Climate Change and Innovative Stormwater Control

This report is submitted in fulfillment of a grant from FHWA

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Summary

Since 2014, the Federal Highway Administration (FHWA) and Rijkswaterstaat, the government agency responsible for transportation and water infrastructure in the Netherlands, have been collaborating on the topic of infrastructure resilience. From 2016 through 2018, the agencies conducted an applied comparison of a suite of resilience tools developed and/or used by the respective agencies: the FHWA Vulnerability Assessment and Adaptation Framework (Framework), and Roads Today, Adapted for Tomorrow (ROADAPT). Rijkswaterstaat applied the tools on the InnovA58, a project to widen a highway in the southern part of the Netherlands. FHWA, in coordination with the Washington State Department of Transportation (WSDOT), applied the tools on the State Route 167 Completion Project near Tacoma, Washington. By using the tools, the agencies aimed to both improve the resilience of those transportation projects and identify potential enhancements to the tools that would make the tools easier to use and more effective for other infrastructure projects. Through site visits and webinars, the agencies also shared information and best practices on other topics related to infrastructure resilience. A comprehensive summary report of this collaborative effort has been prepared by FHWA with input from Rijkswaterstaat and WSDOT.

This report focuses on the comparison of the ROADAPT tools with WSDOT's implementation of the FHWA Framework as part of a statewide climate impact vulnerability assessment (CIVA).

Report findings:

- Both the FHWA Framework and ROADAPT provide a comprehensive set of tools that can be used to evaluate the vulnerability of infrastructure assets.
- Both allow analysis at scales ranging from infrastructure systems to individual assets.
- WSDOT's CIVA, like the outputs from ROADAPT's stakeholder engagement, represent static information that is useful for planning purposes, but may become dated due to the advancement of climate science.
- WSDOT's CIVA may not have enough detail to use directly for asset management or other life cycle analyses.
- FHWA Hydraulic Engineering Circulars (HEC) No. 17 and 25 Vol. 2 are useful to evaluate extreme weather and sea level rise, respectively.
- Updates of HEC25 should include examples of successful treatments for retrofitting existing highways for each region of the United States.

Introduction

The Washington State Department of Transportation (WSDOT) has written this report in fulfillment of a grant from the Federal Highway Administration (FHWA) to compare the conceptual climate risk assessment models developed in the United States and Europe for transportation infrastructure and provide additional feedback on tools developed by FHWA to assist in these analyses. This analysis and report are a part of a large data exchange between WSDOT, FHWA, and Rijkswaterstaat**.** Climate resilience tools have been developed in the United States and Europe to help transportation agencies find and process relevant climate data, identify vulnerabilities to extreme weather, and develop adaptation strategies.

The analysis prepared for this pilot project was completed in parallel to a similar analysis prepared by Rijkswaterstaat. Each team selected a project in the early stages of development. The WSDOT analysis focused on the State Route (SR) 167 Completion Project, which is part of the Puget Sound Gateway program linking the state's largest ports to key distribution centers in the region. Rijkswaterstaat applied the tools on the InnovA58, a project to widen a highway in the southern part of the Netherlands. The approaches taken by each team were slightly different. The Dutch applied the assessment tools for the first time on their project, whereas WSDOT leveraged the results and data collected as part of its statewide climate impacts vulnerability assessment (CIVA) and revised the results for the SR167 area to include the SR167 Completion Project.

It is important to emphasize that the changes made to the CIVA data or extrapolations of that data used and presented in this report do not represent official WSDOT updates or changes to the CIVA. The changes to the data were used in a desktop exercise to evaluate the tools, outside of the stakeholder process, and consequently only represent the assumptions made by the author to illustrate the use of the tools.

The suite of tools tested as part of this pilot project assist transportation agencies in conducting vulnerability assessments and assessing strategies to build resilience. Vulnerability assessments involve analyzing the impact of climate and extreme weather on transportation infrastructure, and can focus on particular assets or classes of assets, or on a region's transportation system as a whole. Agencies can use the results of a vulnerability assessment to develop strategies to address the vulnerabilities identified and to increase resilience.

The tools compared as part of this pilot project were:

- FHWA Vulnerability Assessment and Adaptation Framework, a guide and set of associated tools for transportation agencies interested in assessing vulnerability and integrating resilience considerations into transportation decision making.
- Roads Today, Adapted for Tomorrow (ROADAPT), a risk-based climate adaptation framework and associated tools developed by the Conference of European Directors of Roads (CEDR).

Overview of FHWA Framework

The FHWA Vulnerability Assessment and Adaptation Framework (FHWA Framework, Figure 1) is a guide for transportation agencies interested in assessing their vulnerability to extreme weather events and integrating the results into decision-making. The FHWA Framework discusses the key steps in conducting a vulnerability assessment and provides options for how the process can be conducted with varying levels of effort and resources – for example, through a stakeholder-based assessment or a project-level engineering analysis.

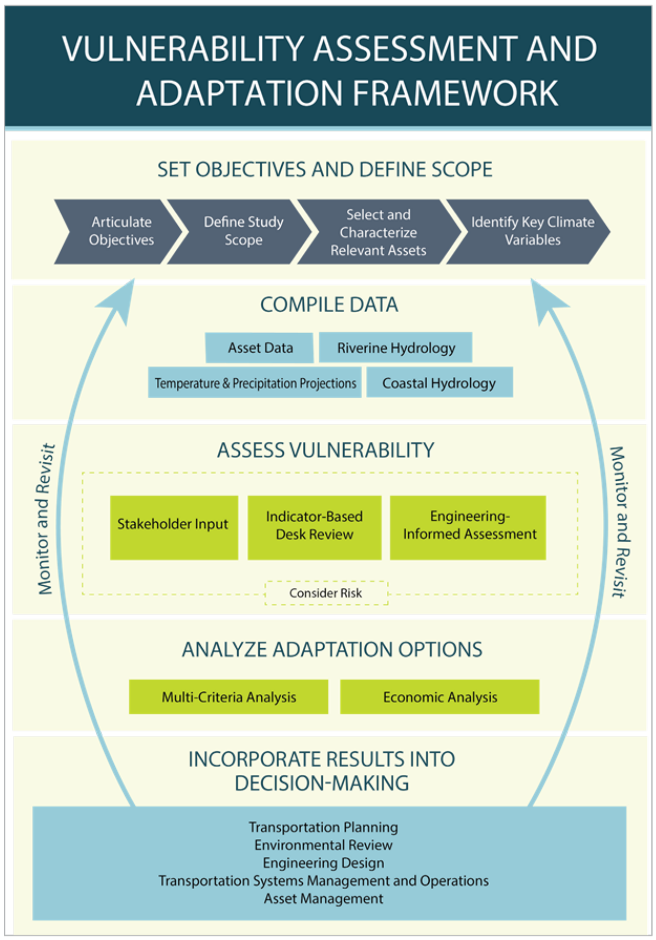


Figure 1. FHWA Vulnerability Assessment and Adaptation Framework

In addition to the Framework, FHWA developed several associated tools and resources that support transportation practitioners with conducting particular aspects of the vulnerability assessment process. These tools and resources include:

The Sensitivity Matrix is a spreadsheet tool that documents the sensitivity of roads, bridges, airports, ports, pipelines, and rail to 11 potential climate impacts. Sensitivity refers to how an asset or system fares when exposed to a climate or extreme weather impact.

The Guide to Assessing Criticality in Transportation Planning is a short report that describes common challenges associated with assessing criticality, options for defining criticality and identifying the scope of the analysis, and the process of applying criteria and ranking assets.

The CMIP Data Processing Tool is a spreadsheet tool that processes raw climate model outputs from the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP) CMIP3 and CMIP5 databases into relevant statistics for transportation planners, including changes in the frequency of very hot days and extreme precipitation events that may affect transportation infrastructure and services by the middle and end of the century.

The Vulnerability Assessment Scoring Tool (VAST) is a spreadsheet tool that guides users through conducting a quantitative, indicator-based vulnerability screening. It is intended for agencies assessing how components of their transportation system may be vulnerable to climate stressors.

The Transportation Engineering Approaches to Climate Resiliency (TEACR) study provides detailed information for a range of engineering disciplines on integrating climate considerations into transportation project development. The study includes a Synthesis Report, the Adaptation Decision-Making Assessment Process tool, and case studies covering the topics of coastal and riverine hydraulics, pavement and soils, and economic analysis.

WSDOT's vulnerability assessment implemented the first version of FHWA's framework, with funding support from FHWA as part of the 2010-2011 Vulnerability Assessment Pilot Program. WSDOT's Climate Impacts Vulnerability Assessment (CIVA) is a qualitative assessment of risks to the state's transportation infrastructure from climate change. WSDOT collected an inventory of department-owned and managed assets and climate change data using geographic information systems (GIS). University of Washington climate scientists provided climate data for all areas of the state.

Key points about the CIVA include:

- WSDOT leveraged its 10 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.
- 14 workshops engaged experts across all regions of the state, encompassing highways, ferries, rail, and aviation.
- Each workshop yielded a qualitative assessment of the vulnerability agreed upon by workshop participants.

WSDOT uses the CIVA results in planning-level studies, including corridor plans and studies conducted under the National Environmental Policy Act (NEPA).

The final report containing methods and results is posted on WSDOT's "Climate Change Adapting and Preparing" website https://www.wsdot.wa.gov/construction-planning/environment/sustainable/climate-change

Overview of ROADAPT

Roads for Today, Adapted for Tomorrow (ROADAPT) was developed in response to the CEDR 2012 research program "Road owners adapting to climate change".

The ROADAPT tool consists of five parts:

- Part A provides guidelines for producing focused and consistent climate data and information with which to determine the impact of extreme weather and climate change on national and international motorways in Europe.
- Part B was designed to quickly and efficiently determine the effects of climate change on infrastructure using an approach called "Quickscan." In the Quickscan methodology, groups of stakeholders filter relevant threats from a comprehensive list, identify the risks those threats pose to transportation assets, and identify potential adaptation strategies.
- Part C offers methods for determining vulnerability to extreme weather and climate change using a GIS approach.
- Part D helps determine the socio-economic impact of the consequences of extreme weather and climate change on roads.
- Part E provides a 10-step process for selecting adaptation strategies for limiting the impact of extreme weather and climate change, as well as a list of potential adaptation measures for different climate threats.

The intended audience of ROADAPT is a broad spectrum of professionals within national road authorities, including road engineers, asset managers, climate adaptation professionals, and project managers. It follows a risk-based approach using the Risk Management for Roads in a Changing Climate (RIMAROCC) framework, a risk management framework familiar to road owners in Europe (Figure 2).

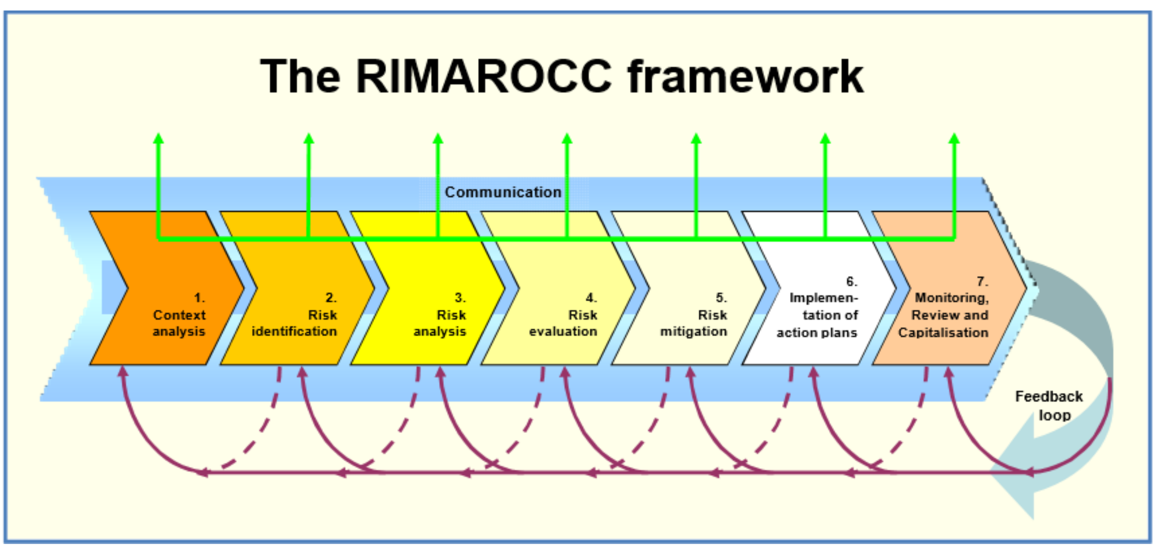


Figure 2. The RIMAROCC framework; Bles et al. (2010)

Comparison of ROADAPT QuickScan (Part B) to the FHWA Framework

The following sections step through the ROADAPT Quickscan process and compare and contrast the information developed for CIVA, WSDOT's implementation of the FHWA Framework and additional information needed to evaluate the SR167 Completion Project. The steps in the comparison are:

1. Desktop study before first workshop
2. Workshop I
3. Desktop study between workshop I and II
4. Workshop II
5. Desktop study between workshop I and II
6. Workshop III
7. Analysis of results and reporting

Step 1. Desktop study before first workshop

The goal of this step is to establish the context in which the Quickscan will be performed: determine which threats seem relevant to be studied in the Quickscan based on the current climate and expected climate change given the limits of the network and area under consideration. These steps are made in advance in preparing for the first workshop (Step 2).

The steps parallel the FHWA Framework: articulate objectives, identify climate factors, and identify and characterize infrastructure. WSDOT's CIVA generally followed this outline.

For this pilot project, the previously developed CIVA data was leveraged. The existing data was reviewed and modified for the highway segments in proximity to the SR167 Completion Project to reflect the proposed SR167 Completion Project highway segments.

Step 1.1. Scope Definition / Establish Context:

This step is used to determine the road network or individual road segment that will be studied during the Quickscan. Both Quickscan and the FHWA Framework have similar processes of selecting segments, interconnections and alternate routes, making both suitable for evaluating highway networks or individual project segments

WSDOT's CIVA evaluated all existing segments of the state highway system. Since the SR167 Completion Project will be a new highway segment it was not included in the initial vulnerability assessment. WSDOT selected the following segments for this comparative analysis: segments of Interstate 5 (I-5), I-705, SR99, SR167 (Old SR167), SR161, SR509, and SR167 Completion Project segments (SR167 Proj. and SR509 Proj.).

Step 1.2. Identify risk sources and possible relevant threats:

This step focuses on describing relevant climate change or extreme weather threats and related climate variables and their expected time horizons, together with a list of relevant threats that are going to be studied in the rest of the Quickscan. It is only necessary to have a general overview of climate information, together with an estimation of the possible changes in different scenarios in the future. It is not necessary to have detailed climate information with a high spatial resolution for the Quick Scan.

The WSDOT CIVA followed a similar path in describing the climate impacts in a regional manner; the SR167 Completion Project is located in the Puget Sound Region which has a predominately rainfall based hydrology, although large rivers flow to the Puget Sound from mountainous areas where runoff is primarily snowmelt. Although changes in the precipitation/snow accumulation/snow melt dynamics may have profound effects on the runoff patterns of Washington's major rivers that originate in the Cascade Mountains, the local precipitation patterns that are used for highway stormwater management are expected to produce similar volumes of runoff, although the seasonal distribution is expected to change in the future.

Since the climate data used for the CIVA was very general, and not intended for site specific use, WSDOT examined other sources. WSDOT used the CIMP5 tool to evaluate the SR167 Completion Project area and found that the results were useful as a discussion tool to describe local climate effects, although they did not have a direct engineering use. WSDOT also reached out to universities in Washington State to evaluate research projects focused on converting the downscaled climate model data to short duration rainfall intensities needed for analysis of highway drainage systems.

The Port of Tacoma is a seaport at the western edge of the SR167 Completion Project area. The port and the western part of the project area are exposed to sea level rise and related hazards. WSDOT's CIVA used three estimates of future sea level rise: 2, 4, and 6 feet, which correspond to the higher estimates of sea level rise given the CMIP3 emission scenarios. Although WSDOT now uses different sea level rise estimates based on the best available science, the sea level rise assumptions were not changed for this analysis.

Both Quickscan and the FHWA Framework have a similar process of describing potential climate and extreme weather effects. Based on the FHWA/WSDOT visit to the Netherlands and KNMI (Royal Netherlands Meteorological Institute, which is the Dutch national weather forecasting service), it appears that the information is moving from academia to applied engineering at a more rapid pace in the Netherlands than in Washington State.

KNMI has developed rainfall IDF (intensity, duration, frequency) relationships that reflect nationwide climate projections for use in engineering design of highway drainage systems. Although Washington State universities were studying these relationships at the time this report was prepared, they had been unsuccessful in downscaling the climate data to sub-daily time steps needed for design. The highly variable annual weather in Washington, the numerous climate regions that exist in the state, and the general lack of long-term records, like those found in Europe, contributed to inability to create IDF curves that reflect potential future conditions.

Step 1.3 - Determine importance of road sections in road network (sensitivity):

This step provides an allocation of different road importance categories, or criticality, to different road segments. Factors may include:

- Traffic intensity – annual average daily trips (AADT)
- Part of the National Highway System (NHS)

- Economic importance of the geographic area surrounding the road
- Redundancy of the road (are alternative routes present)

While the Quickscan method suggests a 1 to 4 scale, the WSDOT CIVA used a 1 to 10 scale (Figure 3). The process was similar, but the expanded range used in the CIVA provided a greater comfort level to participants as it allowed for some discrimination between similar segments in the statewide process.

The CIVA results were updated for this analysis to include implementation of the SR167 Completion Project (Figure 4). Because the new project completes a missing piece in the regional highway network, WSDOT found that this reduced the sensitivity of some segments, as they became the redundant or alternate routes to traffic, although they still serve as arterials to local traffic, as the new highway segments became the primary route. For example, the existing highway segment of Old SR167 (6) along the Puyallup River became redundant as well as the segment of SR99 (6) north of the Port of Tacoma. I-5 remained very critical (10) as a vital north-south route through the area and the State. The SR167 Completion Project was rated as critical (8). WSDOT's CIVA did not present figures showing "Criticality" but the information is available in the supporting data.

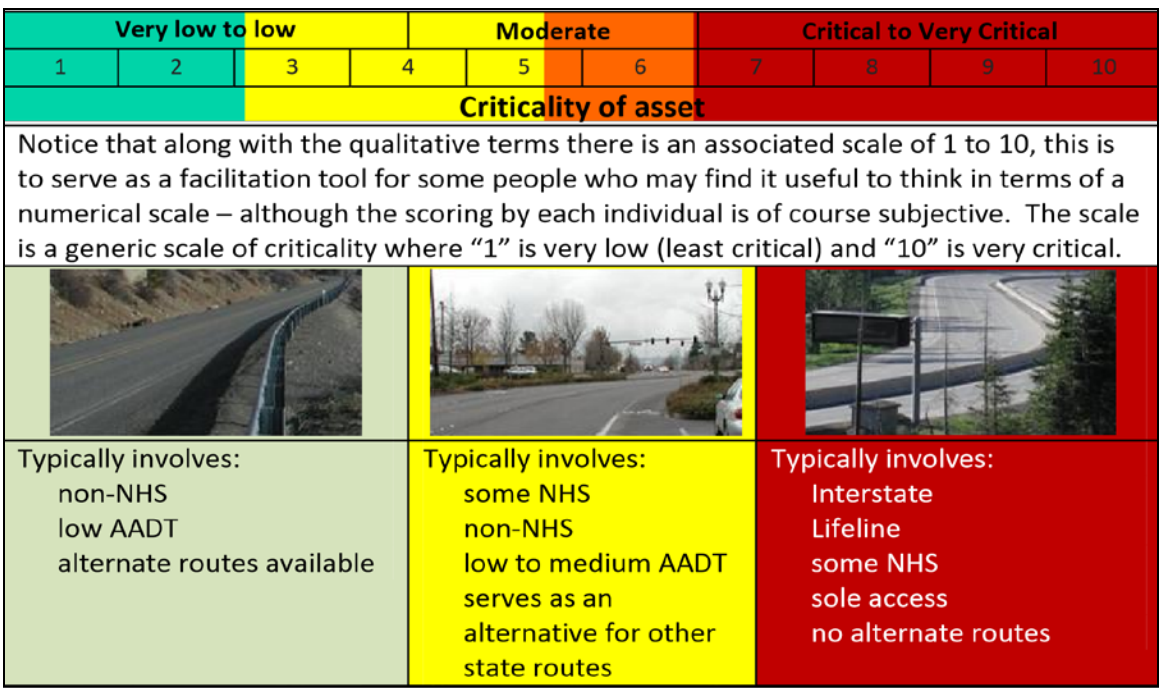
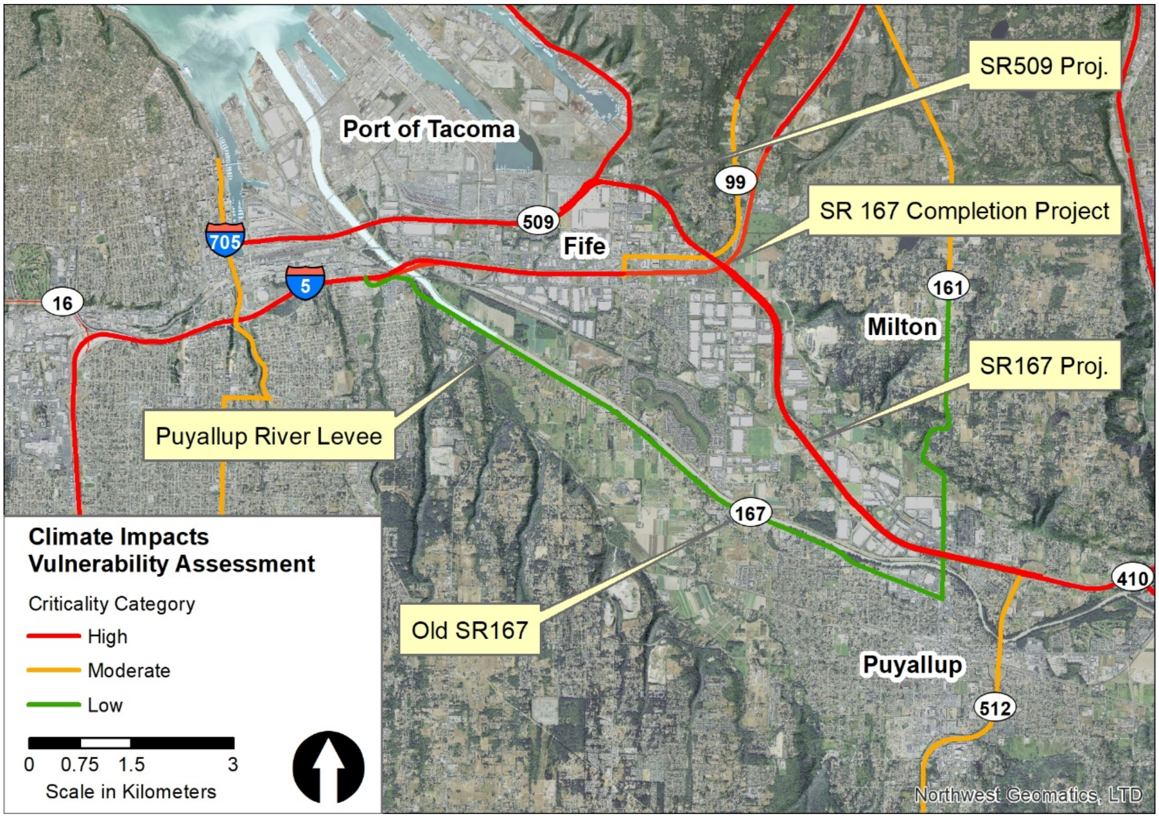


Figure 3. WSDOT CIVA Criticality Score.



Highway Segment	SR99	SR161	Old SR167	SR167	SR167 Proj.	SR509	SR509 Proj.	I705	I5
Criticality Score	6	3.5	3	8	8	7	8	5	10

Figure 4. CIVA Criticality Categories

Step 2. Workshop 1.

The goal of this workshop is to identify the consequences of the previously identified threats on the selected highway segments. WSDOT held 14 workshops across the state, but each segment was considered and rated in only one workshop. In comparing the CIVA and Quickscan, WSDOT found that the CIVA accomplished the goals of Quickscan Workshops 1 and 2. The CIVA workshops were focused on identifying climate or extreme weather related effects on the highway and then, based on the high-level or generalized climate change knowledge, made qualitative judgements regarding the change in severity of the existing problems.

WSDOT's CIVA focused on how climate change may make existing problems worse and did not really go into depth of identifying new hazards that could occur due to climate change. The segmentation of the highway system and generalization of the climate change data necessary to prepare a statewide assessment precluded the site-specific detail that would be needed to identify new/emerging site-specific hazards. WSDOT's CIVA did not consider new projects or the potential for increased or decreased resilience from different asset management strategies.

As part of the SR167 Completion Project a separate sea level rise analysis was completed that considered the effects that sea level may have on a variety of hazards including coastal flooding, riverine flooding, groundwater flooding, and tsunami run up (Page 2016). As part of the riverine flooding analysis, the CMIP tool and university research were used to evaluate the hydrologic models developed previously for the project. These analyses generally followed the guidance presented in FHWA's HEC17 and HEC25 Vol. 2.

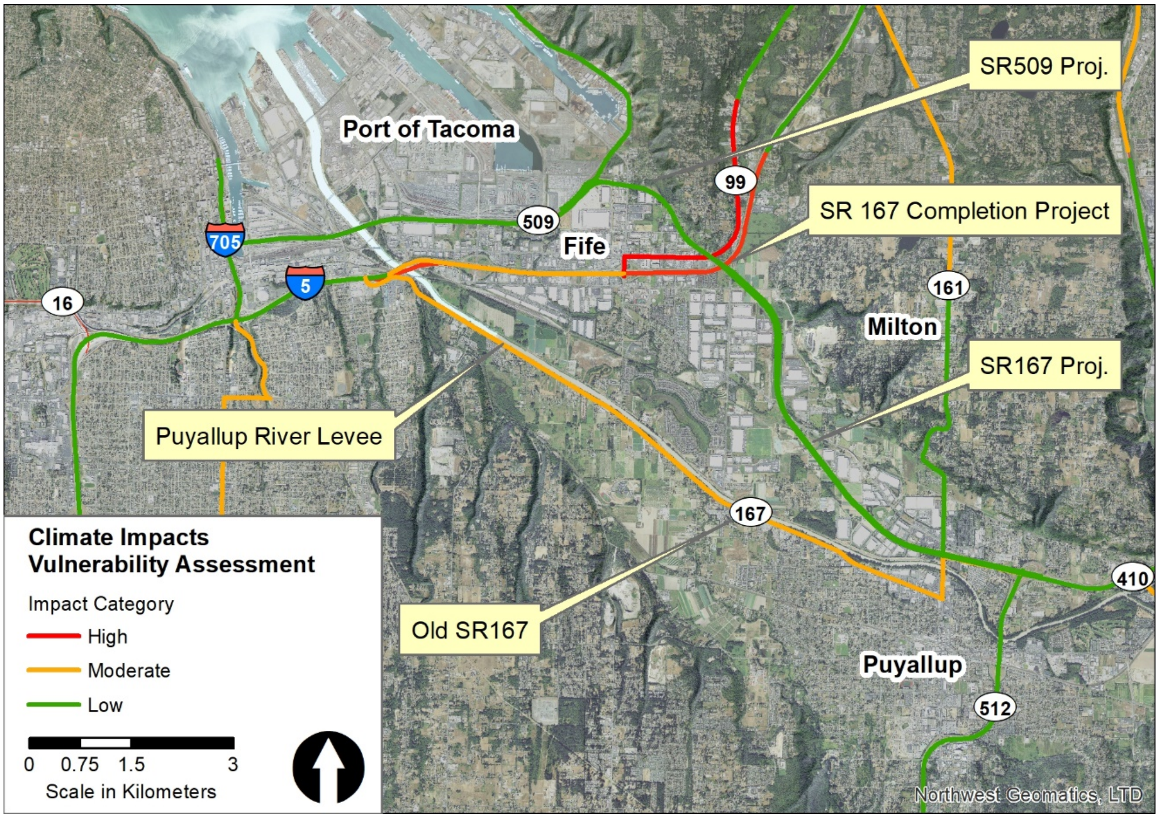
The CIVA analysis identified a segment of SR99 as being at risk of complete failure due to local flooding exacerbated by future sea level rise. The segment of road is vulnerable to flooding from local drainages, the Puyallup River (a glacial fed river), and coastal flooding under current conditions. I-5 and Old SR167 are at risk of temporary operational failure due to Puyallup River flooding and coastal flooding during extreme events under future conditions. These site specific studies found that the SR167 Completion project will be at low risk to damage as it is being designed to accommodate the projected Puyallup River flooding and local flooding, and the highway will be elevated in the area that is currently at risk to coastal flooding.

Step 2.3 Estimate the consequences of the threats:

Like the criticality scoring, the Quickscan guidance recommended a simple 1 to 4 scoring system, with 1 being the lowest impact and 4 the highest. WSDOT again used a 1 to 10 scale with a more descriptive set of categories (Figure 5). Figure 6 shows the segments of the SR167 Completion project having low impact scores.

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.

Figure 5. WSDOT CIVA Consequences Score



Highway Segment	SR99	SR161	Old SR167	SR167	SR167 Proj.	SR509	SR509 Proj.	I705	I5
Impact Score	4	3	4	2	2	2	2	2	4

Figure 6. CIVA Impact Categories.

Step 2.4 Evaluate Scoring:

The purpose of this step is to evaluate the scores, in order to check whether the results are in line with expectations. The evaluation of the scoring is mainly required if the scoring of the consequences is done individually. In that case, one other objective of this step is to focus on threats associated with scores showing a wide spread among workshop participants.

The WSDOT CIVA was done in a group setting so the scores were not evaluated outside of the workshop. For the purposes of this pilot project analysis, the scores were revisited and adjusted. However, these adjustments do not reflect official WSDOT positions as they were made outside the review team and are the opinions of the report author based on the preliminary design plans for the SR167 Completion Project.

A key take home message based on the results of this step in the pilot study is to investigate wide ranges of scoring. A wide spread of scores in Quickscan may indicate some misunderstanding or possibly a participant has particular firsthand knowledge that should be shared with the group.

Step 3. Prepare for Workshop 2

Depending on the complexity of the system being analyzed, it may be necessary to have a second workshop. For this workshop the information gathered at the first workshop should be refined to eliminate non-issues from the range of possible climate impacts as well as to focus on the likely threats and the scores of the consequences and risks collected previously.

Quickscan guidance suggests that, if possible, the first and second workshops be combined in a morning/afternoon format with this step being completed by the workshop facilitators during a break following the first workshop session. This step helps participants to focus on the real impacts and allows discarding or removing from further discussion climate impacts that are really not pertinent to the analysis to focus future planning efforts.

Completing workshops 1 and 2 back-to-back may be especially helpful in maintaining the participant pool rather than requiring attendance at multiple meetings on different days.

Step 4. Workshop 2

Workshop 2 works towards assessment of the risks, based on the consequences of the threats that were previously identified. A key focus of this workshop is defining the probability of a threat actually having an impact on the use of the highway network. After evaluation of the risk profile, the top risks should be identified. Selection of the risks that are to be examined during the remainder of the study may be done using color indicators as a basis, i.e. to focus on the 'red' or 'red and orange' threats. The resulting "heat" chart promotes focusing on the most critical problems, those with significant consequences and high likelihood that they could occur (Figure 7).

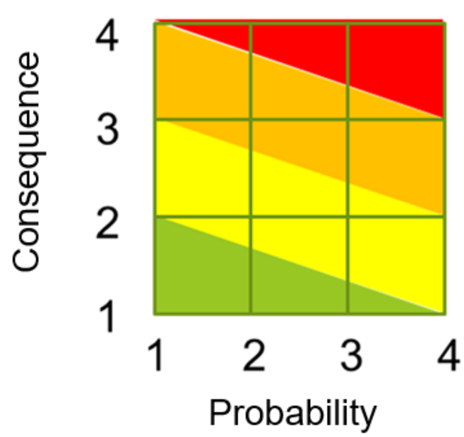


Figure 7. ROADAPT "Heat Chart".

The fact that the magnitude of the risks is determined based on the assessment of the workshop participants, as opposed to extensive research, emphasizes the importance of having the right people at the workshop. Generally speaking, it is not necessary to invite specialists with a narrow focus. Generalists (with experience in, and knowledge of, varying fields including engineering, traffic coordination, public affairs, economy, etc.) who understand the impact of a threat without going into too much detail seemed to provide the most relevant insights. A climate expert may be useful for qualitative estimates of climate variables, but it is not necessary to have such an expert participating during the workshops. WSDOT's CIVA workshops were attended by WSDOT employees who were most familiar with the highway assets (lead staff from maintenance, design and planning).

The WSDOT CIVA yields a similar "heat" chart that combines the impacts with the criticality of the highway segment (Figure 8); the rating system is biased to the criticality of the highway segment. WSDOT did not isolate the probability of the impacts, as the entire process was focused on known impacts that already occur under existing conditions and would potentially be worse based on the regional understanding of future climate change.

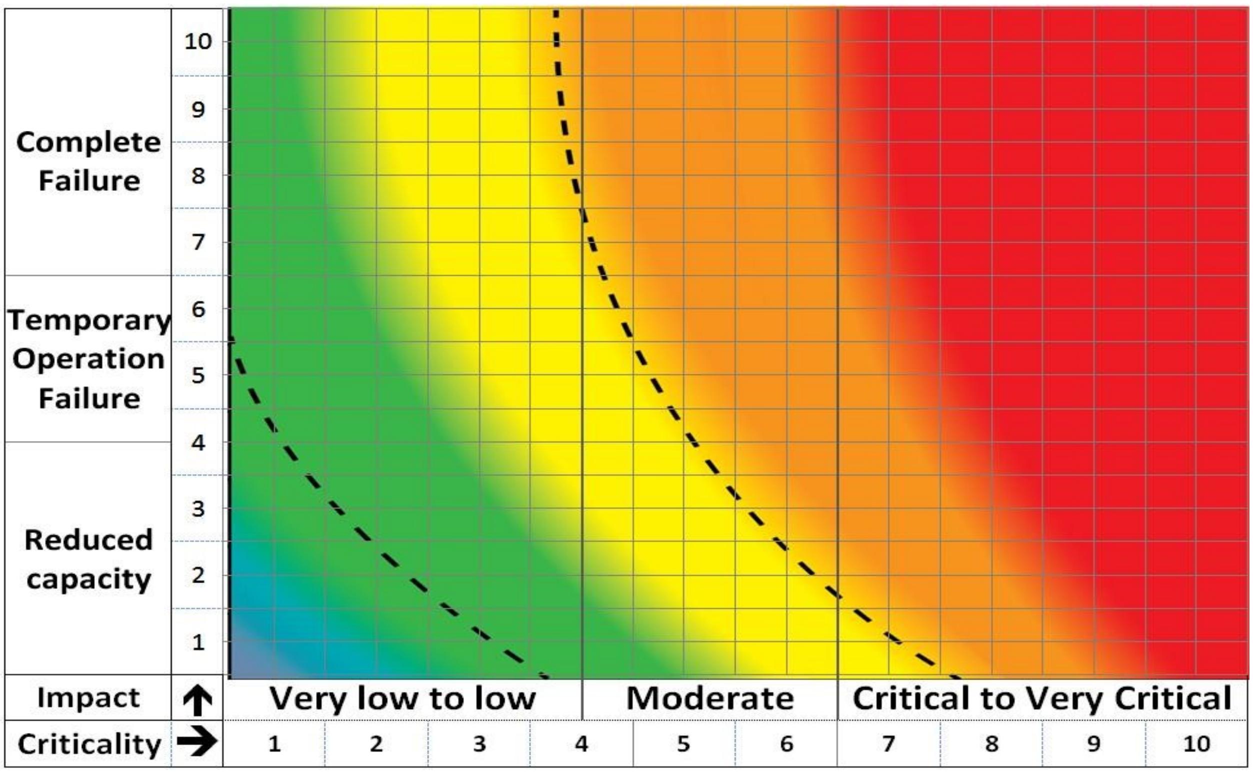
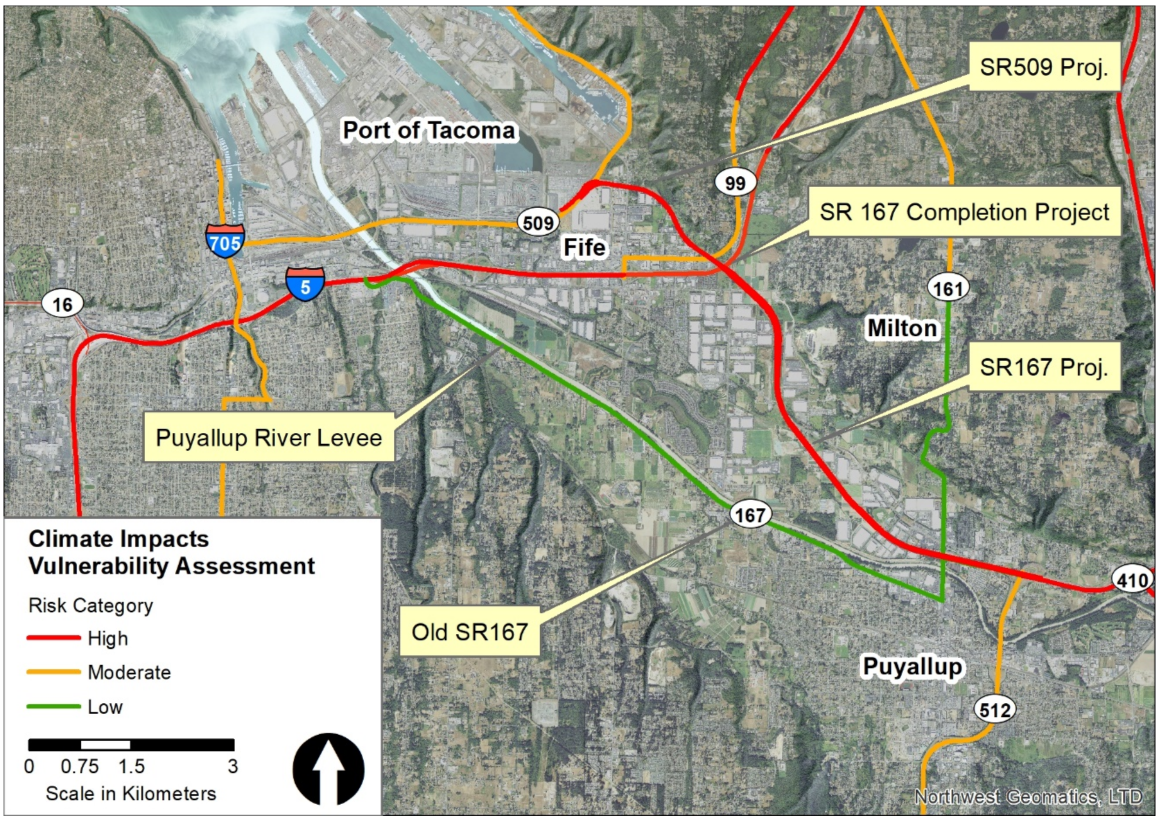


Figure 8. WSDOT CIVA "Heat Chart". Note that almost any impact to a critical segment of highway results in a "High" rating.

For example, in the SR167 Completion Project area, lanes of I-5 and SR99 flood under existing conditions causing temporary operational impacts to the system. With increased severity of storms and rising sea level the frequency of impacts may increase, the duration of impacts may increase, and the severity of impacts may change from operational to structural. In the CIVA, it was assumed that the impact would occur with certainty. A greater understanding of the probability of impacts would be necessary for evaluating segments of highways or specific assets if an existing concern was not identified.

It is important to note that while WSDOT assigned criticality scores and impact scores as part of the CIVA analysis during the workshops, WSDOT only presented the impacts scores in the resultant report. The "Criticality" scores and other detailed data from the workshops are found in the supporting CIVA materials. As part of this pilot study, the impact and criticality scores were combined, as shown in Figure 8, to arrive at the "Risk" category shown in Figure 9 to parallel the process in the Quickscan.

Implementation of the SR167 Completion Project will reduce the likelihood of flooding from Hylebos Creek at the locations where it currently floods adjacent roads. Consequently, those areas would have a reduced impact score (moderate), similar to the I-5 corridor, although the overall risk score would remain the same as the rating is driven by the criticality of those highway segments. The new segments of the SR167 Completion Project warrant a "High" risk rating even though they are being designed to accommodate flooding and the impact scores will be very low; as shown in Figure 8, the criticality of the highway segments drives the rating.



Highway Segment	SR99	SR161	Old SR167	SR167	SR167 Proj.	SR509	SR509 Proj.	I705	I5
Risk Category	Mod.	Low	Low	High	High	Mod.	High	Mod.	High

Figure 9. WDOT CIVA Risk Categories

Step 5 Prepare for Workshop 3

This step consists of a desktop study to make a synopsis of the previous workshops and desktop studies. In the Quickscan examples, this was accomplished by preparing risk maps using GIS.

Before preparing the maps, any outstanding data issues should be resolved. Outliers present in the scoring produced in Workshop 2 should be examined. If some workshop participants are consistently answering the questions different from other participants, it should be investigated whether these estimates need to be retained, changed, or removed, by consulting with the specific participant.

Does the scoring make sense? For example, if the intensity of a certain climate variable is likely to increase due to climate change, the related threats should have been scored larger or maybe remain the same as in existing conditions but cannot be scored lower. Also, the consequences generally should increase with increasing road criticality.

There was not a parallel step in the FHWA Framework, however this is part of the continuous feedback looping that is described in both the FHWA Framework and ROADAPT approaches.

In the WSDOT CIVA process, all the scoring decisions were made as a group and scoring disparities were discussed by the group.

Step 6. Workshop 3

The main objective of this workshop is to determine an action plan based on the previous results and factors such as urgency and expected impact on life span of the infrastructure evaluated. At this workshop, the participants:

- Review and confirm previous results
- Determine unacceptable risk(s); which threats require action?
- Determine action plan
- Prioritize actions

The purpose of Quickscan is to gain preliminary insight into the risks due to climate change. The level of detail of the risk assessment in previous steps is probably not enough to identify the specific measures that need to be taken to address those risks. The results of applying Quickscan include an action plan that should provide enough direction so that decisions made in the future result in infrastructure becoming adapted to climate change.

The results of Quickscan are adequate if they lead to adoption of an adaptation strategy even if the strategy needs to be analyzed in more detail at a future date. The ROADAPT overview of adaptation measures and guidelines on choosing a strategy are helpful in developing a strategy.

This step is comparable to the FHWA Framework: Step 4 Integrating Vulnerability into Decision Making. The WSDOT CIVA analysis did not recommend specific action items for each segment of highway, rather it set forth a process for further evaluation in corridor planning studies, project development, and environmental review, which is an acceptable strategy under ROADAPT.

The Quickscan guidance examples were more project-focused, rather than system-focused, wherein the actions have greater impact on design decisions for projects under development.

Generally, appropriate resilience adaptation actions or strategies are based on the scale of the project. For systemwide analyses, actions may be oriented to future evaluation processes as was done with the WSDOT CIVA project.

Step 7. Analysis of results and reporting

Although the Quickscan guidance lists this step in the introduction, it does not provide any details about what this step entails. However, based on the other guidance provided, the intent is to make the information available to the public and other stakeholders so that informed decision-making takes place with respect to climate change effects and the vulnerability of the infrastructure. As discussed previously the Quickscan tool is the starting point for more detailed analysis, providing stakeholders with a common basis for more detailed discussion and analysis.

WSDOT's CIVA is similar, in that the resultant report provides a starting point for discussion and more detailed analysis on a project-by-project basis.

It is simple to populate a table with appropriate adaptation actions, but actions may have long-term consequences or expenses. However, it is necessary to get buy-in from all stakeholders for the selection and prioritization of future actions. WSDOT's CIVA was completed without external stakeholder input, which further illustrates that it is a starting place for communication with other stakeholders.

Tools like ROADAPT provide an example for how stakeholders could be brought into the discussion about future actions. The SR167 Completion Project started some early discussions about the best available climate science for sea-level rise and potential future precipitation patterns in the project area. The pilot project tour and site visit also helped expand the discussion to include local government and port representatives. Going forward, there are likely to be opportunities to discuss long-range planning in a coastal environment amongst different stakeholders not only near the SR167 Completion Project, but everywhere in the state where a highway is near the coast or provides access to a coastal community.

As the SR167 Completion Project links freight movements to and from the Port of Tacoma on Commencement Bay to I-5 and industrial areas to the east, one must consider the long-term sustainability of the port and associated infrastructure and the cities of Tacoma and Fife. As a marine port, the Port of Tacoma's infrastructure is subject to risks due to rising sea levels. In the short-term, the Port of Tacoma and the local community may be able to accommodate infrequent flooding during extreme tidal conditions coupled with storms that have temporary operational impacts. As sea level rises, the frequency of flooding events will increase. At some time in the future, the impacts will become regular and the Port of Tacoma, local governments, and the private sector will need to act to maintain a viable seaport. What will those actions be and how will they influence the highway system?

Adaptation strategies and investments made by the Port of Tacoma, the other transportation providers (rail) and the cities may have an impact on the highway system. If the Port of Tacoma, the railroads, the local municipalities, and WSDOT do not have the same vision moving forward, WSDOT's highway infrastructure may not provide the desired function throughout its service life or it may need expensive retrofits to accommodate the adaptation actions of others. ROADAPT, the FWHA Framework, and by extension WSDOT's CIVA provide a starting point for coordinating these necessary adaptation plans.

Associated FHWA Assessment Tools

VAST

The FHWA VAST tool aims to determine the most vulnerable assets for one or more climate aspects (stressors) or undesirable events. A spreadsheet-based tool requires input information regarding the exposure, sensitivity, and adaptive capacity of each asset to be analyzed.

WSDOT attempted to use the VAST tool, but immediately found that WSDOT's asset management database is set up linking assets to road miles, not geometric coordinates. Although VAST does not require using geometric coordinates, hazard exposure data, topographic data, and other data to describe adaptive capacity are generally a product of geographic location and elevation. Many of the details of WSDOT's assets are in the form of hard copy design plan sheets and record drawings. WSDOT has been going to great lengths to digitally scan and preserve these records in electronic format, but the preserved records are PDF files of scanned images. The individual assets cannot be extracted automatically from these files. To extract the data, the images would need to be georeferenced and the individual features traced over to be cataloged. Although this may be practical for an individual site investigation, it is not practicable on a statewide level.

Although WSDOT has the ability to evaluate the criticality of a highway segment, and can identify stressors that may impact highway segments, in broad terms, without the detailed georeferenced information it is not possible to really assess the sensitivity to a stressor or the adaptive capacity of the asset. For instance, WSDOT has highway segments that traverse floodplains. FEMA-derived base flood elevations are available at many locations in the state highway network, enabling assessment of the sensitivity of the highway to flooding, but we need to know the elevation of the highway and the individual assets to perform that assessment. The asset management database does not include that elevation data, so we cannot flag individual assets that may be vulnerable. Furthermore, FEMA's floodplain maps do not document estimated velocity of the floodwaters, so where we can identify assets subject to inundation, we cannot tell if the highway would just be inundated or potentially damaged by scouring flows during a large flood.

The VAST tool is useful for asset management planning, but at the moment WSDOT's assets are not adequately cataloged to make effective use of the tool.

CMIP5 Climate Data Processing Tools

WSDOT found FHWA's tools for processing downscaled CMIP data useful, especially for identifying regional trends. Although useful for planning, the precipitation data is not suitable for engineering design of stormwater infrastructure. It may be a useful indicator to evaluate stormwater runoff volumes for systems that require runoff flow control. In general, these types of engineering calculations are made based on sub-hourly time-step precipitation records, so the daily data available in the CMIP program, consequently, is not suitable for design of those facilities.

Although the air temperature is well regulated in the SR167 Completion Project vicinity due to the location on the Puget Sound, temperature data may be useful in other parts of the state for designing pavement expansion joints and specifying asphalt mixes that will perform well during their service life in the future.

Temperature data in conjunction with precipitation data is useful to assess potential for wildfire, rain on snow events, landslides, and other stressors. Since WSDOT became involved in this pilot project, the Climate Impacts Group at the University of Washington has used the same downscaled CMIP data to develop numerous tools and has provided them on the internet for all users. Consequently, in Washington State the CMIP tools may be redundant.

HEC17

FHWA's Hydraulic Engineering Circular 17 (HEC17) (FHWA 2016) provides guidance with respect to extreme precipitation events, climate change, and related impacts on highways in riverine floodplains. The purpose of the document is to provide guidance needed to quantitatively describe risks in light of non-stationarity (i.e., change over time in the probability of a certain event), primarily associated with climate change. In conventional engineering practice, design analysis assumes an event based upon a simple extrapolation of past observations, assuming future behavior will be similar to that experienced in the past, such as the notion of a "100-year" (1 percent annual probability of exceedance) flood event. However, with the realization that climate change is altering the frequency (recurrence interval) of floods of a given magnitude, it has become necessary to characterize the time-dependency of flood hazards.

HEC17 also puts emphasis on two key terms for analysis of hazards and risks that address non-stationarity: design life and service life. Design life is a reference period over which a project feature is expected to meet a particular service objective. Service life is the actual duration that project features provide a given service, often longer than the design life.

For the SR167 Completion Project, WSDOT revisited the hydrology information used as the basis of the hydraulic design. WSDOT used the CMIP5 tool described previously and reached out to the University of Washington Climate Impacts Group and Washington State University researchers regarding downscaling of climate data for development of IDF curves. The CMIP5 data indicated an increased frequency of days with extreme precipitation and other regional climate assessments suggest that extreme events will increase in magnitude in the Puget Sound region in the future.

Local flooding on Hylebos Creek and Wapato Creek that cross the SR167 Completion Project corridor and pluvial flooding on the highway is related to shorter duration, high intensity precipitation events embedded within larger storm systems. Demissie (2016) found that in the Seattle-Tacoma area the IDF curves in use by WSDOT are conservative compared to the predicted future conditions. Consequently, it was determined that the Hylebos Creek hydrologic model previously developed for the project assuming future watershed "buildout" conditions (with application of current stormwater management standards) is appropriate for design of the stormwater infrastructure as well as assessing local flooding for the design life of the project.

HEC17 focuses on riverine flooding, which does not accommodate sea level rise as a compounding source of non-stationarity at the SR167 Completion Project site. The downstream (western) end of the SR167 Completion Project is close to Commencement Bay, which is part of the Puget Sound estuary. Thus, HEC17 guidance cannot completely address design considerations for the project's long-term resilience to anticipated sea level rise.

HEC17 is helpful for WSDOT project designs considering non-stationarity processes. It is important to consider differences in the projected design life and service life to address the concepts of non-stationarity. For project locations where sea level rise is a compounding source of non-stationarity, additional analyses not covered in HEC17 will be necessary.

HEC25 Vol2

The focus of FHWA's Hydraulic Engineering Circular 25 Second Edition (HEC25 Vol2) is on roads near the coast that are always, or occasionally during storms, influenced by coastal tides and waves. A primary goal of HEC 26 Vol2 is the integration of coastal engineering principles and practices in the planning and design of coastal highways. This document provides an excellent overview of issues to consider for coastal engineering on a nationwide level, but it is lacking information for Pacific Ocean coastlines and associated estuaries. The guidance focuses on storm surge, which has greater applicability to the Atlantic and Gulf coasts of the U.S. Because of the prevalence of extreme tides on the Pacific coast, surge is only a minor component of coastal inundation and erosion in proximity to WSDOT's highway network. As pointed out in the document, a "total" tide method including wave run up is typically used in the region.

Because of the extreme variability in the Puget Sound bathymetry and wind patterns, most agencies, including WSDOT, are prepared to only do a Level 1 analysis for storm or tsunami damages, which in the most simple terms consists of adding sea level rise to existing hazard maps. A Level 1 analysis was done for the SR167 Completion Project (Page 2016), where various levels of sea level rise added to FEMA flood hazard maps and USGS tsunami inundation maps and the resulting inundation areas were mapped with the best available topographic information. Because the SR167 Completion Project does not directly abut the coast, the most applicable hazard to the project and adjoining roads is the "coastal weir-flow-damage". This damage mechanism occurs when marine water flows inland over ordinarily dry uplands during an extreme high water (tide or tsunami) event, and encounters and overtops a weir-like feature such as a level roadway surface.

The next levels of analysis require a tremendous amount of data to capture all the processes. Fortunately, the US Geological Survey (USGS) is expanding its CoSMoS program to Washington State. In a few years, detailed information developed by the USGS will be available for greater levels of analysis.

WSDOT hosted a regional meeting to provide input on the update to HEC-25. One of the key takeaways from that meeting and the written feedback was that examples of successful treatments, especially retrofitting existing highways, are needed for our region.

ADAP

The FHWA Adaptation Decision-Making Assessment Process (ADAP) is a tool for planners and designers to account for the increasing role of climate change in the design of civil works projects.

Climate change adds a significant new wrinkle to the science of asset management. Many agencies are struggling with the concepts and the uncertainty of climate change predictions, especially when considering relocation or retreat as a viable adaptation strategy. With highways, much of the asset management planning currently focuses on how repaving needs relate to the need to expand facilities or replace facilities that have exceeded their design life. Relocation or abandonment of the highway corridor is extremely rare.

ADAP is intended to be a risk-based tool to aid decision makers in determining which project alternative makes the most sense in terms of life cycle cost, resilience, regulatory and political settings, etc.

ADAP provides a framework for generating the information needed to identify preferred approaches to project design based upon costs and benefits in terms of life cycle cost, regulatory environment, and resilience. ADAP, like the FHWA Framework and the ROADAPT model, is versatile in that it can be used to evaluate individual assets or systems to assess existing assets for their sensitivity to projected climate changes or for the design of new infrastructure projects.

For new projects, ADAP is intended to be applied during the planning stage of project development to provide the maximum opportunity to explore project alternatives. However, the effort required to prepare engineering cost estimates with sufficient detail and accuracy to adequately develop a valid cost/benefit analysis that weighs future climate effects at the planning stage of project development can be a challenge.

Conclusions

Both the FHWA Framework and the ROADAPT Quickscan procedure provide a comprehensive set of tools that can be used to evaluate the vulnerability of infrastructure assets, and both allow analysis at scales ranging from infrastructure systems to individual assets.

Although there are slight differences in the approaches, the results are comparable. WSDOT found that application of the ROADAPT process did not bring to light new impacts or issues that had not already been evaluated as part of the SR167 Completion Project.

The FHWA Framework and tools yield primarily tabular information whereas the ROADAPT tools tend to produce more graphic results, although ROADAPT also generates several tables as well. While working through these tools, WSDOT noted that the graphical presentations in the ROADAPT examples were more powerful for public, stakeholder and decision maker presentations, whereas the tabular information was better shared amongst project designers and asset managers.

WSDOT's pilot study implementation of the FHWA Framework, known as Climate Impacts Vulnerability Assessment (CIVA), was similar in character to the ROADAPT Quickscan process in that it allowed a relatively coarse level of assessment of climate impacts on highway assets and sets the stage for future stakeholder engagement and analysis to facilitate design.

Finally, WSDOT acknowledges the excellent information exchange that was made possible through this pilot study and collaboration with the Netherlands and FHWA.

With regard to the SR167 Completion Project, WSDOT's planned restoration of a tidally-influenced creek in the project corridor represents an effective climate adaptation measure. The project design demonstrates a nature-based solution that reconnects creeks to their historic floodplains, improves salmon habitat, and manages stormwater flows from the new highway. Importantly, the proposed stream and floodplain restoration within the project area will reduce flood risks not only to SR167, but also to Interstate 5 and the surrounding community.

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