Climate Impacts Vulnerability Assessment

REPORT

Prepared by the Washington State Department of Transportation for submittal to the Federal Highway Administration

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Washington State Department of Transportation

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Executive Summary

The Washington State Department of Transportation (WSDOT) has written this report in fulfillment of a grant from the Federal Highway Administration (FHWA) to test its conceptual climate risk assessment model developed for transportation infrastructure. WSDOT applied the model using scenario planning in a series of statewide workshops, using local experts, to create a qualitative assessment of climate vulnerability on its assets in each region and mode across Washington.

This report conveys WSDOT's feedback on the conceptual model and the lessons learned while applying the model to our assets. Below is a summary of the key elements of WSDOT's Climate Impacts Vulnerability Assessment:

- WSDOT collected an inventory of department-owned assets and climate change data using GIS. University of Washington climate scientists provided us with climate data.
- WSDOT leveraged its ten years of project risk management experience through its signature Cost Estimate Validation Process® and Cost Risk Assessment Workshops to develop an appropriate risk assessment method for the climate change analysis.
- Fourteen workshops engaged experts across all regions, state ferries, rail, and aviation.
- The outcome of each workshop is a qualitative assessment of the vulnerability agreed upon by participants.

The FHWA conceptual methodology provided a helpful launching point for assessing the impacts of extreme weather events and projected climate impacts on WSDOT's system. We captured qualitative ratings for impacts and asset criticality and recorded descriptions into spreadsheets that were used to create a GIS layer that was used to provide maps of projected climate impacts. Because we used scenarios and did not assign probabilities to an impact, WSDOT views this as a vulnerability assessment rather than a risk assessment in the traditional sense.

We offer the following recommendations to improve the FHWA conceptual model:

- Provide a more general flow diagram for initial qualitative assessments (see our revised methodology in Exhibit 3-2).
- Include a feedback loop to incorporate adaptation actions.
- Define terms and clarify "risk assessment" vs. "vulnerability assessment."
- Prompt the use of the model with key questions that departments of transportation or metropolitan planning organizations will be able to answer by applying the model.

The result of this FHWA pilot project is the first step toward meeting one of WSDOT's 2011–2013 strategic goals: *Identify WSDOT facilities vulnerable to the effects of climate change; evaluate risks and identify possible strategies to reduce risk.* The vulnerability assessment will be presented to WSDOT's executive management and the department's Sustainable Transportation Team for their use in defining next steps.

Understanding future conditions is essential for WSDOT's mission: to keep people and business moving. WSDOT is committed to sustainability goals designed to meet society's needs today without compromising the ability of future generations to meet their needs.

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** Maps

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Acronyms, Abbreviations, and Resources

DOT	department of transportation
FHWA	Federal Highway Administration
GIS	Geographic Information System
GHG	greenhouse gas
LiDAR	Light Detection And Ranging
MP	milepost
MPO	metropolitan planning organization
NEPA	National Environmental Policy Act
NHS	National Highway System
NOAA	National Oceanic and Atmospheric Administration
SEPA	State Environmental Policy Act
SR	state route
WSDOT	Washington State Department of Transportation

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http://www.cses.washington.edu/db/pdf/wacciareport681.pdf

MacArthur, J. , P. Mote, J. Ideker, M. Lee, M. Figliozzi, (pre-publication drafts 2011) "Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska," Region X Northwest Transportation Consortium of four state DOTs (WA, OR, ID, AK).

Puget Sound Regional Council White Paper L2: Climate Change Adaptation link:
http://www.psrc.org/assets/4888/Appendix_L_-_Climate_Change_-_FINAL_-_August_2010.pdf

Climate Impacts Vulnerability Assessment

1.0 Introduction

The Washington State Department of Transportation (WSDOT) is working to create an integrated 21st century transportation system that is reliable, responsible, and sustainable. Sustainable transportation supports a healthy economy, environment, and community and adapts to weather extremes, diminished funding, and changing priorities. Further, a sustainable transportation system is built to last, uses fewer materials and energy, and is operated efficiently.

The work we do now to prepare and adapt to our changing climate will protect taxpayer investments and our transportation system for conditions both today and in the future. This work is a key component of our sustainable transportation effort at WSDOT.

> *WSDOT has a responsibility to look ahead and ensure we protect our infrastructure and prepare for potential risks. Our transportation structures are critical to keep people and goods moving and the economy growing.*
>
> **Paula Hammond**
> Washington State Secretary of Transportation

Weather emergencies and climate variability are very closely tied to WSDOT's day-to-day business. Our maintenance crews are literally on the "front line." Our designers and project teams closely examine site-specific environmental conditions. Our materials experts look at the strength and resilience of various pavement mixes and structural materials to withstand the forces of water, wind, and temperature.

Like other risks we plan for, such as retrofitting bridges against earthquakes, we plan to take action, including updating planning and design policies, to protect our transportation infrastructure from climate impacts. This is responsible asset management. We build highways, bridges, and state ferries to last decades, so the need to improve structure resiliency to better adapt to weather extremes is essential to reducing risk.

1.1 Projected changes in the Pacific Northwest

There is widespread consensus among the world's leading climate scientists that global climate changes are now occurring and will continue into the future, particularly increasing temperatures (IPCC, 2007and 2011). Washington State is currently experiencing the effects of melting glaciers and extreme weather events.

The scientific community's understanding of climate impacts continues to evolve as the models and collective understanding of feedback systems improve. We do not have perfect information about exactly how, when, where, and to what magnitude climate changes will unfold in Washington State. The choice of any future date for changes to

occur is a best estimate of future conditions based on current science, and does not imply an end date or slowing of change. At current levels of atmospheric greenhouse gases (GHG), we are advised by scientists that a pattern of long-term change will play out over centuries. More information on projected climate impacts, including all related publication references, is found in Appendix A.

In 2009 the Climate Impacts Group (CIG) at the University of Washington completed a comprehensive assessment of the impacts of climate change on Washington State, as mandated by the 2007 Washington State Legislature. CIG downscaled global climate models that were found in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007) to the greater Columbia River basin.

WSDOT used this information from CIG as the basis for scenario planning in the vulnerability assessment workshops we conducted as part of the pilot project (see Appendix B). That same year, the State Agency Climate Leadership Act (Senate Bill 5560) directed state agencies to examine the climate data and help prepare for the impacts of climate change.

While impacts will vary by location, the *Washington Climate Change Impacts Assessment* and other published works find that Washington is likely to see the following impacts from climate change:

Higher Temperatures

Increases in average annual temperature of 2.0°F (range: 1.1°F to 3.4°F) by the 2020s, 3.2°F (range: 1.6°F to 5.2°F) by the 2040s, and 5.3°F (range: +2.8°F to +9.7°F) by the 2080s (compared to 1970–1999) are projected. There is an increasing likelihood of extreme heat events (heat waves) that can stress energy, water, and transportation infrastructure.

Enhanced Seasonal Precipitation Patterns

Wetter autumns and winters, drier summers, and small overall increases in annual precipitation in Washington (+1 to +2% by the 2040s) are projected. Increases in extreme high precipitation in western Washington are also possible.

Declining Snowpack

Spring snowpack is projected to decline, on average, by approximately 28% by the 2020s, 40% by the 2040s, and 59% by the 2080s (relative to 1916–2006).

Seasonal Changes in Streamflow

Increases in winter streamflow, shifts in the timing of peak streamflow in snow-dominant and rain/snow mix basins, and decreases in summer streamflow are expected. Also, the risk of extreme high and low flows is expected to increase.

Sea Level Rise

Medium projections of sea level rise for the 2100s are 2 to 13 inches (depending on location) in Washington State. Higher increases (up to 50 inches depending on location) are possible depending on trends in ice loss from the Greenland ice sheet, among other factors.

Increase in Wave Heights

An increase in significant wave height of 2.8 inches per year is projected through the 2020s (Ruggiero et al., 2010).

1.2 WSDOT's Climate Impacts Vulnerability Assessment background

Since 2007 Washington State's elected officials and state agencies have been working to understand and address the impacts of climate change and greenhouse gas emissions. WSDOT has been very actively engaged in state-level efforts. WSDOT executives served on the state's Climate Action Team, and technical experts participated in numerous workgroups on preparation and adaptation, transportation emission reduction strategies, and more.

In 2009, under the leadership of Secretary Hammond, WSDOT created a team of executive managers to sponsor and direct the agency's sustainable transportation effort and to develop a work plan. One of the tasks of the work plan is to assess our infrastructure and identify its vulnerabilities to extreme weather events and potential changes in climate.

In that same year, the Federal Highway Administration (FHWA) initiated a project to create a conceptual model for departments of transportation (DOTs) and Metropolitan Planning Organizations (MPOs) to use in conducting infrastructure vulnerability and risk assessments of the projected impacts of global climate change. As a part of this project, FHWA requested proposals from DOTs and MPOs to test the methodology beginning in the fall of 2010.

Chronology

2007 – Governor forms State Climate Action Teams

2008 – WSDOT develops project-level guidance for NEPA/SEPA

2009 – State elected officials enact major legislation and executive order on climate change

– WSDOT directs a series of climate- and GHG-related efforts in its internal strategic plan

– WSDOT establishes Sustainable Transportation Team to further efforts

– University of Washington's Climate Impacts Group releases the *Washington Climate Change Impacts Assessment*

2010 – FHWA selects WSDOT to receive one of five pilot grants

– WSDOT partners with other state agencies on integrated climate change response strategy

2011 – WSDOT hosts State Smart Transportation Initiative (SSTI)

– WSDOT conducts vulnerability assessment workshops across the state for all modes

– Report published for FHWA pilot

The products FHWA anticipated from this project were:

- A synthesis of national and international approaches for conducting such assessments.
- A review and synthesis of current and ongoing climate science and what can reasonably be assumed by transportation practitioners with regard to climate change impacts.
- Testing of the conceptual model provided by FHWA and recommended changes to the model.

In the summer of 2010, WSDOT applied for and was accepted as one of the pilot projects to test this conceptual model on department-owned and -managed infrastructure across the state.

While WSDOT has excellent information resources regarding our assets, and a comprehensive statewide climate change assessment done by the University of Washington's Climate Impacts Group (CIG), the FHWA pilot project offered two essential pieces that were lacking: funding and the conceptual framework to move into action.

1.3 What is included in Washington's state-owned transportation infrastructure?

WSDOT currently manages a system with:

- Over 7,000 centerline miles of roadway
- Over 8,500 bridge structures
- 39 tunnels and covered sections of highway
- 42 safety rest areas on more than 185 numbered highway routes
- 22 ferry terminals, all with multiple sailings per day
- 1 ferry maintenance facility
- 4 freight rail lines in eastern Washington
- 3 high-speed commuter trains in western Washington
- 16 airports used for firefighting, search and rescue, and recreation

The goal of the pilot project is to assess the current vulnerability of these assets. The result of the project is the first step in meeting one of WSDOT's 2011–2013 strategic goals: Identify WSDOT facilities vulnerable to the effects of climate change; evaluate the risks and identify possible strategies to reduce risk.

1.4 How does the pilot project fit within the scope of WSDOT's other work?

Understanding future conditions is essential to WSDOT's mission to keep people and business moving. It is also required to meet our longer-term sustainability goals, which are designed to meet society's needs today without compromising the ability of future generations to meet their needs.

Moving Washington is WSDOT's framework for making transparent, cost-effective decisions that keep people and goods moving and support a healthy economy, environment, and communities.

State law directs public investments in transportation to support economic vitality, preservation, safety, mobility, and the environment and transportation system stewardship. Moving Washington reflects the state's transportation goals and objectives for planning, operating, and investing.

WSDOT is firmly committed to the long-term viability of our state's transportation infrastructure. We build to last and use the best information available to create strong, durable infrastructure.

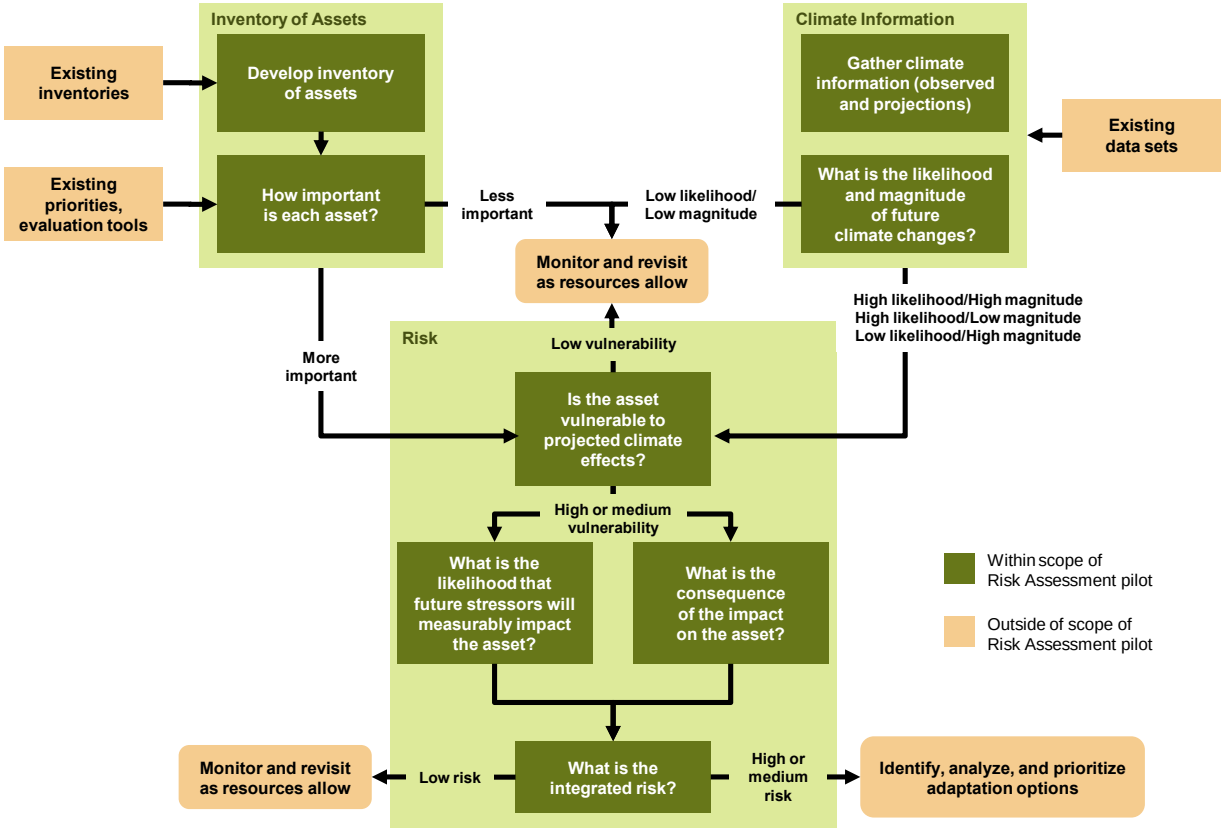
Sample efforts related to WSDOT's assets management include:

- Emergency response planning and preparedness.
- Maintenance accountability and risk management.
- Improvement programs targeting areas of concern such as unstable slopes, bridge scour, stormwater retrofit, chronic environmental deficiencies, and repeat flooding.

For WSDOT project-level planning and design that incorporates best science, including climate information, see the following website:
http://www.wsdot.wa.gov/Environment/Air/Energy.htm

1.5 Implementing the FHWA methodology

WSDOT implemented the FHWA methodology on a statewide scale for all WSDOT-owned and -managed assets. We used existing climate information, compiled an asset inventory, and then conducted a series of workshops (see Appendix B) to complete the methodology in Exhibit 1.1. The end result was a vulnerability assessment and a test of the usefulness of the FHWA methodology.



2.0 How did WSDOT implement the FHWA methodology?

WSDOT used a qualitative approach and chose workshops to conduct the vulnerability assessment. GIS analysis was an integral part of our process.

2.1 Inventory of assets

For the first few months of the pilot project timeline, we surveyed the department for asset inventory data, especially in spatial form, as an input into the FHWA methodology. WSDOT defined assets as all WSDOT-owned and -managed infrastructure. This includes:

- Airports
- Ferry terminals and operations
- 4 WSDOT-owned rail lines in eastern Washington
- State routes and Interstate roadways, including all bridges, culverts, ramps, and adjacent pedestrian and shared-use paths within the right of way
- Roadsides and mitigation sites
- WSDOT-owned buildings, such as maintenance sheds and radio towers

Evaluating the results showed that we had multiple data sources and that the information varied widely in its level of detail and the extent of descriptive information included. Additional time was needed to convert all the varied data into a format that could be used with other data in WSDOT's GIS Workbench.[1]

2.2 Gathering climate data

WSDOT's pilot project benefited from the state's investment in climate data. WSDOT used the CIG report and continued to meet and correspond with CIG staff throughout the life of this project. They also provided us with the raw data for our use in developing impact maps. While we had data for other impacts, we used the data listed below and the variable of increased high-wind events to assess the vulnerability of our assets.

2.2.1 Sea level rise

The Puget Sound Regional Council had already begun mapping potential 2- and 4-foot sea level rise impacts using CIG data. WSDOT worked with them to obtain that information and to develop the same projections for more of Washington's coastline. The mapping we used was based on the most recently available local-scale LiDAR data. Some custom work was done at WSDOT to fill gaps in sea level rise mapping to meet the project timeline. In addition to the 2- and 4-foot scenarios, the workshops included a 6-foot sea level rise scenario. All sea level rise projections were from mean higher high water. An example of our sea level rise impact mapping can be seen in Exhibit 2.7.

2.2.2 Precipitation change

Because there is no significant change in average annual precipitation amounts expected for Washington over the next century, it was important to help workshop participants understand how and when the precipitation was expected to change. CIG had data and maps on historical and projected precipitation. We used those maps as a starting point and did further work to transform the data into GIS layers we could use.

Since GIS modeling of flooding and hydrologic changes was not feasible at the statewide level, the University of Washington's climate change projections were used to create two different map layer sets for communicating those projections to workshop participants. The first was watershed-level data that showed the changes over time from snow-dominant to transitional or rain-dominant watersheds. This map is shown in Exhibit 2-1.

[1] WSDOT's GIS Workbench is an internal custom tool that supports multiple business functions throughout the agency. It is used in conjunction with ArcGIS Desktop software. The GIS Workbench presents menus of data and tools tailored for selected business functions: one GIS Workbench to meet the needs of many.

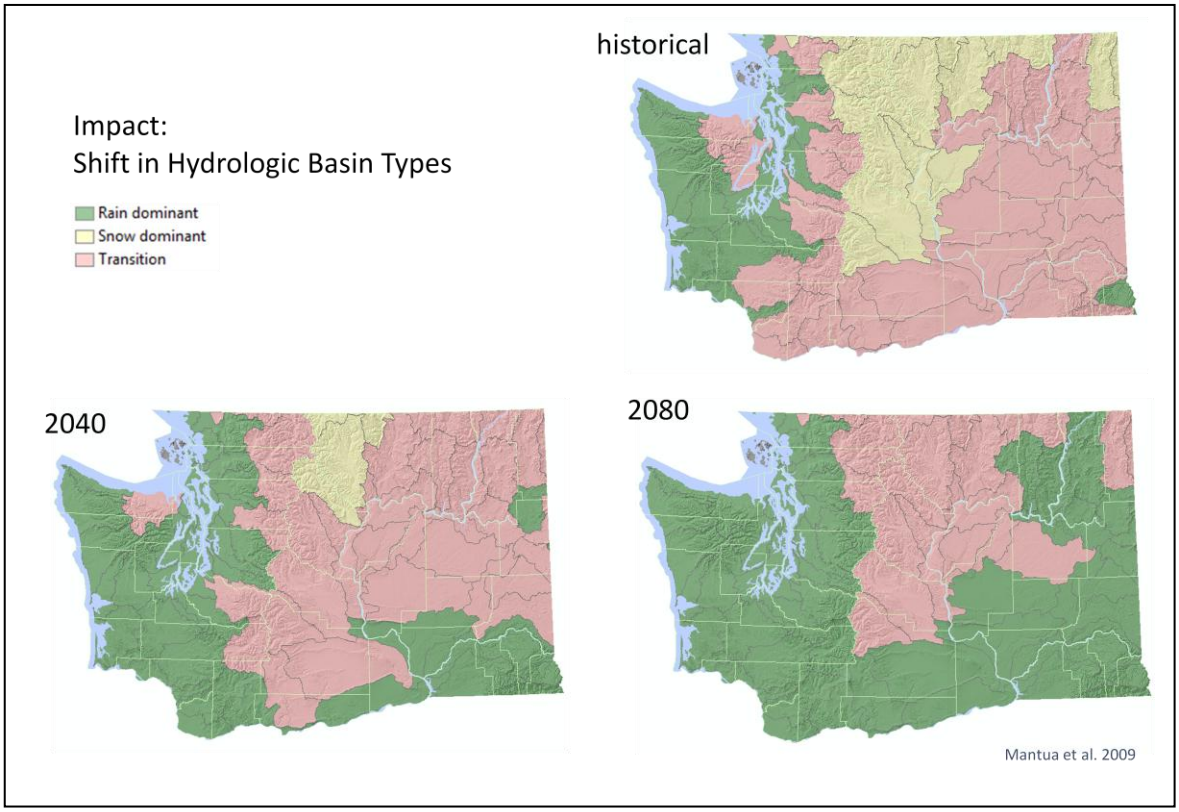


Exhibit 2-1 Change in Hydrologic Basin Types

The second map layer was a raster dataset that WSDOT created using the CIG precipitation data. Using the 2030–2059 ("2040s") projections and historical data, a map layer was created showing percent change from the present. It was used during the workshops. Percent change maps were also created using a composite of all the soil moisture layers from the same 2030–2059 dataset to show how the precipitation changes might affect unstable slopes and other climate-dependent effects. This map is shown in Exhibit 2-3.

2.2.3 Temperature change

Temperature changes were handled much the same way as precipitation changes. Using the CIG 2030–2059 raster and historical data, we generated maps with the changed values. These proved less useful than the precipitation and soil moisture percent change datasets. Instead, we chose to use the average maximum monthly temperature for June, July, and August for both current and projected datasets to show how the average maximums would change over time. This map is shown in Exhibit 2-2. We also discussed the changes in minimum temperature during the winter months and how that might affect plowing needs and the use of deicers.

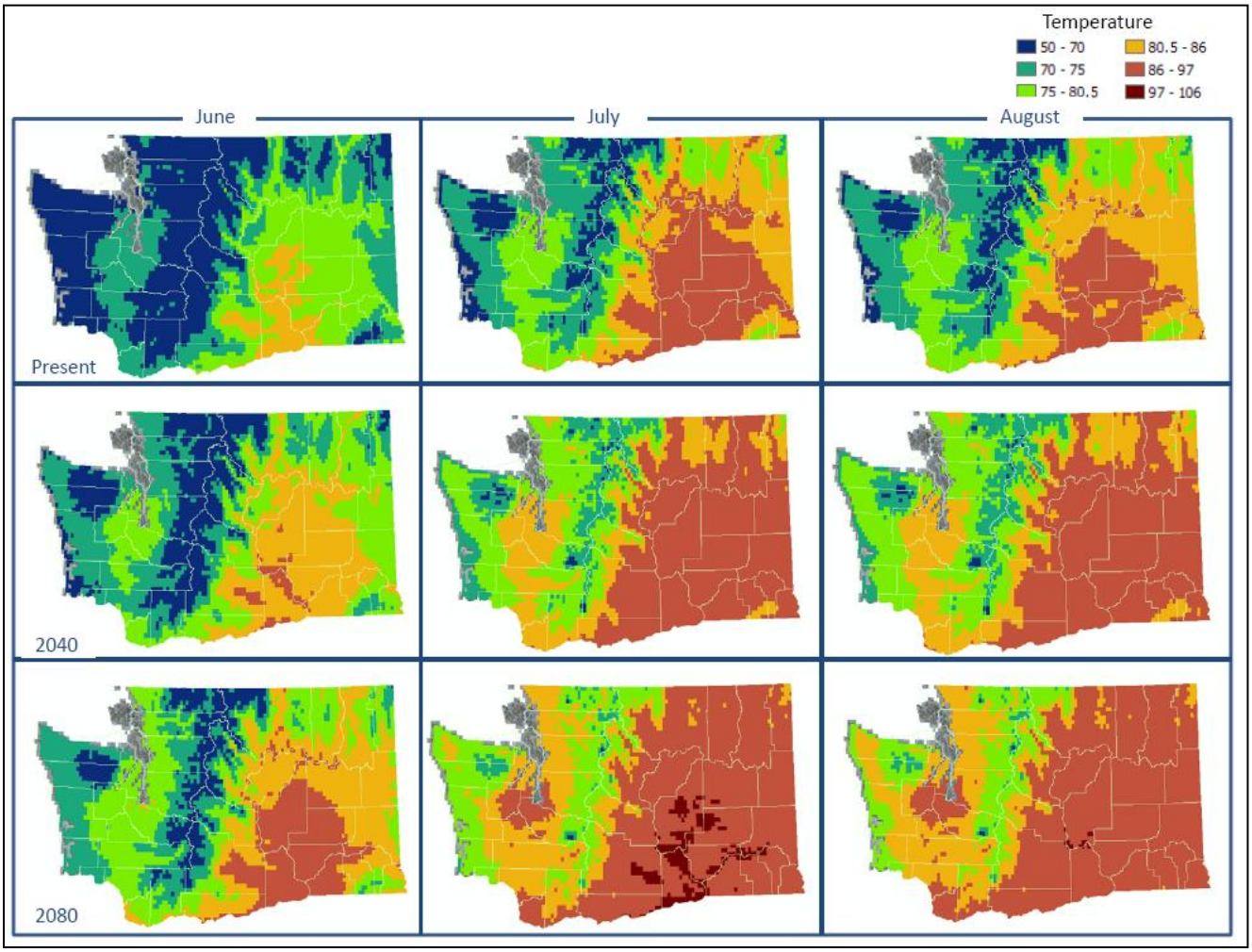


Exhibit 2-2 Change in Temperature – Present to 2080

2.2.4 Fire risk

WSDOT conducted a GIS assessment to determine whether the climate change variables of Temperature, Precipitation, and Soil Moisture could be used to evaluate the risk of fire. This analysis was limited to climate variables because future fuel load, land cover, and other variables normally used for fire risk were not available as projections. One data source was a Department of Natural Resources database of fires recorded in Washington from 1970 to 2007.

WSDOT found that there is a moderate correlation between *soil moisture* and *precipitation* at fire locations, as well as a moderate correlation between *soil moisture* and *temperature* at fire locations; however, there is no correlation between *temperature* and *precipitation* at fire locations.

The data regarding the locations of historic fires was used as a layer during the workshops. The CIG's projection of 47% probability of 2 million acres burned annually by 2080 was difficult to conceptualize because, at some point, the area may run out of fuel to burn.

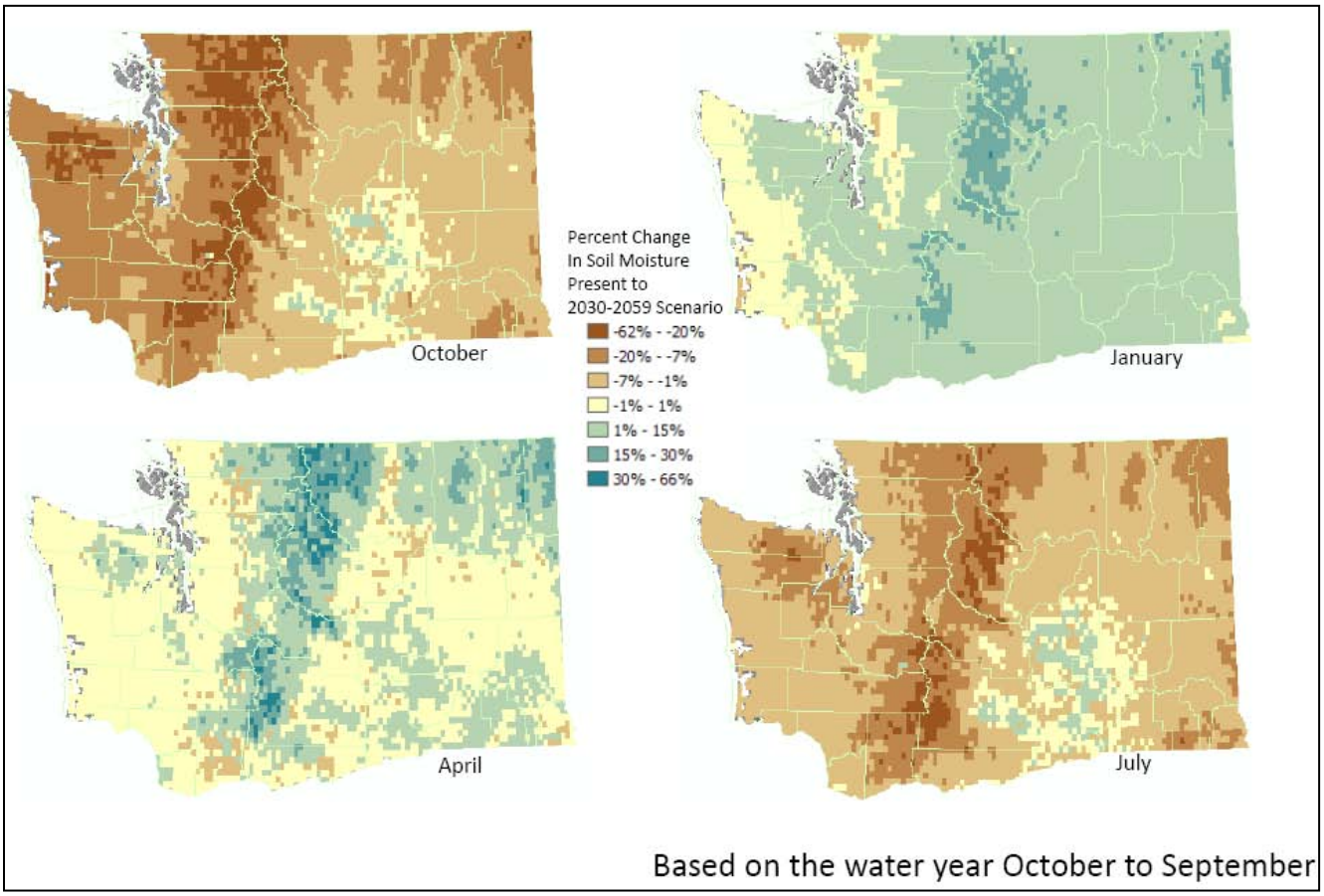


Exhibit 2-3 Change in Soil Moisture from Present to 2030–2059

2.2.5 Impact Summary

In summary, we applied the GIS analysis tools that were on hand, and secured additional information where possible, to illustrate the climate change threats of sea level rise, temperature changes, precipitation, wind, and fire risks facing WSDOT's infrastructure. We did not field-truth any of the data due to lack of resources, with the exception of using local subject matter experts in our vulnerability assessment.

2.3 How did WSDOT conduct the vulnerability assessment?

2.3.1 Asset Management Approach

WSDOT leveraged its ten years of project risk management experience through its signature Cost Estimate Validation Process (CEVP®) and Cost Risk Assessment Workshops to develop an appropriate methodology for the climate change vulnerability assessment.

We chose *qualitative analysis* because it could be used as:

- An initial screening or review of assets and vulnerability to the climate change effect(s) under consideration.
- The preferred approach when information is limited or only available in the form of intuition, personal judgment, or subjective opinions, and/or when a lengthy quantitative analysis is more than is required.
- A quick assessment.

A *qualitative assessment* relates to the character and subjective elements of an asset and climate change effect—those that cannot be or have not yet been quantified accurately. Qualitative techniques include the definition and recording of the asset and the climate change effect. For the pilot project, the asset categorization, details, and relationships were recorded in an asset spreadsheet. A qualitative scoring system was established to ensure consistent treatment when making qualitative statements about each asset.

For this assessment of transportation infrastructure, there were two variables that allowed us to make a qualitative assessment:

- Asset criticality (which was defined by the workshop participants and should not be confused with other measures, such as highway functional class, etc.).
- Potential impacts of the CIG climate change scenarios.

For the purposes of this pilot project, the rating scale shown in Exhibit 2-4 was used to guide the workshop discussion and assessment of criticality.

#4 Based on the above objective information for three key features, and augmented with subjective judgment regarding the utility of the asset, make an assessment of the criticality of the asset, an example scoring system of the criticality of the asset is provided below:

Very low to low				Moderate		Critical to Very Critical			
1	2	3	4	5	6	7	8	9	10
Criticality of asset									

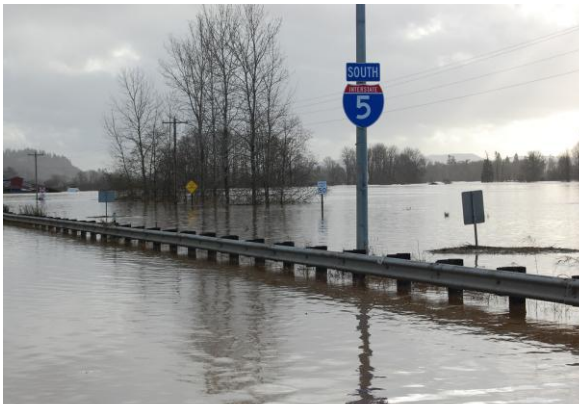
Notice that along with the qualitative terms there is an associated scale of 1 to 10, this is to serve as a facilitation tool for some people who may find it useful to think in terms of a numerical scale – although the scoring by each individual is of course subjective. The scale is a generic scale of criticality where "1" is very low (least critical) and "10" is very critical.

Typically involves: non-NHS low AADT alternate routes available	Typically involves: some NHS non-NHS low to medium AADT serves as an alternative for other state routes	Typically involves: Interstate Lifeline some NHS sole access no alternate routes

Exhibit 2-4 Rating Scale for Asset Criticality

The analogy of a pain scale was used during the workshops to describe these ratings. A doctor will often ask "What is your pain level on a scale of 1 to 10?" Climate impacts were rated in a similar way. While each person may have had a slightly different answer, the group could agree upon a number to indicate the subjective criticality of a highway segment, airport, rail line, or ferry terminal.

Impact ratings were determined using Exhibit 2-5.

10 9 8 7		**Complete Failure** Results in **total loss or ruin of asset**. Asset *may* be available for *limited* use after at least 60 days and **would require major repair or rebuild over an extended period of time**. "Complete and/or catastrophic failure" typically involves: ▪ Immediate road closure ▪ Travel disruptions ▪ Vehicles forced to reroute to other roads ▪ Reduced commerce in affected areas ▪ Reduced or eliminated access to some destinations May sever some utilities. May damage drainage conveyance or storage systems.
6 5 4		**Temporary Operational Failure** Results in **minor damage and/or disruption** to asset. Asset would be available with either full or limited use within 60 days. "Temporary operational failure" typically involves: ▪ Temporary road closure, hours to weeks ▪ Reduced access to destinations served by the asset ▪ Stranded vehicles Possible temporary utility failures.
3 2 1		**Reduced Capacity** Results in **little or negligible impact** to asset. Asset would be available with full use within 10 days and has **immediate limited use still available**. "Reduced capacity" typically involves: ▪ Less convenient travel ▪ Occasional/brief lane closures, but roads remain open ▪ Some vehicles may move to alternate routes.

Adapted from Oregon Transportation Research and Education Consortium – Risk Assessment Presentation

Exhibit 2-5 Workshop Impact Rating Scale

Having a qualitative measure of these two variables allowed participants to plot the asset on an impact – asset criticality matrix (see Exhibit 2-6). This provided a basic understanding of the overall rating for the assets being evaluated in the initial workshops.

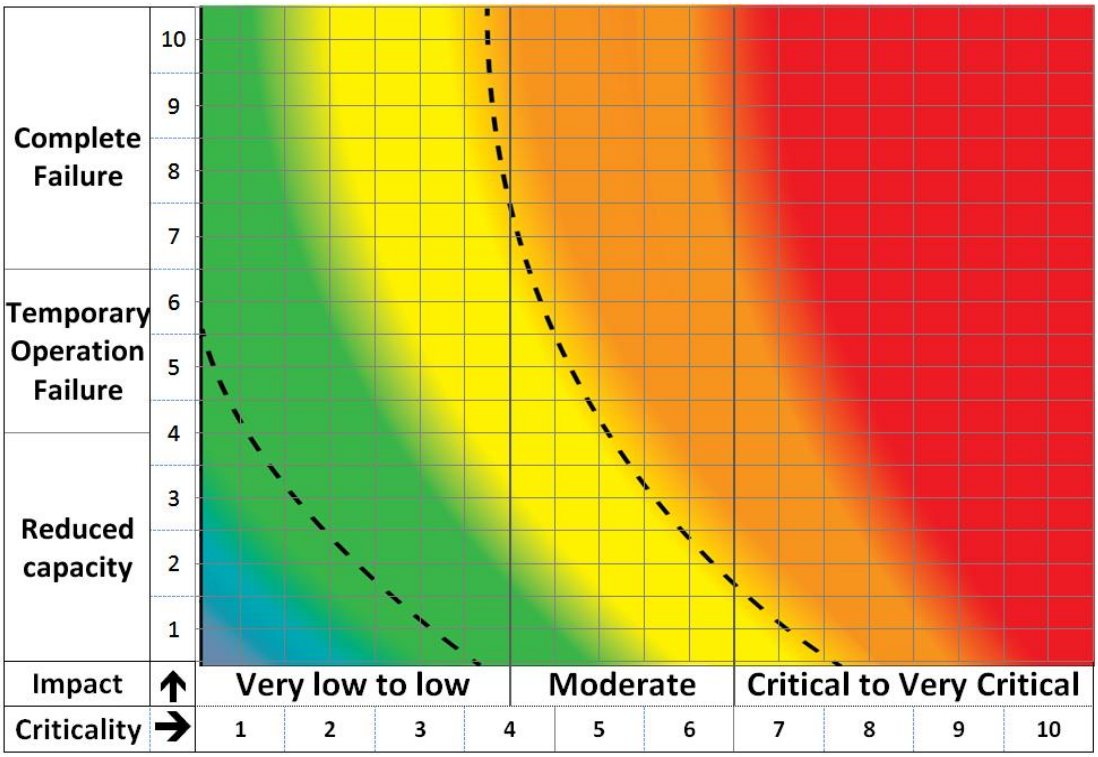


Exhibit 2-6 Impact – Asset Criticality Matrix or "Heat Sheet"

The examination and qualitative evaluation of the WSDOT transportation assets impacted by climate change followed a simple three-step approach:

STEP 1 Determine existing condition

- **Existing condition (assets and environment): Inventory transportation assets for review.** Establish base existing condition of environment, including factors to be considered in climate change.

STEP 2 Establish qualitative criteria for initial screening (for both asset criticality and climate change impact)

- **Qualitative criteria for asset criticality** may include: level of roadway classifications (interstate, NHS, lifeline, non-NHS), traffic volumes, availability of alternative routes, and other characteristics.
- **Qualitative criteria for climate change impact varies by risk** (example: for sea level rise, we might consider scour and inundation)

STEP 3 Qualitative screening

- **Review inventory by appropriate subject matter experts.** The qualitative "scale" uses words to rate the asset for screening.

2.4 Workshop Process

The workshops brought together WSDOT subject matter experts in materials, hydrology, geology, and those with local knowledge and experience, including Area Maintenance Superintendents and their staff and, in some cases, project development staff. We sought active participation, so we kept the workshops small, and we made it convenient for people to participate by conducting the workshops in the regions, by modes, and in maintenance areas.

A video was prepared as part of this pilot project to inform workshop participants about climate impacts and about how the pilot project fits into WSDOT's overall asset management.

We tested the workshop format with a two-day workshop in March 2011. Then we took a two-month break before we initiated the remaining workshops, as we incorporated the lessons learned from the initial test and prepared the GIS data we would need for subsequent workshops.

From the first workshop, it was evident that a statewide rating for each separate bridge or culvert was not feasible. Assessing roadway segments allowed us to work through the entire state highway network within a six-month time frame. Each roadway segment included elements such as culverts, bridges, or guardrail, and the adjacent slopes that could impact the roadway. We used data from WSDOT's Bridge Engineering Information System during the workshops. It provided access to bridge locations, plans, rating reports, inspection reports, and photographs for all bridges in the WSDOT system. Off-roadway facilities like maintenance sheds and ferry terminals were also included in the assessment.

WSDOT is already seeing changes in weather events, river dynamics impacted by melting glaciers, and extreme high tides. That made it relatively easy for the participants to assess worst-case scenarios and rate possible changes and the effect those changes would have on WSDOT infrastructure. We asked the participants **"What keeps you up at night?"** and used the maps to see whether climate changes might make those situations worse or better.

The workshop participants assessed roadway segments for criticality and the potential impacts of the CIG climate change scenarios. After making a determination of worse, better, or no change, the participants rated the impacts as high, moderate, or low.

In all, we conducted 14 workshops with region and division staff across the state, concluding in October 2011. (See Appendix B for a detailed description of the workshops and a summary of the results.)

2.4.1 How was GIS used during the workshops?

In the workshops, a GIS Specialist was able to show the available detailed asset inventories, basemap information, and recent aerial photography for each roadway segment or facility. Then, the climate impact data was overlaid so that the group could evaluate how those impacts might affect the roadway segment or facility.

The soil moisture maps were used to discuss both precipitation changes and fire risk potential. Temperature maps were also used in the discussion about fire risk and to ask questions about materials and their vulnerability to increased periods of high temperatures.

Sea level rise impacts were discussed for the areas along the coast and Puget Sound. Exhibit 2.7 shows an example of our GIS mapping for one ferry terminal location in Mukilteo. Red indicates the area impacted by a 4-foot sea level rise.

Exhibit 2-8 shows an example of one of the early sea level rise maps that were developed as part of this pilot project at the scale appropriate to Puget Sound.

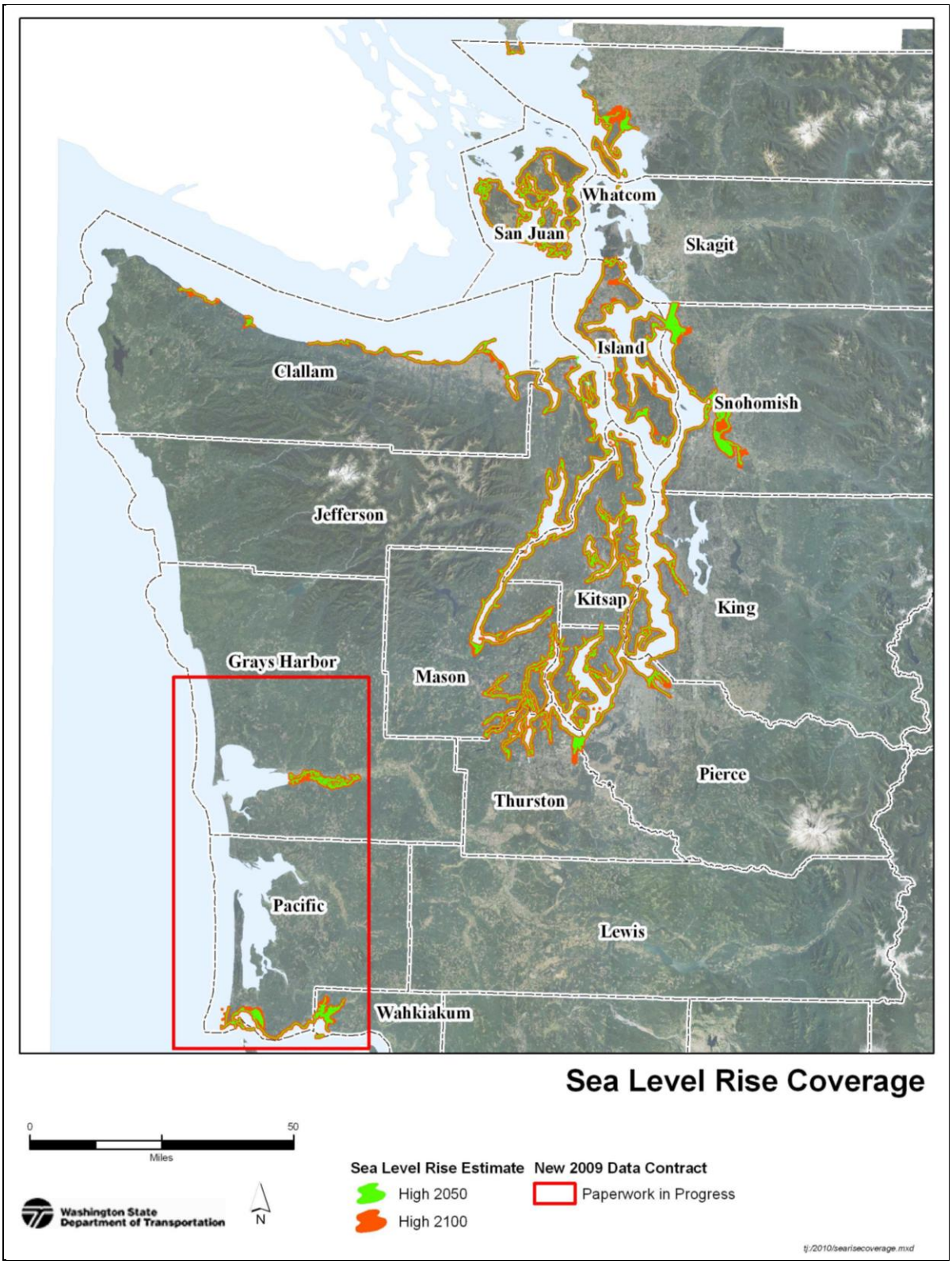


Exhibit 2-8 Example Map of Sea Level Rise Impacts in Western Washington

2.4.2 How was information from the workshops captured?

Throughout the workshops, two or three members of the Vulnerability Assessment Team would capture information from the workshop participants and enter it into an Excel spreadsheet. The notes from all the recorders were combined into one file along with the road identification, the segment length by state route milepost, and criticality and impact ratings and other information from WSDOT databases. These files were then used to create maps of the regions that show the ratings for each road segment. Maps were developed for each WSDOT region and for airports, ferries, and rail lines. More detailed descriptions of the impacts and region maps are found in Appendix B, Section B-4.

2.4.3 How did the workshop process work?

The workshop format worked very well. We captured the expertise of people who knew each area in detail, and we were also able to obtain input from people who might not have considered the effects of climate change in their daily work.

The controversy that sometimes surrounds climate change discussions was minimized or eliminated by using a scenario-planning approach that assumed a 100% probability that an impact could occur. We asked what impacts people are already seeing, which further grounded our discussions. Participants rated roadway segments based on the scenarios that varied by regions of the state.

3.0 How did the FHWA methodology work?

The FHWA conceptual methodology provided a helpful launching point for assessing the impacts of extreme weather events and climate impacts on WSDOT's system. WSDOT made adjustments as we worked the model and prepared the workshops. The vulnerability team, using climate impact information from CIG, had some general sense of potential impacts on a facility. But it was the local experts who had the best knowledge about how the asset is used and what problems currently exist.

WSDOT altered the order of work for determining the asset's importance and its vulnerability by determining climate changes that could impact asset vulnerability before each workshop. This graphic depicts our work through the original model during the workshops. Red arrows and boxes in Exhibit 3-1 point to segments of the model we worked on.

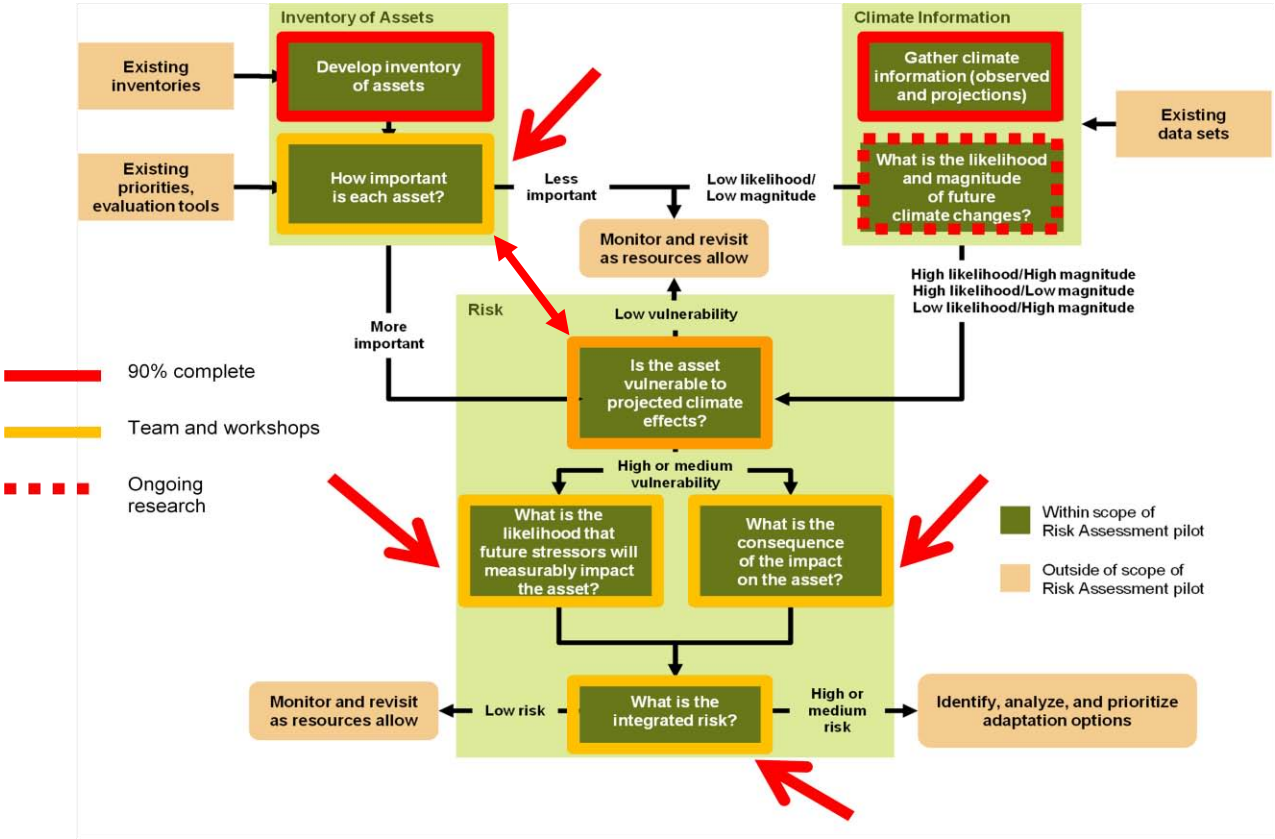


Exhibit 3-1 WSDOT's Approach to the Methodology

Likelihood and probability were only addressed in a very general way for the types of impacts that could be felt in the different regions of Washington State. The consequences of the impacts were captured by the impact ratings and descriptions entered into spreadsheets. Because we used scenarios and did not assign probabilities to an impact, WSDOT views this as a vulnerability assessment rather than a risk assessment in the traditional sense.

3.1 Recommendations for methodology improvement

The FHWA model provided an excellent starting point. WSDOT and the four other pilot groups each approached the project differently. WSDOT's goal was to create a statewide assessment in less than a year's time. That necessitated a broad interpretation of the model, and an equally broad-brush approach to data collection. WSDOT relied on existing data to the maximum extent possible.

We modified the model, as received from FHWA, to fit the process we developed. We found that developing an inventory of assets was much more difficult and time consuming than we thought it would be because, even though we had the data, it was not in a form we could use to query. In other cases, we had to gather the data (in the case of some LiDAR data) or transform it before it could be used in GIS.

Because we decided to do the analysis in the workshops using a qualitative method rather than a quantitative method, we found that it was better for the participants to set the importance, or criticality, of each asset rather than using other rating methods. Using the workshop format allowed us to gain local knowledge and highlighted issues that might not be apparent through other metrics such as average annual daily traffic or emergency response route designations.

We offer the following recommendations to improve the FHWA conceptual model:

- Provide a more general flow diagram for initial qualitative assessments (see our revised methodology in Exhibit 3-2).
- Include a feedback loop to incorporate adaptation actions.
- Define terms and clarify "risk assessment" vs. "vulnerability assessment."
- Prompt the use of the model with key questions that the DOT or MPO will be able to answer by applying the model.

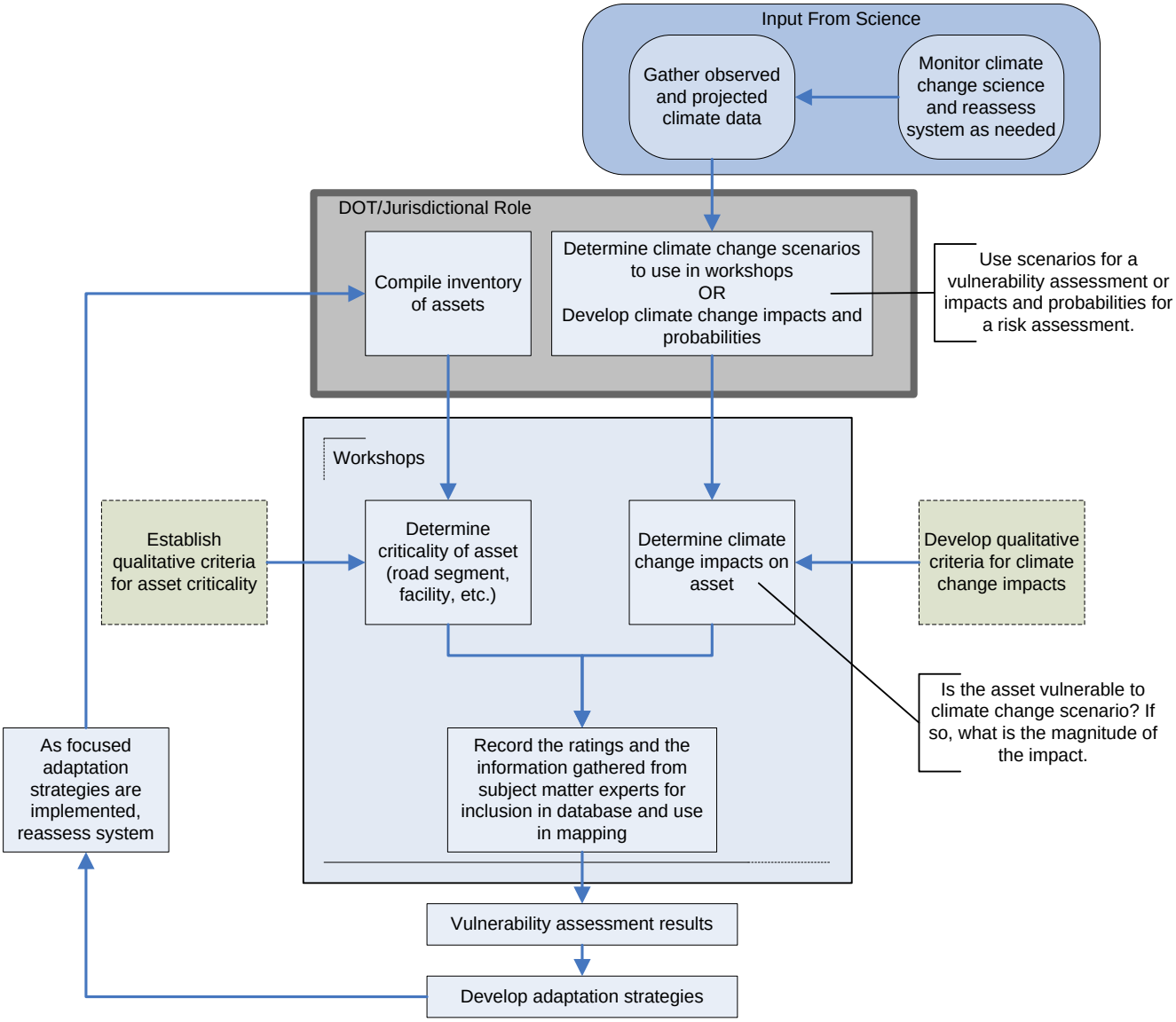


Exhibit 3-2 WSDOT Recommended Vulnerability Assessment Methodology

4.0 Conclusions

4.1 Findings

The information gathered in the workshops is a "treasure trove" of current observations and real-world perspectives on what is likely to happen in the future. This statewide look offers WSDOT a unique, comprehensive perspective on a diverse set of climate-related risks. This information will be very useful as a starting place to help WSDOT and our partners **prepare** for changes ahead of time.

WSDOT is adapting to climate changes now. In the Seattle area, sea levels have risen by 8 inches in the past century. We are already seeing water near the roadway and in some medians during extreme high tides. Glaciers are melting, releasing large sediment loads that are moving down the river systems, raising the elevation of the river beds and causing lateral instability of the channels.

This assessment shows that the majority of our assets are resistant to climate change impacts.

- Many of the improvements we have made for other reasons, such as seismic retrofits, fish passage improvements, culvert replacement, and drilled shaft bridges, have made our system more resistant to extreme weather events. These "no-regrets" strategies are examples of what can be done in the future to increase the resiliency of our infrastructure so we can keep people and goods moving.
- In general, we found that climate change will exacerbate existing conditions such as unstable slopes, flooding, and coastal erosion.
- We learned through the pilot project that most of our newer bridges are resistant to climate change impacts, some up to 4 feet of sea level rise.
- Road approaches to bridges are often more vulnerable than the bridges.
- The areas where impacts are anticipated are already experiencing problems or are on "watch lists," such as scour critical bridges or chronic environmental deficiency sites.
- Many of the high-impact ratings are in the mountains, along rivers, and in low-lying areas subject to flooding or inundation due to sea level rise.

4.2 Next Steps

Next steps and recommendations for future work based on this project will be presented to WSDOT executive management for their consideration, and a summary will be published at a later date.

Some of the recommendations being considered internally are:

- Analyze the results and conduct queries in GIS to show % of highways at risk. Communicate these to WSDOT programs and executive management.
- Incorporate the climate change vulnerability assessment into investment decisions.
- Develop a focused strategic plan to address long-term needs of key routes.
- Integrate climate change projections as another input into planning, design, and operational programming.

Appendix A Summary of Projected Pacific Northwest Climate Change Impacts

Climate information used in the WSDOT pilot project was prepared by the University of Washington Climate Impacts Group.

December 16, 2010

The following information is largely assembled from work completed for the 2009 Washington Climate Change Impacts Assessment. Other sources have been used where relevant, but this summary should not be viewed as a comprehensive literature review of Pacific Northwest climate change impacts. Confidence statements are strictly qualitative, with the exception of IPCC text regarding rates of 20th century global sea level rise. Note that periods of months are abbreviated by each month's first letter (DJF = Dec, Jan, Feb).

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
TEMPERATURE	Increasing temperatures expected through 21st century.	Projected multi-model change in average annual temperature (with range) for specific benchmark periods: • 2020s: +2°F (1.1 to 3.4°F)** • 2040s: +3.2°F (1.6 to 5.2°F) • 2080s: +5.3°F (2.8 to 9.7°F) These changes are relative to the average annual temperature for 1970-1999. The projected *rate* of warming is an average of 0.5°F per decade (range: 0.2-1.0°F). ---------- *** Mean values are the weighted (REA) average of all 39 scenarios. All range values are the lowest and highest of any individual global climate model and greenhouse gas emissions scenario coupling (e.g., the PCM1 model run with the B1 emissions scenario).*	Projected warming by the end of this century is much larger than the regional warming observed during the 20th century (+1.5°F), even for the lowest scenarios.	Warming expected across all seasons with the largest warming in the summer months (JJA) Mean change (with range) in winter (DJF) temperature for specific benchmark periods, relative to 1970-1999: • 2020s: +2.1°F (0.7 to 3.6°F)** • 2040s: +3.2°F (1.0 to 5.1°F) • 2080s: +5.4°F (1.3 to 9.1°F) Mean change (with range) in summer (JJA) temperature for specific benchmark periods, relative to 1970-1999: • 2020s: +2.7°F (1.0 to 5.3°F)** • 2040s: +4.1°F (1.5 to 7.9°F) • 2080s: +6.8°F (2.6 to 12.5°F)	High confidence that the PNW will warm as a result of increasing greenhouse gas emissions. All models project warming in all scenarios (39 scenarios total) and the projected change in temperature is statistically significant.	Mote and Salathé 2010

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
PRECIPITATION *(extreme precipitation addressed in separate field)*	A small increase in average annual precipitation is projected (based on the multimodel average, Mote and Salathé 2010), although model-to-model differences in projected precipitation are large (see "Confidence"). Potentially large seasonal changes are expected.	Projected change in average annual precipitation (with range) for specific benchmark periods: • 2020s: +1% (-9 to 12%)** • 2040s: +2% (-11 to +12%) • 2080s: +4% (-10 to +20%) These changes are relative to the average annual temperature for 1970-1999. ---------- *** Mean values are the weighted (REA) average of all 39 scenarios. All range values are the lowest and highest of any individual global climate model and greenhouse gas emissions scenario coupling (e.g., the PCM1 model run with the B1 emissions scenario).*	Projected increase in average annual precipitation is small relative to the range of natural variability observed during the 20th century and the model-to-model differences in projected changes for the 21st century.	***Summer:*** Majority of global climate models (68-90% depending on the decade and emissions scenario) project decreases in summer (JJA) precipitation. Mean change (with range) in JJA precipitation for specific benchmark periods, relative to 1970-1999: • 2020s: -6% (-30% to +12%) ** • 2040s: -8% (-30% to +17%) • 2080s: -13% (-38% to +14%) ***Winter:*** Majority of global climate models (50-80% depending on the decade and emissions scenario) increases in winter (DJF) precipitation. Mean change (with range) in DJF precipitation for specific benchmark periods, relative to 1970-1999: • 2020s: +2% (-14% to	Low confidence. The uncertainty in future precipitation changes is large given the wide range of natural variability in the PNW and uncertainties regarding if and how dominant modes of natural variability may be affected by climate change. Additional uncertainties are derived from the challenges of modeling precipitation globally. Model to model differences are quite large, with some models projecting decreases in winter and annual total precipitation and others producing large increases. Expect that the region will continue to see	Mote and Salathé 2010; Salathé et al. 2010

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
				+23%)** • 2040s: +3% (-13% to +27%) • 2080s: +8% (-11% to +42%)	years that are wetter than average and drier than average even as that average changes over the long term.	
EXTREME PRECIPITATION	Precipitation intensity may increase but the spatial pattern of this change and changes in intensity is highly variable across the state.	State-wide *(Salathé et al. 2010)*: More intense precipitation projected by two regional climate model simulations but the distribution is highly variable; substantial changes (increases of 5-10% in precipitation intensity) are simulated over the North Cascades and northeastern Washington. Across most of the state, increases are not significant. For sub-regions *(Rosenberg et al. 2010)*: Projected increases in the magnitude (i.e., the amount of precipitation) of 24-hour storm events in the Seattle-Tacoma area over the next 50 years are 14.1%-28.7%, depending upon the data employed. Increases for Vancouver and Spokane are not statistically significant and therefore cannot be distinguished from natural variability.	Projected increases in the magnitude of 24-hour storm events for the period 2020-2050 for the Seattle-Tacoma area (14.1 to 28.7%) is comparable to the observed increases for 24-hour storms over the past 50 years (24.7%) *(Rosenberg et al. 2009).*	The ECHAM5 simulation produces significant increases in precipitation intensity during winter months (Dec-Feb), although with some spatial variability. The CCSM3 simulation also produces more intense precipitation during winter months despite reductions in total winter and spring precipitation. *(Salathé et al. 2010)*	Low confidence. Anthropogenic changes in extreme precipitation difficult to detect given wide range of natural precip variability in the PNW. Computational requirements limit the analysis of sub-regional impacts within WA to two scenarios, reducing the robustness of possible results. Simulated changes are statistically significant only over northern Washington.	Salathé et al. 2010 Rosenberg et al. 2009 Rosenberg et al. 2010

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
EXTREME HEAT	More extreme heat events expected	Generally projecting increases in extreme heat events for the 2040s, particularly in south central WA and the western WA lowlands *(Salathé et al. 2010).*** Changes in specific regions vary with time period (2025, 2045, and 2085), scenario (low, moderate, high), and region (Seattle, Spokane, Tri-Cities, Yakima) but all four regions and all scenarios show increases in the mean annual number of heat events, mean event duration, and maximum event duration *(Jackson et al. 2010, Table 4).* ---------- ** *Definitions of extreme heat varied between the two studies cited here. Salathé et al. 2010 defined a heat wave as an episode of three or more days where the daily heat index (humidex) value exceeds 90°F. Jackson et al. 2010 defined heat events as one or more consecutive days where the humidex was above the 99th percentile.*	Projected increases in number and duration of events is significantly larger than the number and duration of events between 1980-2006 (specific values vary with location, warming scenario, and time period). In western Washington, the frequency of exceeding the 90th percentile daytime temperature (Tmax) increases from 30 days per year in the current climate (1970-1999) to 50 days per year in the 2040s (2030-2059).	n/a (relevant to summer only)	Medium confidence. There is less confidence in sub-regional changes in extreme heat events due to the limited number of scenarios used to evaluate changes in extreme heat events in Jackson et al. 2010 (9 scenarios) and Salathé et al. 2010 (2 scenarios), although confidence in warmer summer temperatures overall is high (see previous entry for temperature).	Salathé et al. 2010 Jackson et al. 2010

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
SNOWPACK (SWE)	Decline in spring (April 1) snowpack expected.	The multi-model means for projected changes in mean April 1 SWE for the B1 and A1B greenhouse gas emissions scenarios are: • 2020s: -27% (B1), -29% (A1B) • 2040s: -37% (B1), -44% (A1B) • 2080s: -53% (B1), -65% (A1B) All changes are relative to 1916-2006. Individual model results will vary from the multi-model average.	Projected declines for the 2040s and 2080s are greater than the snowpack decline observed in the 20th century (based on a linear trend from 1916-2006).	n/a (relevant to cool season [Oct-Mar] only)	High confidence that snowpack will decline even though specific projections will change over time. Projected changes in temperature, for which there is high confidence, have the most significant influence on SWE (relative to precipitation).	Elsner et al. 2010
STREAMFLOW	Expected seasonal changes include increases in winter streamflow, earlier shifts in the timing of peak streamflow in snow-dominant and rain/snow mix (transient) basins, and decreases in summer streamflow. Increasing risk of extreme high and low flows also expected.	The multi-model averages for projected changes in mean annual runoff for Washington state for the B1 and A1B greenhouse gas emissions scenarios are: • 2020s: +2% (B1), 0% (A1B) • 2040s: +2% (B1), +3% (A1B) • 2080s: +4% (B1), +6% (A1B) All changes relative to 1916-2006; numbers rounded to nearest whole value *(Elsner et al. 2010)* The risk of lower low flows (e.g., lower 7Q10** flows) increases in all	During the period from 1947-2003 runoff occurred earlier in spring throughout snowmelt influenced watersheds in the western U.S. *(Hamlet et al. 2007)*.	Projected changes in mean cool season (Oct-Mar) runoff for WA state: • 2020s: +13% (B1), +11% (A1B) • 2040s: +16% (B1), +21% (A1B) • 2080s: +26%(B1), +35% (A1B) Projected changes in mean warm season (Apr-Sept) runoff for WA state:	*Regarding changes in total annual runoff:* There is high confidence in the direction of projected change in total annual runoff but low confidence in the specific amount of projected change due to the large uncertainties that exist for changes in winter (Oct-Mar) precipitation. The large uncertainties in winter precipitation	Elsner et al. 2010 Hamlet et al. 2007 Mantua et al. 2010 Tohver and Hamlet 2010

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
	In all cases, results will vary by location and basin type.	basin types to varying degrees. The decrease in 7Q10 flows is greater in rain dominant and transient basins relative to snow-dominant basins, which generally see less snowpack decline and (as a result) less of a decline in summer streamflow than transient basins. *(Mantua et al. 2010; Tohver and Hamlet 2010)* Changes in flood risk vary by basin type. Spatial patterns for the 20-year and 100-year flood ratio (future/historical) indicate slight or no increases in flood risk for snowmelt dominant basins due to declining spring snowpack. There is a progressively higher flood risk through the 21st century for transient basins, although changes in risk in individual transient basins will vary. Projections of flood risk for rain-dominant basins do not indicate any significant change under future conditions, although increases in winter precipitation in some scenarios nominally increase the risk of flooding in winter. *(Tohver and Hamlet 2010, in draft)*		• 2020s: -16% (B1), -19% (A1B) • 2040s: -22% (B1), -29% (A1B) • 2080s: -33%(B1), -43% (A1B) All changes relative to 1916-2006; numbers rounded to nearest whole value. *(Elsner et al. 2010)*	are due primarily to uncertainty about the timing of, and any changes in, dominant models of natural decadal variability that influence precipitation patterns in the PNW (e.g. the Pacific Decadal Oscillation) as well as changes in precipitation caused by climate change. *Regarding streamflow timing shifts:* There is high confidence that peak streamflow will shift earlier in the season in transient and snow-dominant systems due to projected warming and loss of April 1 SWE. There is less confidence in the specific size of the shift in any specific basin given	

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
		---------- *** 7Q10 flows are the lowest stream flow for seven consecutive days that would be expected to occur once in ten years.*			uncertainties about changes in winter precipitation *(see previous comment)*. *Regarding summer streamflows:* Overall, there is high confidence that summer streamflow will decline due to projected decreases in snowpack (relevant to snow dominant and transient basins) and increasing summer temperatures (relevant to all basin types). There is medium confidence that late summer streamflow will decline given (1) the sensitivity of late summer streamflow to uncertain precipitation changes, and (2) uncertainties about if and how groundwater	

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
					contributions in any given basin may affect late summer flows. For all changes in streamflow, confidence in *specific* projected values is low due to high uncertainty about changes in precipitation and decadal variability.	
SEA LEVEL	Varying amounts of sea level rise (or decline) projected in Washington due to regional variations in land movement and coastal winds.	Projected global change (2090-2099) according to the IPCC: 7-23", relative to 1980-99 average *(Solomon et al. 2007)*** 2050: Projected medium change in Washington sea level (with range) *(Mote et al. 2008)*: • NW Olympic Pen: 0" (-5-14") • Central & So. Coast: 5" (1-18") • Puget Sound: 6" (3-22") 2100: Projected medium change in WA sea level (with range) *(Mote et al. 2008)*: • NW Olympic Peninsula: 2" (-9-35")	Relative change in Washington varies by location. Globally, the average rate of sea level rise during the 21st century very likely[‡] (>90%) exceeds the 1961-2003 average rate (0.07 ± 0.02 in/year) *(Solomon et al. 2007)* ---------- [‡] *= as defined by the IPCC's treatment of uncertainties. (Solomon et al. 2007, Box TS1)*	Wind-driven enhancement of PNW sea level is common during winter months (even more so during El Niño events). On the whole, analysis of more than 30 scenarios found minimal changes in average wintertime northward winds in the PNW. However, several models produced strong increases. These potential increases contribute to the upper estimates for WA sea level rise. *(Mote et al. 2008)*	High confidence that sea level will rise globally. Confidence in the amount of change at any specific location in Washington varies depending on the amount of uncertainty associated with the global and local/regional factors affecting rates of sea level rise. Regionally, there is high confidence that	Mote et al. 2008 Solomon et al. 2007

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
		• Central & So. Coast: 11" (2-43") • Puget Sound: 13" (6-50") ---------- *** Since 2008, numerous peer-reviewed studies have offered alternate estimates of global sea level rise. The basis for these updates are known deficiencies in the IPCC's 2007 approach to calculating of global sea level rise, including assumptions of a near-zero net contribution from the Greenland and Antarctic ice sheets to 21st century sea level rise. A comparison of several studies in Rahmstorf 2010 (Figure 1) shows projections in the range of 1.5ft to over 6ft. Overall, recent studies appear to be converging on projected increases in the range of 2-4ft (e.g., Vermeer and Rahmstorf (2009), Pfeffer et al. 2008, Grinsted et al. 2009, Jevrejeva et al. 2010).*			the NW Olympic Peninsula is experiencing uplift at >2 mm/yr. There is less confidence about rates of uplift along the central and southern WA coast due to sparse data, but available data generally indicate uplift in range of 0-2mm/yr. There is high uncertainty about subsidence, and rates of subsidence where it exists, in the Puget Sound region. Although annual rates of current and future uplift and subsidence (a.k.a. "VLM") are well established at large geographic scales, determining rates at specific locations requires additional analysis and/or monitoring.	

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
					Uncertainties around future rates are unknown and would be affected by the occurrence of a subduction zone earthquake.	
WAVE HEIGHTS	Increase in "significant wave height" ** expected in the near term (through 2020s) based on research showing that a future warmer climate may contain fewer overall extra-tropical cyclones but an increased frequency of very intense extra-tropical cyclones (which may affect the extreme wave climate). ----------	Based on extrapolation of historical data[‡] and assumptions that the historical trends continue into the future, the 25-, 50-, and 100-year significant wave height events are projected to increase approximately 0.07m/yr (2.8 in/yr) through 2020s. ---------- [‡] *The five highest significant wave heights measured at Washington NDBC Buoy #46005 (at the WA/OR border)*	Projected changes through 2020 are comparable to the observed increase in the average of the five highest significant wave heights for the mid 1970s-2007 (0.07m/yr, or 2.6 in/yr). *More on past changes:* Over the last 30 years, the rate of increase for more extreme wave heights has been greater than the rate of increase in average winter wave height. For the WA/OR outer coast	These findings relate to the winter season (Oct-March), which is the dominant season of strong storms	*Regarding general trend:* There is low confidence that significant wave height will increase given the dependence of this increase on a limited number of studies showing potential increases in the intensity of the extra-tropical cyclones that can affect the extreme wave climate. *Regarding specific projected increases in wave height:* There is low confidence in the calculated trend for 25-, 50-, and 100-year significant wave	Ruggiero et al. 2010

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
	*** "Significant wave height" is defined as the average of the highest 1/3 of the measured wave heights within a (typically) 20 minute period.*		(mid 1970s-2007): • The average of all winter significant wave heights increased at a rate of 0.023m/yr (0.9 in/yr) • Annual maximum significant wave height increased 0.095m/yr (3.7 in/yr).		height events given that this calculation is based on extrapolation of historical data and assumptions of continued historical trends rather than physical modeling.	
SEA SURFACE TEMPERATURE (SST)	Warmer SST expected	Increase of +2.2°F projected for the 2040s (2030-59) for coastal ocean between 46°N and 49°N. Changes are relative to 1970-99 average.	Projected change is substantially outside the range of 20th century variability.	*No information currently available*	Medium to low confidence in the degree of warming expected for the summertime upwelling season. Global climate models do not resolve the coastal zone and coastal upwelling process very well, and uncertainty associated with summertime upwelling winds also brings uncertainty to coastal SSTs in summer.	Mote and Salathé 2010

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
COASTAL UPWELLING	Little change in coastal upwelling expected.	The multimodel average mean change in winds that drive coastal upwelling is minimal.	Comparable to what has been observed in the 20th century.	Little change in seasonal patterns.	Low confidence given the fact that this hasn't been evaluated with dynamical downscaling of many climate model scenarios at this point.	Mote and Salathé 2010
OCEAN ACIDIFICATION	Continuing acidification expected in coastal Washington and Puget Sound waters.	The global surface ocean is projected to see a 0.2 - 0.3 drop in pH by the end of the 21st century (in addition to observed decline of 0.1 units since 1750) (Feely et al. 2010). pH in the North Pacific, which includes the coastal waters of Washington State, is projected to decrease 0.2 and 0.3 units with increases in the atmospheric concentration of CO_2 to 560 and 840 ppm, respectively (Feely et al. 2009). pH in Puget Sound is projected to decrease, with ocean acidification accounting for an increasingly large part of that decline. Feely et al. 2010 estimated that ocean acidification accounts for 24-49% of the pH decrease in the deep waters	Projected global changes are larger than the decrease of 0.1 units since 1750, and greater than the trend in last 20 years (0.02 units/decade). The observed decrease of 0.1 units since 1750 is equivalent to an overall increase in the hydrogen ion concentration or "acidity" of about 26%.	The contribution of ocean acidification to Dissolved Inorganic Carbon (DIC) concentrations within the Puget Sound basin can vary seasonally. Ocean acidification has a smaller contribution to the subsurface increase in DIC concentrations in the summer (e.g., 24%) compared to winter (e.g., 49%) relative to other processes (Feely et al. 2010).	For global changes, confidence that oceans will become more acidic is high. Results from large-scale ocean CO_2 surveys and time-series studies over the past two decades show that ocean acidification is a predictable consequence of rising atmospheric CO_2 that is independent of the uncertainties and outcomes of climate change (Feely et al. 2009).	Feely et al. 2009 Feely et al. 2010

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources
		of the Hood Canal sub-basin of Puget Sound relative to estimated pre-industrial values. Over time, ocean acidification from a doubling of atmospheric CO_2 could account for 49-82% of the pH decrease in Puget Sound subsurface waters.			For Puget Sound, estimates of the contribution of ocean acidification to future pH decreases in Puget Sound have very high uncertainty since other changes that may occur over the intervening time were not taken into account when calculating that estimate (a percentage) (Feely et al. 2010).	

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Appendix B Assessing Infrastructure, Impacts, and Criticality

B-1 PILOT PROJECT WORKSHOP DETAILS

Workshop Structure

The workshops consisted of three main phases:

- Introduction to climate change science and the workshop process
- Determining the road segments and rating them for criticality and impacts
- Wrap-up and lessons learned

The workshop began by introducing the project team and followed with introductions from all the participants so we would know who was in the room and what area they represented, either geographically or by experience (see Exhibit B-1.1 for a sample agenda). Some of the Headquarters staff were not able to travel to all the workshops because of time constraints or other commitments. In those cases, we used Go-To-Meeting and a phone bridge to allow them to participate remotely. For several of the workshops, our GIS analyst attended the workshops using this method and controlled the maps from a remote location. For the most part, this worked well; however, there was a slight delay in some cases due to the internet connection or failure to communicate correctly what we wanted to see.

Following the introductions, we provided a brief overview of the project, including:

- Testing the FHWA model
- The role WSDOT is taking in statewide climate change adaptation
- The expectations placed on WSDOT by the Governor and the Legislature

Next was an overview of the climate change science. During this segment, we presented information more specific to the area of the state where we held the workshop. We reviewed anticipated changes and the scenarios we would be exploring during the workshop. We also looked at the maps to show the differences between the historical climate data and the projected changes. This gave the participants some potential issues to keep in mind as we worked through the road segments.

Our cost risk specialist then gave an overview of the workshop process, including the definitions of "criticality" and "impact" that would be so important in successfully completing the workshop. We provided handouts of the descriptions, which helped as we rated the roadways. He also emphasized that this was in reality scenario planning rather than a true risk assessment because we were not taking probability into account. For this exercise, we presented scenarios and asked, "If "X" happens, what does it mean for our infrastructure?" After that, we started the actual segment definitions and the assessment.

Time	Agenda Item
9:00	Welcome and Introductions *Introduce the team and explain why we are here. We are looking for a good assessment from field staff who know the roads well, to tell us what is going on now and what it would mean under different climate scenarios. This will inform the policy, planning, and project-level decisions.*
9:10	Vulnerability assessment project and context
9:20	Climate changes presentation
9:40	Vulnerability assessment process
9:50	Begin vulnerability assessment
12:00	Lunch
1:00	Resume assessment
3:40	Wrap up and critique workshop ~ What worked, what didn't, what could we improve? Next steps.
4:00	Adjourn

Exhibit B-1.1 Sample Agenda

Assessments

For the first workshop, we prepared forms for each asset, which we filled out during the workshop. This was based on the risk assessment model that evaluated specific issues related to a project. We found that this process was cumbersome because we had to find the proper form for a particular asset. It also proved very time consuming to analyze each asset, so we switched to analyzing roadway segments instead. For the subsequent workshops, we prepared an Excel spreadsheet with a list of all the roads and facilities in a workshop focus area. Generally, we worked down the list in numerical order; however, we also moved around to rate roads in the same geographical area that may face the same issues. This allowed us to maintain the flow of information and to work smaller geographic areas that had the same issues within the larger area that may have different issues.

We normally started with the busiest, and presumably most critical, road within the study area. The workshop participants determined the segment lengths by considering factors that included:

- Geology
- Hydrology
- River systems
- Elevation
- Grade
- Land use
- Common maintenance issues

We recorded the segment length by state route milepost and asked for specific information about that section, such as available detours, detour length, whether the detour could handle the traffic, what problems were currently being experienced in the segment (What keeps you up at night?), and what happens during certain events like extreme high tides or extreme rain events. Then we asked the participants to determine the criticality of the section based on the criteria described in Section 2.3. Occasionally, we found it necessary to revisit the first couple of criticality rankings to see whether we had indeed ranked that section of roadway correctly given later rankings.

We then talked about the possible climate impacts to the section. For instance, the projected sea level rise for the Washington coast and Puget Sound ranges from 6" to 54" by 2100 depending on location. Maps were developed for coastal areas showing the flooding caused by a 2- and 4-foot sea level rise (see Exhibit 2-7). If the segment in question was in the coastal area, the participants would consult the maps and use their knowledge of existing local conditions as they examined a segment of roadway to determine whether a 2-, 4-, or 6-foot sea level rise would have any impacts.[2] Then they rated the impacts as low, moderate, or high.

For other possible climate impacts, we took into account the answers we got to the "What keeps you up at night?" question. In those cases, we either looked at the GIS differential maps to see whether there were any potential impacts or we used our knowledge of the Washington Assessment data to come up with a scenario to assess potential impacts. We also prompted participants to consider such things as increased fire risk, high winds, more extreme flooding, or changes in temperature to determine impacts. Often, there were low to moderate risks for the overall segment, but one point or small subset of the segment would have the potential for high impacts. We captured that in the notes and included it as a point with a different rating in the spreadsheet.

[2] The 2, 4, and 6 foot sea level rise increments were rated and recorded separately for each location.

We created a chart we called the "heat sheet" (see Exhibit B-1.2) and took a laminated copy to each of the earlier workshops. Once we had the criticality and impacts scores for a certain road segment, we would plot it on the chart. This chart was helpful for several reasons. At the beginning of the workshops, it allowed the participants to visualize where on the spectrum their ratings would fall. Secondly, plotting the ratings made it easier to spot which areas were important to look at in the future. It also gave us an idea of where the road segments were resistant to climate change impacts. In later workshops we moved so quickly through the road segments that we stopped using the "heat sheet."

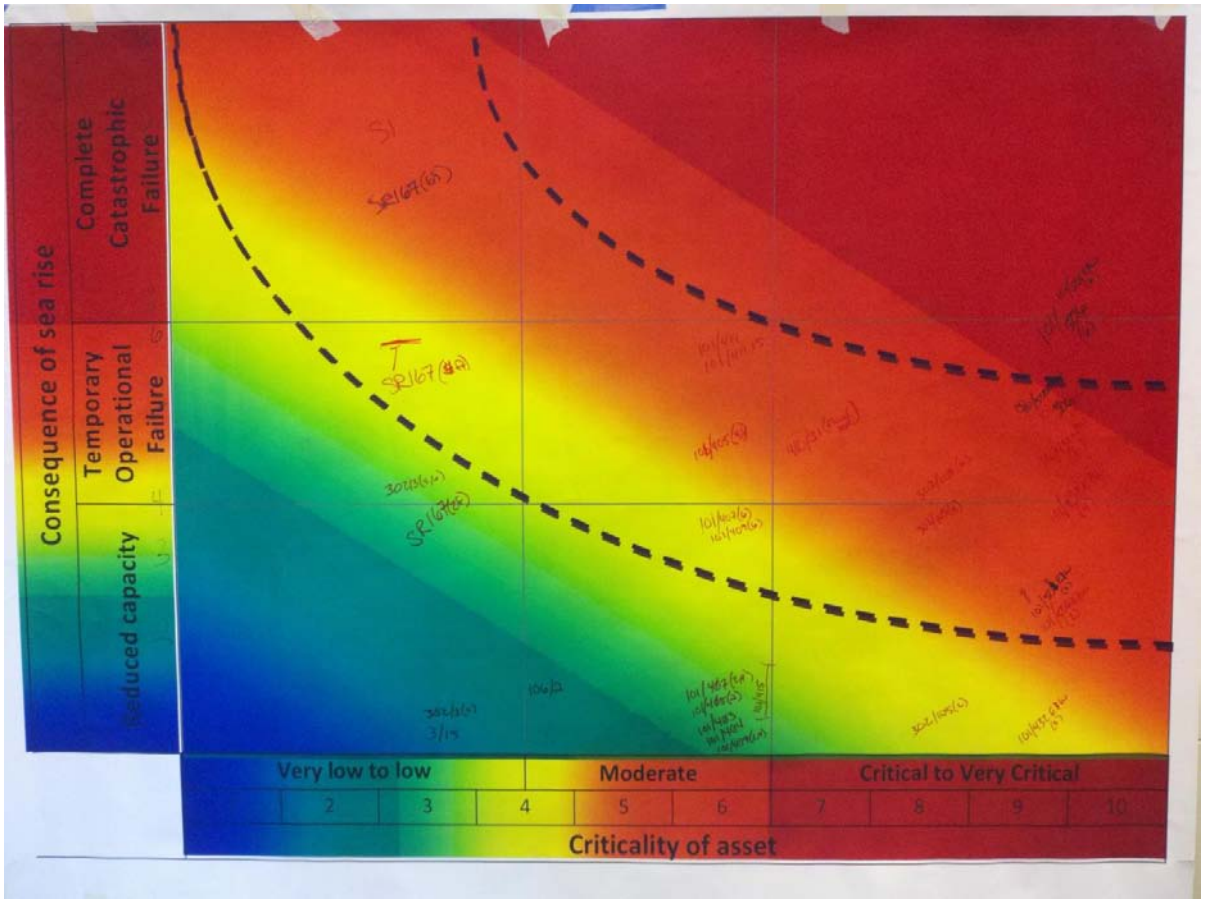


Exhibit B-1.2 Criticality – Impact Chart or "Heat Sheet"

To end the workshop, we did a debriefing and asked what worked well and what we could have done better. This was particularly important for the first couple of workshops, as we learned through doing. It took several workshops before we were able to streamline the process and make it easier and less time consuming for the participants. For instance, we streamlined the presentations at the beginning of the workshops to provide the information they needed so they could provide us with the ratings. We also made the information much more focused for the participants' needs in their areas of the state.

Other Documents and Databases Used

Several documents other than the maps became very useful during the workshops. We relied on the State Highway Log to determine the mileposts at the beginning and end of the segments. We initially started out using GIS to determine the points, but we found it was quicker and more precise if someone from the region looked up beginning and ending mileposts. This worked better because the State Highway Log is very detailed, with highway features located to the hundredth of a mile, and the region staff knew which feature to look for.

We also used the Bridge Engineering Information System (BEIST) to determine the condition of bridges and whether they would be impacted by climate change. BEIST is a WSDOT database that stores information about bridges, such as plans, inspection history, photos, and scour information (if applicable).

Conclusions

Because we chose to pursue a qualitative, scenario-based assessment, using a workshop format was an appropriate method for analyzing the vulnerability of our assets. While the analysis was subjective and based on local knowledge, we endeavored to define and explain our terms in such a way that it would lead to statewide consistency. In addition, several members from the core team were always at the workshop to guide the participants and discuss ratings and examples from other areas. This aspect also helped to promote statewide consistency. It should be noted that after every workshop, we reviewed the results. If any discrepancies were found, we went back to the regions and asked for clarification. On occasion, we found instances where roads of a similar nature were rated differently from region to region, especially in terms of criticality. In those cases, we made sure to check with the regions to confirm whether the original ranking was still valid.

Workshop Participants

All the workshop participants were WSDOT staff from Headquarters, divisions, or the regions.

Headquarters staff included:

- Landscape Architect
- Hydrologist
- Hydraulics Engineer
- Stormwater Engineer
- Environmental Policy Manager
- GIS Analyst
- Risk Cost Assessment Specialist
- Materials Engineer

- Bridge Preservation Engineer
- Utilities, Rail, and Agreements Manager
- Pavement Engineer

Division staff included:

- Rail Branch
  - Co-Director
  - Freight Systems Manager
- Aviation
  - Director's Office Representative
  - Construction Project Coordinator
  - Planning
- Ferries
  - Director of Terminal Engineering
  - Customer Service Representative
  - Director of Vessel Preservation and Management
  - Senior Port Captain
  - Project Management Engineering Manager
  - Marine Project Engineer
  - Deputy Chief of Ferries Construction
  - Safety Systems Manager

Region staff included:

- Region Administrator
- Maintenance Superintendents
- Assistant Maintenance Superintendent
- Region Materials Engineer
- Environmental Manager
- Environmental Permit Coordinator
- Region Biologist
- Region Landscape Architect
- Region Maintenance Engineer
- Region Environmental Maintenance Coordinator
- Region Hydraulics Engineer

Please note that all the subject matter experts did not attend all the workshops. Attendance was determined by region and division needs and availability. Follow-up meetings were held if a subject matter expert was not available for the workshop and their input was needed.

B-2 ASSET MANAGEMENT

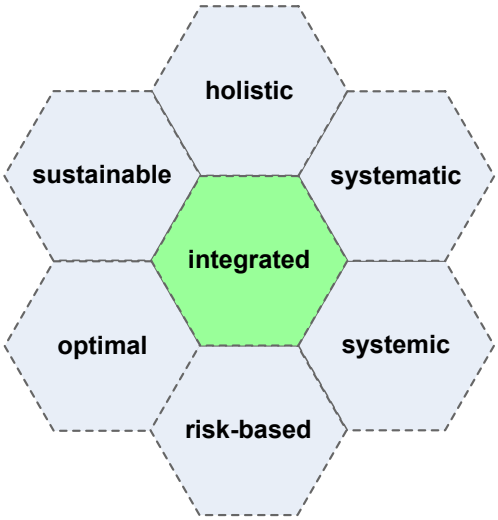
The context for WSDOT's pilot project is a blend of concerns involving economics, risk, preservation of assets and the service they provide, public safety, and decision making that affects future generations. The development of a climate change asset management program and the associated analysis must consider key principles of asset management.

Exhibit B-2.1 shows the principles of asset management commonly used in that area of study.

Key Principles: We have been managing assets for a long time. Some adjectives discern good practices and optimize asset management rather than historically merely managing the assets.

These adjectives are generic attributes:

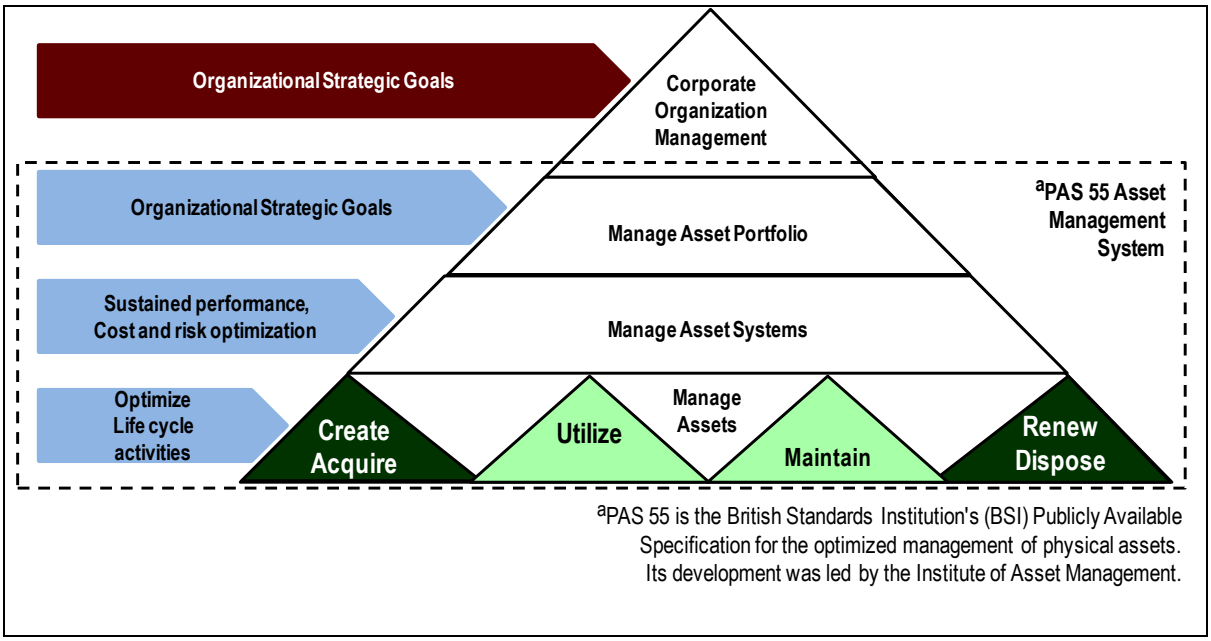
- **Holistic**: Asset management must be cross-disciplinary, total value focused.
- **Systematic**: Rigorously applied in a structured management system.
- **Systemic**: Looking at assets in their systems context, again for net, total value.
- **Risk-based**: Incorporating risk appropriately into all decision making.
- **Optimal**: Seeking the best compromise between conflicting objectives, such as costs versus performance versus risks, etc.
- **Sustainable**: Plans must deliver optimal asset life cycles, ongoing systems performance, and environmental and other long-term consequences.
- **Integrated**: The heart of good asset management relies on the need to be joined-up. The total jigsaw puzzle needs to work as a whole—and this is not just the sum of the parts.



Credit: Institute of Asset Management (IAM) www.IAM.org

Exhibit B-2.1 Key Principles of Asset Management

When managing assets, a four-tiered conceptual model is used by the asset management profession. Departments of transportation use all levels, but at the base, they acquire, use, maintain, and make decisions about renewing or disposing of assets. Exhibit B-2.2 shows this conceptual model.



Credit: Institute of Asset Management (IAM) www.IAM.org

Exhibit B-2.2 Levels of an Asset Management System

During the workshops, we simplified the discussion about the theory behind risk assessment. Most of our workshop participants had participated in one or more risk assessment workshops in the past and were familiar with the process. Since we were not considering the probability of certain things happening, we were not truly doing a risk assessment but a vulnerability assessment. Therefore, we focused the presentation on a short explanation of the workshop mechanics and how we would do the scoring. (See Section 2.4 for more information.)

B-3 GIS FOR CLIMATE IMPACTS – LESSONS LEARNED

Lessons Learned in Using Climate Data for the Pilot Project

Sea level rise (SLR) analysis proved to be very complex and difficult to determine. Without accurate elevation values for the roadway and infrastructure, it was difficult to determine whether an asset would be affected by the chosen sea level rise scenarios. Analysis was limited to proximity of an asset to the sea level rise layers created by either the internally developed or contracted version of the data, depending on location. Further, the 5-foot Digital Elevation Model[3] level data was too fine a resolution dataset for the statewide analysis. However, it worked well for the workshops because we could zoom to specific areas for a closer look.

Sea level rise estimates for the Washington coast are dependent on location due to tidal variation, especially within Puget Sound and the coastal estuaries. Where to put the boundaries and how to break up the LiDAR data required more time and resources than could be allotted during the workshops, so we made a compromise to use the 2-, 4- and 6-foot SLR layers globally as part of the scenario analysis.

The "bathtub effect"[4] also limited the local accuracy of our SLR data. Low-lying inland areas are filled, or inundated, by elevation-based modeling even when they are protected by higher coastal features. This creates disconnected areas that, while not technically inundated, show up as affected. NOAA's SLR analysts are also finding this phenomenon at the 10- and 30-meter resolutions. The problem is that removing those areas could be inaccurate because the raster elevation is a generalization of the area, and there could be small channels for water to get to the discontiguous areas. Additionally, if you are looking at a road, there could be a culvert or some other conveyance that would allow water throughput unless you know the elevation of the culvert itself. We chose to leave the discontiguous areas for this reason, knowing that at this level of analysis, it might be problematic, as it might generate an overestimation of risk. We qualified that in the workshop discussions.

We encountered challenges coordinating disciplines to produce a product useful for GIS analysis. The Photogrammetry department was unable to output polygon boundaries, which would have worked well for our intended use. Instead, the Photogrammetry department created elevation contour lines, which are widely used in Computer Aided Design work and engineering. Unfortunately, our GIS approach required elevation zone polygons for determining whether an asset intersected with an SLR scenario. We

[3] A DEM is a digital version of the terrain or land elevations for a given surface. It consists of a regularly spaced grid with elevation values for each grid. A 5-foot DEM denotes the size of the grid used for this work. Elevations are averaged within that 5-foot grid.

[4] "Bathtub effect" is a term used to describe a type of analysis that simply increases a base value by X amount. It doesn't take into account variability in terrain or connections that may or may not exist. This analysis overestimates results en masse, but depending upon the question, may be appropriate.

undertook a short-lived work process of closing the contours to create polygons, but quickly were mired in more detailed editing than we could afford.

We concluded that there was a technical solution to get the correct output, but we didn't have the internal expertise, so we couldn't solve the problem during the workshops. When WSDOT needs to do project-level analysis in the future, this problem will need resolution as well as the ability to model stream or river water exiting land into Puget Sound.

Land use practices are also problematic with sea level rise data analysis. If sea level rises, dikes may or may not be effective for several reasons; some are practical in nature, while others are more political. While local and county infrastructure would be at greater risk of damage in these areas, there is some state-owned infrastructure that is currently below the mean higher high water elevation behind dikes.

B-4 SUMMARY OF WORKSHOP RESULTS

Vulnerabilities of WSDOT-Owned Aviation, Ferries, and Rail Infrastructure

Workshops were held in all WSDOT regions and for all WSDOT modes, including airports, ferries, and rail.

Aviation

WSDOT –owned or managed airports serve search and rescue needs as well as providing locations for pilot training and recreational uses. Impacts to airports were rated as either low or moderate. In a climate impact scenario that includes both wetter winters and drier summers, there is potential for more flow in rivers during the winter and early spring months, which could lead to lateral instability in the rivers. Where airports are adjacent to rivers, they could be temporarily flooded or parts of the runways could be eroded by channel migration. The Woodland Airport (shown above right) is one airport that may be temporarily impacted by flooding.

Drier summers could lead to more wildfires. Nearby fires could impact airports by closing them temporarily. However, the airport improves fire fighting ability so closures would likely be of short duration. Wind and dust storms also close runways temporarily. If winds increase in the future, temporary closures may increase.

The Copalis Beach airport (shown at right) is located on the beach near the Copalis River. There is no paving or surfacing at this location. The river is migrating north and may affect the beach. Currently, planes cannot land there at high tide. As sea level rises, this airport will be closed more often or may be closed permanently.

Exhibit B-4.1 shows the impacts to WSDOT-owned or -managed airports.

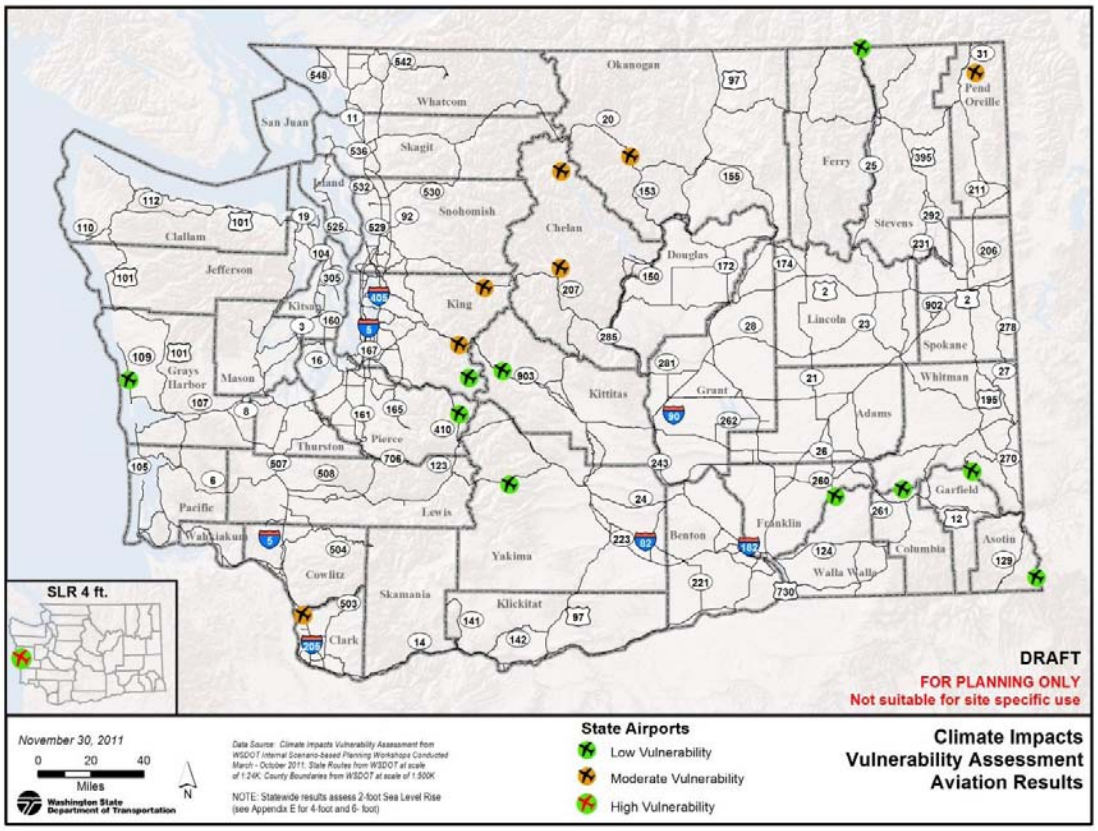


Exhibit B-4.1 Climate Impacts to State-Owned Airports

Ferries

Ferry terminals are all generally resistant to sea level rise impacts, or they can accommodate rising sea levels in future terminal or loading ramp designs. Current closures due to low tides may not occur with higher sea levels. When terminals close now due to severe weather, vessels and users are rerouted to other terminals. The Eagle Harbor ferry maintenance facility is located near sea level. If this facility is inundated permanently, other options would need to be explored.

If rivers bring more debris into Puget Sound, operational expenses would need to be increased to clean out debris that could damage ferries or docks. Large waves that come over decks can move cars, and ferry elevators do not work if the vessel is rocked by large waves. With larger waves and more extreme storms, this risk may increase. With 4-foot and 6-foot sea levels, power lines to docks may be inundated. Exhibit B-4.2 shows the impacts to WSDOT-owned ferry facilities.

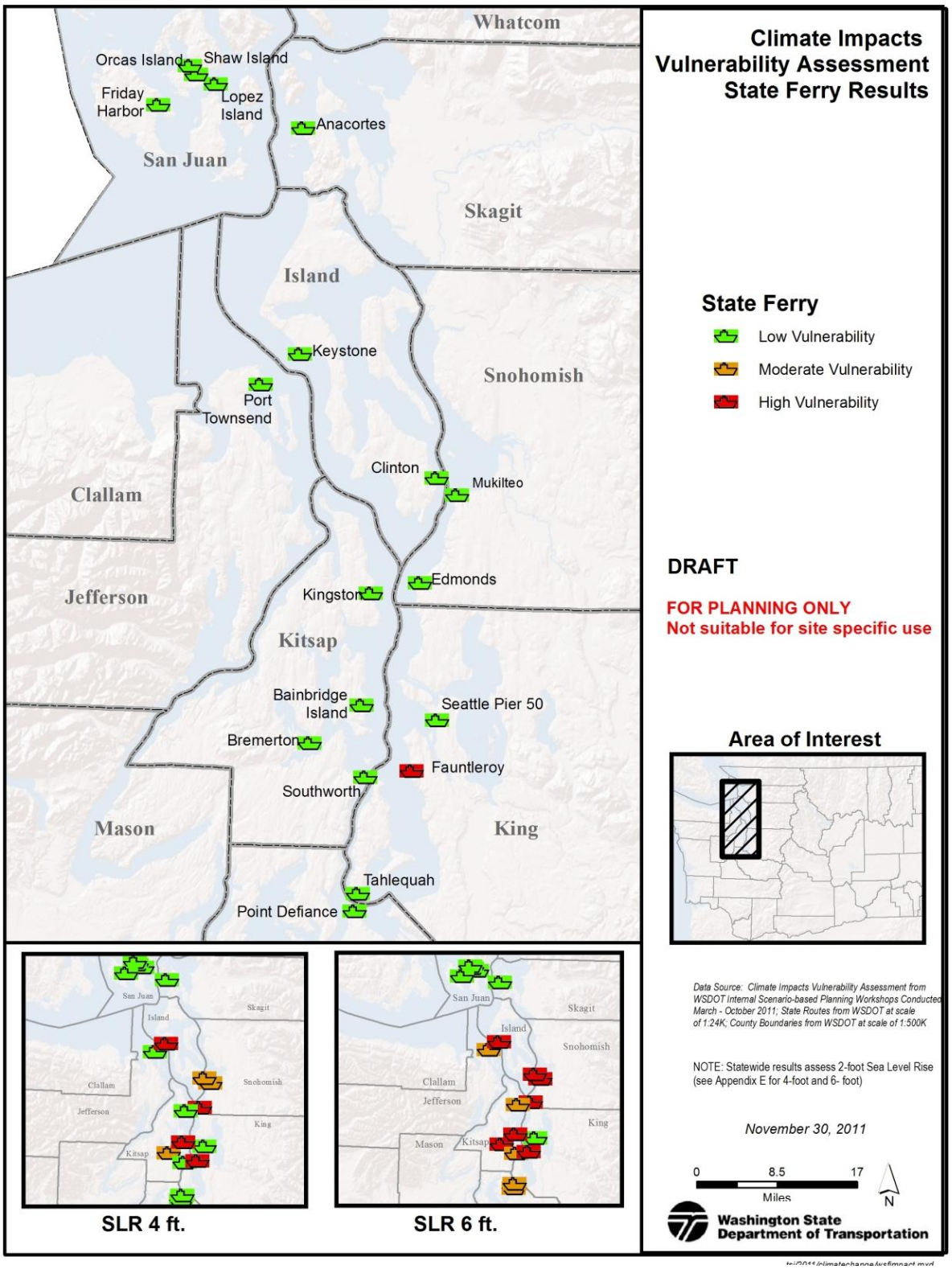


Exhibit B-4.2 Climate Impacts to Ferry Facilities

Rail Lines

All WSDOT-owned rail lines are very old and consist of jointed track, which can deform with extreme heat. As the rail cools, it will straighten; however, the ballast needs to be recompacted after this occurs. Short temporary operational closures are needed.

Over 140 wooden trestle bridges are on these lines, and some are over 100 years old. These bridges are vulnerable to fire now. This is the reason the rail lines have a high impact rating. The trestles are creosote coated and can burn for weeks. (The photo above right shows a trestle fire in eastern Washington.) This vulnerability will increase under a scenario that has more wildfires.

Exhibit B-4.3 shows the locations of WSDOT-owned rail lines with their impact categories.

There was no anticipated vulnerability to train cars.

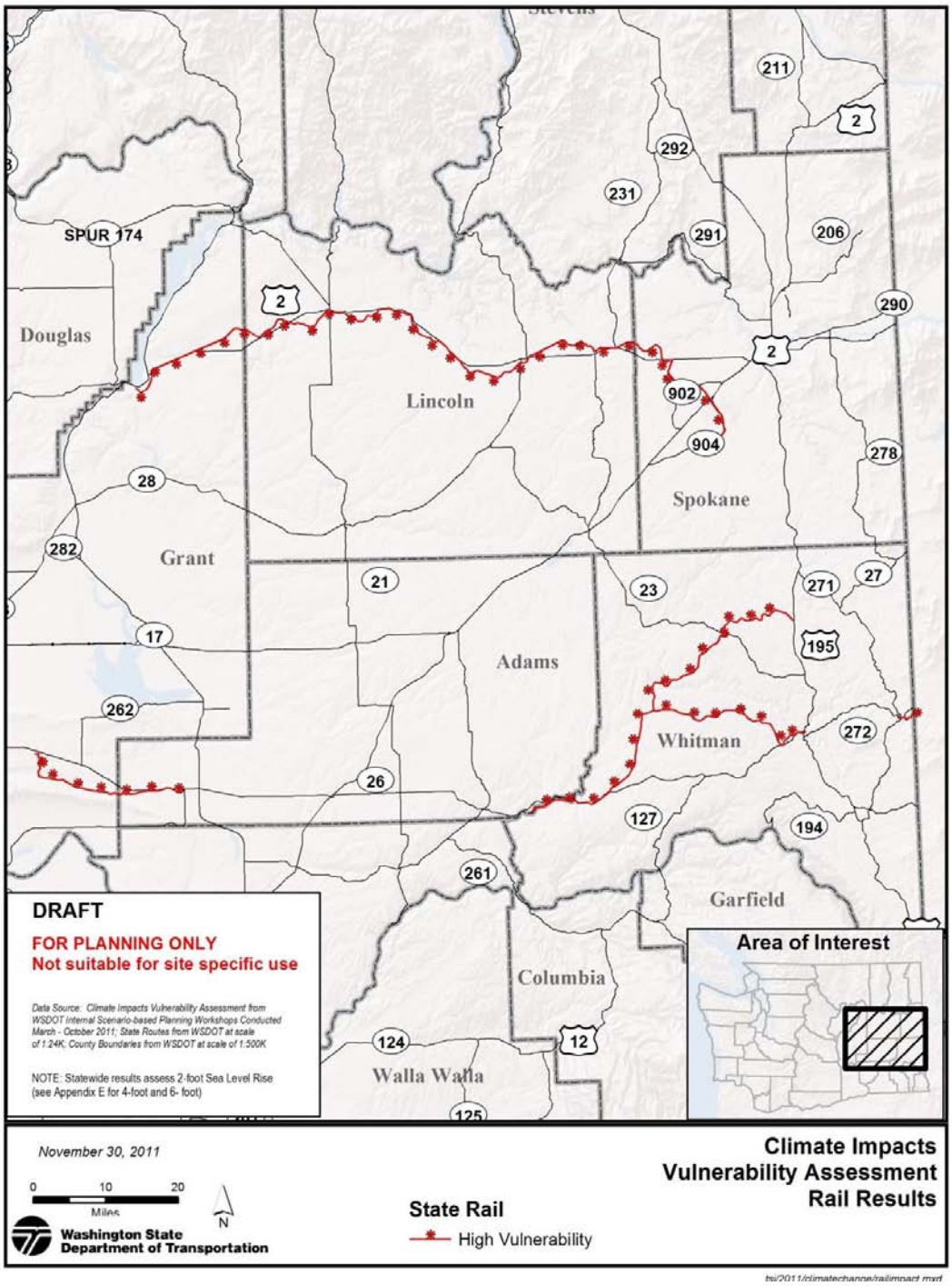


Exhibit B-4.3 Climate Impacts for WSDOT-Owned Rail Facilities

Highway Infrastructure and Climate Impact Vulnerabilities

Vulnerability assessments were carried out in each WSDOT region across the state. Washington State has many climate zones, and impacts vary from region to region. Washington State is already experiencing impacts due to weather events, but the climate impact scenarios explored in the workshops looked at even more extreme events. Each workshop rated impact and criticality separately.

Eastern Region

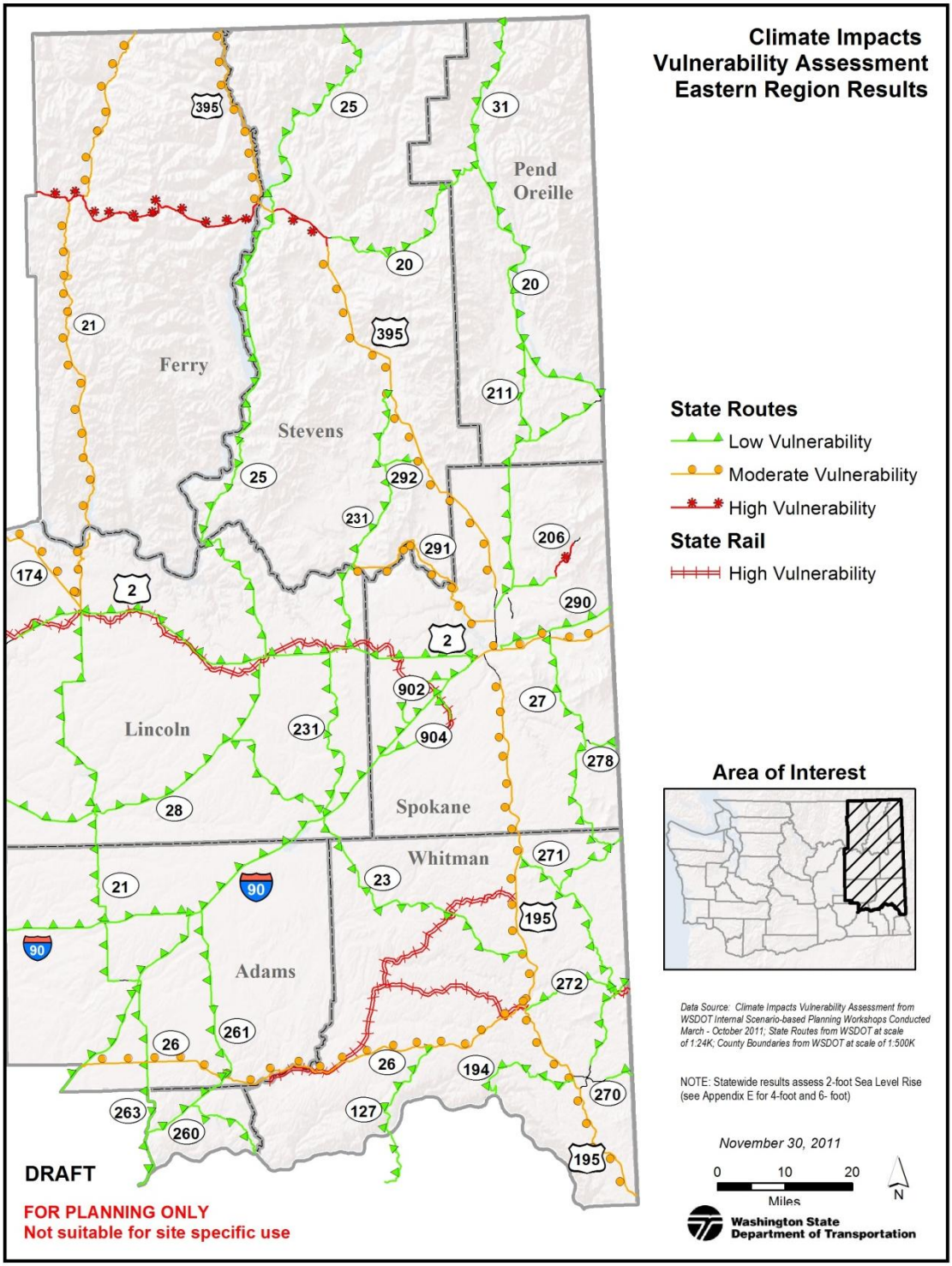


Exhibit B-4.4 Eastern Region Impacts

Projected climate impacts to the Eastern Region consist of increased temperatures, more severe weather events and the potential for increased winds. Highways through mountains may experience increased erosion and landslides, with more precipitation falling as rain and the potential for more fires that will decrease the erosion protection that mature vegetation provides. Impacts to roads are anticipated to be either reduced capacity or temporary operational failure due to wind storms or fires, which cause temporary closures. These are expected to increase based on the scenario explored in the workshops. Impacts are shown in Exhibit B-4.4. The exception to this is in the mountains where current problems are encountered with landslides and wash-outs. Areas shown in the high-impact category may have impacts that can close the roadway for more than 60 days for any one event.

North Central Region

The scenario explored in the workshops of increased temperatures and changes in the type and seasonality of precipitation and more extreme weather events resulted in the North Central Region impacts shown in Exhibit B-4.5.

Highways along rivers are expected to experience flooding due to more precipitation falling as rain in the fall, winter, and early spring. Flooding is expected to result in temporary closures shown as a moderate impact. Some roadways in drier areas of the state already experience temporary road closures due to wind. This is expected to increase under the scenario explored.

Roadways through the mountains are anticipated to experience more fires and more landslides due to more extreme weather events and the decrease in snowpack that will melt earlier in a warmer climate. Roads at the base of steep slopes are expected to experience more landslides that can close the roadway for 60 days or more.

Roads in the low-impact category are expected to have conditions that will not close the roadway, but may result in reduced capacity or no impact.

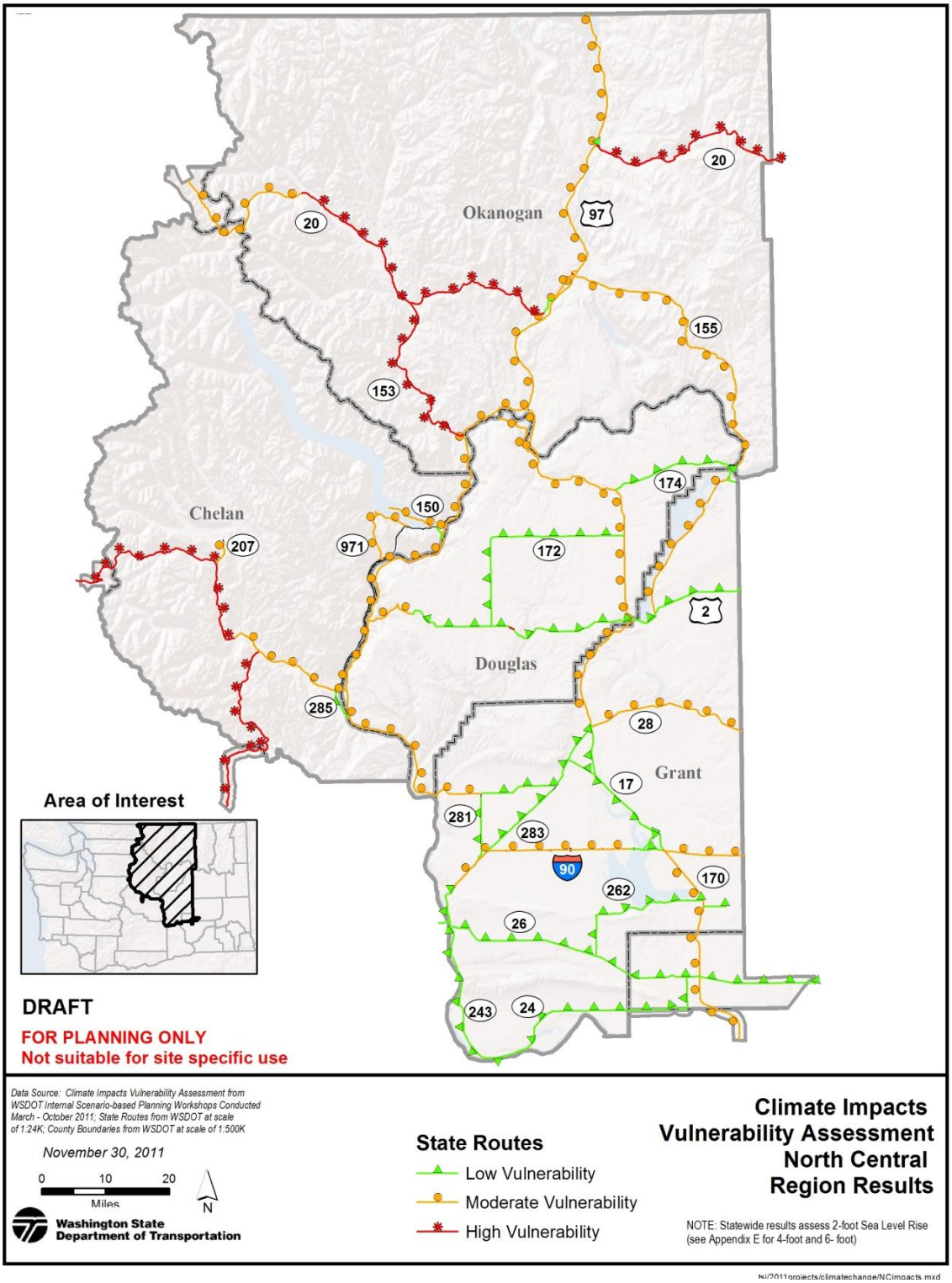


Exhibit B-4.5 North Central Region Impacts

Northwest Region

Because of the road density within the Northwest Region, workshops were divided by Maintenance Areas.

Northwest Region – Areas 1 and 2

Northwest Region Areas 1 and 2 were combined into one workshop because climate impacts are similar and the road density could be evaluated in one workshop. Exhibit B-4.6 shows this area of the state assuming a 2-foot sea level rise scenario for the main map. Insets show impacts for 4- and 6-foot sea level rise scenarios.

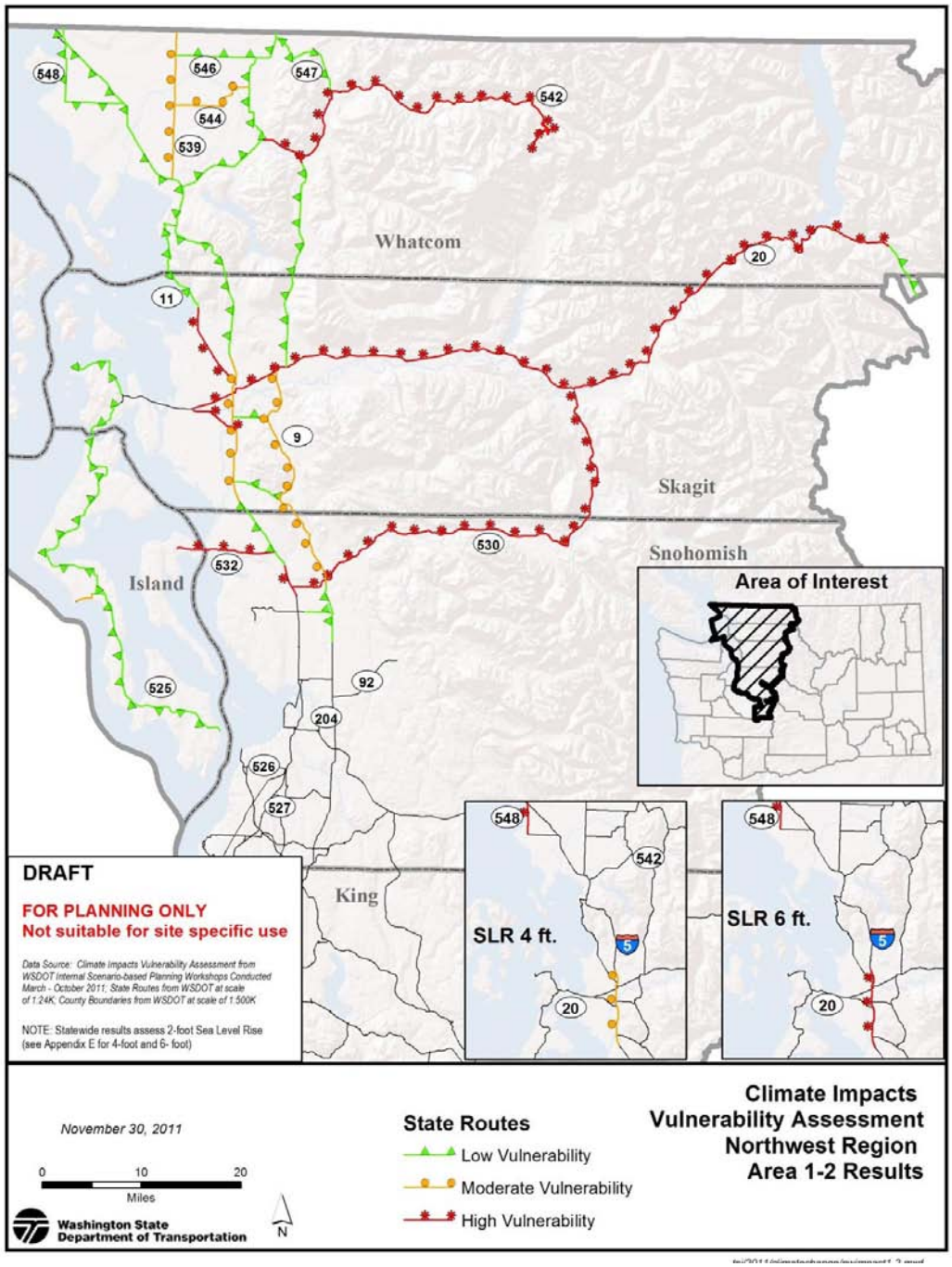


Exhibit B-4.6 Northwest Region – Areas 1 and 2

Some low-lying elevations may be impacted by a 2-foot sea level rise. However, most roadways are high enough above sea level that inundation will not be an issue.

As in other regions, the roads with the highest impacts are anticipated to be in the mountains, especially roads along rivers that are fed from glaciers. Glaciers are already melting and are carrying large sediment loads from exposed soil. Sediment loads fall out on the journey to the sea and raise the beds of rivers. This causes lateral instability of the river channel, which impacts roadways along those rivers. Glacier melting and sediment loads are expected to continue until vegetation can establish and minimize erosion. This will take decades.

Highway 20 is already closed because of snow each winter. If there are fewer snow closures, this may be offset by an increase in landslides because of rain events on slopes that are not protected by snow and because of the increase in extreme weather events.

Northwest Region – Area 3

Northwest Region Area 3 consists predominantly of urban and suburban roads in Snohomish County and US 2 to the region boundary and SR 203 in northern King County. In general, most climate impacts would result in either reduced capacity or temporary road closures due to heavy rain events.

US 2 has impacts now from flooding and debris moving down the Skykomish River. If sea level rises 2 feet, US 2 could see more log jams collecting on bridge piers, but they would be easier to reach. With 4- and 6-foot sea level rises, the river could overtop the dikes and the water would spread, easing pressure on the bridge.

US 2 is the sole mountain pass in this Maintenance Area. Climate impacts are anticipated to result in temporary closures rather than closures lasting over 60 days.

SR 104 at the intersection to the Edmonds ferry terminal already has flooding during high tides and during average tides in heavy rain events. This is expected to increase with higher sea levels. Low-lying roads will be impacted by higher sea levels, as shown in Exhibit B-4.7.

SR 203 is impacted now by high winds coming off the Cascades. Winds may increase with more extreme weather events.

In general, with increased heavy rain events, existing drainage ditches and culverts may be undersized for larger events. Roads at the base of steep slopes may see more landslides, but these are not anticipated to close the road for more than 60 days.

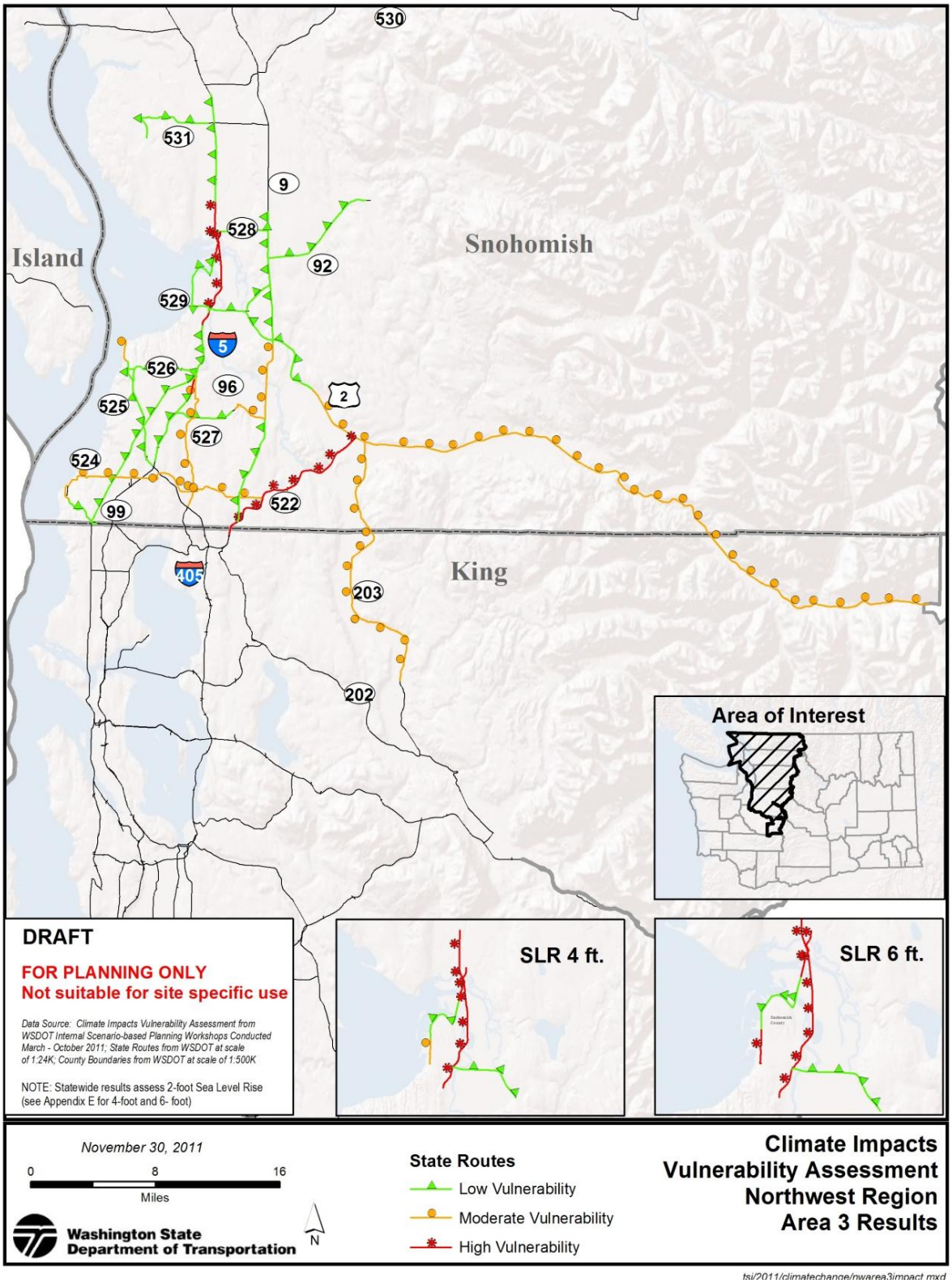


Exhibit B-4.7 Northwest Region – Area 3

Northwest Region – Area 4

Northwest Region Area 4 covers southern King County and eastern Pierce County with both urban roads and roads that lead into Mount Rainier National Park (see Exhibit B-4.8).

Impacts are mostly low to moderate, with the exception of low-lying highways and highways along steep slopes and through the mountains. SR 410 is being impacted by the White River, which is higher in elevation than the roadway in one stretch. The White River is fed by melting glaciers and its bed is building up due to increased sediment deposition. This area is also impacted now by high winds that force road closures.

Increased rainfall during extreme weather events lubricates soil, or flows across the roadway because of clogged drainage structures, causing slope failures. These have occurred in the past causing long-term road closures. The photo at left shows a section of SR 123 that failed. This is an example of a scenario explored in the workshops.

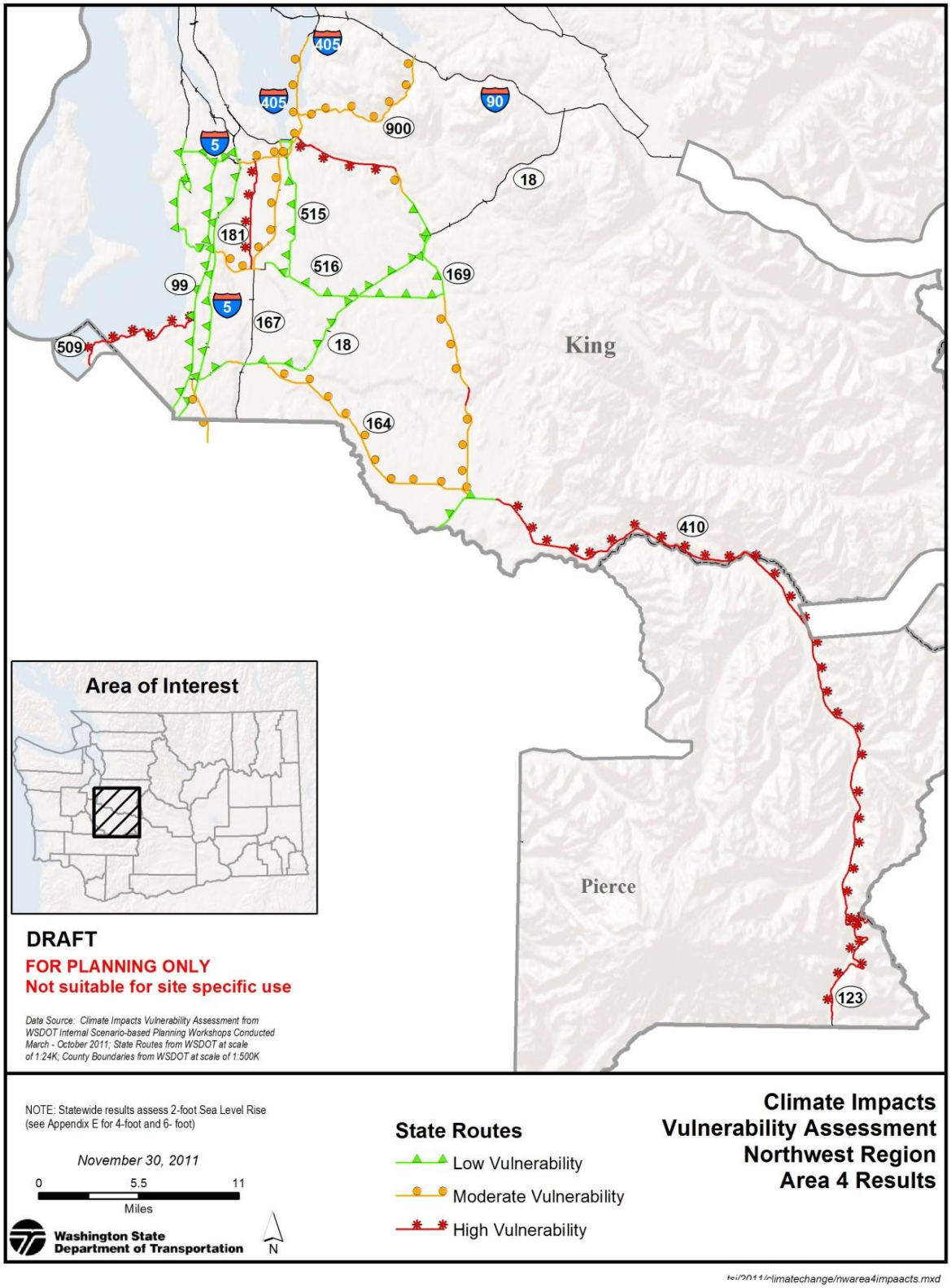


Exhibit B-4.8 Northwest Region – Area 4

Northwest Region – Area 5

Northwest Region Area 5 encompasses southern Snohomish County and northern King County. The highest climate impacts are projected to be in the mountains and along rivers coming out of the mountains (see Exhibit B-4.9).

Major highways in the Puget Sound area are generally at high elevations relative to sea level and adjacent water bodies. Increased storm intensity is anticipated to result in reduced capacity and some temporary road closures in this area.

Locations along I-90 impacted by the Raging River, steep slopes, and historical slides have the potential for long-term closure for repairs. SR 18 in the Tiger Pass area is built on the same geological formation: glacial outwash over clay. SR 18 crosses several creeks and the Raging River. Wind and tree fall are currently issues in this area and could become worse in the future.

SR 202 runs next to a section of the Snoqualmie River that is experiencing channel migration issues due to a large sediment load. When it floods, it takes out sections of the roadway due to erosion. There have been three instances of the river taking out the road in the past few years. This is anticipated to get worse as temperatures rise and glaciers continue to melt.

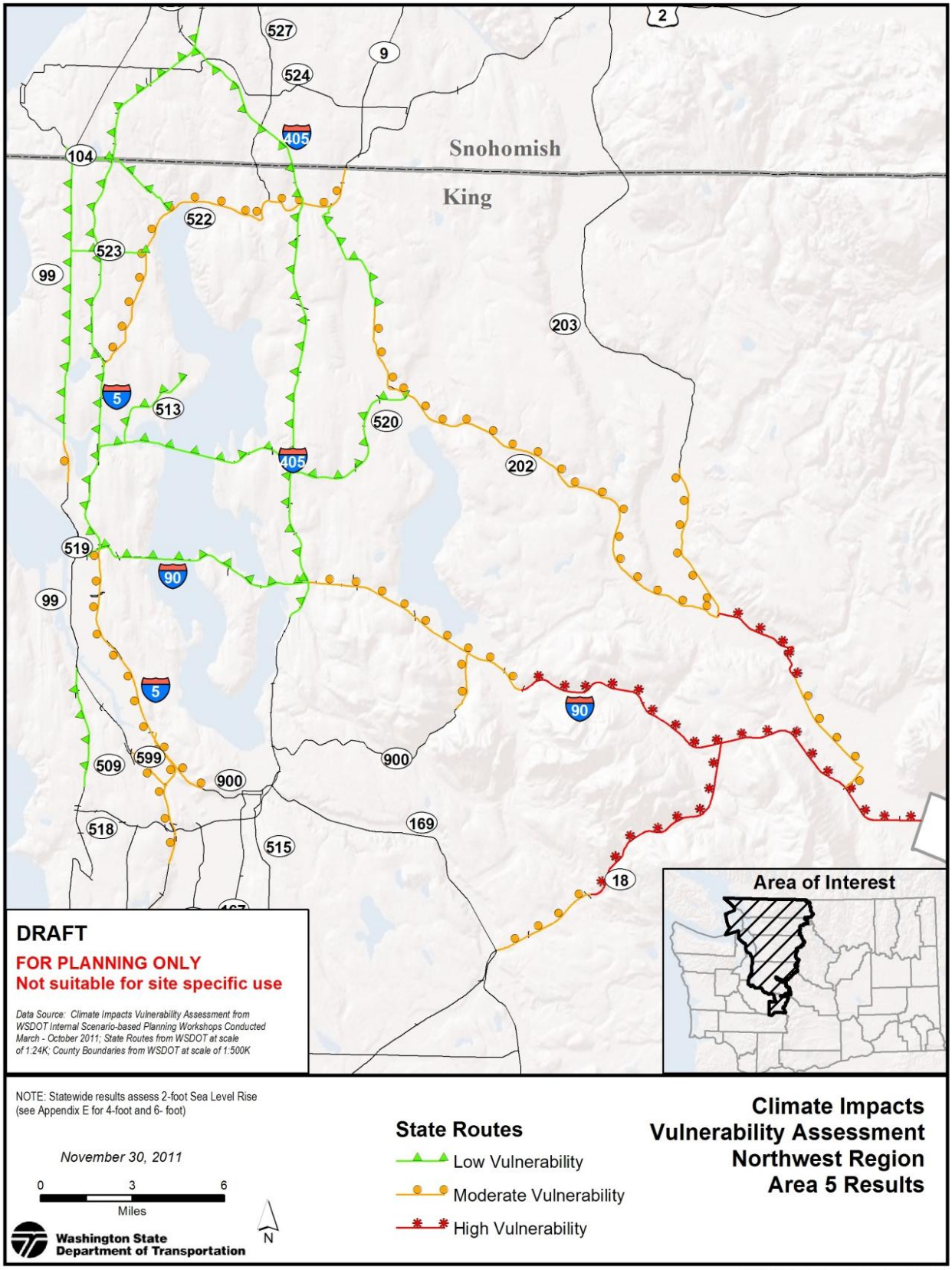


Exhibit B-4.9 Northwest Region – Area 5

Olympic Region

Olympic Region – Area 1

Olympic Region Area 1 (see Exhibit B-4.10) consists of Pierce and parts of Thurston counties. This area was one of the first areas we analyzed (the "pilot of the pilot").

The major highway that runs through this area is I-5, which is raised enough that it is not affected by flooding except in a few instances. At the north end near the King County line, the Hylebos Creek floods occasionally and sometimes encroaches onto I-5. The SR 167 project is working on a flood plain restoration project for the Hylebos that is expected to fix this problem; however, it may still be impacted by future sea level rise. That project office was represented at the workshop and is going to re-run their hydrology models to take sea level rise into account. Other areas that may be impacted along I-5 are some of the ramps. The McAllister Creek occasionally floods the on- and off-ramps, and this would be made worse by sea level rise.

Other areas of concern in Area 1 were SR 167 along the Puyallup River. While the river has not overtopped the dikes in this area, an event in 2010 came close. Sea level rise will make this situation worse because it will lead to more sediment dropping out higher up the river, raising the elevation of the river bed, which decreases the capacity of the river. Rising sea levels will also send the tidal influences higher up the river and affect this section.

SR 165 from MP 0 to MP 14 is a low-use road that runs from Mount Rainier National Park to Carbonado. It is subject to flooding, slides as a result of flooding, high winds, and tree blow-down, which may increase with more extreme weather events.

In general, most of the other road segments are resistant to climate change impacts. In a few instances, there are locations along SR 101 that might be impacted by a 4- or 6-foot sea level rise. At Mud Bay, water is currently backing up in culverts into the median during higher high tides. There is the potential for the water to flood the roadway at this location due to sea level rise.

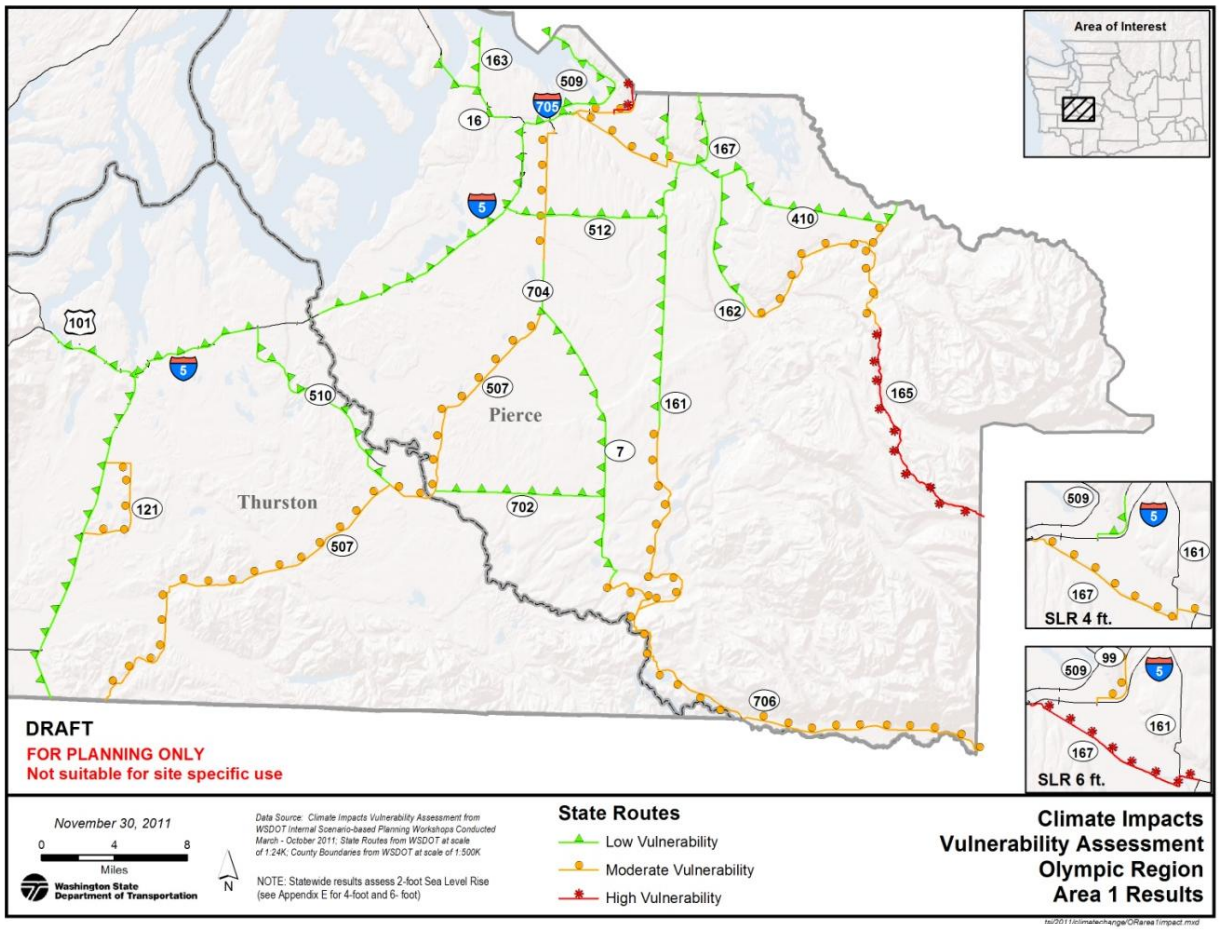


Exhibit B-4.10 Olympic Region – Area 1

Olympic Region – Area 2

Olympic Region Area 2 comprises parts of Thurston, Mason, Kitsap, and Jefferson counties. This area lies between the Puget Sound and the Olympic Mountains. SR 101 runs almost the full length of the Hood Canal in this area.

There were only a few road segments of concern in this area (see Exhibit B-4.11). The longest segment was on SR 101 along the Hood Canal. This segment is sandwiched between the Hood Canal and the Olympic Mountains and currently experiences downed trees, landslides, and tidal influences. Rising sea levels would affect this area, as would more extreme precipitation events.

SR 300 is affected by higher high tides now. Higher sea levels will make this situation worse and could close the road daily.

Sections of SR 3 will be affected by rising sea level. The area from Gorst to SR 304 would likely be highly impacted by a 6-foot sea level rise.

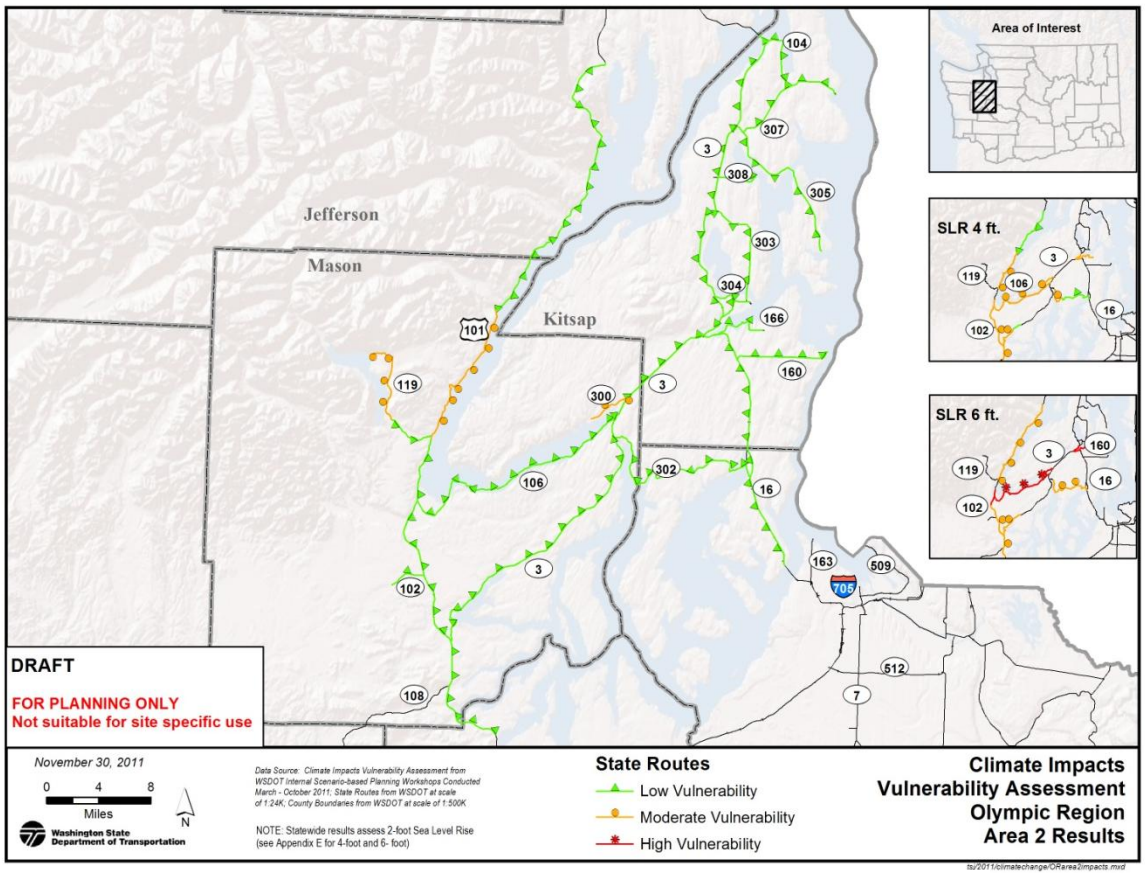


Exhibit B-4.11 Olympic Region – Area 2

Olympic Region – Areas 3 and 4

Olympic Region Areas 3 and 4 are located in Jefferson, Clallam, and Grays Harbor counties, with small road segments in Thurston and Mason counties (see Exhibit B-4.12). These areas ring the Olympic Mountains and run along the Strait of Juan De Fuca, the Pacific Coast, Grays Harbor, and the Chehalis River.

SR 101 between mileposts 165 and 185 is subjected to impacts from creeks and rivers that are aggrading due to increased sedimentation. This is likely to increase as the glaciers and snow fields melt in the mountains. This area is also likely to experience more extreme weather events. SR 101 near Discovery Bay is susceptible to impacts from higher sea levels at 4 and 6 feet.

SR 105 would be affected by a 4- and 6-foot sea level rise and flood the road.

SR 112 between mileposts 29 and 40 is affected by unstable soils. This would be made worse by more extreme precipitation events that would saturate the soils.

SR 116 currently has only a few feet of freeboard. The road is an earthen causeway with culverts at the susceptible points, and sea level increases will flood the road. Flooding the road could lead to roadway instability in addition to closure during high tide events.

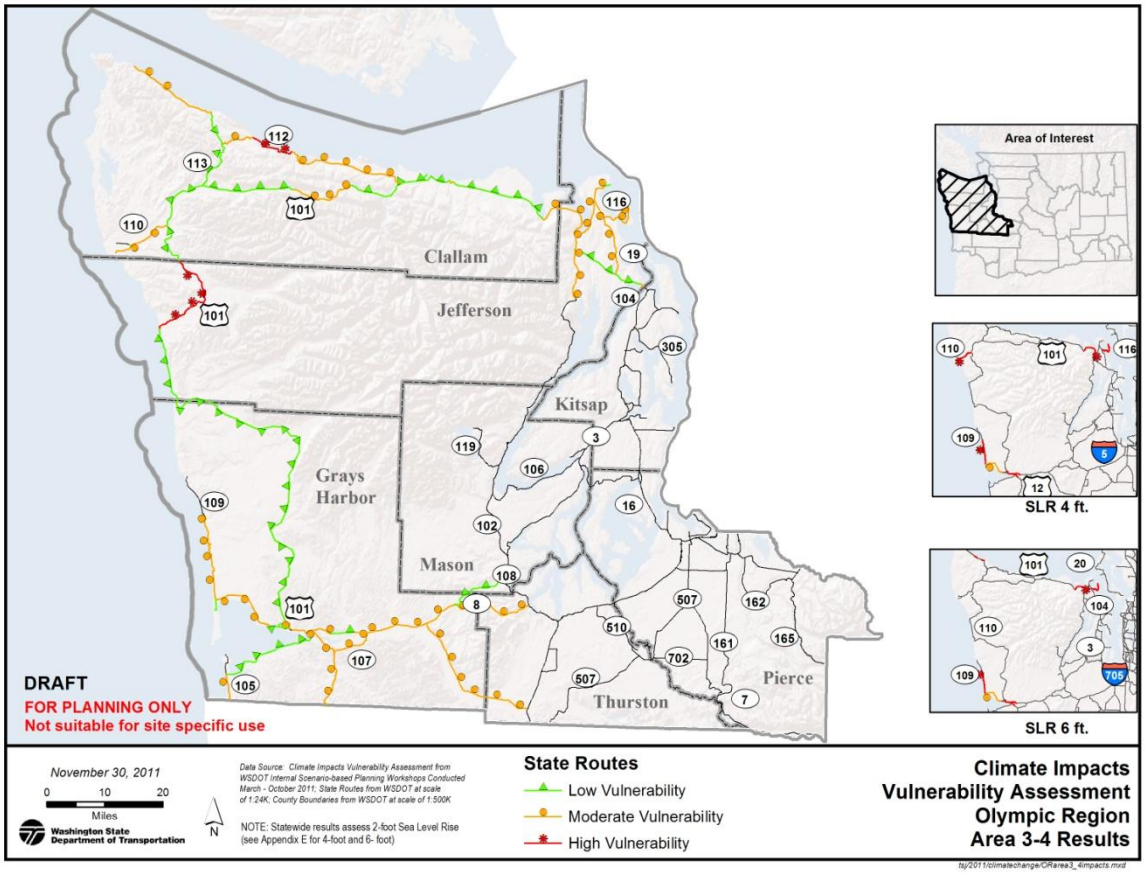


Exhibit B-4.12 Olympic Region – Areas 3 and 4

South Central Region

The South Central Region is comprised of Kittitas, Yakima, Benton, Walla Walla, Columbia, Franklin, Garfield, and Asotin counties. It runs from the east slopes of the Cascade Mountains, through the Columbia River Basin, and over to the Palouse and Blue Mountains. The main concerns in this region are flooding, landslides, river sedimentation and aggradation, dust storms, and fires. Many of these issues are expected to be affected negatively by climate change and will have a moderate to high effect on WSDOT infrastructure.

SR 410 has the longest section of roadway that will be highly impacted by climate change (see Exhibit B-4.13). In this section, the Naches River runs parallel to the road and causes flooding. This area is also prone to landslides. Extreme weather events will make this situation worse.

SR 225 is currently affected by flooding. Extreme weather events will make this situation worse in the future.

SR 129 is regularly impacted by landslides that will be made worse if hit by more extreme weather events.

Many sections of roadway in the Columbia basin would face increased disruptions from dust storms under climate change scenarios. This region is likely to see less soil moisture during the summer, which may inhibit plant growth to hold soil. Coupled with high winds, this will create more dust storms. In addition, brush fires may become more frequent. However, these tend to be short lived and cause only temporary operational closures.

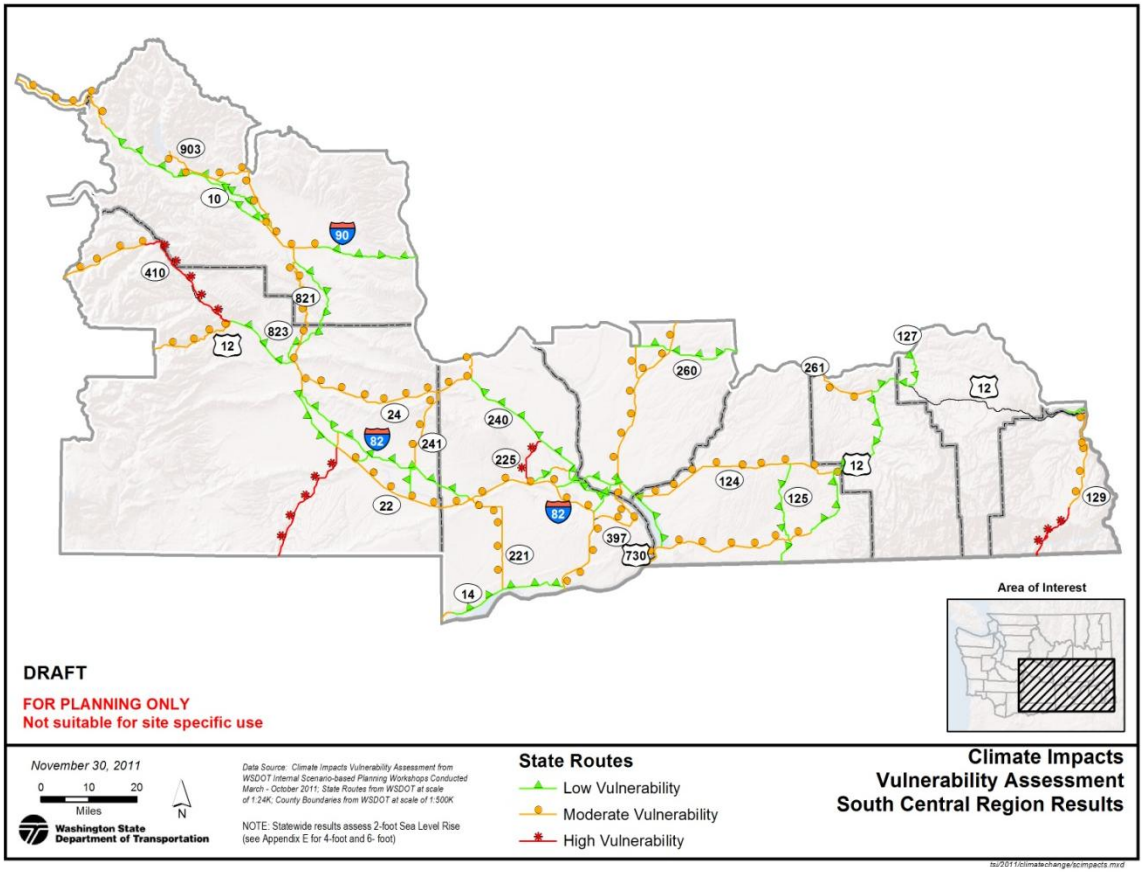


Exhibit B-4.13 South Central Region Impacts

Southwest Region

The Southwest Region covers the Pacific, Wahkiakum, Lewis, Cowlitz, Clark, Skamania, and Klickitat counties. This region is bounded by the Pacific Ocean on the west and the Columbia River, including the Columbia Gorge, to the south and traverses the Cascade Mountains. Because of these geographic conditions, this region has perhaps the highest percentage of overall high-impact road segments in the state (see Exhibit B-4.14).

Despite having some roads along the Pacific coast, these roads are fairly resistant to sea level rise impacts. It is only with a sea level rise of 6 feet or more that one road, SR 105, becomes highly impacted. However, there are roads along the Columbia River that are susceptible to sea level rise.

SR 4 runs along the Columbia River west from Vancouver. Most of this segment will be highly affected by sea level rise. This segment is also affected by river flooding and landslides. This will be worse with more extreme precipitation events.

The I-5 main line through the Southwest Region, with a few exceptions, is resistant to climate change impacts. There are a few bridges that could wash out with the right combination of high water flows and debris build-up. In one other instance, it is a bridge on a parallel road upstream of an I-5 crossing that could pose a problem. If the bridge upstream of I-5 were to go out, it could affect the I-5 bridge. These conditions would be exacerbated by more extreme precipitation events.

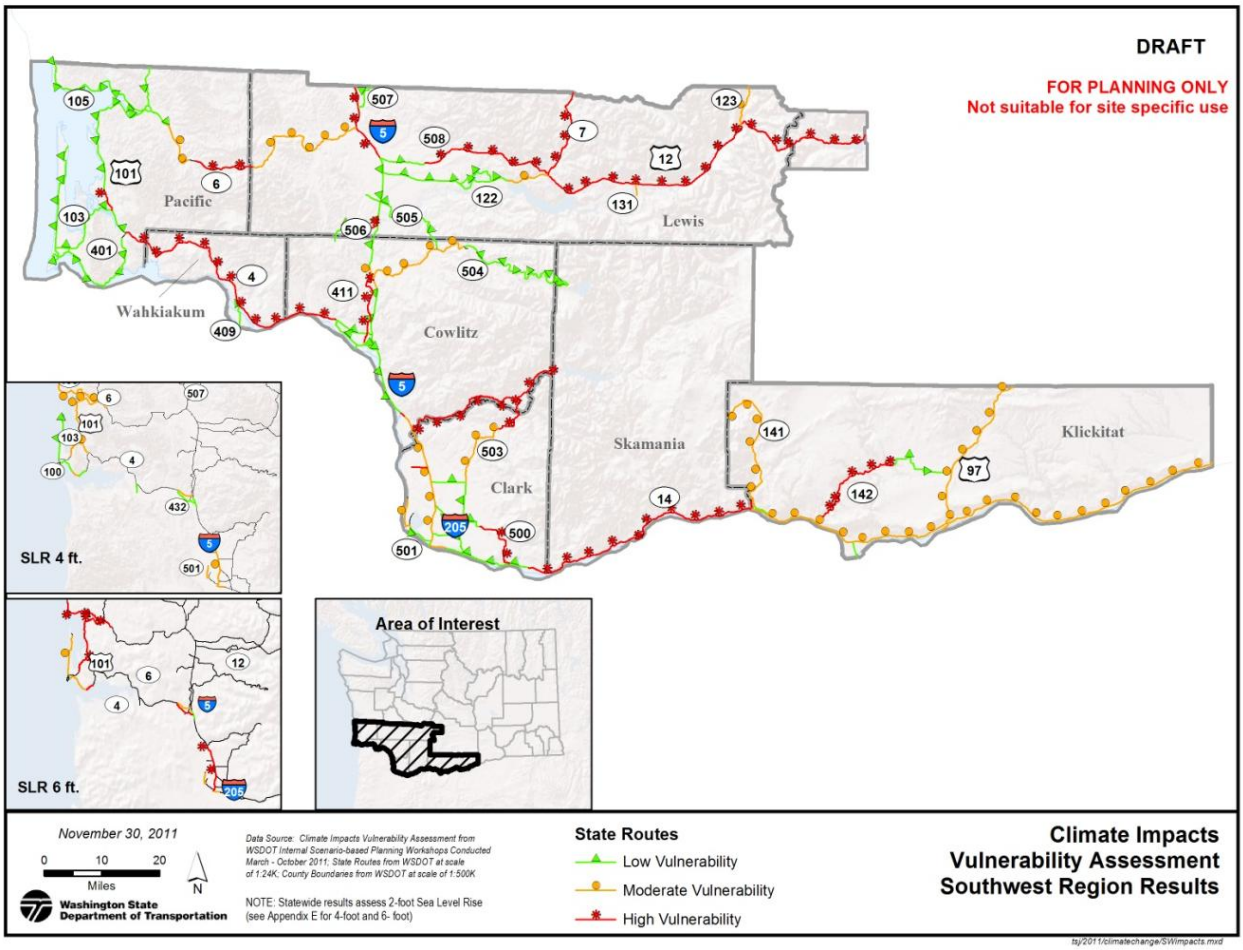


Exhibit B-4.14 Southwest Region Impacts

B-5 STATEWIDE SUMMARY

Though roadway segments may be shown as having a high impact, this does not mean the whole segment is vulnerable—rather that one or two areas along that segment are vulnerable to catastrophic failure. In Exhibit B-4.15, yellow denotes roads that could experience temporary operational failures at one or more locations, and green indicates roads that could experience reduced capacity somewhere along that roadway segment. Data accuracy is *generally* suitable for statewide planning purposes. However, any dataset of this nature will have significant errors when applied to *specific* locations. This was discussed in the workshops. For example, local experts were able to highlight areas where highway flooding from extreme tides is mitigated by culverts and tide gates.

In general, areas shown with locations having a high impact are:

- In the mountains
- Either above or below steep slopes
- In low-lying areas subject to flooding
- Along rivers that are aggrading due to glaciers melting
- In low-lying coastal areas subject to inundation from sea level rise

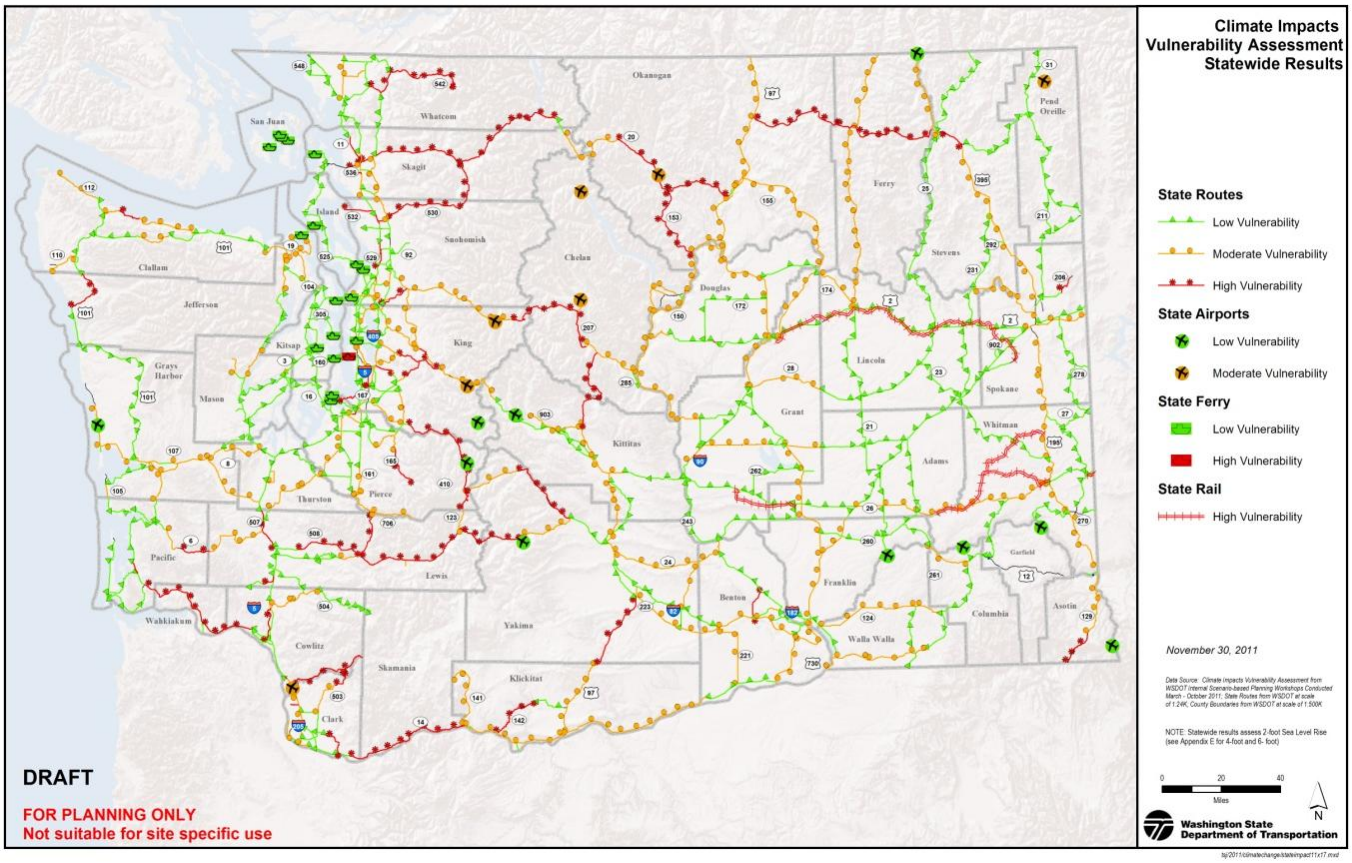


Exhibit B-4.15 Statewide Impacts