, or any similar large-scale study, is the availability of information in a usable format. Information may be captured in the heads of personnel, cataloged in paper reports or in computer aided drawings, but if the information isn't captured in a database format compatible with the appropriate software, access to the information for use in the model is curtailed. In a reflection of the old saying, 'you get out what you put in', the quality of the modelled results can only be as accurate as the data used.

The quality of the data available was such that the model was able to produce accurate snapshots of the existing vulnerability of the assets, but there is always room for improvement. In the process of developing these layers of inquiry for the assets, an action plan was prepared identifying those areas where new data are needed, where updates to existing data are needed, and where existing data can be streamlined. Further, the action plan identifies strategies to integrate components of the model into decision making processes. With respect to a key limiting factor related to data needs moving forward, a completed update of risk evaluation for flooding under the climate change scenarios was not possible for all assets due a lack of data availability.

As a steward of the transportation system in this state, IDOT will be focused on identifying ways to measure and mitigate for all forms of hazards today and tomorrow.

The study developed the methodology to use the hydraulic information for each structure passing over water as a means to estimate changes to flooding potential; however, these data are not currently stored in a database. Copies of the hydraulic studies were obtained for several hundred structures randomly selected from across the state and manually entered into the models created for the project. Not all structures pass over water (e.g. highway overpasses), thus not all structures are affected by flooding. The manual collection does provide a representative subset of those structures that do pass over water to gain an understanding of how changes in flow may affect flooding.

Approximately 3% of the bridges reviewed were impacted by a 3% increase in the 100-year event; approximately 8% were impacted by a 10% increase. A key point to take away from the study is that while we often focus on the 'big one', even a modest increase of 3% to flooding events has the potential to substantially impact our transportation resources.

'Extreme' weather events are considered extreme from our current perspective. As the decades pass with more data collected and weather events better understood, what we consider extreme now may not necessarily be considered extreme in the future. Ongoing and planned national and international studies on climate change will help refine predictions of what the high and low edges of weather events will become. As a steward of the transportation system in this state, IDOT will be focused on identifying ways to measure and mitigate for all forms of hazards today and tomorrow.

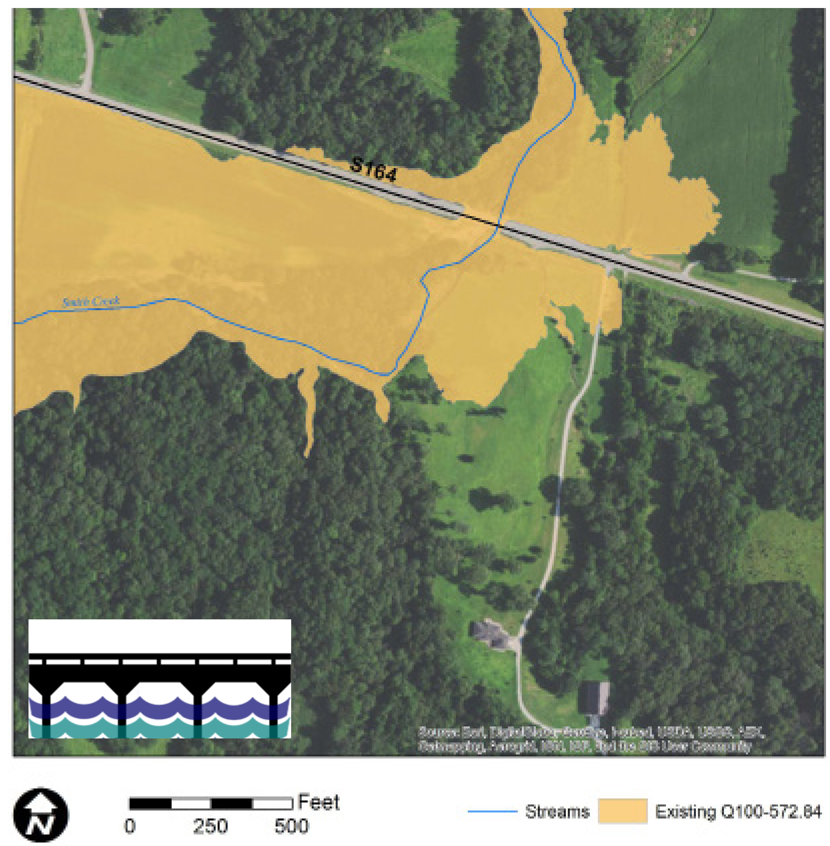
WHAT DOES A 3% AND 10% CHANGE IN FLOODING LOOK LIKE?

The geospatial representation of the assets are lines and points. Modelling associated water elevations with the asset points and lines to create trigger zones which could be viewed in a tabular format. These were essentially a yes-or-no result output for the road segments and bridge points, but this doesn't provide a true sense of what the increases in flooding look like. Provided here is a visual extrapolation of what these increases mean to a bridge crossing along Route 164.

With this kind of information, IDOT can identify the degree of sensitivity the infrastructure has to changes in flooding events. Further, the model has been established such that the percentage of change can be interactively modified. If future research provides better projections, the percent increase can be applied to the model to prepare new estimated flood elevations. Planners can use specific local conditions or criticality values to justify implementing climate change flooding contingencies within future projects.

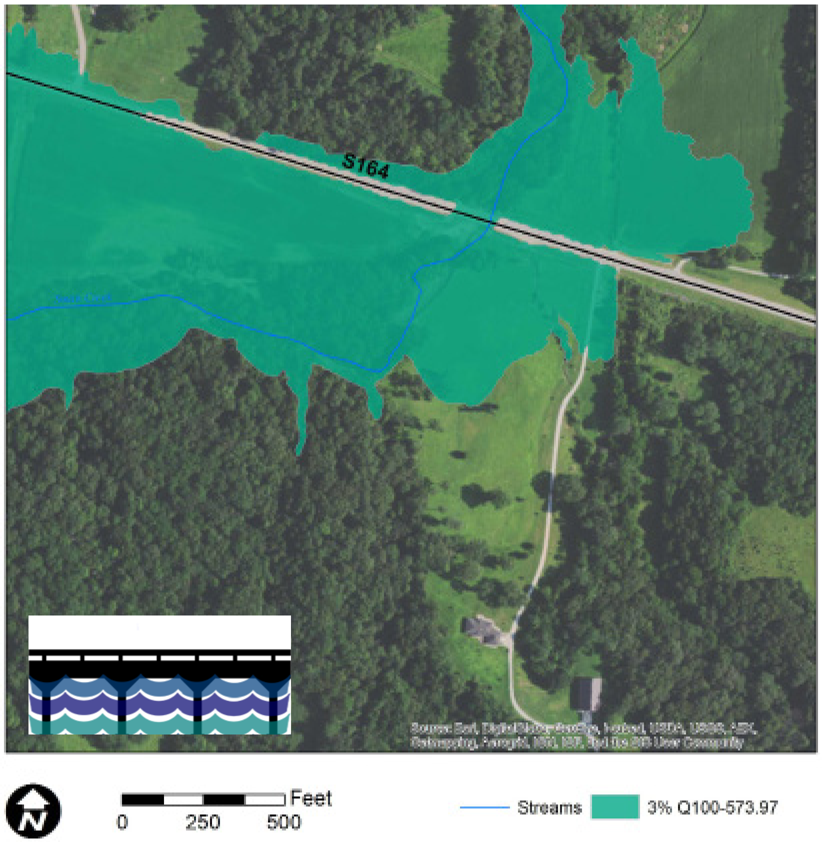
DESIGNED 100-YEAR EVENT

The highlighted land represents the area of flooding which should occur under its designed 100-year event. Note the highlighted area under the bridge was left to indicate where the channel flow is, the bridge is not inundated in this scenario.



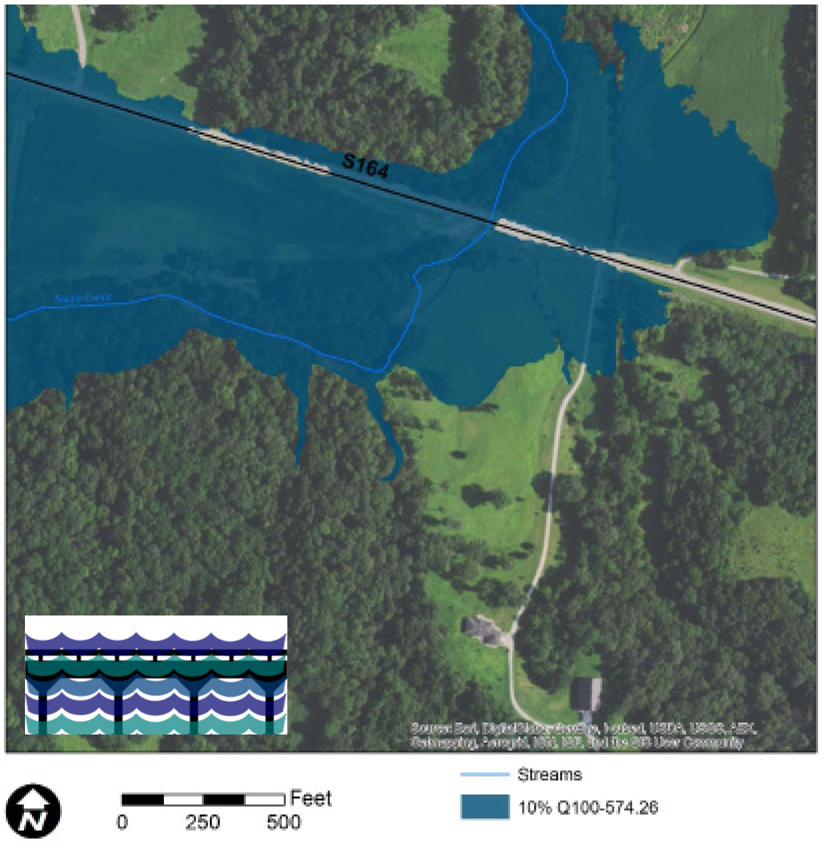
100-YEAR EVENT + 3% INCREASE IN FLOW

A 3% increase causes the water to approach the bottom of the bridge but not overtop it; however, the approaching road from the west does become inundated in this scenario.



100-YEAR EVENT +10% INCREASE IN FLOW

A 10% increase projects the water to rise above the bottom of the bridge. Once the water reaches the underside, the deck acts like a dam causing the water to back up behind it. Depending on that interaction, the flood could potentially damage or overtop the bridge.



PART 6:
LITERATURE REVIEW

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PILOT STUDIES

2040 Long Range Transportation Plan – Needs Assessment: Vulnerability Reduction Costs and Benefits. Florida Department of Transportation, 2014. Print. http://www.planhillsborough.org/wp-content/uploads/2014/09/2040-LRTP-Vulnerability-Reduction-Tech-Memo.pdf

Almodovar-Rosario, Natalia and Chris Dorney. MnDOT Flash Flood Vulnerability and Adaptation Assessment Pilot Project. Parsons Brinkerhoff, 2014. Print. http://www.dot.state.mn.us/climate/pdf/MnDOTFldVulnPilotFinalRpt.pdf

Anderson, Chris, David Claman, and Ricardo Mantilla. Iowa's Bridge and Highway Climate Change and Extreme Weather Vulnerability Assessment Pilot. Iowa Department of Transportation, 2015. Print. http://publications.iowa.gov/19341/1/IADOT_InTrans_HEPN_707_Anderson_Iowas_Bridge_and_Highway_Climate_Change_and_Extreme_Weather_Vulnerability_2015.pdf

Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot. Federal Highway Administration. Print. http://www.virginia.edu/crmes/fhwa_climate/files/finalReport.pdf

Crook, Geoff and Curran Mohney. Climate Change Vulnerability Assessment and Adaptation Options Study. Oregon Department of Transportation, 2014. Print. http://www.oregon.gov/ODOT/Programs/TDD%20Documents/Climate-Change-Vulnerability-Assessment-Adaptation-Options-Study.pdf

Crow, Rebecca, et al. District 1 Climate Change Vulnerability Assessment and Pilot Studies: FHWA Climate Resilience Pilot Final Report. Caltrans District 1, 2014. Print. http://www.dot.ca.gov/hq/tpp/offices/orip/climate_change/documents/ccps.pdf

FHWA Climate Resilience Pilot Program: Massachusetts Department of Transportation. Massachusetts Department of Transportation. Print. http://www.massdot.state.ma.us/highway/Departments/EnvironmentalServices/EMSSustainabilityUnit/ClimateChangeResiliency.aspx

Hillsborough County MPO: Vulnerability Assessment and Adaptation Pilot Project. Cambridge Systematics, Inc., 2014. Print. http://www.planhillsborough.org/wp-content/uploads/2013/10/NoAppendix_Hillsborough-MPO_FHWA-Pilot-Final-Report1.pdf

Hogan, Michael, David Elder, and Stephanie Molden. Connecticut Department of Transportation Climate Change and Extreme Weather Vulnerability Pilot Project Final Report. Connecticut DOT, 2014. Print. https://www.fhwa.dot.gov/environment/climate_change/adaptation/resilience_pilots/2013-2015_pilots/connecticut/final_report/ctclimatepilot.pdf

Maryland State Highway Administration. Maryland State Highway Administration Climate Change Adaptation Plan with Detailed Vulnerability Assessment. Maryland State Highway Administration, 2014. Print. http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/vulnerability_assessment_pilots/2013-2015_pilots/index.cfm

Michigan DOT Climate Vulnerability Assessment Pilot Project Final Report. Michigan DOT and Cambridge Systematics, Inc. Print. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/

New York City Natural Hazard Mitigation Plan; Section III: Natural Hazard Risk Assessment. The City of New York, 2009. 102-79. Print. http://www.nyc.gov/html/oem/downloads/pdf/hazard_mitigation/plan_update_2014/3.13_severe_weather_public_review_draft.pdf

CLIMATE CHANGE

2014 U.S. Department of Transportation Climate Adaptation Plan. US Department of Transportation, 2014. Print.

Andresen, Jeff, Steve Hilberg, and Ken Kunkel. *Historical Climate and Climate Trends in the Midwest USA; In: White Paper Prepared for the U.S. Global Change Research Program National Climate Assessment Midwest Technical Input Report*. Tech. Great Lakes Integrated Sciences and Assessments (GLISA) Center, 2012. Print.

Angel, James R., and Kenneth E. Kunkel. "The Response of Great Lakes Water Levels to Future Climate Scenarios with an Emphasis on Lake Michigan-Huron." Journal of Great Lakes Research 36 (2010): 51-58. Print.

Angel, Jim. *Climate of Illinois Narrative*. Rep. University of Illinois at Urbana-Champaign, IL: Illinois State Water Survey, Prairie Research Institute. Print.

Asam, Susan, et al. Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance. United States Department of Transportation Federal Highway Administration, 2015. Print.

Assessment of the Body of Knowledge on Incorporating Climate Change Adaptation Measures into Transportation Projects. ICF International, 2013. Print.

Blumenfeld, Kenneth A., and Richard H. Skaggs. "Using a High-density Rain Gauge Network to Estimate Extreme Rainfall Frequencies in Minnesota." *Applied Geography* 31.1 (2011): 5-11. Print.

Center for Disease Control and Prevention, National Center for Environmental Health. Climate Change and Extreme Heat Events. N.p.: Center for Disease Control and Prevention, National Center for Environmental Health, n.d. Print. http://www.cdc.gov/climateandhealth/pubs/ClimateChangeandExtremeHeatEvents.pdf

Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure. Cambridge Systematics, Inc., 2015. Print.

Chicago Metropolitan Agency for Planning. *Appendix A: Primary Impacts of Climate Change in the Chicago Region*. Chicago: Chicago Metropolitan Agency for Planning, 2013. Print.

Christiansen, Daniel E., John F. Walker, and Randall J. Hunt. "Basin-scale Simulation of Current and Potential Climate Changed Hydrologic Conditions in the Lake Michigan Basin, United States." *U.S. Geological Survey Scientific Investigations Report 2014-5175* (2014). Print. Prepared in cooperation with the U.S. Environmental Protection Agency, Great Lakes Restoration Initiative

Climate Change – Model Language in Transportation Plans. ICF International, 2010. Print.

Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure. New Jersey Partnership. Print.

Climate Impacts Vulnerability Assessment. Washington State Department of Transportation, 2011. Print.

Coder, Kim D. *Historic Ice Storm Patterns*. Warnell School of Forestry & Natural Resources, University of Georgia, Jan. 2015. PDF. Tree & Ice Storm Series, WSFNR15-1

Confronting Climate Change in the U.S. Midwest Illinois. Rep. Sci Writer. Freese, Barbara. Comp. Melanie Fitzpatrick. Ed. Bryan Wadsworth. Union of Concerned Scientists, 2009. Print.

Deepak Gopalakrishna, Jeremy Schroeder, Amy Huff, Amy Thomas and Amy Leibrand. Planning for Systesms Management & Operations as part of Climate Change Adaption. Federal Highway Administration Office of Operations (HOP), 2013. Print.

Easterling, D. R. "Climate Extremes: Observations, Modeling, and Impacts." Science 289.5487 (2000): 2068-074. Print.

Farhangfar, Sarvenaz, Mohammad Bannayan, Hamid Reza Khazaei, and Mohammad Mousavi Baygi. "Vulnerability Assessment of Wheat and Maize Production Affected by Drought and Climate Change." International Journal of Disaster Risk Reduction 13 (2015): 37-51. Print

Filosa, Gina and Alexandra Oster. International Practices on Climate Adaption in Transportation: Findings from a virtual review. US Department of Transportation Federal Highway Administration Office of Natural Environment, 2015. Print.

FLMA Southeast Region Climate Change Transportation Tool. U.S. Department of Transportation Federal Highway Administration. Print

Gade, Kris. Arizona Department of Transportation Extreme Weather Vulnerability Assessment. [PowerPoint slides]. ADOT Environmental Planning Group, 2015. Print.

Gopalakrishna, Deepak, et al. Planning for Systems Management & Operations as part of Climate Change Adaptation. Federal Highway Administration Office of Operations (HOP), 2013. Print.

Gregg, Rachel M., Kirsten M. Feifel, Jessi M. Kershner, and Jessica L. Hitt. The State of Climate Change Adaptation in the Great Lakes Region. Tech. Bainbridge Island, WA: EcoAdapt, 2012. Print.

Hayden, Timothy J., et al. Department of Army: High-level Climate Change Vulnerability Assessment. U.S. Army Corp of Engineers Engineer Research Development Center, 2013. Print.

Hayhoe, Katharine, Jeff VanDorn, Vaishali Naik, and Donald Wuebbles. Climate Change in the Midwest Projections of Future Temperature and Precipitation. Rep. Print.

Hilberg, Steven, and Jim Angel. The Cold, Hard Facts about Winter Storms. State Climatologist Office for Illinois, Illinois State Water Survey - University of Illinois at Urbana-Champaign. Web. 25 June 2015. <http://www.isws.illinois.edu/atmos/statecli/Winter/cold-hard.htm>.

Illinois State Water Survey, Prairie Research Institute. University of Illinois at Urbana-Champaign. Web. 27 Aug. 2015. <http://www.isws.illinois.edu/>.

Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2. U.S. Department of Transportation, 2011. Print.

Jaffe, Martin and Mary Woloszyn. "An Initial Assessment of Winter Climate Change Adaptation Measures for the City of Chicago." Sea Grant Law and Policy Journal 6 (2) (2014): 5-25. Print.

Jaffe, Martin, and Mary Elizabeth Woloszyn. Development of an Indicator Suite and Winter Adaptation Measures for the Chicago Climate Action Plan. Ed. D. Brown, D. Bidwell, and L. Briley. Available from Great Lakes Integrated Sciences and Assessments (GLISA) Center, 2013. Print. 2011 Project Reports.

Jaroszweski, David, Lee Chapman, and Judith Petts. "Assessing the Potential Impact of Climate Change on Transportation: The Need for an Interdisciplinary Approach." Journal of Transport Geography 18.2 (2010): 331-35. Print.

Jones, Kathy, Ron Thorkildson, and Neal Lott. The Development of a U.S. Climatology of Extreme Ice Loads. Tech. no. 2002-01. Asheville, NC: US Department of Commerce, NOAA/NESDIS, National Climatic Data Center, 2002. Print.

Khailani, Dzul Khaimi, and Ranjith Perera. "Mainstreaming Disaster Resilience Attributes in Local Development Plans for the Adaptation to Climate Change Induced Flooding: A Study Based on the Local Plan of Shah Alam City, Malaysia." *Land Use Policy* 30.1 (2013): 615-27. Print.

Kovacik, Carly, and Kevin Kloesel. Changes in Ice Storm Frequency Across the United States. Southern Climate Impacts Planning Program, U of Oklahoma, 2014. Print.

Kunkel, Kenneth E., and Xin-Zhong Liang. Climate of Illinois and Central United States: Comparison of Model Simulations of the Current Climate, Comparison of Model Sensitivity to Enhanced Greenhouse Gas Forcing, and Regional Climate Model Simulations. Rep. Champaign, IL: Illinois State Water Survey, 2004. Print.

Kunkel, Kenneth E., Karen Andsager, and David R. Easterling. "Long-Term Trends in Extreme Precipitation Events over the Conterminous United States and Canada." Journal of Climate J. Climate 12.8 (1999): 2515-527. Print.

Kunkel, Kenneth E., Laura E. Stevens, Scott E. Stevens, Liqiang Sun, Emily Janssen, Donald Wuebbles, and J. Greg Dobson. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment; Part 9. Climate of the Contiguous United States. Rep. no. NOAA Technical Report NESDIS 142-9. Washington, D.C.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 2013. Print.

Kunkel, Kenneth E., Laura E. Stevens, Scott E. Stevens, Liqiang Sun, Emily Janssen, Donald Wuebbles, Steven D. Hilberg, Michael S. Timlin, Leslie Stoecker, Nancy E. Westcott, and J. Greg Dodson. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment; Part 3. Climate of the Midwest U.S. Rep. no. NOAA Technical Report NESDIS 142-3. Washington, D.C.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 2013. Print.

Kunkel, Kenneth E., Laura E. Stevens, Scott E. Stevens, Liqiang Sun, Emily Janssen, Donald Wuebbles, and J. Greg Dobson. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment; Part 9. Climate of the Contiguous United States. Rep. no. NOAA Technical Report NESDIS 142-9. Washington, D.C.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 2013. Print.

Kunkel, Kenneth E., Laura E. Stevens, Scott E. Stevens, Liqiang Sun, Emily Janssen, Donald Wuebbles, Steven D. Hilberg, Michael S. Timlin, Leslie Stoecker, Nancy E. Westcott, and J. Greg Dodson. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment; Part 3. Climate of the Midwest U.S. Rep. no. NOAA Technical Report NESDIS 142-3. Washington, D.C.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 2013. Print.

Kunkel, Kenneth E., Michael A. Palecki, Leslie Ensor, David Easterling, Kenneth G. Hubbard, David Robinson, and Kelly Redmond. "Trends in Twentieth-Century U.S. Extreme Snowfall Seasons." Journal of Climate 22.23 (2009): 6204-216. Print. American Meteorological Society

Kunkel, Kenneth E., Michael Palecki, Leslie Ensor, Kenneth G. Hubbard, David Robinson, Kelly Redmond, and David Easterling. "Trends in Twentieth-Century U.S. Snowfall Using a Quality-Controlled Dataset." J. Atmos. Oceanic Technol. Journal of Atmospheric and Oceanic Technology 26.1 (2009): 33-44. Print. American Meteorological Society

Kunkel, Kenneth E., Thomas R. Karl, Harold Brooks, James Kossin, Jay H. Lawrimore, Derek Arndt, Lance Bosart, David Changnon, Susan L. Cutter, Nolan Doesken, Kerry Emanuel, Pavel Ya. Groisman, Richard W. Katz, Thomas Knutson, James O'Brien, Christopher J. Paciorek, Thomas C. Peterson, Kelly Redmond, David Robinson, Jeff Trapp, Russell Vose, Scott Weaver, Michael Wehner, Klaus Wolter, and Donald Wuebbles. Monitoring and Understanding Trends in Extreme Storms. Rep. American Meteorological Society, 2013. Print. State of Knowledge.

Leggett, Jane A., Coordinator, et al. Climate Change Adaptation by Federal Agencies: An Analysis of Plans and Issues for Congress. Congressional Research Service, 2015. Print.

Liang, Xin-Zhong, Hyan I. Choi, Kenneth E. Kunkel, Yongjiu Dai, Everette Joseph, Julian X.L. Wang, and Praveen Kumar. *Development of the Regional Climate-Weather Research and Forecasting (CWRF) Model: Surface Boundary Conditions*. Rep. no. 2005-01. Illinois State Water Survey, A Division of the Illinois Department of Natural Resources, 2005. Print.

Liang, Xin-Zhong, Jianping Pan, Jinhong Zhu, Kenneth E. Kunkel, Julian X. L. Wang, and Aiguo Dai. "Regional Climate Model Downscaling of the U.S. Summer Climate and Future Change." *J. Geophys. Res. Journal of Geophysical Research* 111.D10108 (2006). Print.

Liang, Xin-Zhong, Min Xu, Xing Yuan, Tiejun Ling, Hyn I. Choi, Feng Zhang, Ligang Chen, Shuyan Liu, Shenjian Su, Fengxue Qiao, Yuxiang He, Julian X.L. Wang, Kenneth E. Kunkel, Wei Gao, Everette Joseph, Vernon Morris, Tsann-Wang Yu, Jimy Dudhia, and John Michalakes. "Regional Climate-Weather Research and Forecasting Model." *American Meteorological Society* D01.10.1175/BAMS-D-11-00180.1 (2012): 1363-387. Print.

Lofgren, Brent M., Frank H. Quinn, Anne H. Clites, Raymond A. Assel, Anthony J. Eberhardt, and Carol L. Luukkonen. "Evaluation of Potential Impacts on Great Lakes Water Resources Based on Climate Scenarios of Two GCMs." *Journal of Great Lakes Research* 28.4 (2002): 537-54. Print.

Love, Geoff, Alice Soares, and Herbert Püempel. "Climate Change, Climate Variability and Transportation." *Procedia Environmental Sciences* 1 (2010): 130-45. Print.

Melillo, Jerry M., Terese Richmond, and Gary W. Yohe, eds. Climate Change Impacts in the United States: The Third National Climate Assessment. Rep. U.S. Government Printing Office, 2014. Print. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Meyer, Michael D., Anne F. Choate, and Emily Rowan. Adapting Infrastructure to Extreme Weather Events: Best Practices and Key Challenges. AASHTO, 2012. Print.

Meyer, Michael D., Anne F. Choate, and Emily Rowan. Adapting Infrastructure to Extreme Weather Events: Best Practices and Key Challenges. AASHTO, 2012. Print

Music, Biljana, Anne Frigon, Brent Lofgren, Richard Turcotte, and Jean-François Cyr. "Present and Future Laurentian Great Lakes Hydroclimatic Conditions as Simulated by Regional Climate Models with an Emphasis on Lake Michigan-Huron." Climatic Change 130.4 (2015): 603-18. Print.

Music, Biljana, Anne Frigon, Brent Lofgren, Richard Turcotte, and Jean-François Cyr. "Present and Future Laurentian Great Lakes Hydroclimatic Conditions as Simulated by Regional Climate Models with an Emphasis on Lake Michigan-Huron." *Climatic Change* 130.4 (2015): 603-18. Print.

Nam, Won-Ho, Michael J. Hayes, Mark D. Svoboda, Tsegaye Tadesse, and Donald A. Wilhite. "Drought Hazard Assessment in the Context of Climate Change for South Korea." Agricultural Water Management 160 (2015): 106-17. Print.

National Oceanic and Atmospheric Administration. Web. 27 Aug. 2015. <http://www.noaa.gov/index.html>.

Posey, John. "Climate Change in St. Louis: Impacts and Adaptation Options." The International Journal of Climate Change: Impacts and Responses 5.2 (2014). Print. ISSN 1835-756

Posey, John. "Climate Change in St. Louis: Impacts and Adaptation Options." The International Journal of Climate Change: Impacts and Responses 5.2 (2014). Print. ISSN 1835-756

Posey, John. Climate Change Impacts on Transportation in the Midwest. U.S. GLOBAL CHANGE RESEARCH PROGRAM, NATIONAL CLIMATE ASSESSMENT, MIDWEST TECHNICAL INPUT REPORT. Comp. J. Winkler, J. Andresen, J. Hatfield, D. Bidwell, and D. Brown. N.p.: Great Lakes Integrated Sciences and Assessments (GLISA) Center, 2012. Print.

Posey, John. Climate Change Impacts on Transportation in the Midwest. U.S. GLOBAL CHANGE RESEARCH PROGRAM, NATIONAL CLIMATE ASSESSMENT, MIDWEST TECHNICAL INPUT REPORT. Comp. J. Winkler, J. Andresen, J. Hatfield, D. Bidwell, and D. Brown. N.p.: Great Lakes Integrated Sciences and Assessments (GLISA) Center, 2012. Print.

Regional Climate Change Effects: Useful Information for Transportation Agencies. ICF International, 2010. Print

Schweikert, Amy, Paul Chinowsky, Xavier Espinet, and Michael Tarbert. “Climate Change and Infrastructure Impacts: Comparing the Impact on Roads in Ten Countries through 2100.” Procedia Engineering 78 (2014): 306-16. Print.

Schweikert, Amy, Paul Chinowsky, Xavier Espinet, and Michael Tarbert. “Climate Change and Infrastructure Impacts: Comparing the Impact on Roads in Ten Countries through 2100.” Procedia Engineering 78 (2014): 306-16. Print.

SMelillo, Jerry M., Terese Richmond, and Gary W. Yohe, eds. Climate Change Impacts in the United States: The Third National Climate Assessment. Rep. U.S. Government Printing Office, 2014. Print. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2

Stamos, Iraklis, Evangelos Mitsakis, Josep Maria Salanova, and Georgia Aifadopoulou. “Impact Assessment of Extreme Weather Events on Transport Networks: A Data-driven Approach.” Transportation Research Part D: Transport and Environment 34 (2015): 168-78. Print.

Stamos, Iraklis, Evangelos Mitsakis, Josep Maria Salanova, and Georgia Aifadopoulou. “Impact Assessment of Extreme Weather Events on Transport Networks: A Data-driven Approach.” Transportation Research Part D: Transport and Environment 34 (2015): 168-78. Print.

Stoffel, M., D. Tiranti, and C. Huggel. “Climate Change Impacts on Mass Movements — Case Studies from the European Alps.” Science of The Total Environment 493 (2014): 1255-266. Print.

Stoffel, M., D. Tiranti, and C. Huggel. “Climate Change Impacts on Mass Movements — Case Studies from the European Alps.” Science of The Total Environment 493 (2014): 1255-266. Print.

Suarez, Pablo, William Anderson, Vijay Mahal, and T.r. Lakshmanan. “Impacts of Flooding and Climate Change on Urban Transportation: A Systemwide Performance Assessment of the Boston Metro Area.” Transportation Research Part D: Transport and Environment 10.3 (2005): 231-44. Print.

The Federal Highway Administration’s Climate Change & Extreme Weather Vulnerability Assessment Framework. Federal Highway Administration, 2012. Print.

The Use of Climate Information in Vulnerability Assessments. ICF International, 2011. Print

Trapp, R. J., N. S. Diffenbaugh, H. E. Brooks, M. E. Baldwin, E. D. Robinson, and J. S. Pal. “Changes in Severe Thunderstorm Environment Frequency during the 21st Century Caused by Anthropogenically Enhanced Global Radiative Forcing.” Ed. Kerry A. Emanuel. Proceedings of the National Academy of Sciences 104.50 (2007): 19719-9723. Print.

Walker, Lindsay, et al. Identifying Surface Transportation Vulnerabilities and Risk Assessment Opportunities Under Climate Change: A Portland, Oregon Case Study. 90th Annual Meeting of the Transportation Research Board. January 2011. Unpublished conference paper. Portland, Oregon. Print.

Wall, Thomas. A Risk-Based Assessment Tool to Prioritize Roadway Culvert Assets for Climate Change Adaptation Planning. Georgia Institute of Technology, 2013. Print.

Weather Forecast Office Hydrologic Products Specification. NATIONAL WEATHER SERVICE INSTRUCTION 10-922. Department of Commerce $ National Oceanic & Atmospheric Administration $ National Weather Service, 2011. Print. Operations and Services Hydrologic Services Program, NWSPD 10-9.

Weaver, C. P., E. Cooter, R. Gilliam, A. Gilliland, A. Grambsch, D. Grano, B. Hemming, S. W. Hunt, C. Nolte, D. A. Winner, X-Z. Liang, J. Zhu, M. Caughey, K. Kunkel, J-T. Lin, Z. Tao, A. Williams, D. J. Wuebbles, P. J. Adams, J. P. Dawson, P. Amar, S. He, J. Avise, J. Chen, R. C. Cohen, A. H. Goldstein, R. A. Harley, A. L. Steiner, S. Tonse, A. Guenther, J-F. Lamarque, C. Wiedinmyer, W. I. Gustafson, L. R. Leung, C. Hogrefe, H-C. Huang, D. J. Jacob, L. J. Mickley, S. Wu, P. L. Kinney, B. Lamb, N. K. Larkin, D. Mckenzie, K-J. Liao, K. Manomaiphiboon, A. G. Russell, E. Tagaris, B. H. Lynn, C. Mass, E. Salathé, S. M. O’neill, S. N. Pandis, P. N. Racherla, C. Rosenzweig, and J-H. Woo. “A Preliminary Synthesis of Modeled Climate Change Impacts on U.S. Regional Ozone Concentrations.” *Bull. Amer. Meteor. Soc. Bulletin of the American Meteorological Society* 90.12 (2009): 1843-863. Print.

Williams, Caroline. “Earth Shattering: How Global Warming Will Shake up the Planet.” New Scientist 211.2832 (2011): 38-42. Print.

Winguth, Ame, et al. Climate Change/Extreme Weather Vulnerability and Risk Assessment for Transportation Infrastructure in Dallas and Tarrant Counties. University of Texas at Arlington (UTA). Print.

Zhou, Q., P.s. Mikkelsen, K. Halsnæs, and K. Arnbjerg-Nielsen. "Framework for Economic Pluvial Flood Risk Assessment considering Climate Change Effects and Adaptation Benefits." *Journal of Hydrology* 414-415 (2012): 539-49. Print.

HAZARDS

Acosta-Martínez, V., S. Van Pelt, J. Moore-Kucera, M.c. Baddock, and T.m. Zobeck. "Microbiology of Wind-eroded Sediments: Current Knowledge and Future Research Directions." *Aeolian Research* 18 (2015): 99-113. Print.

Allen, Alice S. "Types of Land Subsidence." *Guidebook to Studies of Land Subsidence Due to Ground-water Withdrawal*. 133-42. Print.

Ash, Kevin D., Susan L. Cutter, and Christopher T. Emrich. "Acceptable Losses? The Relative Impacts of Natural Hazards in the United States, 1980–2009." *International Journal of Disaster Risk Reduction* 5 (2013): 61-72. Print.

Aubert, J.e., and M. Gasc-Barbier. "Hardening of Clayey Soil Blocks during Freezing and Thawing Cycles." *Applied Clay Science* 65-66 (2012): 1-5. Print.

Bailing Li and Matthew Rodell. "Evaluation of a Model-based Groundwater Drought Indicator in the Conterminous U.S." *Journal of Hydrology* 526 (2015): 78-88. Print.

Baker, Donald G., and David L. Ruschy. "Calculated and Measured Air and Soil Freeze-Thaw Frequencies." *Journal of Applied Meteorology J. Appl. Meteor.* 34.10 (1995): 2197-205. Print.

Baykal, Gokhan, and Altug Saygılı. "A New Technique to Improve Freeze–thaw Durability of Fly Ash." *Fuel* 102 (2012): 221-26. Print.

Berariu, Romana, Christian Fikar, Manfred Gronalt, and Patrick Hirsch. "Understanding the Impact of Cascade Effects of Natural Disasters on Disaster Relief Operations." International Journal of Disaster Risk Reduction 12 (2015): 350-56. Print.

Braile, Lawrence W., William J. Hinze, G.randy Keller, Edward G. Lidiak, and John L. Sexton. "Tectonic Development of the New Madrid Rift Complex, Mississippi Embayment, North America." *Tectonophysics* 131.1-2 (1986): 1-21. Print.

Cheng, Q., Y. Sun, S.b. Jones, V.i. Vasilyev, V.v. Popov, G. Wang, and L. Zheng. "In Situ Measured and Simulated Seasonal Freeze–thaw Cycle: A 2-year Comparative Study between Layered and Homogeneous Field Soil Profiles." *Journal of Hydrology* 519 (2014): 1466-473. Print.

Chleboard, Alan F. Preliminary Method for Anticipating the Occurrence of Precipitation-Induced Landslides in Seattle, Washington. Rep. no. Open-File Report 00-469. U. S. Geological Survey, 2000. Web. 28 Aug. 2015.

Corfidi, Stephen F., Jeffry S. Evans, and Robert H. Johns. "About Derechos." Facts About Derechos - Very Damaging Windstorms. NOAA-NWS-NCEP Storm Prediction Center, 9 June 2015. Web. 28 Aug. 2015. <http://www.spc.noaa.gov/misc/AbtDerechos/derechofacts.htm>.

Cova, T J. GIS in Emergency Management. Print.

Cova, Thomas J., and Steven Conger. "Transportation Hazards." Ed. M. Kutz. *Handbook of Transportation Engineering* (2004): 171.1-7.24. Print.

Creutin, Jean Dominique, Marco Borga, Eve Gruntfest, Céline Lutoff, Davide Zoccatelli, and Isabelle Ruin. "A Space and Time Framework for Analyzing Human Anticipation of Flash Floods." *Journal of Hydrology* 482 (2013): 14-24. Print.

Cutter, Susan L., Jerry T. Mitchell, and Michael S. Scott. Handbook for Conducting a GIS-Based Hazards Assessment at the County Level. Hazards Research Lab, Department of Geography, University of South Carolina, 1997. Print.

Eisenberg, Daniel. "The Mixed Effects of Precipitation on Traffic Crashes." *Accident Analysis & Prevention* 36.4 (2004): 637-47. Print. School of Public Health, University of California, Berkeley, CA, USA

Federal Emergency Management Agency. Web. 27 Aug. 2015. <http://www.fema.gov/>.

Fullerton, David S., Charles A. Bush, and Jean N. Pennell. Map of Surficial Deposits and Materials in the Eastern and Central United States (East of 102° West Longitude). [map]. 1:2,500,000. Geologic Investigations Series I-2789. Denver, CO: U.S. Geological Survey, 2003. Print.

Galloway, D. L., D. R. Jones, and S. E. Ingebritsen. Land Subsidence in the United States. USGS Fact Sheet-165-00. U.S. Geological Survey, 2000. Print.

Galloway, D. L., K. W. Hudnut, S. E. Ingebritsen, S. P. Phillips, G. Peltzer, F. Rogez, and P. A. Rosen. "Detection of Aquifer System Compaction and Land Subsidence Using Interferometric Synthetic Aperture Radar, Antelope Valley, Mojave Desert, California." Water Resources Research Water Resour. Res. 34.10 (1998): 2573-585. Print.

Godon, Nancy A., and Paul E. Todhunter. "A Climatology of Airborne Dust for the Red River Valley of North Dakota." Atmospheric Environment 32.9 (1998): 1587-594. Print.

Gonzalez-Caban, Armando. *Proceedings of the Fourth International Symposium on Fire Economics, Planning, and Policy: Climate Change and Wildfires*. Rep. no. General Technical Report PSW-GTR-245 (English). Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 2013. Print.

Goudie, Andrew S. "Dust Storms: Recent Developments." Journal of Environmental Management 90.1 (2009): 89-94. Print.

Güneralp, Burak, Inci Güneralp, and Ying Liu. "Changing Global Patterns of Urban Exposure to Flood and Drought Hazards." Global Environmental Change 31 (2015): 217-25. Print.

Guo, Ying, and Wei Shan. "Monitoring and Experiment on the Effect of Freeze-Thaw on Soil Cutting Slope Stability." Procedia Environmental Sciences 10 (2011): 1115-121. Print. 2011 3rd International Conference on Environmental Science and Information Application Technology (ESIAT 2011)

Hahnenberger, Maura, and Kathleen Nicoll. "Meteorological Characteristics of Dust Storm Events in the Eastern Great Basin of Utah, U.S.A." Atmospheric Environment 60 (2012): 601-12. Print.

Hansson, K., M. Danielson, and L. Ekenberg. "A Framework for Evaluation of Flood Management Strategies." Journal of Environmental Management 86.3 (2008): 465-80. Print.

Harriman, Lindsey. "Forecasting and Early Warning of Dust Storms." Environmental Development 6 (2013): 117-29. Print.

Hastak, Makarand, et al. 2008 Midwest Floods Impact Analysis on Critical Infrastructure, Associated Industries, and Communities. NSF Engineering Research and Innovation Conference, 2009. Print.

Henry, Hugh A. L. "Soil Freezing Dynamics in a Changing Climate: Implications for Agriculture." Plant and Microbe Adaptations to Cold in a Changing World DOI 10.1007/978-1-4614-8253-6_2 (2013): 17-27. Print.

Highland, Lynn M., and Peter Bobrowsky. "Section III. Mitigation Concepts and Approaches." The Landslide Handbook—A Guide to Understanding Landslides. Reston, VA: U.S. Geological Survey, 2008. 51-58. Print. Circular 1325.

Illinois State Geological Survey. *Karst Landscapes of Illinois: Dissolving Bedrock and Collapsing Soil*. Illinois State Geological Survey. Web. 2 June 2015. <https://www.isgs.illinois.edu/outreach/geology-resources/karst-landscapes-illinois-dissolving-bedrock-and-collapsing-soil>.

Kachroo, P. N., and N.G. K. Raju. *Freeze-Thaw Effects on Roadways Approach to Pavement Design with Special References to Roads in Mongolia*. Print.

Khademi, Navid, Behrooz Balaei, Matin Shahri, Mojgan Mirzaei, Behrang Sarrafi, Moeid Zahabiun, and Afshin S. Mohaymany. "Transportation Network Vulnerability Analysis for the Case of a Catastrophic Earthquake." *International Journal of Disaster Risk Reduction* 12 (2015): 234-54. Print.

Kilgore, Roger T., et al. Hydraulic Engineering Circular No. 17, 2nd Edition Highways in the River Environment — Floodplains, Extreme Events, Risk, and Resilience. Federal Highway Administration Office of Bridges and Structures, 2016. Print.

Kim, Hungsoo, Jongyong Park, Jiyoung Yoo, and Tae-Woong Kim. "Assessment of Drought Hazard, Vulnerability, and Risk: A Case Study For administrative Districts in South Korea." *Journal of Hydro-environment Research* 9.1 (2015): 28-35. Print.

Kothavala, Zavareh. "Extreme Precipitation Events and the Applicability of Global Climate Models to the Study of Floods and Droughts." *Mathematics and Computers in Simulation* 43.3-6 (1997): 261-68. Print.

Leathers, Daniel J., Andrew W. Ellis, and David A. Robinson. "Characteristics of Temperature Depressions Associated with Snow Cover across the Northeast United States." *Journal of Applied Meteorology J. Appl. Meteor.* 34.2 (1995): 381-90. Print.

Li, Zhigang, Xiaojing Liu, Xiumei Zhang, and Weiqiang Li. "Infiltration of Melting Saline Ice Water in Soil Columns: Consequences on Soil Moisture and Salt Content." *Agricultural Water Management* 95.4 (2008): 498-502. Print.

Lipiec, Jason. Toxic Chemicals Transported by Rail and Public Health Safety using GIS in Montgomery County, Ohio. Wright State University, 2011. Print.

Luman, Donald, and Doug Jacoby. "Sinkhole ID." *Point of Beginning* 38.2 (2012). Print.

Lumbroso, Darren, and Eric Gaume. “Reducing the Uncertainty in Indirect Estimates of Extreme Flash Flood Discharges.” *Journal of Hydrology* 414-415 (2012): 16-30. Print.

Maddox, Ivan. “Three Common Types of Flood Explained.” *Intermap*. The Risks of Hazard Blog, 31 Oct. 2014. Web. 28 Aug. 2015. <http://www.intermap.com/risks-of-hazard-blog/three-common-types-of-flood-explained>.

Mantovani, Franco, Alessandro Pasuto, S. Silvano, and A. Zannoni. “Collecting Data to Define Future Hazard Scenarios of the Tessina Landslide.” *International Journal of Applied Earth Observation and Geoinformation* 2.1 (2000): 33-40. Print.

Mcbride, Michael F. “Railroad Transportation of Nuclear Waste and Other Hazardous Materials.” *The Electricity Journal* 21.3 (2008): 55-60. Print.

Murthy, C.s., B. Laxman, and M.v.r. Sesha Sai. “Geospatial Analysis of Agricultural Drought Vulnerability Using a Composite Index Based on Exposure, Sensitivity and Adaptive Capacity.” *International Journal of Disaster Risk Reduction* 12 (2015): 163-71. Print

Oggero, A., R. Darbra, M. Munoz, E. Planas, and J. Casal. “A Survey of Accidents Occurring during the Transport of Hazardous Substances by Road and Rail.” *Journal of Hazardous Materials* 133.1-3 (2006): 1-7. Print.

Pappenberger, Florian, Keith Beven, Kevin Frodsham, Renata Romanowicz, and Patrick Matgen. “Grasping the Unavoidable Subjectivity in Calibration of Flood Inundation Models: A Vulnerability Weighted Approach.” *Journal of Hydrology* 333.2-4 (2007): 275-87. Print.

Park, S.h., S.l. Gong, W. Gong, P.a. Makar, M.d. Moran, C.a. Stroud, and J. Zhang. “Sensitivity of Surface Characteristics on the Simulation of Wind-blown-dust Source in North America.” *Atmospheric Environment* 43.19 (2009): 3122-129. Print.

Peterson, Thomas C., Richard R. Heim, Jr., Robert Hirsch, Dale P. Kaiser, Harold Brooks, Noah S. Diffenbaugh, Randall M. Dole, Jason P. Giovannettone, Kristen Guirguis, Thomas R. Karl, Richard W. Katz, Kenneth Kunkel, Dennis Lettenmaier, Gregory J. McCabe, Christopher J. Paciorek, Karen R. Ryberg, Siegfried Schubert, Viviane B. S. Silva, Brooke C. Stewart, Aldo V. Vecchia, Gabriele Villarini, Russell S. Vose, John Walsh, Michael Wehner, David Wolock, Klaus Wolter, Connie A. Woodhouse, and Donald Wuebbles. *Monitoring and Understanding Changes in Heat Waves, Cold Waves, Floods, and Droughts in the United States*. Rep. American Meteorological Society, 2013. Print. State of Knowledge.

Phillips, Andrew J., and Nathaniel K. Newlands. “Spatial and Temporal Variability of Soil Freeze-thaw Cycling across Southern Alberta, Canada.” *Agricultural Sciences AS* 392-405 02.04 (2011): 392-405. Print.

Rashed, Tarek and John Weeks. “Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas.” Int. J. Geographical Information Science 0 (2003). Print.

Rivera, Nancy I. Rivera, Thomas E. Gill, Max P. Bleiweiss, and Jenny L. Hand. “Source Characteristics of Hazardous Chihuahuan Desert Dust Outbreaks.” *Atmospheric Environment* 44.20 (2010): 2457-468. Print.

Rønning, Terje Finnerup. Free-Thaw Resistance of Concrete Effect of: Curing Conditions, Moisture Exchange and Materials. The Norwegian Institute of Technology, Division of Structural Engineering, Concrete Section, 2001. Print.

Ronza, A., J.a. Vílchez, and J. Casal. “Using Transportation Accident Databases to Investigate Ignition and Explosion Probabilities of Flammable Spills.” *Journal of Hazardous Materials* 146.1-2 (2007): 106-23. Print.

Saat, Mohd Rapik, et al. “Environmental risk analysis of hazardous material rail transportation.” Journal of Hazardous Materials 264 (2014): 560-569. Print.

Sanders, Brett F. “Evaluation of On-line DEMs for Flood Inundation Modeling.” *Advances in Water Resources* 30.8 (2007): 1831-843. Print.

Shahabi, Mehrdad, Aung Hlaing, David R. Martinelli, and Avinash Unnikrishnan. *Fog Detection for Interstate and State Highways*. Rep. no. WVU-2010-01. Morgantown, WV: West Virginia U, 2012. Print.

Sinclair, William C. Sinkhole Development Resulting from Ground-Water Withdrawal in the Tamp Area, Florida. U.S. Geological Survey Water Resources Division, 1982. Print.

Sinha, Tushar, and Keith A. Cherkauer. “Time Series Analysis of Soil Freeze and Thaw Processes in Indiana.” *J. Hydrometeor Journal of Hydrometeorology* 9.5 (2008): 936-50. Print.

Sneed, Michelle, and D.L. Galloway. “Aquifer-System Compaction and Land Subsidence: Measurements, Analyses, and Simulations—the Holly Site, Edwards Air Force Base, Antelope Valley, California.” U.S. Geological Survey Water-Resources Investigations Report 00-4015 (2008): 1-65. Print.

Sperry, Sidney K., and Steven F. Piltz. *SPIA Index*. Sperry-Piltz Ice Accumulation Index. Web. 27 Aug. 2015. <http://www.spia-index.com/>.

Synthesis of Highway Practice 228: Reduced Visibility Due to Fog on the Highway, A Synthesis of Highway Practice. National Cooperative Highway Research Program (NCHRP). Print. The following information is from "NCHRP Synthesis of Highway Practice 228: Reduced Visibility Due to Fog on the Highway." Reproduced here is "Summary" and "Chapter Six: Conclusions." These sections outline the contents of the publication.

Tacnet, Jean-Marc, Eric Mermet and Somsakun Maneerat. Analysis of importance of road networks exposed to natural hazards. Multidisciplinary Research on Geographical Information in Europe and Beyond, 2012. Print.

Threat and Hazard Identification and Risk Assessment Guide. 2nd edition. Homeland Security, 2013. Print.

Turner, Ted R., Steven D. Duke, Brian R. Fransen, Maryanne L. Reiter, Andrew J. Kroll, Jim W. Ward, Janette L. Bach, Tiffany E. Justice, and Robert E. Bilby. "Landslide Densities Associated with Rainfall, Stand Age, and Topography on Forested Landscapes, Southwestern Washington, USA." *Forest Ecology and Management* 259.12 (2010): 2233-247. Print.

Velásquez, C.a., O.d. Cardona, M.l. Carreño, and A.h. Barbat. "Retrospective Assessment of Risk from Natural Hazards." *International Journal of Disaster Risk Reduction* 10 (2014): 477-89. Print.

Vries, Daniel H. De. "Temporal Vulnerability in Hazardscapes: Flood Memory-networks and Referentiality along the North Carolina Neuse River (USA)." *Global Environmental Change* 21.1 (2011): 154-64. Print.

Wald, David J., Vincent Quitoriano, Thomas H. Heaton, and Hiroo Kanamori. "Relationships between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California." Earthquake Spectra 15.3 (1999): 557-64. Print.

Wang, Yaqiang, Ariel F. Stein, Roland R. Draxler, Jesús D. De La Rosa, and Xiaoye Zhang. "Global Sand and Dust Storms in 2008: Observation and HYSPLIT Model Verification." *Atmospheric Environment* 45.35 (2011): 6368-381. Print.

Wehner, Michael, David R. Easterling, Jay H. Lawrimore, Richard R. Heim, Russell S. Vose, and Benjamin D. Santer. "Projections of Future Drought in the Continental United States and Mexico." *J. Hydrometeor Journal of Hydrometeorology* 12.6 (2011): 1359-377. Print.

Xu, Chong. "Preparation of Earthquake-triggered Landslide Inventory Maps Using Remote Sensing and GIS Technologies: Principles and Case Studies." Geoscience Frontiers (2014): 1-12. Print.

Zhaoli, Wang, Ma Hongliang, Lai Chengguang, and Song Haijuan. "Set Pair Analysis Model Based on GIS to Evaluation for Flood Damage Risk." *Procedia Engineering* 28 (2012): 196-201. Print.

Zimmerman, Laura I., Raquel Lima, Ricardo Pietrobon, and David Marcozzi. "The Effects of Seasonal Variation on Hazardous Chemical Releases." *Journal of Hazardous Materials* 151.1 (2008): 232-38. Print

CRITICALITY / VULNERABILITY STUDIES

2012 Bridge Manual. Illinois Department of Transportation Bureau of Bridges and Structures Division of Highways, 2012. Print.

Assessing Criticality in Transportation Adaptation Planning. ICF International, 2014. Print.

Balijepalli, Chandra, and Olivia Oppong. "Measuring Vulnerability of Road Network considering the Extent of Serviceability of Critical Road Links in Urban Areas." *Journal of Transport Geography* 39 (2014): 145-55. Print.

City of Everett Hazard Inventory & Vulnerability Analysis. University of Washington Institute for Hazards Mitigation Planning and Research, 2011. Print.

City of Pleasanton All-Hazard Vulnerability Analysis. 2005. Print.

Critical Transportation Assets and Their Vulnerability to Sea Level Rise Final Report. Cape Cod Commission, 2015. Print.

DeKalb County Hazard Mitigation Planning Committee. DeKalb County All Hazards Mitigation Plan. 2013. Print.

Dojutrek, M.S., S. Labi, and J. Eric Dietz. A Multicriteria Methodology for Measuring the Resilience of Transportation Assets and Prioritizing Security Investments. Purdue University, 2014. Print.

Effati, Meysam, et al. "Developing a Novel Method for Road Hazardous Segment Identification Based on Fuzzy Reasoning and GIS." Journal of Transportation Technologies 2 (2012): 32-40. Print.

Fuller, D.O., R. Williamson, M. Jeffe, and D. James. "Multi-criteria Evaluation of Safety and Risks along Transportation Corridors on the Hopi Reservation." *Applied Geography* 23.2-3 (2003): 177-88. Print.

Guide for All-Hazard Emergency Operations Planning. The Federal Emergency Management Agency (FEMA), 1996. Print.

Guide to Highway Vulnerability Assessment for Critical Asset Identification and Protection. Science Applications International Corporation (SAIC) Transportation Policy and Analysis Center, 2002. Print.

Høj, Niels Peter, and Wolfgang Kröger. "Risk Analyses of Transportation on Road and Railway from a European Perspective." Safety Science 40.1-4 (2002): 337-57. Print.

Hubbard, Shane, Kathleen Stewart, and Junchuan Fan. "Modeling Spatiotemporal Patterns of Building Vulnerability and Content Evacuations before a Riverine Flood Disaster." Applied Geography 52 (2014): 172-81. Print.

Hughes, JF and K Healy. "Measuring the resilience of transport infrastructure." NZ Transport Agency research report 546. NZ Transport Agency, 2014. Print.

Illinois Emergency Management Agency. State of Illinois, 2014. Web. 27 Aug. 2015. <http://www.iema.illinois.gov/>.

Jenelius, Erik and Lars-Göran Mattsson. Road Network Vulnerability Analysis: Conceptualization, Implementation and Application. KTH Royal Institute of Technology Department of Transport Science. Print.

Jenelius, Erik. Large-Scale Road Network Vulnerability Analysis. Division of Transport and Location Analysis, Department of Transport Science, KTH Royal Institute of Technology, 2010.

Kaundinya, Ingo. Security of Road Transport Networks – Identifying and Assessing Critical Road Infrastructure. Transport Research Arena, 2014. Print.

Lyles, Ward, Philip Berke, and Gavin Smith. "A Comparison of Local Hazard Mitigation Plan Quality in Six States, USA." *Landscape and Urban Planning* 122 (2014): 89-99. Print.

Martin & Chock. State of Hawai'i Multi-Hazard Mitigation Plan 2013 Update. 2013. Print.

Matthews, Elizabeth C., Meredith Sattler, and Carol J. Friedland. "A Critical Analysis of Hazard Resilience Measures within Sustainability Assessment Frameworks." *Environmental Impact Assessment Review* 49 (2014): 59-69. Print.

Mens, Marjolein J.p., Frans Klijn, Karin M. De Bruijn, and Eelco Van Beek. "The Meaning of System Robustness for Flood Risk Management." *Environmental Science & Policy* 14.8 (2011): 1121-131. Print.

Merrill, Sam and Judy Gates. Integrating Storm Surge and Sea Level Rise Vulnerability Assessments and Criticality Analyses into Asset Management at MaineDOT. Maine DOT, 2014. Print.

Mississippi River, Fire Protection Plan, Appendix C to the Master Plan. Rock Island District, U.S. Army Corps of Engineers, 1980. Print.

Mitigation Advisory Committee. Prince George's County City of Laurel, Maryland Hazard Mitigation Plan. 2005. Print.

Moteff, John, Claudia Copeland, and John Fischer. Critical Infrastructures: What Makes an Infrastructure Critical? Congressional Research Service, 2003. Print.

Murray-Tuite, Pamela, and Brian Wolshon. "Evacuation Transportation Modeling: An Overview of Research, Development, and Practice." *Transportation Research Part C: Emerging Technologies* 27 (2013): 25-45. Print.

Nam, Won-Ho, Michael J. Hayes, Mark D. Svoboda, Tsegaye Tadesse, and Donald A. Wilhite. "Drought Hazard Assessment in the Context of Climate Change for South Korea." *Agricultural Water Management* 160 (2015): 106-17. Print.

National Oceanic and Atmospheric Administration. Web. 27 Aug. 2015. <http://www.noaa.gov/index.html>.

Nelson, Debra, Michelle Brown and Jessica Levine. Climate Vulnerability and Economic Assessment for At-Risk Transportation Infrastructure in the Lake Champlain Basin, New York. US Department of Transportation Federal Highway Administration Office of Natural Environment, 2015. Print

Oh, Eun Ho, Abhijeet Deshmukh and Makarand Hastak. Criticality Assessment of Lifeline Infrastructure forEnhancing Disaster Response. American Society of Civil Engineers, 2013. Print.

Omo--Irabor, Omoleomo Olutoyin and Samuel Bamidele Olobaniyi. Application of Multi-criteria Decision Analysis and GIS Techniques in Vulnerability Assessment of Coastal Inhabitants in Nigeria to Crude Oil Production and Transportation Activities. Print.

Regional Climate Change Effects: Useful Information for Transportation Agencies. ICF International, 2010. Print.

Roalkvam, Carol Lee. Creating a Resilient Transportation Network in Skagit County: Using Flood Studies to Inform Transportation Asset Management. Washington State Department of Transportation, 2015. Print.

Rodríguez-Núñez, Eduardo and Juan Carlos García-Palomares. "Measuring the vulnerability of public transport networks." Journal of Transport Geography 35 (2014): 50-63. Print.

Schulz, Carola. The Identification of Critical Road Infrastructures – The Case of Baden-Wuerttemberg. Karlsruher Institut für Technologie (KIT), 2012. Print.

Science Applications International Corporation. "Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA)." Surface Transportation Security 15 (2009). Print.

Sohn, Jungyul. "Evaluating the Significance of Highway Network Links under the Flood Damage: An Accessibility Approach." *Transportation Research Part A: Policy and Practice* 40.6 (2006): 491-506. Print.

Springfield Sangamon County Regional Planning Commission. Sangamon County Multi-Jurisdictional Natural Hazards Mitigation Plan. 2015. Print.

St. Croix County All Hazard Mitigation Plan Steering Committee, et al. St. Croix County All Hazard Mitigation Plan. 2012. Print

Sullivan, J.l., D.c. Novak, L. Aultman-Hall, and D.m. Scott. "Identifying Critical Road Segments and Measuring System-wide Robustness in Transportation Networks with Isolating Links: A Link-based Capacity-reduction Approach." Transportation Research Part A: Policy and Practice 44.5 (2010): 323-36. Print.

Taylor, M A P and G M D'Este. Concepts of network vulnerability and applications to the identification of critical elements of transport infrastructure. 26th Australasian Transport Research Forum Wellington, 2003. Print.

Toma-Danila, Dragos. Transport Network Vulnerability Assessment Methodology, Based on the Cost-Distance Method and GIS Integration. National Institute for Earth Physics, 2013. Print.

Transportation Systems: Critical Infrastructure and Key Resources Sector-Specific Plan as input to the National Infrastructure Protection Plan. Transportation System Sector, 2007. Print.

U.S. Dot Vulnerability Assessment Scoring Tool User's Guide. ICF International, 2015. Print.

US Department of Transportation Federal Highway Administration Report 5: Managing External Threats Through Risk-Based Asset Management. Risk-Based Transportation Asset Management: Building Resilience into Transportation Assets, 2013. Print.

Venner, Marie. Culvert and Storm Drain Management Case Study: Vermont, Oregon, Ohio, and Los Angeles County. Federal Highway Administration Office of Asset Management, Pavement, and Construction, 2014. Print.

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